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The dynamic role of soil phosphatase enzymes in sustainable crop growth and links with yield

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PhD Thesis

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Saber de tot està mal vist. Només l’especialització desperta respecte. Malament, perquè l’especialització no és l’objectiu de la ciència, sinó la limitació dels científics.

Ramon Folch (Barcelona, 1946)

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1. General abstract

Agricultural and livestock production cover more than a third of the Earth's land surface and are essential to food supply. Soil enzymes play a critical role in the transformation of elements and compounds in soil. In particular, acid (ACP) and alkaline (ALP) phosphomonoesterases collectively known as APase are crucial for alleviating phosphorus (P) deficiency in plants. Phosphorus is a vital macronutrient for crop productivity, and while plants absorb P salts, mainly orthophosphate, from the soil, the primary source of P is organic material. APase enzymes are important because they can transform non-assimilable P into assimilable forms. Many articles have investigated APase activity responses to various factors such as climatic effects, soil properties, and pollution across different ecosystems. However, this is the first attempt to globally consider the role of these factors in agricultural soils assessing all the published studies since 1977.

The aim of Chapter 1 was to summarize the relationships between various factors affecting APase activity in agricultural soils and to identify knowledge gaps. To achieve this, we reviewed research papers, reviews, and meta-analyses published from 1977 to December 2022 in several databases. We used vote counting to categorize the direction of the effect as positive, negative, or neutral. The results indicated that APase activity was strongly linked to soil pH and positively influenced by clay content, organic matter, microbial biomass carbon (C), and nitrogen (N). Practices that promote soil health, such as using balanced organic fertilizers, maintaining optimal soil moisture, reducing tillage, rotating crops, and incorporating beneficial plant microbes, can boost APase activity. However, the relationship between APase activity and crop productivity remained unclear due to limited research. Additionally, gaps in knowledge were identified concerning meso-macrofauna and essential plant nutrients like potassium (K), nutrient ratios, and the synergistic effects of various factors on APase activity. Thus, a better understanding of how APase activity promotes P assimilation in the plant-soil or plant-microbiota ecosystem could be key to improving crop productivity.

Chapter 2 highlighted that cropland soils, subjected to more intensive human disturbance and receiving fewer plant residues, root exudates, and senescent leaves than natural and semi-natural ecosystems, cause management-induced changes in APase activity due to the decline in P and C cycling. This chapter compiled a global database of APase activity in cropland areas (between 1977 and 2022) to examine the effects of climate variables, species family classification and management practices on ACP and ALP activity as well as their relationship with yield. The results showed that higher temperatures decreased ACP and ALP activity, but higher precipitation increased only ACP activity. ALP activity was negatively affected by the increase of precipitation and temperature. The crop species greatly influenced APase activity suggesting that deeper investigation into their genotype, physiology, and morphology would be crucial for more targeted enzyme responses in particular crop species. ACP and ALP activity showed varying trends depending on cropping system design and irrigation practices, with ACP activity influenced by fertilization, cropping

system design, and irrigation. Meanwhile, ALP activity was more influenced by the interaction between fertilization and tillage, highlighting the link between microbial response and nutrient input. Furthermore, crop yield was strongly positively influenced by APase activity, suggesting that a deeper understanding of enzyme responses could improve crop productivity. This could pave the way for future sustainable crop growth and better cost-benefit ratios.

Chapter 3 focused on the effect of organic fertilization on soil ACP and ALP activity, P availability, and forage yield in South Tyrol (NE Italy) mountain permanent meadows. Grassland comprises a significant part of Europe's agricultural landscape, covering more than a third of its land area. It plays a vital role in livestock farming by providing forage for herbivores, and it also offers crucial ecosystem services like erosion control, water management, and water purification. When used for forage production, grassland can support both adequate yield and forage quality while preserving biodiversity. Permanent meadows are one of the most common forms of agriculturally managed grassland in Europe, typically harvested by mowing and not renewed for at least ten years. The study employed a split-plot design with three experimental factors: initial vegetation class (moderately species-poor or moderately species-rich), manure type (slurry, farmyard manure, and a combination of farmyard manure and manure effluent), and N fertilization input (0, 55.5, and 111 kg N ha^{-1} yr^{-1}). Soil samples were collected from the top 10 cm before the last cut in the summer of 2022. The results indicated that the combined use of farmyard manure and manure effluent caused a decrease in ACP activity with increased N input, while ALP activity remained unaffected. This suggests that organic N input at this sampling stage did not increase APase activity. Additionally, ACP activity was higher in species-rich (C2) meadows compared to species-poor (C1) meadows, suggesting a correlation with species diversity and management practices. Moreover, ACP and ALP activity were influenced by pH (negative for ACP and positive for ALP), and both were negatively affected by soil moisture, emphasizing their sensitivity to changing soil conditions. ALP activity was positively correlated with total organic carbon (TOC) levels and the Shannon diversity index of plant communities at the time of the first cut. Soil available P was influenced by several factors, including pH, TOC, soil moisture, and K_2O content, but also by organic N input, especially when using farmyard manure, which provided the most significant P input. The yield from the last growth cycle was positively influenced by organic N input but negatively influenced by TOC, with no significant effect from APase activity. However, annual yield was positively influenced by organic N input and was higher in C1 than in C2 meadow class. Further studies might reveal if APase activity plays a role in specific stages of grass growth, and repeated sampling throughout the growing season would help test this hypothesis.

Overall, these chapters emphasize the role of ACP and ALP activity in agricultural productivity and highlight the need for further research to understand how management practices influence APase activity, P availability, and crop yields.

2. Resum general

La producció agrícola i ramadera ocupa més d'un terç de la superfície terrestre del planeta i és essencial per a subministrar aliments. Els enzims del sòl juguen un paper important en la transformació d'elements i compostos en el sòl. En particular les fosfomonoesterases àcides (ACP) i alcalines (ALP) i ambdues anomenades APase, són crucials per a alleujar la deficiència de P en les plantes. El P és un macronutrient vital per a la productivitat dels cultius. Les plantes absorbeixen sals de P, principalment ortofosfat, del sòl tot i que la font principal de P resideix en materials orgànics. Per aquest motiu, l'activitat de les APase juga un paper vital en l'agricultura ja que tenen la capacitat de transformar el P no assimilable en assimilable per les plantes. Nombrosos articles han investigat la resposta de la seva activitat a diversos factors com ara les variables climàtiques, les propietats del sòl i la contaminació en diferents ecosistemes. No obstant això, aquest és el primer intent de considerar globalment el paper d'aquests factors en els sòls agrícoles, avaluant tots els estudis publicats des de 1977.

L'objectiu del Capítol 1 era resumir la direcció de les relacions entre diversos factors influents en l'activitat de les APase en sòls agrícoles i identificar aspectes que els mancaria investigació. Per fer-ho, es va realitzar una cerca d'articles d'investigació, revisions i metaanàlisis publicats des de 1977 fins a desembre de 2022 en diverses bases de dades. Es va usar un recompte de vots per categoritzar la direcció de l'efecte com a positiu, negatiu o inexistent (neutre). Els resultats mostraren una forta relació entre l'activitat de les APase i el pH del sòl, influïda positivament pel contingut d'argila, la matèria orgànica, el C de la biomassa microbiana i el N. L'adopció de pràctiques de sòl conservadores com ara l'ús equilibrat de fertilitzants orgànics, mantenir els nivells òptims d'aigua del sòl, la reducció de la llaurada, la rotació de cultius i l'ús de microorganismes vegetals beneficiosos poden augmentar l'activitat de les APase. No obstant això, la connexió entre l'activitat de les APase i la productivitat dels cultius va quedar per determinar a causa dels pocs estudis relacionant aquest aspecte. En aquesta investigació va quedar pendent de resoldre la veritable relació de l'activitat de les APase amb la meso-macrofauna i nutrients essencials per la planta com el K, les ràtios entre nutrients i els efectes sinèrgics de diversos factors. Una millor comprensió de com l'activitat de les APase fomenta l'assimilació de P a l'ecosistema planta-sòl i/o planta-microbiota es considera crucial per millorar la productivitat dels cultius.

El Capítol 2 va emfatitzar que les terres llaurables, que experimenten més pertorbacions humanes i reben menys inputs per exemple de residus vegetals o exudats de les arrels i fulles en descomposició, comparats amb els sòls d'ecosistemes naturals i semi-naturals, causen canvis induïts pel maneig a l'activitat de les APase degut a una disminució en el cicle del P i del C. En aquest Capítol, es va fer una compilació de la base de dades global de l'activitat de les APase en terres llaurables (entre 1977 i 2022), amb l'objectiu d'examinar els efectes del clima, les espècies classificades per famílies i la gestió a l'activitat de l'ACP i l'ALP, així com la seva relació amb el rendiment. Els resultats obtinguts van demostrar que les altes temperatures redueixen l'activitat de l'ACP i l'ALP però que l'alta precipitació només afavoria l'activitat de l'ACP. L'activitat de l'ALP estava negativament afectada per l'increment de la precipitació i la temperatura. Les espècies cultivades van influir considerablement en la resposta de l'activitat de les APase, no obstant això, una investigació més profunda sobre el seu genotip, fisiologia i morfologia seria crucial per saber més sobre les respostes dels enzims en referència a les espècies. L'activitat de l'ACP i l'ALP va respondre diferentment en funció del disseny del sistema de cultiu i les pràctiques d'irrigació, ja que l'activitat de l'ACP estava particularment influenciada per diverses interaccions relacionades amb la gestió com la fertilització, el disseny del sistema de cultiu i la irrigació. Mentrestant, l'activitat de l'ALP estava influenciada per la interacció entre la fertilització i la llaurada, connectant la resposta microbiana a l'entrada de nutrients. A més, el rendiment dels cultius es veia influenciat positivament per l'activitat de les APase, suggerint que un millor coneixement de les respostes dels enzims podria incrementar el rendiment. Això podria obrir el camí per a un futur creixement sostenible dels cultius i millors relacions cost-benefici.

El Capítol 3 es va centrar en l'efecte de la fertilització orgànica sobre l'activitat de l'ACP i l'ALP del sòl, la disponibilitat de P i el rendiment del farratge en prats permanents de muntanya del Tirol del Sud (NE Itàlia). Els prats abasten una part substancial del paisatge agrícola d'Europa, ocupant més d'un terç de la seva superfície terrestre. Juguen un paper crucial en els sistemes ramaders al subministrar aliments per als herbívors i a més a més, proporcionen serveis ecosistèmics essencials com ara el control de l'erosió, la gestió de l'aigua o la purificació de l'aigua. Quan els prats s'usen per la producció de farratge proporcionen un doble propòsit; el de garantir un rendiment i qualitat del farratge adequats mentre que milloren o preserven els nivells de biodiversitat. Els prats de dall permanents són una forma d'utilitzar els prats mitjançant dalls en els darrers cinc anys i que no s'han renovat completament durant deu anys o més. L'estudi va emprar un disseny de parcel·les dividides amb tres factors experimentals amb una parcel·la principal aleatoritzada dins de tres àrees d'estudi amb tres factors en el disseny experimental: la classe de vegetació inicial (moderadament pobra en espècies o moderadament rica en espècies), el tipus de fertilitzant orgànic aplicat (purí, fems o una combinació de fems i efluent de purí (amb menys proporción d'orina)) i l'entrada de N orgànic fixada a 0, 55,5 i 111 kg N ha^{-1} any^{-1}. Es van recollir mostres de sòl dels primers 10 cm abans de l'últim dall a l'estiu de 2022. Els resultats van mostrar que l'ús combinat de fems amb efluent de purí causava una disminució de l'activitat de l'ACP amb l'augment de N orgànic, mentre que l'activitat de l'ALP va romandre inalterada. Això suggeria que una entrada orgànica de N en aquest moment no implicava un augment de l'activitat de les APase. A més, es van trobar valors d'activitat de l'ACP més alts en prats categoritzats com C2 en comparació als categoritzats com C1 suggerint una correlació entre el nombre d'espècies i la freqüència del dall. En paral.lel, tant l'activitat de l'ACP com la de l'ALP estaven influenciades pel pH segons la seva classificació (negativament per a l'activitat de l'ACP i positivament per a l'activitat de l'ALP) i les dues activitats estaven negativament influenciades per la humitat del sòl, emfatitzant la seva sensibilitat als canvis de les condicions del sòl. L'activitat de l'ALP rebia una influència positiva dels nivells de TOC i de l'índex de diversitat de Shannon de les comunitats vegetals avaluat abans del primer dall. El P disponible del sòl estava afectat positivament per diferents paràmetres del sòl com ara el pH, el TOC, la humitat del sòl i el contingut de K_2O, així com per l'augment de l'entrada orgànica de N, però especialment quan s'utilitzaven fems, que proporcionaven una major entrada de P. El rendiment del prat de dall en el moment del mostreig va ser influït positivament per la entrada orgànica de N però negativament pel TOC mentre que l'activitat de les dues APase no en sortia representada. No obstant, el rendiment anual va ser influït positivament per l'entrada orgànica de N i va ser més alt en C1 que en C2. Més investigacions al respecte podrien indicar-nos si l'activitat de l'activitat de les APase juga un paper important en altres etapes específiques del creixement del farratge i un mostreig repetit al llarg de tot el procés de producció podria resoldre aquest dubte.

En general, aquests capítols posen de relleu el paper de l'activitat de l'ACP i l'ALP en la productivitat agrícola i destaquen la necessitat de més investigacions per entendre com les pràctiques de gestió influeixen en l'activitat de les APase, la disponibilitat de P i els rendiments dels cultius.

3. General introduction

3.1 Global view

Soil serves as the foundation for the growth of plants, grasses, forests, and crops. Additionally, it acts as the medium through which rivers flow and provides habitats for animals. Soil plays a crucial role in (i) provisioning services (direct or indirect food for humans, fresh water, wood, fiber, and fuel); (ii) regulating services (regulation of gas and water, climate, floods, erosion, biological processes such as pollination and diseases); (iii) cultural services (esthetic, spiritual, educational and recreational); and (iv) supporting services (nutrient cycling, production, habitat, biodiversity) (Adhikari and Hartemink, 2016). The interaction of physical, chemical, biological and biochemical properties is essential for maintaining soil health (da Silva, 2019).

One of the significant natural cycles boosting ecosystem productivity is the P cycle which is among the slowest biogeochemical cycles on Earth. Although P is vital for plants and animals, its transference from rock through soils to the oceans occurs at an extremely slow pace (over 500 million years) (Van Mooy et al., 2015). In natural terrestrial ecosystems, P usually cycles closely between soils and living organisms (Smil, 2000), and explained by several factors such as the limited erosion under dense vegetation cover, the retention of orthophosphate anions by iron and aluminium oxy-hydroxides, the low solubility of calcium-phosphate compounds, and the absence of a gaseous phase. As a result, the processes of immobilization and mineralization between inorganic and organic forms are generally more significant than transport processes (Nannipieri et al., 2011; Tiessen et al., 2011). Nonetheless, in agroecosystems, human intervention disrupts the P cycle, leading to open and intensified transport processes. While the cycling of P may have been insignificant in the past, it has now become crucial in modern times since human activities, particularly mining and the widespread distribution of P through fertilizers, animal feeds, and detergents, have significantly interrupted the recycling system from aquatic to terrestrial environments (Tiessen et al., 2011). Sustainable soil management practices, such as crop rotation, cover cropping, reduced tillage, and organic amendments which help to maintain soil structure, fertility, and biological diversity (Redlich et al., 2020) align with the principles of a circular economy, where resources are reused, recycled, and regenerated. By preserving soil health, these practices enhance nutrient cycling, including P availability, and reduce the need for external inputs like mineral fertilizers (Brodt et al., 2011). The indiscriminate use of P fertilizers globally has led to a significant increase in its concentration in soil, eventually causing detrimental effects on ecosystems. Phosphorus losses from land to freshwater bodies result in eutrophication (Tiessen et al., 2011), leading to increased algal blooms, a major threat to water quality, biodiversity, and human and environmental health (Brownlie et al., 2021). Furthermore, it is crucial to acknowledge that mineral P reserves are finite and contains heavy metals and trace elements which should be minimized in agricultural use (Juma and Tabatabai, 1988). Consequently, P must be treated as a finite resource and prioritized for recycling (USGS, 2021; Tiessen et al., 2011).

To effectively manage P for economic plant production, ecosystem services, and environmental protection, it is imperative to comprehend the various forms of P present in soils and how these interact with the soil and the broader environment. The process of P cycling within the soil, transitioning from soil to plants and back again, is illustrated in Figure 1. Humans, plants, and animal wastes deposit soluble forms of organic P in the soil which are not readily available for plant growth because this soluble P must be in inorganic form. The concentration of soluble inorganic forms of P in the soil can increase with mineral inputs. The dominant form of inorganic P depends on soil pH; for instance, in alkaline and calcareous soils, the predominant forms of soil inorganic soluble P are precipitated with calcium, while in acidic soils, is absorbed onto clay and iron-aluminium oxide surfaces and precipitated with iron or aluminium. Soluble inorganic P, which plants can absorb, is subject to losses through leaching, and part of the soluble organic P also experiences losses through runoff or eroded particles.

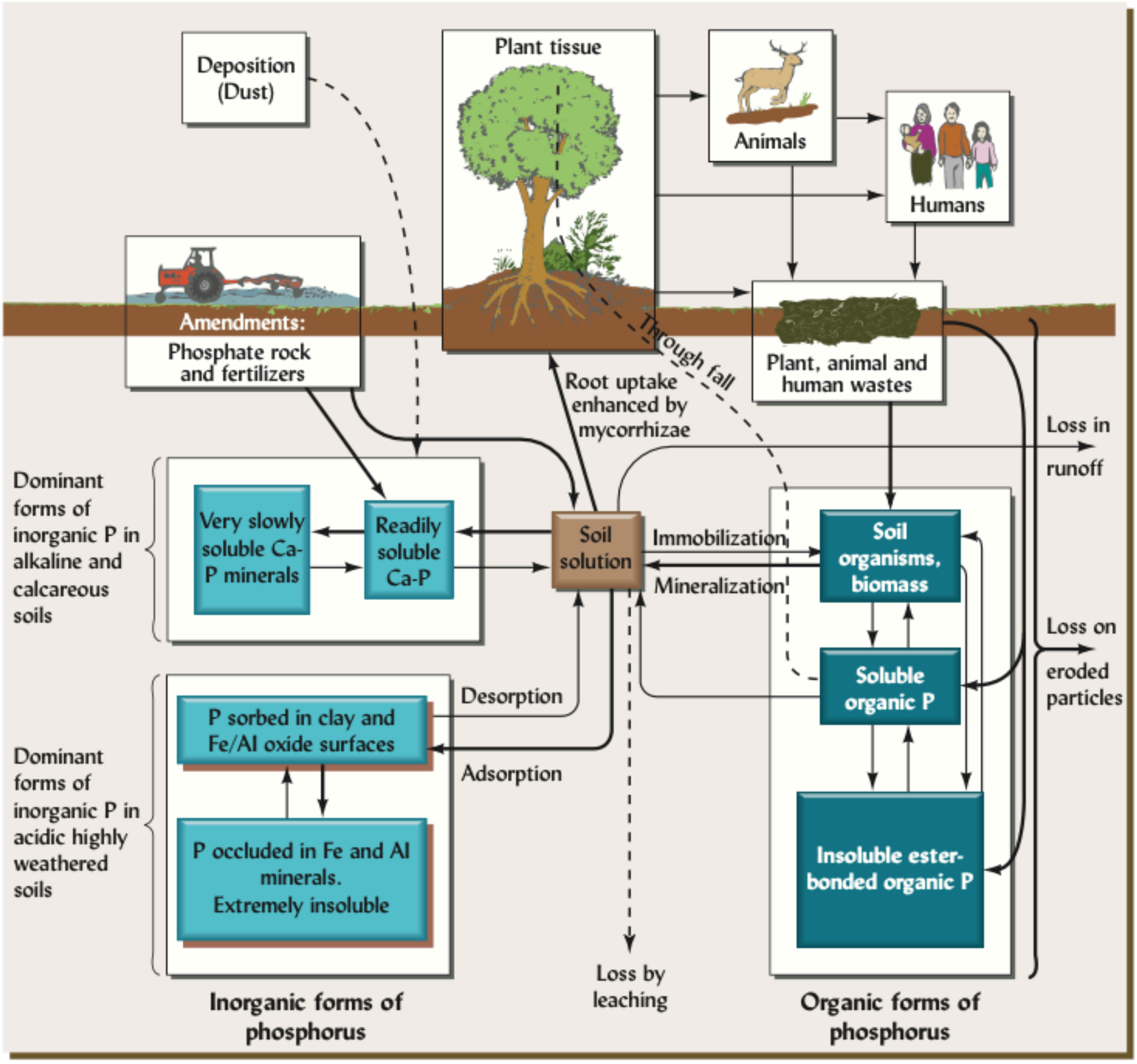

Figure 1. The phosphorus (P) cycle in soils. The boxes denote reservoirs of different P forms in the cycle, and the arrows signify movements and changes among these reservoirs. The three largest white boxes highlight the main categories of P-containing compounds present in soils. In each group, the less soluble and less accessible forms are typically predominant. The thick arrows depict the primary pathways. (Diagram courtesy of Ray R. Weil). Source: Weil and Brady, 2017.

Only about 0.1% of P available from the soil solution is assimilable by plants representing a small fraction of total soil P. Although this might seem low, it can limit primary production in crops and ecosystems (Ghosh et al., 2015). Phosphorus is a vital component of key biological molecules such as DNA, RNA, and ATP (adenosine triphosphate), which are essential for energy transfer and storage within plant cells (Malhotra et al., 2018). These molecules are involved in fundamental processes like photosynthesis, respiration, and the synthesis of proteins and enzymes necessary for plant growth and metabolism. Furthermore, P is integral to the development of robust root systems in plants (Santoro et al., 2024) since adequate P levels promote root growth and branching, enhancing the plant's ability to absorb water and nutrients from the soil (Niu et al., 2012). This improved nutrient uptake not only supports the plant's immediate growth but also contributes to its resilience against environmental stresses such as drought or nutrient deficiencies (Khan et al., 2023). The availability of inorganic forms of P in the soil ensures that plants obtain this element easily, thereby enhancing their growth. Plant roots only assimilate P when it is dissolved in the soil solution as orthophosphates ($H_2PO_4^-$ or HPO_4^{2-}). The relative proportion of orthophosphates are strongly dependent on the soil pH where the dominant forms of inorganic P in acidic soils are linked the monovalent anion ($H_2PO_4^-$) while alkaline solutions are characterized by the divalent anion (HPO_4^{2-}) (Weil and Brady, 2016). Phosphate ions in soil solution are not only scarce but also largely immobile due to strong reactions with soil particle surfaces and move slowly toward roots via diffusion, impeding P uptake as well as that of other nutrients like zinc and K. For this reason, soil enzymes play a key role in nutrient cycling (Uwituze et al., 2022). Due to limited inorganic forms of P in the soil, the activity of soil P enzymes plays an important and fundamental role remobilizing P; they can cleave the phosphate group from organic compounds (i.e., especially in dissolved organic P) such as in organic matter structures, making P easily available for their reuse by living organisms (Burns and Dick, 2002). Enzyme activities related to the P cycle are sensitive to management practices, with their activity strongly influenced by P stress in soil (Ndakidemi, 2006). Understanding the role of these enzymes can guide optimization of activities in managed soils, with the aim of soil conservation, P recycling, and enhance agricultural sustainability (Adetunji et al., 2017).

3.2 Phosphoric monoester hydrolases

Enzymes have been integral to biological processes for centuries, playing profound roles and proving essential for soil health (Daunoras et al., 2024). Hydrolases represent a class of hydrolytic enzymes frequently employed as biochemical catalysts, utilizing water as a hydroxyl group donor in the process of substrate breakdown, thereby converting large molecules into small fragments (Shukla et al., 2022). Based on enzyme commission number (EC number) hydrolases belong to enzyme class 3 (EC 3) and particularly phosphoric monoester hydrolases (or phosphomonoesterases, phosphatases) cleave the ester bonds and they are categorized with the EC number 3.1. Advancing in the classification, EC 3.1.3 categorizes the hydrolysis of monophosphoric esters with the production of one mole of $H_2PO_4^-$ or HPO_4^{2-} and some examples include alkaline phosphatase (EC 3.1.3.1), acid phosphatase (EC 3.1.3.2), phosphoserine phosphatase (EC 3.1.3.3), phosphatide phosphatase (EC 3.1.3.4) and continuing in this manner, progressing through 110 subcategories (McDonald et al., 2009).

Acid phosphatase (ACP) and alkaline phosphatase (ALP) (both, APase) are a family of enzymes that are widespread in nature thus they can be found in many animals and plant species (Alef and Nannipieri; 1995; Sharma et al., 2014; Bull et al., 2002). The transformation of the soil monoester phosphate (an organic compound containing one phosphate group (PO_4^{3-}) esterified with an alcohol) to phosphate, is carried out by ACP or ALP depending on the soil pH, and therefore associated with the release of an alcohol. The predominant available ions within the pH range considered suitable for most crops are the dissolved forms of plant-available P in the soil solution, mostly $H_2PO_4^-$ or HPO_4^{2-} (Hinsinger, 2001) (Fig. 2).

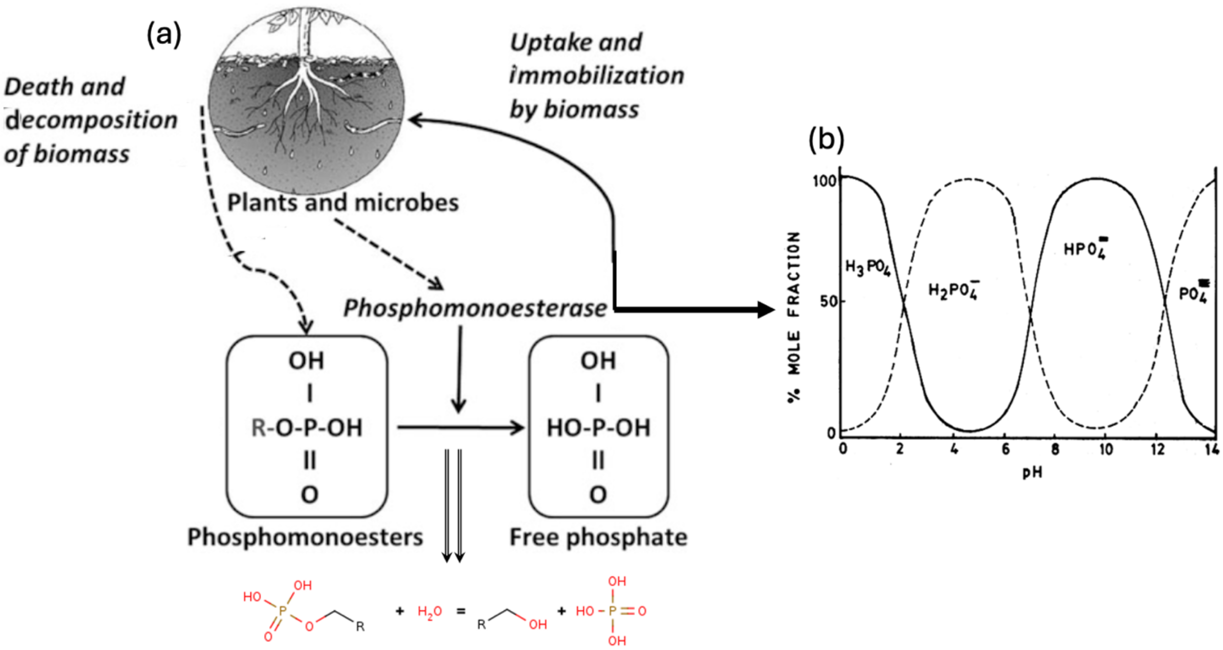

Figure 2. (a) A conceptual model of the turnover of organic phosphorus in the soil, outlining the sequential action of APase; R represent organic properties of P compounds, dashed arrows indicate inputs from plants, residues, and microbial biomass and the hydrolysis reaction is detailed in red (original graphic by Heidi Waldrip and modified by Patrícia Campdelacreu Rocabruna. Source: Waldrip and Acosta-Martínez, 2014) and (b) various forms of orthophosphate in soil solution at different pH levels. Source: Hinsinger, 2001.

Given the multitude of processes and reactions in soils, which frequently involve various forms of inorganic P exhibiting contrasting geochemical behaviours, it is challenging to anticipate the extent and direction (whether positive or negative) of soil P bioavailability response to changes in soil pH (Hinsinger, 2001). However, pH is a crucial factor to consider, with ACP and ALP have pH optima at ≤ 7 and >7, respectively (Nannipieri et al., 2011). Although microbes can produce both ACP and ALP, plants only produce ACP, and fauna only produce ALP (Waldrip and Acosta-Martínez, 2014; Alef et al., 1995). Then, plants, microorganisms and fauna produce extracellular APase to mineralize organic P, emphasizing their important role mainly in plant nutrition (Alef and Nannipieri, 1995).

APase activity is generally higher in soils with low inorganic P content compared to those with high content (Nannipieri et al., 2011), underscoring its importance in soil management practices. Understanding this enzymatic activity can provide valuable information on how management practices, such as fertilizer management, tillage practices, crop species, and soil type, influence soil quality and P cycling (Waldrip and Acosta-Martínez, 2014). As is stated in Dick et al., (1997), APase activity: i) is often closely associated with crucial soil quality parameters such as organic matter, soil physical properties, and microbial activity or biomass; ii) can change much earlier (within 1 to 2 years) than other properties, such as soil organic C, thus offering an early indication of soil quality trajectory with changes in soil management; iii) can serve as an integrative soil biological index reflecting past soil management practices; and iv) involves procedures that are relatively simple compared to other important soil quality properties, such as some physical and biological measurements. Furthermore, measurement of APase activity has the potential to be routinely conducted in environmental laboratories (Tabatabai et al., 1994). Here, special focus will be placed on ACP and ALP activity, which have received the most attention among soil phosphomonoesterases in agro ecosystems. Understanding the importance of measuring APase activity and improving our comprehension of APase's role in the soil depends, among other factors, on the knowledge and use of enzymatic assays to assess ACP and ALP activity.

3.3 Assessing soil phosphatase activity: methodological options

Several approaches have been proposed for assessing APase activity, often differing in the substrate used and the technique employed to measure hydrolysis (Tabatabai and Bremner, 1969). Multiple methods were proposed for estimation of APase activity of soils (Kramer, 1957, Kramer and Yerdei, 1969; Halstead, 1964; Skujins et al. 1967), where the basic difference was the substrate used. For instance, the first three authors used the measurement of phenol released to quantify APase activity following incubation of soil with phenyl phosphate, which is still a commonly used method nowadays. However, this method has low precision due to the instability of the colorimetric reaction used for phenol quantification. Specifically, the blue colour developed by phenol when combined with for instance, Gibbs reagent (2,6-dibromoquinone-chloroimide), is only stable after 30 minutes and lasts 2 hours. Skujins et al. (1967) assayed APase activity by incubation of soil with glycerophosphate and then extracting and measuring the nonreacted ß-glycerophosphate hydrolyzed. This technique, however, was complex, with low precision and high time requirements. This is why Tabatabai and Bremner (1969) proposed the use of p-nitrophenyl phosphate as a substrate for evaluating ACP activity at pH 6.5. With this method, a stable colourless solution is obtained which lasts for 24 hours without changes in its intensity. Moreover, compared with the Gibbs reagent, it does not require a strict control of pH and temperature; the optimum temperature has been found to range from 40 to 60ºC however, the assays are usually carried out at 37ºC. After a few years, Tabatabai (1994) described the method including ALP with pH buffered at 11, and the substrate was changed to disodium p-nitrophenyl phosphate tetrahydrate (pNPP). The method is based on the concentration of a product, para-nitrophenol (pNP), hydrolysed from pNPP by the APase activity. Namely, 1 g of soil sieved (<2 mm) is mixed with toluene, a modified universal buffer (MUB) stock solution (i.e., composed by tris(hydroxymethyl)aminomethane (THAM), maleic acid, citric acid, boric acid, and sodium hydroxide), and pNPP. The MUB stock solution has pH 6.5 for the assessment of ACP activity, and pH 11 for the ALP activity. The solution must be incubated at 37ºC during 1 h, and after the incubation, $CaCl_2$ and NaOH are added. The soil suspension is filtered, the amount of pNP produced is observed as a yellow colour, and the absorbance is read with a spectrophotometer at a wavelength of 400-410 nm. The actual pNP concentration is extrapolated from a calibration curve relating the pNP and absorbance obtained in increasing concentrations of a phosphate salt, which is used to assess the enzymatic activity (expressed in μmol of pNP g^{-1} h^{-1} or mg of pNP kg^{-1} h^{-1}) (Fig. 3).

$pNPP_{sol} + H_2O \longrightarrow pNP + PO_4^-$

1 g soil ↓ **ACP / ALP** - - - - - - - - →

Toluene
Tris(hydroxymethyl)aminomethane (THAM)
Maleic Acid
Citric Acid
Boric Acid
Calcium chloride ($CaCl_2$)
Sodium hydroxide (NaOH)

$$AE = \frac{C}{Pm \times G \times T} \times V$$

C= Concentration of p-nitrophenol (μg/mL)
Pm= Molecular weight of p-nitrophenol (139,11 μg μmol^{-1})
G= Dry soil weight (g)
T= Incubation time (1h)
V= Dilution (if applicable) (mL)
AE = Enzymatic activity (μmol pNP g^{-1} h^{-1})

Figure 3. Simplified reaction of the hydrolysis of pNPP to pNP and APase activity (AE) formula. Source: Tabatabai, 1994; García Izquierdo et al., 2003; Saá et al., 1993.

The use of toluene is controversial. According to Tabatabai (1994), it inhibits microbial growth and the assimilation of enzymatic reaction products. On the other hand, Drouillon and Merckx (2005) suggest that toluene increases microbial cell membrane permeability, facilitating the exchange of substrate and product so it acts as intermediate between extracellular activity solely and total (intra+extracellular) activity. For these reasons, some studies reported that its addition is not necessary because: i) toluene might act as a substrate for microbial biomass growth (Tabatabai, 1994), ii) shaking the solution with toluene could improve the contact between intracellular APase and substrate (Elsgaard et al., 2002), iii) when the substrate solution already has some other non-electroactive substrates which produces an electroactive product then the reaction is extremely high; the solution has an intense yellow coloration because the substrate solution already has some pNP concentration (Stege et al., 2009). For this last reason, Drouillon and Merckx (2005) proposed MUP (4-methylumbelliferyl phosphate) as alternative substrate, especially in soils with high organic matter content and low pH due to the negative effect on ACP activity under high concentration of soil organic matter (Vuorinen and Saharinen, 1996). However, after their study they concluded that variability exists, and the quantity of organic matter content was similarly affecting either using MUP and pNPP.

The addition of $CaCl_2$ can prevent clay dispersion and the extraction of soil organic matter caused by NaOH, since clay dispersion complicates filtration and the dark-coloured organic matter extracted interferes the colorimetric analysis. Moreover $CaCl_2$-NaOH treatment serves to stop the activity of APase activity, generate the yellow colour used for estimating the pNP, and ensure quantitative recovery of pNP from soils (Tabatabai, 1994). APase activity can indeed be measured within all types of soils, regardless of their pH (whether acidic or alkaline). The main difference between assays lies in the pH of the buffer used, which is adjusted according to the optimal pH range of each APase activity, either using wet and dry soil (Acosta-Martínez and Tabatabai, 2001; Alef and Nannipieri, 1995; Brohon et al., 1999; Gianfreda et al., 1996). Tabatabai, (1994) and Burns et al., (2013) examined the disadvantages and advantages of each approach, proving that in air-dried soil samples, the values of ACP activity increased, and ALP activity decreased comparing to wet soil. The wet approach, commonly used for soil samples post-short-term storage, involves maintaining at field moisture levels and promptly storing it at 4ºC. Enzyme assays measure potential rather than actual enzyme activities due to variations in assay conditions compared to those occurring in situ. These conditions include optimal pH, temperature, substrate concentration, buffer presence, soil slurry, and shaking, which may not precisely mimic their natural environment (Nannipieri et al., 2011). However, according to the current literature, there has been little focus on the specific enzymes that cleave pNPP as a substrate or on correlations between the hydrolysis of pNPP and natural substrates (Joner et al., 2000) which would require further research on the matter.

3.4 Methodology of the thesis

Since 1977, numerous articles published in journals have explored the enzymatic activity of APase. Several quantitative studies have investigated how APase activity responds to various factors, including climatic effects (Margalef et al., 2021; Sun et al., 2020; Meng et al., 2020; Gao et al., 2020), soil properties (Margalef et al., 2017), fertilization practices (Janes-Bassett et al., 2022; Pokharel et al., 2020; Miao et al., 2019; Jian et al., 2016; Marklein and Houlton et al., 2012), and pollution (Aponte et al., 2020; Riah et al., 2014) across different ecosystems. Nevertheless, none of these studies have globally addressed the collective body of evidence regarding the effects of all these factors on agricultural soils worldwide. This study is relevant since according to the Food and Agriculture Organization of the United Nations, which estimated that agricultural and livestock production covers approximately 5 billion hectares (38%) of the Earth's land surface, with around 66% consisting of permanent meadows and pastures, and a 33% corresponding to cropland (Faostat 2021, 2023). Improving nutrient recirculation, which leads to enhanced crop yields, should be a priority for sustainable agriculture in the future.

Utilizing the Web of Science and Scopus databases, we conducted a comprehensive bibliographic search encompassing research articles spanning from 1977 to mid 2022. This search employed various combinations of terms such as "phosphatase* AND soil AND agriculture", "phosphatase* AND soil AND agricultural", "phosphatase* AND soil AND crop", "phosphatase* AND soil AND arable", and "phosphatase* AND grassland" within the title, abstract, or keywords. Our selection criteria focused on papers that specifically examined field, glasshouse, and laboratory studies conducted on arable land and managed grassland, where ACP and ALP activity was experimentally evaluated. These studies were required to assess APase activity alongside other parameters derived from bulk soil, and restricted to studies where pNPP was used as a substrate. The database comprised a compilation of various data, including geographical data, seasonal data, and management practices, soil physicochemical properties, soil type, biological abundance and activity, and crop yield, totalling 351 columns. In total, a dataset was generated with 16,019 observations reported in 823 published papers.

3.5 Objectives and hypotheses of the thesis

The main objective of the thesis was to elucidate the role of ACP and ALP activity in agricultural soils at the global and local scale and how their activity is affected by environmental factors and agricultural management. The thesis was divided into three chapters, each corresponding to the content of a published or submitted paper. In Chapters 1 and 2, data was extracted from the database formed by the collected articles focused on agricultural land.

Specifically, the aim of Chapter 1 was to provide a qualitative analysis to summarize the direction of the relationships between various influential factors and APase activity in agricultural land and to identify gaps in existing knowledge. The goal was to establish a solid qualitative foundation to guide future quantitative studies with the aim to guide professional practice on one hand and future research on the other.

In Chapter 2, the objective was to explore the effects of climate, crop species family and agricultural management on APase activity in croplands, as well as its relationship with yield. This analysis was global in scope, designed to test the following hypotheses:

i) ACP and ALP activity is higher in regions with a warm and wet climate due to enhanced plant production and microbial activity.

ii) Strong species-specific effects on APase activity are expected, particularly in legumes, as N-fixing plants are typically P-limited.

iii) The activity of both enzymes will increase under management practices promoting soil health (e.g., conservation techniques such as reduced or zero tillage, crop rotation, cover crops, and organic fertilization).

iv) Crop yields are positively influenced by ACP and ALP activity.

In Chapter 3 a field study was conducted to experimentally assess APase activity, complementing the theoretical and statistical work from Chapters 1 and 2. The objective was to examine the impact of organic fertilization on APase activity, based on different vegetation classes, and to determine whether this has a role in productivity changes in permanent meadows. The hypotheses were:

i) The short-term application of organic N would positively affect the activity of both ACP and ALP activity.

ii) Phosphorus availability would increase with APase activity.

iii) Soil physiochemical parameters, along with vegetation-related parameters and meteorological indices, would affect the activity of both APase activity and P availability.

iv) Forage yield would be positively affected by increased APase activity and P availability.

3.6 References

Acosta-Martínez, V., Tabatabai, M., 2001. Tillage and residue management effects on arylamidase activity in soils. Biology and Fertility of Soils 34, 21–24. https://doi.org/10.1007/s003740100349.

Adetunji, A.T., Lewu, F.B., Mulidzi, R., Ncube, B., 2017. The biological activities of β-glucosidase, phosphatase and urease as soil quality indicators: A review. Journal of Soil Science and Plant Nutrition 17, 794–807. https://doi.org/10.4067/S0718-95162017000300018.

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services — A global review. Geoderma 262, 101–111. https://doi.org/10.1016/j.geoderma.2015.08.009.Alef, K., Nannipieri, P. (Eds.), 1995. 7 - Enzyme activities, in: Methods in Applied Soil Microbiology and Biochemistry. Academic Press, London, pp. 311–373. https://doi.org/10.1016/B978-012513840-6/50022-7.

Alef K., Nannipieri P., Trazar-Cepeda C., 1995. Phosphatase activity. in: Methods in Applied Soil Microbiology and Biochemistry. Alef K., Nannipieri P. (eds.), Academic Press, Harcourt Brace & Company, Publishers, London: 335-344.

Aponte, H., Meli, P., Butler, B., Paolini, J., Matus, F., Merino, C., Cornejo, P., Kuzyakov, Y., 2020. Meta-analysis of heavy metal effects on soil enzyme activities. Science of the Total Environment 737, 139744. https://doi.org/10.1016/j.scitotenv.2020.139744.

Brodt, S., Six, J., Feenstra, G., Ingels, C., Campbell, D. 2011. Sustainable Agriculture. Nature Education Knowledge 3(10):1.

Brohon, B., Delolme, C., Gourdon, R., 1999. Qualification of soils through microbial activities measurements influence of the storage period on int-reductase, phosphatase and respiration. Chemosphere 38, 1973–1984. https://doi.org/10.1016/S0045-6535(98)00410-X.

Brownlie, W.J., Sutton, M.A., Reay, D.S., Heal, K.V., Hermann, L., Kabbe, C., Spears, B.M., 2021. Global actions for a sustainable phosphorus future. Nature Food 2, 71–74. https://doi.org/10.1038/s43016-021-00232-w.

Bull, H., Murray, P.G., Thomas, D., Fraser, A.M., Nelson, P.N. 2002. Acid phosphatases. Molecular Pathology 55(2):65-72. https://doi.org/10.1136/mp.55.2.65.

Burns, R.G. and Dick, R.P., 2002. Enzymes in the Environment: Activity, Ecology, and Applications (1st ed.). CRC Press. https://doi.org/10.1201/9780203904039.

Burns, R.G., DeForest, J.L., Marxsen, J., Sinsabaugh, R.L., Stromberger, M.E., Wallenstein, M.D., Weintraub, M.N., Zoppini, A., 2013. Soil enzymes in a changing environment: Current knowledge and future directions. Soil Biology and Biochemistry 58, 216–234. https://doi.org/10.1016/j.soilbio.2012.11.009.

da Silva, R.R., 2019. Agricultural Enzymes, Phosphatases, Peptidases, and Sulfatases and the Expectations for Sustainable Agriculture. J Agric Food Chem 67, 4395–4396. https://doi.org/10.1021/acs.jafc.9b01784.

Daunoras, J., Kačergius, A., Gudiukaitė, R., 2024. Role of Soil Microbiota Enzymes in Soil Health and Activity Changes Depending on Climate Change and the Type of Soil Ecosystem. Biology 13, 85. https://doi.org/10.3390/biology13020085.

Dick, R.P., Breakwell, D.P., Turco, R.F., 1997. Soil Enzyme Activities and Biodiversity Measurements as Integrative Microbiological Indicators, in: Methods for Assessing Soil Quality. John Wiley & Sons, Ltd, pp. 247–271. https://doi.org/10.2136/sssaspecpub49.c15.

Drouillon, M., Merckx, R., 2005. Performance of para-nitrophenyl phosphate and 4-methylumbelliferyl phosphate as substrate analogues for phosphomonoesterase in soils with different organic matter content. Soil Biology and Biochemistry 37, 1527–1534. https://doi.org/10.1016/j.soilbio.2005.01.008.

Elsgaard, L., Andersen, G.H., Eriksen, J., 2002. Measurement of arylsulphatase activity in agricultural soils using a simplified assay. Soil Biology and Biochemistry 34, 79–82. https://doi.org/10.1016/S0038-0717(01)00157-2.

Faostat. FAO 2021. Land use. In: FAO.org [online]. Available at http://www.fao.org/faostat/en/#data/RL.

Faostat. FAO 2023. Land use. In: FAOSTAT. Rome [cited July 2023]. http://www.fao.org/faostat/en/#data/RL.

Gao, D., Bai, E., Li, M., Zhao, C., Yu, K., Hagedorn, F., 2020. Responses of soil nitrogen and phosphorus cycling to drying and rewetting cycles: A meta-analysis. Soil Biology and Biochemistry 148, 107896. https://doi.org/10.1016/j.soilbio.2020.107896.

García Izquierdo, C., Gil, F., Hernández, T., Trasar, C. 2003. Técnicas de análisis de parámetros bioquímicos en suelos: medida de actividades enzimáticas y biomasa microbiana. Ediciones Mundi-Prensa.

Ghosh, P., Rathinasabapathi, B., Ma, L.Q., 2015. Phosphorus solubilization and plant growth enhancement by arsenic-resistant bacteria. Chemosphere 134, 1–6. https://doi.org/10.1016/j.chemosphere.2015.03.048.

Gianfreda, L., Bollag, J.M. 1996. Influence of natural and anthropogenic factors on enzyme activity in soils. Soil biochemistry 9: 123-193.

Halstead, R.L., 1964. Phosphatase activity of soils as influenced by lime and other treatments. Canadian Journal of Soil Science 44, 137–144. https://doi.org/10.4141/cjss64-017.

Hinsinger, P., 2001. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: A review. Plant and Soil 237, 173–195. https://doi.org/10.1023/A:1013351617532.

Janes-Bassett, V., Blackwell, M.S.A., Blair, G., Davies, J., Haygarth, P.M., Mezeli, M. M., Stewart, G., 2022. A meta-analysis of phosphatase activity in agricultural settings in response to phosphorus deficiency. Soil Biology and Biochemistry 165, 108537. https://doi.org/10.1016/j.soilbio.2021.108537.

Jian, S., Li, J., Chen, J., Wang, G., Mayes, M.A., Dzantor, K.E., Hui, D., Luo, Y., 2016. Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. Soil Biology and Biochemistry 101, 32–43. https://doi.org/10.1016/j.soilbio.2016.07.003.

Joner, E.J., van Aarle, I.M., Vosatka, M., 2000. Phosphatase activity of extra-radical arbuscular mycorrhizal hyphae: A review. Plant and Soil 226, 199–210. https://doi.org/10.1023/A:1026582207192.

Juma, N.G., Tabatabai, M.A., 1988. Comparison of kinetic and thermodynamic parameters of phosphomonoesterases of soils and of corn and soybean roots. Soil Biology and Biochemistry 20, 533–539. https://doi.org/10.1016/0038-0717(88)90069-7.

Khan, F., Siddique, A,B,, Shabala, S., Zhou, M., Zhao, C. 2023. Phosphorus Plays Key Roles in Regulating Plants' Physiological Responses to Abiotic Stresses. Plants 12(15):2861. https://doi.org/10.3390/plants12152861.

Kramer, M. 1957. Phosphatase-Enzym-Aktivität als Anzeiger des biologisch nutzbaren Phosphors im Boden. Naturwissenschaften 44:13.

Kramer, M., Yerdei, G. 1959. Application of the method of phosphatase activity determination in agricultural chemistry. Soviet Soil Sci. 9:1100-1103.

Margalef, O., Sardans, J., Fernández-Martínez, M., Molowny-Horas, R., Janssens, I.A., Ciais, P., Goll, D., Richter, A., Obersteiner, M., Asensio, D., Peñuelas, J., 2017. Global patterns of phosphatase activity in natural soils. Scientific Reports 7(1), 1337. https://doi.org/10.1038/s41598-017-01418-8.

Margalef, O., Sardans, J., Maspons, J., Molowny-Horas, R., Fernández-Martínez, M., Janssens, I. A., Richter, A., Ciais, P., Obersteiner, M., Peñuelas, J., 2021. The effect of global change on soil phosphatase activity. Global Change Biology 27(22), 5989–6003. https://doi.org/10.1111/gcb.15832.

Marklein, A.R., Houlton, B.Z., 2012. Nitrogen inputs accelerate phosphorus cycling rates across a wide variety of terrestrial ecosystems. New Phytologist 193, 696–704. https://doi.org/10.1111/j.1469-8137.2011.03967.x.

Meng, C., Tian, D., Zeng, H., Li, Z., Chen, H.Y.H., Niu, S., 2020. Global meta-analysis on the responses of soil extracellular enzyme activities to warming. Science of the Total Environment

705, 135992. https://doi.org/10.1016/j.scitotenv.2019.135992.

Miao, F., Li, Y., Cui, S., Jagadamma, S., Yang, G., Zhang, Q., 2019. Soil extracellular enzyme activities under long-term fertilization management in the croplands of China: A meta-analysis. Nutrient Cycling in Agroecosystems 114(2), 125–138. https://doi.org/10.1007/s10705-019-09991-2.

McDonald, A.G., Boyce, S., Tipton, K.F., 2009. ExplorEnz: the primary source of the IUBMB enzyme list. Nucleic Acids Research 37, D593–D597. https://doi.org/10.1093/nar/gkn582.

Nannipieri, P., Giagnoni, L., Landi, L., Renella, G., 2011. Role of Phosphatase Enzymes in Soil, in: Bünemann, E., Oberson, A., Frossard, E. (Eds.), Phosphorus in Action: Biological Processes in Soil Phosphorus Cycling. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 215–243. https://doi.org/10.1007/978-3-642-15271-9_9.

Ndakidemi, P.A., 2006. Manipulating legume/cereal mixtures to optimize the above and below ground interactions in the traditional African cropping systems. African Journal of Biotechnology 5, 2526–2533.

Niu, Y. F., Chai, R. S., Jin, G. L., Wang, H., Tang, C. X., Zhang, Y. S. 2013. Responses of root architecture development to low phosphorus availability: a review. Annals of botany 112(2), 391–408. https://doi.org/10.1093/aob/mcs285.

Pokharel, P., Ma, Z., Chang, S.X., 2020. Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: a global meta-analysis. Biochar 2, 65–79. https://doi.org/10.1007/s42773-020-00039-1.

Redlich, S., Martin, E.A., Steffan-Dewenter, I., 2021. Sustainable landscape, soil and crop management practices enhance biodiversity and yield in conventional cereal systems. Journal of Applied Ecology 58, 507–517. https://doi.org/10.1111/1365-2664.13821.

Riah, W., Laval, K., Laroche-Ajzenberg, E., Mougin, C., Latour, X., Trinsoutrot-Gattin, I., 2014. Effects of pesticides on soil enzymes: A review. Environmental Chemistry Letters 12, 257–273. https://doi.org/10.1007/s10311-014-0458-2.

Saa, A., Trasar-Cepeda, M.C., Gil-Sotres, F., Carballas, T., 1993. Changes in soil phosphorus and acid phosphatase activity immediately following forest fires. Soil Biology and Biochemistry 25, 1223–1230. https://doi.org/10.1016/0038-0717(93)90218-Z.

Santoro, V., Schiavon, M., Celi, L., 2024. Role of soil abiotic processes on phosphorus availability and plant responses with a focus on strigolactones in tomato plants. Plant and Soil 494, 1–49. https://doi.org/10.1007/s11104-023-06266-2.

Sharma, U., Pal, D., Prasad, R., 2014. Alkaline Phosphatase: An Overview. Ind J Clin Biochem 29, 269–278. https://doi.org/10.1007/s12291-013-0408-y.

Shukla, E., Bendre, A.D., Gaikwad, S.M., 2022. Hydrolases: The Most Diverse Class of Enzymes, in: Haider, S., Haider, A., Catalá, A. (Eds.), Hydrolases. IntechOpen, Rijeka. https://doi.org/10.5772/intechopen.102350.

Skujins, J.J., 1967. Enzymes in soils. In McLaren, A. D., and Peterson, G. H. (eds.), Soil Biochemistry. New York: Marcel Dekker, Vol. 1, pp. 371–414.

Smil, V., 2000. Phosphorus in the environment: Natural Flows and Human Interferences. Annu. Rev. Energy. Environ. 25, 53–88. https://doi.org/10.1146/annurev.energy.25.1.53.

Stege, P.W., Messina, G.A., Bianchi, G., Olsina, R.A., Raba, J., 2009. Determination of arylsulphatase and phosphatase enzyme activities in soil using screen-printed electrodes modified with multi-walled carbon nanotubes. Soil Biology and Biochemistry 41, 2444–2452. https://doi.org/10.1016/j.soilbio.2009.08.024.

Sun, Y., Goll, D.S., Ciais, P., Peng, S., Margalef, O., Asensio, D., Sardans, J., Peñuelas, J., 2020. Spatial Pattern and Environmental Drivers of Acid Phosphatase Activity in Europe. Frontiers in Big Data 2, 1–13. https://doi.org/10.3389/fdata.2019.00051.

Tabatabai, M.A., 1994. Soil Enzymes, in: Methods of Soil Analysis, SSSA Book Series. pp. 775–833. https://doi.org/10.2136/sssabookser5.2.c37.

Tabatabai, M.A., Bremner, J.M., 1969. Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. Soil Biology and Biochemistry 1, 301–307. https://doi.org/10.1016/0038-0717(69)90012-1.

Tiessen, H., Ballester, M.V., Salcedo, I., 2011. Phosphorus and Global Change, in: Bünemann, E., Oberson, A., Frossard, E. (Eds.), Phosphorus in Action: Biological Processes in Soil Phosphorus Cycling. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 459–471. https://doi.org/10.1007/978-3-642-15271-9_18.

USGS. Science for a changing world. https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

Uwituze, Y., Nyiraneza, J., Fraser, T.D., Dessureault-Rompré, J., Ziadi, N., Lafond, J., 2022. Carbon, Nitrogen, Phosphorus, and Extracellular Soil Enzyme Responses to Different Land Use. Front. Soil Sci. 2, 814554. https://doi.org/10.3389/fsoil.2022.814554.

Van Mooy, B.A.S., Krupke, A., Dyhrman, S.T., Fredricks, H.F., Frischkorn, K.R., Ossolinski, J.E., Repeta, D.J., Rouco, M., Seewald, J.D., Sylva, S.P., 2015. Phosphorus cycling. Major role of planktonic phosphate reduction in the marine phosphorus redox cycle. Science 348, 783–785. https://doi.org/10.1126/science.aaa8181.

Vuorinen, A.H., Saharinen, M.H., 1996. Effects of soil organic matter extracted from soil on acid phosphomonoesterase. Soil Biology and Biochemistry 28, 1477–1481. https://doi.org/10.1016/S0038-0717(96)00166-6.

Waldrip, H.M., Acosta-Martínez, V., 2014. Phosphatase Activities and Their Effects on Phosphorus Availability in Soils Amended with Livestock Manures, in: He, Z., Zhang, H. (Eds.), Applied Manure and Nutrient Chemistry for Sustainable Agriculture and Environment. Springer Netherlands, Dordrecht, pp. 123–140. https://doi.org/10.1007/978-94-017-8807-6_7.

Weil R.R., Brady N.C., 2016. The Nature and Properties of Soils, 15th Edition, 15th Edition. ed. Pearson Press., Upper Saddle River NJ, 2017.

4. Chapter 1

Review

Relationship among soil biophysicochemical properties, agricultural practices and climate factors influencing soil phosphatase activity in agricultural land

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4.1 Abstract

Phosphorus (P) is a vital macronutrient crucial for crop productivity. Plants absorb P salts, mainly orthophosphate, from the soil, yet the primary P source resides in organic materials. Acid and alkaline phosphatases (the predominant forms of soil phosphomonoesterases (APases)) are crucial for alleviating P deficiency in plants and play a vital role in releasing P from organic materials via hydrolysis. Our aim was to summarize the direction of the relationship between a variety of influential factors on acid and alkaline phosphatase activity in agricultural lands and identify gaps in knowledge. Our findings indicate a strong linkage between both APases and soil pH, positively influenced by clay content, organic matter, microbial biomass carbon, and nitrogen. Adopting healthy soil practices like balanced organic fertilizer usage, optimal soil water levels, reduced tillage, crop rotation, and using beneficial plant microbes help boost both APase activity. However, the connection between APases and crop productivity remains uncertain due to insufficient research in this area. We identified gaps in knowledge in relation to meso-macrofauna, alongside essential plant nutrients such as potassium, nutrient ratios, and the synergistic effects of various factors on APase response. Understanding the rapid, efficient assimilation of P through APases in the plant-soil and/or plant-microbiota ecosystem it can be crucial for crop productivity and yields.

Keywords: phosphomonoesterases; physicochemical properties; biological properties; management; fertilization; pollution; climate; yield

4.2 Introduction

Phosphorus (P) is an essential element for cell development in all living organisms (Wrage et al., 2010). As a component of nucleic acids (DNA, RNA), P is indispensable for reproduction and protein synthesis. Additionally, it plays a crucial role in energy-storing molecules like adenosine triphosphate (ATP) or cytidine triphosphate (CTP), among others, supplying the energy needed for diverse cellular endergonic processes (Malhotra et al., 2018). This is why P is an important limiting nutrient for crop and plant growth in a range of natural and managed ecosystems, given that only 0.1% of the P available in the soil is in the inorganic form that can be assimilated by plants (Ghosh et al., 2015; Zhu et al., 2018; Peñuelas et al., 2013). Soil enzymes released by plant roots, soil mesofauna, and living or dead microbes (Bandick and Dick, 1999; Dick, 1984; Tabatabai, 1994) contribute to the decomposition of organic matter and allow nutrient recycling (Burns, 1978; Kiss et al., 1998). The mechanisms governing how the composition, timing, spatial location, and quantity of soil enzymes adapt to environmental changes have been studied elsewhere (Allison et al., 2010; Zuccarini et al., 2023). These studies underscore the crucial role of soil enzymes in biogeochemical cycles and ecosystem responses to drivers of global change.

In the P cycle, soil phosphatase enzymes release P contained in organic matter for reuse by living organisms (Burns and Dick, 2002). This process involves the hydrolysis of various P esters (carbon-oxygen-phosphorus monoesters, carbon-oxygen-phosphorus-oxygen-carbon diesters, carbon-phosphorus phosphonates, phosphoric triester hydrolases, triphosphoric acid monoester hydrolases) into soluble phosphate ions. This process provides soil- accessible and assimilable P for plant uptake (Schmidt et al., 1961; Acosta-Martínez et al., 2011). Extracellular phosphatase enzymes are secreted by soil microorganisms, fauna, and plant roots (Cawley, 2006), while intracellular (endogenous) phosphatase enzymes are within the cytoplasm of proliferating microbial, animal and plant cells, restricted to the periplasmic space of gram-negative bacteria or within non-proliferating cells such as fungal spores, protozoan cysts, plant seeds, and bacterial endospores (Burns, 1982; Joner et al., 2000). Extracellular monoester hydrolases (APases) are included in a wide group of phosphoric monoester hydrolases (or phosphomonoesterases) (Park et al., 2022), and its predominant forms across a wide range of soil pH conditions are acid phosphatase (ACP; EC 3.1.3.2) and alkaline phosphatase (ALP; EC 3.1.3.1). ACP is produced by plants in the phloem, cortex, epidermis, and roots (McLean and Gahan, 1970; Juma and Tabatabai, 1988) and also by microorganisms (Carricondo-Martínez et al., 2022) and is active in acid/neutral soils with pH ≤ 7. ALP is produced by microorganisms and animals and is active in basic soils with pH > 7 (Tabatabai, 1994; Alef and Nannipieri, 1995; Tarafdar and Claassen, 1988; Juma and Tabatabai, 1977; Juma and Tabatabai, 1978). The most well-studied group of ALP are encoded by different genes (i.e., phoA, phoD, phoX) (Neal et al., 2018), and the phoD gene is the form that has the highest abundance in soils (Ragot et al., 2017).

Agricultural and livestock production covers approximately 5 billion hectares (38%) of the Earth's land surface, with around 66% consisting of livestock-grazed grasslands and 33% being cropland (Faostat, 2021). While APase activity in managed soils has been reported to be lower compared to natural ecosystems (Margalef et al., 2017), its activity is, in turn, influenced by a combination of natural environmental conditions and anthropogenic factors, together with strong seasonal variations (Arora et al., 2021). APase activity in agricultural soils is significantly impacted by management practices, including tillage, the crop species or crop rotation (Choudhary et al., 2018; Dick et al., 1988; Eichler-Löbermann et al., 2021), as well as fertilization methods (Chen et al., 2021; Dutta et al., 2020; Singh et al., 2018), in combination with various soil biophysicochemical and environmental factors (Grafe et al., 2021; Monkiedje et al., 2006). Several quantitative studies have investigated APase response to various factors such as climatic effects (Margalef et al., 2021; Sun et al., 2020; Meng et al., 2020; Gao et al., 2020), soil properties (Margalef et al., 2017), fertilization (Janes-Bassett et al., 2022; Pokharel et al., 2020; Miao et al., 2019; Jian et al., 2016; Marklein et al., 2012), and pollution (Aponte et al., 2020; Riah et al., 2014) across different ecosystems. However, a comprehensive global analysis specifically centered on APases in agricultural lands is yet to be conducted. Therefore, a preliminary qualitative analysis is needed to assess the APase response in agriculture-managed soils. This should be augmented by incorporating findings from quantitative analyses published to date, thereby enhancing the comprehensiveness of this qualitative study. Such an analysis should encompass all potential factors that could either augment, diminish, or have no effect on APase activity to address the challenge of identifying patterns within agricultural systems. To achieve this goal, we (i) summarize the direction of the relationships between a variety of influential factors on APase activity in agricultural lands and (ii) identify gaps in knowledge. This will help to direct future quantitative studies toward specific areas, leveraging a broad and well-documented qualitative foundation.

4.3 Materials and Methods

Using the Web of Science and Scopus databases, a bibliographic search was carried out, including research papers, reviews, and meta-analyses published from 1977 to December 2022. We carried out a search using different combinations of terms: “phosphatase* AND soil AND agriculture”, “phosphatase* AND soil AND agricultural”, “phosphatase* AND soil AND crop”, “phosphatase* AND soil AND arable”, and “phosphatase* AND grassland” in the title, abstract or keywords. We only selected papers reporting field, glasshouse, and laboratory studies using arable land and managed grassland and where soil APase was experimentally assessed. APase must be evaluated alongside other parameters from bulk soil. Only studies that used para-nitrophenol as a substrate to measure APase activity were included (Tabatabai, 1994; Tabatabai and Bremner, 1969; Eivazi and Tabatabai, 1977), where ACP and potential ALP activity following this method is usually measured at pH 6.5 and pH 11.0, respectively (Wang et al., 2013). The article search and selection process is detailed in Figure S1.

Among all the selected studies for analysis, the response of ACP and ALP activity have been categorized according to these factors: biophysicochemical parameters, including total microbe activity, microbe abundance, microbial biomass P content, microbial biomass carbon content, microbial biomass nitrogen content, microbe diversity, phoD gene abundance and richness, earthworm abundance, soil depth, soil moisture content, clay content, sand content, microaggregate content, pH, cation exchange capacity, electrical conductivity, chlorine anion content, carbonate content, iron content, exchangeable aluminium content, grade of salinity, soil organic carbon/matter, total organic carbon, dissolved organic car- bon, nitrate nitrogen form, ammonium nitrogen form, total nitrogen, soil C:N ratio, labile inorganic P, available P, organic P, labile organic P, soil C:P ratio and available potassium. Regarding the agricultural management practices factor, we registered any land use change, crop rotation, and cover cropping, tillage practices, types of inorganic and organic fertilization and rates, weed and pest management practices, irrigation practices, and livestock, grazing, and mowing management. Pollution was included as soil contaminant content. Concerning climatic variables and climate-change treatments, mean annual temperature, mean annual precipitation, drought, soil water scarcity, soil water availability, seasonal variations, and the impact of carbon dioxide fertilization in these studies were annotated. When available, crop yield responses were also taken.

All analyses underwent a review process involving vote counting, categorizing the direction of the effect as either positive, negative, or non-existent (neutral). When the papers were meta-analyses and reviews, it was not possible to separate the results obtained by different analytical methods. Therefore, only those that had selected studies agreeing with our selection criteria were included (Supplementary material Table S1). Consequently, our dataset comprised 675 papers, encompassing 267 individual observations of ACP activity, 218 individual observations of ALP activity, and 190 paired observations involving both ACP and ALP. Additionally, twelve meta-analyses and one review were also considered in this study, acknowledging that certain studies within these publications overlap with those selected in order to function as a qualitative complement to this analysis (Supplementary material Tables S2–S20).

4.4 Results and Discussion

4.4.1 Soil Biophysicochemical Properties

4.4.1.1 Soil Microbes and Fauna

There is a positive relationship between the activity of soil microbes and APases (Figure 1, Table S3). This is influenced by the structure of bacterial and fungal communities (Gesolmino and Azzellino, 2011; Chowdhury and Rasid, 2021), highlighting the role of microorganisms in facilitating nutrient movement within the soil (Sharma et al., 2013). Accordingly, the availability of soil P for plants is closely associated with the abundance of microorganisms and the presence of exoenzymes like APases (Scaramal da Silva et al., 2015). When the activity of ACP in soil is low, microorganisms may adjust the activity of ALP in response to the nutritional needs of plants and microbes (Wozniak et al., 2022). The activity of soil microorganisms varies throughout crop development, increasing in tandem with APase activity as a response to crop growth, thereby reflecting the complex interactions between soil, plants, and the atmosphere (Dubey et al., 2021). The activities of ACP and ALP are positively linked with the biomass of fungi, bacteria in general, and specifically actinobacteria (Figure 1, Table S4). Additionally, ALP activity is positively associated with soil respiration (Antolín et al., 2005), as well as with the activities of dehydrogenase and urease enzymes (Maini et al., 2022).

A positive relationship between microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) has been demonstrated (Borase et al., 2020), and both are indicative of microbial biomass (Hatti et al., 2018). MBC serves as a crucial nutrient pool for ecosystem nutrient cycling (Angers et al., 1993), and soil properties, such as soil organic matter (SOM), are usually positively associated with MBC (Sepat et al., 2014). Our findings provide evidence of positive associations between APase activity and MBC, but also with microbial biomass P (MBP) and MBN (Figure 1, Table S3).

Although ALP activity has been proposed as an early indicator of change in soil biological status (Angers et al., 1993), it does not show a strong association with specific soil bacterial community composition (Wang et al., 2022), suggesting that it may be less sensitive compared to other enzymatic activities such as urease or dehydrogenase (Chowdhury and Rasid, 2021). Consequently, ALP activity may not be a reliable indicator of soil microbial abundance (Banerjee et al., 1999), plausibly due to the diverse sources of this enzyme originating from both microorganisms and microbial plant secretions (Al-Taweel and Al-Jubouri, 2019).

Figure 1. Number of single studies reporting direction of responses of ACP and ALP activities to soil biological factors. Factors with fewer or equal than three entries in ACP or ALP response are excluded from the figure as they are considered unrepresentative (e.g., microbe diversity (Shannon diversity index), phoD gene abundance and richness and earthworm abundance).

The relationship between soil bacterial diversity (measured by the Shannon diversity index), phoD gene abundance and richness, and earthworm abundance and biomass with ACP and ALP activity is inconclusive (Table S3). Microbial richness demonstrated a moderate but positive linkage with plant diversity (Liu et al., 2020) and the abundance of the bacterial phoD gene is generally positively interrelated with ALP activity. On the other hand, soil microbial activity, in turn influenced by plant root exudates, plays a more substantial role in driving APase activity compared to soil type (Furtak et al., 2017). This positive association with APases contributes to P availability in soil, potentially benefiting plant development (Mandal et al., 2021; Wu et al., 2012). The incorporation of earthworms alongside with crop residues has demonstrated an increase in ALP activity (Tao et al., 2019; Balachandar et al., 2021). This effect has been linked to the mitigation of soil compaction caused by crop residues, thereby microbial conditions through improved water and oxygen supply (Buck et al., 2000; Soane and van Ouwerkerk, 1994). Although ACP activity might also elevate with earthworm addition, it's noteworthy that available studies combined earthworms with biochar, lacking independent analysing of the isolated effects of earthworms (Noronha et al., 2022). Moreover, soil management practices influence on earthworm metabolism and dynamic processes since enzyme activities in the casts produced in compacted soils are less stimulated (Buck et al., 2000). Unfortunately, there is currently no available information regarding the impact of soil mesofauna groups on APase activity, despite their pivotal role in regulating organic matter decomposition and soil ecosystem functioning.

4.4.1.2 Soil depth, moisture, texture and structure

Several studies consistently demonstrated a decrease in ACP and ALP activities with increasing soil depth (Figure 2, Table S4). This decline aligns in root density and lower abundance of heterotrophic microorganisms (bacteria and fungi). Notably, soil moisture content has also a positive linkage with APase activity and the functional potential of soil microbial communities (Brockett et al., 2012), reflecting its role in optimizing soil conditions for plant root and microbial growth (Ojeda et al., 2013) (Figure 2, Table S4). Some studies have consistently shown a positive trend between APase activity and soil structure (microporosity) and a higher clay content (Figure 2, Table S4), which agrees with the well-studied connection between those properties and soil microbial and biochemical properties (Calvarro et al., 2014; Gispert et al., 2013). More specifically, ACP activity has been positively correlated with fine soil particle fractions such as silt (Garg et al., 2008) and clay (Nedyalkova et al., 2020). The increase in ACP and ALP activity with higher clay content is also consistent with a meta-analysis conducted by Aponte et al. (2020) and is likely associated to the increase on enzyme longevity in soil caused by clay minerals while preserving their activity (Barnejee et al., 1999). In contrast, sandy soils often exhibit a decrease in APase activity owing to several factors, including their diminished organic matter content, limited water-holding capacity, and reduced microbial biomass (Gelsomino and Azzellino, 2011). Nevertheless, some studies have suggested a positive relationship between APase activity and soil sand content, potentially attributed to increased bioaccessibility and bioavailability of nutrients such as nitrates or exchangeable cations (Wozniak et al., 2022; Bergstrom et al., 1998). Regarding soil structure, there are no conclusive results to assess whether microaggregates play a significant role in the transformation of soil P via APases thus lower concentrations of phosphate monoesters and diesters (Wei et al., 2014). Consequently, a probable inverse relationship exists between the abundance microaggregates (particle size <0.25 mm) and the activities of ALP and ACP enzymes.

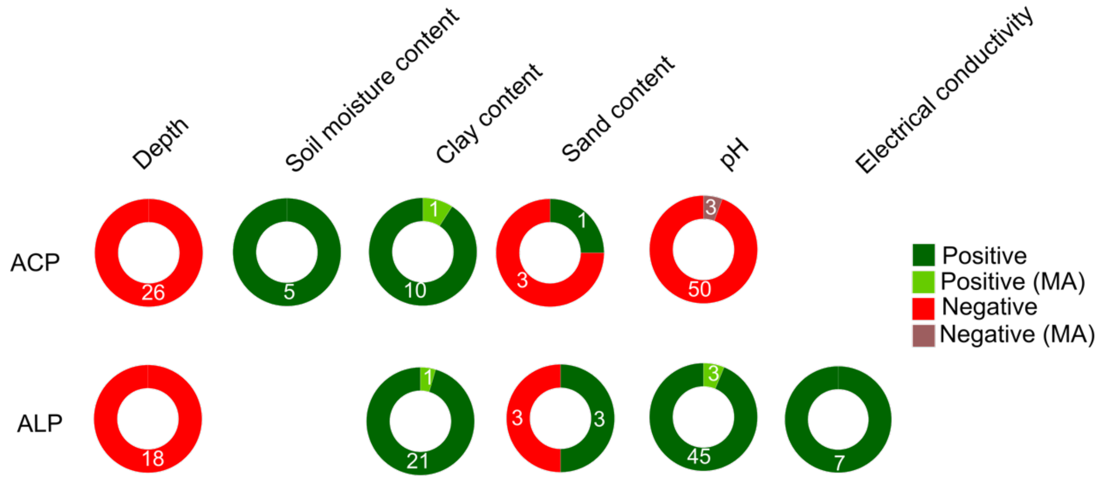

Figure 2. Number of single and meta-analysis studies reporting direction of responses of ACP and ALP to soil depth, moisture, texture and pH-related factors. Factors with fewer or equal than three entries in ACP or ALP response are excluded from the figure as they are considered unrepresentative (e.g., microaggregate content, cation exchange capacity, chlorine anion content, carbonate content, iron content and exchangeable aluminium content). The number of meta-analyses (MA) has been counted in order to complement the qualitative analysis based on vote counting.

4.4.1.3 Soil pH and associated factors

Soil pH influences a variety of chemical and biochemical processes in soil (Odutola, 2019). In agricultural soil studies, the pH range typically spans from pH 5.5 to 7.5, and therefore APase assessments are often focused on ACP, due to the experimental buffer solutions that are typically adjusted to pH 6.5 followed by Tabatabai's method (Tabatabai, 1994). Consistently, the maximum ACP activity is observed in acidic to neutral soils, while the peak potential ALP activity is found in alkaline (calcareous) soils (Gesolmino and Azzellino, 2011; Mandal et al., 2018; Ortiz et al., 2020; Truu et al., 2008; Laxminarayana, 2017) (Figure 2, Table S5). This trend aligns with several meta-analyses (Sun et al., 2020; Janes-Bassett et al., 2022; Pokharel et al., 2020). Nevertheless, the activity of APases is potential and it can be increased or reduced due to agricultural practices that modify soil pH. Factors such as high precipitation, acid rain, oxidative weathering, and crop management practices can lead to a decrease in soil pH which promotes acidic activity. Conversely, weathering of silicates, aluminosilicates, or carbonate mineral compounds can increase soil pH which promotes basic activity. For instance, organic fertilizer application in maize cultivation (Durrer et al., 2021) in acidic soils have demonstrated increased ALP activity due to their positive impact on soil pH. Conversely, practices like the use of rice straw biochar (Yang et al., 2015) or applying a no-till management in maize and bean cropping (Roldán et al., 2007; Swedrzynska et al., 2013) have resulted in decreased ACP activity by elevating soil pH.

Microelements and organic compounds in the soil, such as carbonates (CO_3^{2-}), iron (Fe), and aluminium (Al) oxides, influence the release of P from organic compounds, the size of P fractions, and P uptake, which in turn affect APase activity (Mahmood et al., 2022). Specifically, soil CO_3^{2-} content could be negatively associated with ACP activity and positively associated with ALP activity, likely due to its neutralizing capacity, which shifts soil pH from neutral to alkaline (Siddaramappa et al., 1994). The soil Fe content interacts positively with both ACP and ALP activity, as its availability increases with higher organic matter content (Yu et al., 2006). Lastly, soil exchangeable aluminium (Al^{3+}) content has a negative connection with ACP activity due to pH increases after lime amendments, where calcium ions (Ca^{2+}) hydrolyse and react with soluble Al^{3+} to form insoluble Al hydroxide compounds (Meena and Prakasha, 2021) (Table S5).

The total cation exchange capacity (CEC) and electrical conductivity (EC) of the soil are partly related to soil pH (Purnamasari et al., 2021; Smith and Doran, 1996), and available studies indicate a positive association between APase activity and CEC and EC (Figure 2, Table S5). Additionally, higher concentrations of chloride ions (Cl^-) in the soil can decrease ACP activity by inhibiting the growth of soil microflora, thus affecting enzymatic activity (Dinesh et al., 1995) but there are no conclusive results directly correlated with this ion. However, high salt content in soils is a growing issue exacerbated by climate change, and it poses significant challenges to agricultural production. Salinity and sodicity, the latter referring to a high sodium (Na^+) content, have detrimental effects on crop growth and the biochemical processes essential for maintaining soil quality (Rietz and Haynes, 2003). In relation to APase activity, although the results are not significant it seems that salinity has a negative impact (Table S6) partly due to a decrease in the activity of soil microbes and associated microbial biomass with reductions in the release of enzymes (Rietz and Haynes, 2003) and partly due to the likely direct toxic effects of some ions, particularly Cl^-, on microbial growth (Garcia and Hernandez, 1996) (Table S6).

4.4.1.4 Carbon

Soil organic carbon (SOC) is a crucial component of soil health and is derived from living and decomposing organic matter such as plant litter, root and microbial exudates, dead microorganisms and fauna, and faecal material (Turbé et al., 2010). Both single studies and meta-analyses have clearly demonstrated a positive linkage between indicators of soil organic matter, including SOM, SOC, total organic C, and dissolved organic C, and the two APases (ACP and ALP) (Figure 3, Table S7). This positive association is explained because the substrate for APases, soil organic P, is linked to SOC (Tipping et al., 2016). Quantifying soil organic matter (SOM) often does not provide detailed information about the underlying soil processes that contribute to its accumulation (Bergstrom et al., 1998). Certain agricultural practices, such as reduced tillage and cover cropping, have been shown to increase SOM levels (Kooch et al., 2019; Lungmuana et al., 2019) through higher levels of microbial biomass that stimulate decomposition processes and enhance the stabilization of organic compounds (de Jesus Franco et al., 2020).

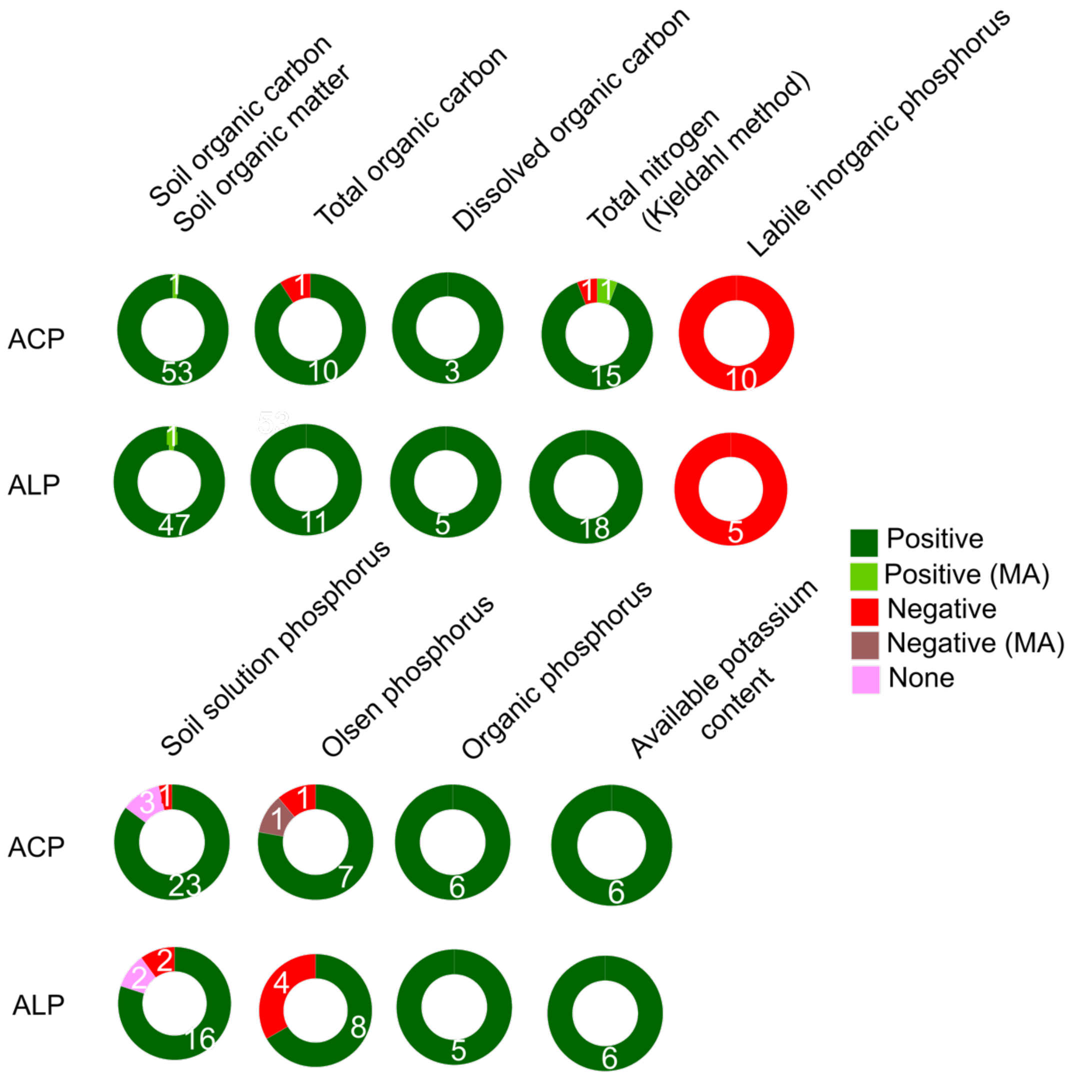

Figure 3. A number of single and meta-analysis studies reported the direction of ACP and ALP responses to carbon, nitrogen, phosphorus, and potassium. Factors with fewer than three entries in in ACP or ALP response are excluded from the figure as they are considered unrepresentative (e.g., microaggregate content, cation exchange capacity, chlorine anion content, carbonate content, iron content and exchangeable aluminium content). The number of meta-analyses (MA) has been counted in order to complement the qualitative analysis based on vote counting.

4.4.1.5 Nitrogen

Nitrogen is a crucial nutrient for plant growth and is considered an indicator of soil fertility and quality. Nitrate (NO_3^-) and ammonium (NH_4^+) are the primary forms of N available for plants, and their concentrations are often positively correlated with the activity of ACP and ALP. Higher concentrations of NO_3^- and NH_4^+ can have a positive impact on the formation and persistence of microbial biomass, which in turn can influence the activity of APases (Monkiedje et al., 2006). However, the fact that negative effects have sometimes also been found between both (NO_3^--N and NH_4^+-N) and APases indicate that there can be interactions among specific soil, environment and management conditions leading to contrasting patterns (Table S8). For instance, when negative effects of NO_3^- on ALP activity have been reported, this has been attributed to the stabilization of

ALP by soil colloids formed by organic matter and clay minerals (Adrover et al., 2017) as well as the influence of SOC on the structure and composition phoD-harboring bacteria and ALP activity (Wang et al., 2022). Both a meta-analysis and multiple studies have shown a positive association between APase activity and total soil N content, often determined using the Kjeldahl method (Figure 3). This relationship is likely due to the positive correlation between N and SOC content (Sun et al., 2020; Palmer et al., 2017), suggesting that APase activity is induced by C and N mineralization and the availability of their decomposition products (Cattaneo et al., 2014) (Figure 3, Table S8). The C:N ratio of soil organic matter also influences APase activity, and a lower C:N ratio indicates rapid decomposition of organic matter, regardless of soil microbial biomass, and can result in increased APase activity. The positive connection between APases and the C:N ratio tends to be stronger than their connection with the C:P ratio (Singh and Ghoshal, 2013).

4.4.1.6. Phosphorus

As expected, and indicated by various studies, APase activity is closely associated with soil P content (Figure 3, Table S9). It is important for comprehending the dynamics of soil P and for effective P management in both natural and agricultural ecosystems (Sigua et al., 2017). The bulk of the soil P exists in three general groups of compounds, namely organic P, calcium-bound inorganic P, and iron or aluminium-bound inorganic P, where organic P is distributed among the biomass, labile or passive fractions of soil organic matter, inorganic P and calcium compounds predominate in most alkaline soils while the iron and aluminium forms are most important in acidic soils (Weil and Brady, 2017). Since most of the P in each group is of very low solubility and not readily available for plant uptake, biotic processes controlled primarily by bacterial and fungal decomposition indirectly affect P availability for plants by influencing the form of soil minerals that chemically bind P (Cross and Schlesinger, 1995). For instance, in cropping systems with low levels of C and inorganic N, it becomes essential to supplement the soil with other mineral nutrients (e.g., P) and implement effective biological control strategies to ensure proper P cycling and availability for plants (Zibilske and Bradford, 2003). In terms of readily plant-available soil P content, studies considered different fractions, notably labile inorganic P (Pi), soil solution P, or other P fractions. The former comprises P fractions dissolved in the soil solution, directly accessible to plants, while the latter encompasses fractionation methods for inorganic P extraction. These extraction methods often involve sodium bicarbonate-P (commonly referred to as Olsen P, detailed separately) or P solubilization using reagents such as dilute acid-fluoride, dilute hydrochloric acid, sulfuric acid, or water, among other techniques (Olsen and Sommers, 1982). Conversely, there are P fractions existing in organic forms, cited as organic P, that are not immediately available to plants, including labile organic P (Po). As previously mentioned, organic P denotes P bound within organic matter, while Po, like $NaHCO_3$-Po, represents P that can be relatively easily mineralized (Zhu et al., 2018).

The activity of APases in soil is influenced by the P content, and its response is dynamic depending on the availability of P to plants. A priori, high levels of available soil P content can lead to a reduction in APase activity as plants and microbes adapt to the abundant P supply. Conversely, under P limitation, APase activity can increase to facilitate P uptake and meet or even surpass plant P demands (Tarafdar and Claassen, 1988) (Table S9). This trend is confirmed by Sun et al. (2020), which showed a negative correlation between both APases and Olsen P and soil solution P. In this case, the negative association has been attributed to the hydrolysis of P compounds by other APase enzymes in the $NaHCO_3$-extractable fraction, leading to an increase in dissolved inorganic P in the soil solution. However, other studies showed a positive association between APase activity (both ACP and ALP) and Olsen P, soil solution P, and organic P (Figure 3), which means that the dynamics of P fractions, particularly Olsen P, are closely related to plant development and can be influenced by climate and intrinsic soil characteristics (Koper and Lemanowicz, 2008; Atoloye et al., 2021). Additionally, the addition of organic P sources, which increase the soluble P content, can negatively impact APase activity, as they contribute to the pool of available inorganic P in the soil (Madejón et al., 2003). It seems that there is a relationship between these enzymes and the promotion of root growth and nutrient uptake by crops (Li et al., 2018), which indicates that the positive relationship is directly associated with particular cases and that management is crucial to determine their correlation. When APase activity shows a negative linkage with the content of Po in the soil (Table S9), it suggests that APases are not the limiting factor in the utilization of organic P, but rather it is the availability of APase-hydrolysable P compounds that limits the process (Tarafdar and Claassen, 1988). It is important to consider that when a wider group of phosphoric monoester hydrolase enzymes are assessed together, the high levels of inter-enzyme variation strengthen the relations of available P (Waldrop et al., 2000).

4.1.7. Potassium

Potassium (K) plays a crucial role in plant growth and soil fertility (Khan et al., 2014). Therefore, the soil content of available K decreases more in cultivated soils than in natural ecosystems during plant growth due to erosion/runoff (Maini et al., 2022). Studies indicate a positive linkage between the activity of ACP and ALP enzymes and the available K content in the soil (Figure 3, Table S10). The studies do not deeply into the relationship of K with other factors that may also affect APase activity. For this reason, further research is needed to fully understand the specific mechanisms and trade-offs associated with K and its impact on P acquisition in managed ecosystems (Honvault et al., 2020).

4.4.2 Responses to agro-ecosystem management

4.4.2.1 Conversion from natural to managed ecosystems

Cropland soils experience more intensive human disturbance and receive lower inputs of plant residues, root exudates, and senescent leaves compared to soils in natural and semi-natural ecosystems (Riffaldi et al., 2022). This human activity negatively impacts the soil biological and biochemical properties, leading to a decline in P and C cycling (Cui et al., 2019). Non-managed ecosystems like native forests, on the other hand, exhibit higher microbial activity due to their abundant SOM and available P content (Li et al., 2021), which facilitates the transformation of organic P into inorganic forms (Da Cunha et al., 2021; Balota et al., 2011). Cropland soils generally have lower SOC and MBC compared to non-managed soils (Barcelos Martins et al., 2019), and the global activity of extracellular enzymes is diminished as a result (Carlos et al., 2022). Furthermore, the activity of APases is influenced by common management practices (Katsalirou et al., 2016), with lower intensity management systems generally exhibiting higher APase activity compared to higher intensity management systems (Figure 4, Table S11).

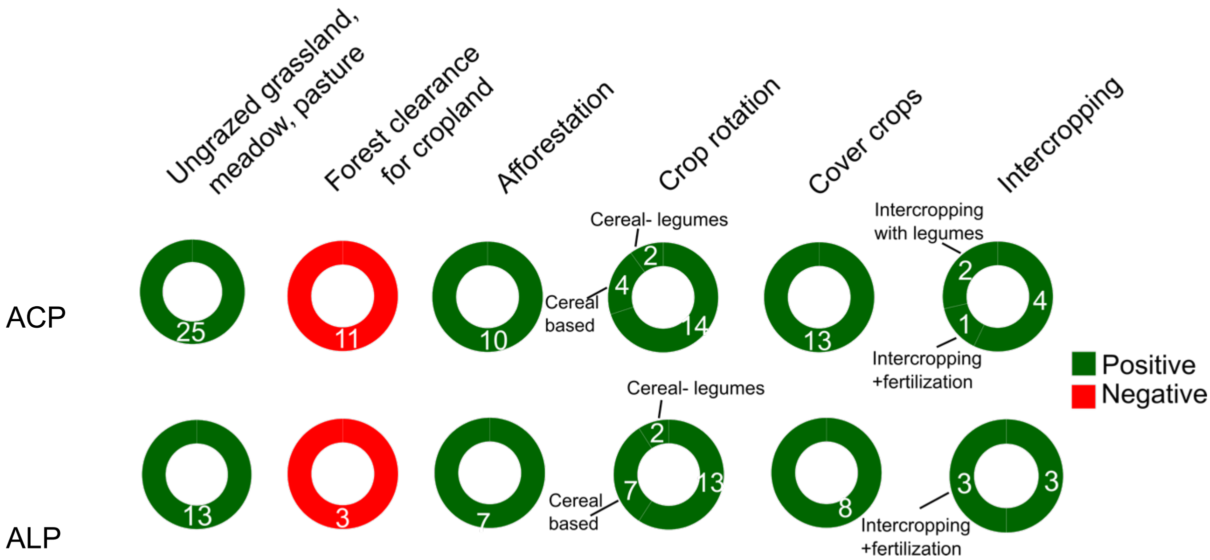

Figure 4. Number of single studies reporting direction of responses of ACP and ALP to land use change, crop rotation, cover crops and intercropping. Factors with fewer or equal than three entries in ACP or ALP response are excluded from the figure as they are considered unrepresentative (e.g., revegetation, plant invasion and forest clearance for cropland).

On the other hand, the conversion of intensively managed agricultural land back to grassland and forest systems, using native plant species (Li et al., 2021; Sciubba et al., 2021; Garcia et al., 1997), improves the supply of organic matter, enhancing APase activity, especially ACP (Paz-Ferreiro et al., 2009). Furthermore, a meta-analysis made by Margalef et al. (2021) has shown that invasive plant species can also increase ACP and ALP activity compared to native species, potentially due to differences in litter quality or quantity and related effects of changes in soil chemistry on microbial communities.

4.4.2.2 Crop rotations and species

APase activity in agricultural systems is influenced by crop rotation type, the crop species concerned, and also cover and intercropping practices (Figure 4, Table S12). Higher levels of ACP and ALP activity are observed in crop rotations in cereal-based rotations compared to cereal-legume rotations. This positive response has been attributed to increased ionic exchange capacity, SOC, MBC, and availability of essential nutrients such as P, K, and magnesium (Mg), as well as a greater presence of earthworms in rotation systems (Borase et al., 2020; Wozniak and Kawecka-Radomska, 2016). The inclusion of legumes and/or grasses in crop rotations, also as an intercrop, increases the synergism of microbial attributes (e.g., MBC, soil basal respiration, metabolic quotient, soil cultivable bacteria, fungi, actinobacteria and microorganisms with cellulolytic activity) (Martins Sousa et al., 2020) leading to higher productivity and economic profitability.

Different crop species influence soil N content, C sequestration, and P accumulation in long-term cropping systems (Dou et al., 2016), promoting efficient water, energy, and C use efficiency for crop production (Ansari et al., 2021). Maize monoculture, for example, exhibits higher soil APase activity compared to soybean, cowpea, or cotton, attributed to its deeper rooting system and this links to its growth advantage in low P availability conditions (Gao et al., 2010; Wang et al., 2017). Legume cultivation, especially lupine, which is the most well studied, enhances soil nutrient availability in a broad sense (Saad et al., 2018), and results in higher ACP and ALP activity compared to grain crops like wheat and rice, as legumes offer benefits on soil microbial communities, ensuring stability in intensive production systems (Aparna et al., 2016). Additionally, genetically modified crops, such as transgenic cotton, have been found to enhance ACP and ALP activity, although the effect is crop-specific and may not apply uniformly (e.g., in rice it is ACP that is enhanced). In horticultural crops like mango, kiwifruit, lettuce, potato, and tomato the activity of ACP is higher compared to cereal crops, attributed partly to intensive fertilization and irrigation management (Lago et al., 2019) (Figure 5, Table S12).

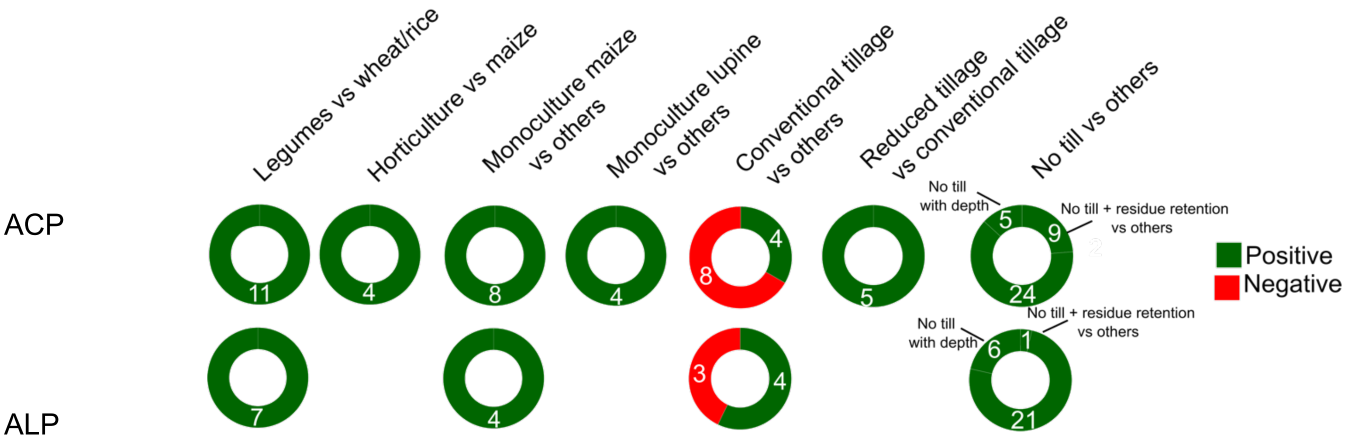

Figure 5. Number of single studies reporting direction of responses of ACP and ALP to crop species and tillage. Factors with fewer or equal than three entries in ACP and ALP response are excluded from the figure as they are considered unrepresentative (e.g. comparison between wheat and maize/rice, barley vs horticulture, monoculture sorghum vs others, monoculture transgenic cotton vs cotton, monoculture transgenic rice vs rice, no till with residue retention vs others and no till with depth vs others).

The use of cover crops (i.e., specific crops planted primarily to manage and could improve soil health rather than for direct harvest) has a positive impact on soil and crop health by improving pest and disease control, increasing water availability, and enhancing the abundance and activity of soil microorganisms (Feng et al., 2021). Cover crops have been shown to promote microbe-mediated processes that enhance ACP and ALP activities, likely through the increase of labile C and moisture in soil, maintenance of high organic matter levels, and stabilization of soil temperature (Adetunji et al., 2021; Yadav et al., 2019; Balota et al., 2010). Intercropping, which involves cultivating two or more crop species within a single cropping season, results in greater ACP and ALP activities compared to monocropping. As mentioned before, the use of legumes leads to an increase in APase activity, as reflected in the study results (Figure 4, Table S12). This may be due to the differential secretion of root exudates by intercropped species, which might provide a higher diversity of labile C substrates, with knock-on effects on soil microorganisms, thereby increasing enzyme activity (Wang et al., 2014). Moreover, when intercropping is associated with fertilization (section 3.2.4), APase activity is evidently enhanced.

4.4.2.3 Soil Tillage

Conventional soil tillage, which involves mechanical soil turning, aims to improve soil structure for sowing, seedling establishment, and weed control (Kroulík et al., 2009; Buhler, 2005). However, intensive tillage practices increase the risk of soil erosion and surface runoff, particularly following heavy rainfall, leading to the loss of SOM (Swedrzynska et al., 2013). In contrast, reduced (conservation) tillage practices minimize soil disturbance, resulting in better conservation of SOM (Melero et al., 2011), increased MBC, MBN (Gajda and Przewloka, 2012), and higher availability of

K and Mg. Along with the improvements in soil physical properties, soil aggregation, and reduced decomposition, reduced tillage contributes to the promotion of APase activity (Parihar et al., 2016) (Figure 5, Table S13).

No-till practices, which involve minimal soil disturbance and surface accumulation of crop residues, have distinct advantages in soil top layers even compared to reduced tillage. No-till practices lead to even greater reductions in the decomposition of labile organic matter, resulting in increased soil moisture, C, and N levels (Hatti et al., 2018; Doran, 1980; Redel et al., 2007). These practices also have positive effects on P fractions (e.g., inorganic, organic, and available P) (Yang et al., 2019). The increased availability of substrates for enzymes in the presence of higher residue inputs enhances the activity of enzymes such as ACP and ALP (Ahmed et al., 2019) (Figure 5, Table S13).

4.4.2.4 Soil Fertilization

Fertilization of agricultural soils to increase crop yields tends to positively impact APase activity (Figure 6, Table S14), although concurrent factors such as fertilizer nutrient balance and type, crop species, and growth stage may determine its activity (Jiang et al., 2019).

The application of combined (NPK) chemical (inorganic) fertilizer generally promotes APase activity (Miao et al., 2019). Nitrogen fertilization, in particular, tends to enhance the activities of ACP (Margalef et al., 2021; Jian et al., 2016; Marklein and Houlton, 2012) and ALP (Margalef et al., 2021; Marklein and Houlton, 2012). This suggests a connection between APases and the cycling of N. However, there are also reports indicating that ACP and ALP activity may decrease after mineral N fertilization, which suggests that substrate availability (i.e., specific organic N or P substrates in soil suspensions and soil filtrates) is more important than P deficiency (Janes-Bassett et al., 2022; Jarosch et al., 2019). Inorganic P fertilization alone tends to decrease the activity of both APases (Margalef et al., 2021; Marklein and Houlton, 2012), although there is also a meta-analysis suggesting no significant effects (Janes-Bassett et al., 2022).

The long-term application of organic fertilizer, derived from plant and animal material, is an important strategy for enhancing soil quality by increasing the abundance of soil microbes and the activity of extracellular enzymes such as ACP and ALP (Miao et al., 2019; Igalavithana et al., 2017). Organic fertilizers have a positive association with soil pH, especially in relation to ALP activity and P content (Durrer et al., 2021), leading to improved availability of soil nutrients, including labile C, N, and P through mineralization, as well as enhanced microbial biomass and abundance (Chatterjee et al., 2021; Dhanker et al., 2021). Various soil amendments, such as vermicompost (i.e., organic material biodegraded by earthworms and microorganisms), biostimulants (e.g., humic substances, marine macro-algae, protein hydrolysates, microbial inoculants, and plant extracts), biowastes (i.e., optimal doses of organic compounds and metals), or sludge (i.e., rich in organic matter, NO_3^--N, copper (Cu), cadmium (Cd), and organic P), have also shown the ability to increase ACP and ALP activity (Aponte et al., 2020) although do not report on their direct correlation over the very long term. The optimization of APase activity in soils without the addition of inorganic fertilizers can improve soil conservation, P release, and overall agricultural sustainability in ecosystems (Adetunji et al., 2017). Finally, the co-application of inorganic and organic fertilizers in agricultural soils is a common practice due to their complementary composition and functions, resulting in increased ACP and ALP activity, thereby providing high levels of plant-available P (Miao et al., 2019; Nobile et al., 2019).

Lime application to acid soils increases pH levels, improving plant access to essential nutrients for growth (Leirós et al., 1999), and has positive effects on ACP and ALP activity. However, it should be noted that when Ca-based lime is applied, reductions in APase activity have been observed, indicating that Ca availability may not be a limiting factor for plant growth (Makoi et al., 2010).

Combining fertilizers (organic or inorganic) with green manures (i.e., refer to non-crop plants, typically legumes, that are cultivated specifically to improve nutrient content in the soil) can have an impact on APase activity. While short-term trials combining green manure with fertilizers have not shown a significant effect on ACP activity, there is evidence for positive impacts on ACP and ALP activity in these trials when legume green manures are added with fertilizers (Bolton et al., 1985; Dhull et al., 2004). This is attributed to the increase in SOM content and the contribution of N fixed by symbiotic legume root bacteria (Balota et al., 2010).

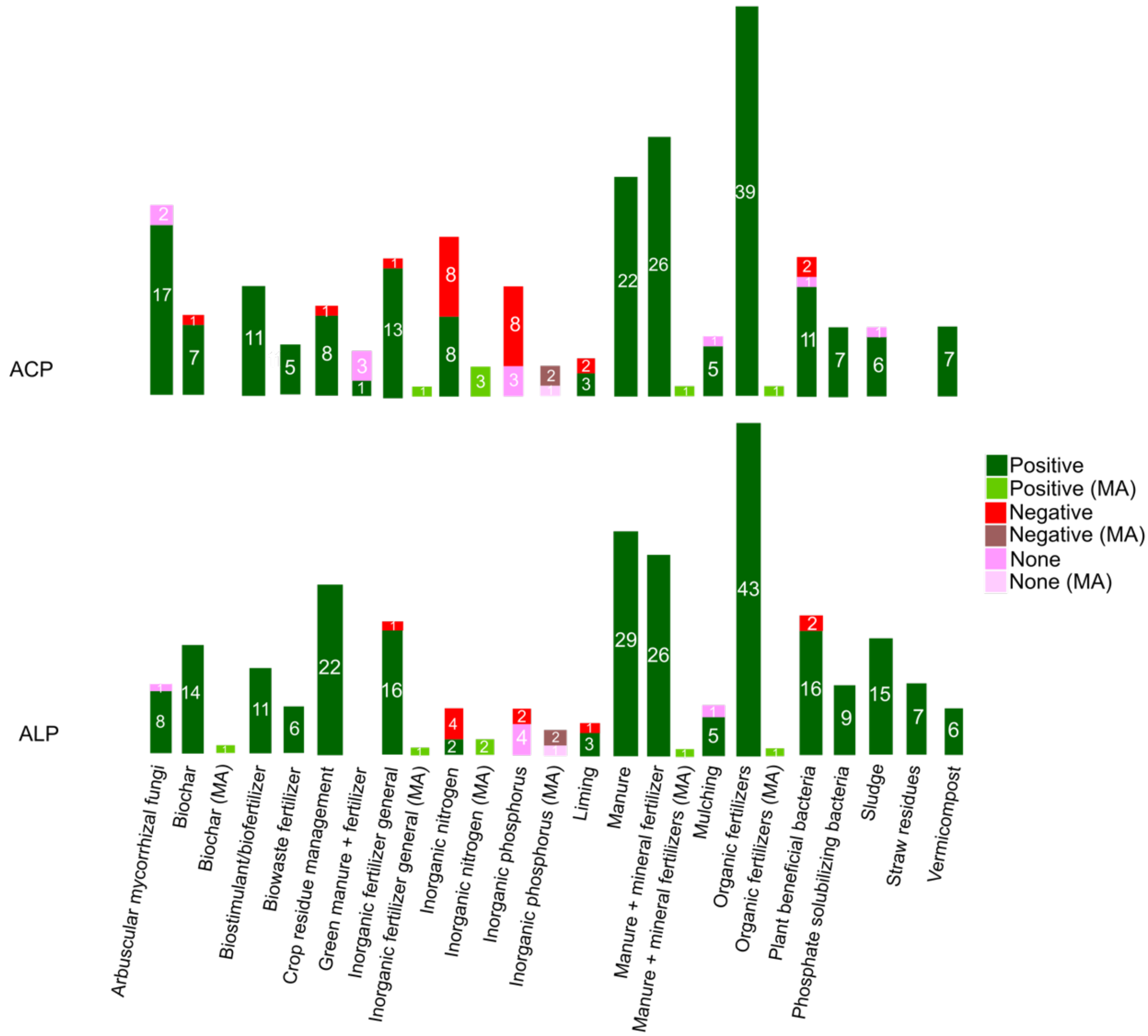

Figure 6. Number of single and meta-analysis studies reporting direction of ACP and ALP responses to agroecosystem fertilizer management practices. Factors with fewer or equal than three entries in ACP and ALP response are excluded from the figure as they are considered unrepresentative (e.g., green manure alone). The number of meta-analyses (MA) has been counted in order to complement the qualitative analysis based on vote counting.

Crop residues, whether applied on the soil surface as mulch or incorporated into the soil, can have positive effects on P transformation rates and soil P plant available pool (Singh et al., 2018). When crop residues, such as straw, are purposefully left on the soil surface, they gradually degrade over time, providing a greater and more sustained supply of substrate for soil (Chellappa et al., 2021). Mulching also increases the supply of carbohydrates and available nutrients such as N, P and K (Tu et al., 2006) having a positive impact on microbial communities (Wyszkowska, 2002). This prolonged breakdown of residues contributes to an increase in SOC content (Sharma and Dhaliwal, 2019) which in turn enhances ACP and ALP activity. The increased activity of APases resulting from crop residue mulching not only improves soil quality but also has the potential to reduce the need for chemical fertilizer inputs, leading to greater economic returns (Gaind and Nain, 2017).

Generally, biochar amendments are known to have a positive effect on both ACP and ALP activity (Table S14). According to the findings of Pokharel et al. (2020), the addition of biochar to soil increases the sensitivity of ALP to changes in pH. This heightened sensitivity results in an increased microbial demand for P and/or the potential limitation of P availability in the soil due to restricted microbial growth. However, despite these effects on ALP activity, the researchers did not observe significant impacts on ACP activity.

The practice of burning crop residues, on the other hand, releases environmental pollutants into the atmosphere (particulates carbon dioxide (CO_2) and carbon monoxide) and has negative impacts on ACP and ALP activity (Table S14). This is due to the changes it induces in soil chemical and biochemical processes, resulting in decreased soil nutrients, bacterial densities and MBC (Hoyle et al., 2006; Trujillo-Narcía et al., 2019).

Plant-beneficial microbes (PBMs) are increasingly used in biotechnology to reduce the reliance on agrochemicals with the aim of increasing soil nutrition, tolerance to stress, soil health, and crop yields (Emami et al., 2022; Parnell et al., 2016). Phosphate solubilizing bacteria (PSB) significantly contribute to the enhancement of APase activity and the availability of P to plants (Figure 6, Table S14). This is achieved through their possession of enzymes and metabolic mechanisms, enabling the conversion of insoluble forms of P into accessible forms for plant uptake (Wang et al., 2022). They accomplish this through the mineralization of organic P and the solubilization of inorganic P minerals, leading to greater P uptake in plant biomass (Tian et al., 2021). Incorporating PSB into the soil also results in faster humification of fresh organic matter and enhances mycorrhizal and endobacterial activities (Valarini et al., 2003). Likewise, soil inputs of bacteria, such as Bacillus, Pseudomonas, Aspergillus, Azospirillium, and Streptomyces, can increase both ACP and ALP activity, restore soil fertility, and promote plant productivity, taking into account addition parameters (e.g., EC, pH, and ionic concentration) to ensure proper nutritional management of the crop (Ruiz and Salas, 2019). The input of arbuscular mycorrhizal fungi to soils assists the plants in absorbing nutrients by hydrolyzing organic P, similar to solubilizing bacteria, which enhances APase activity. Additionally, soil acidification caused by fungi increases the availability of organic P substrates for APases, particularly ACP (Wang et al., 2013).

4.4.2.5 Pest and Weed Management

Plant protection products, including herbicides, fungicides, and insecticides, are widely used in agriculture to mitigate the detrimental effects of competition, disease, and herbivory on crop yields. However, their application can lead to changes in soil function and health, affecting soil respiration, biomass, and APase activity (Figure 7, Table S15). The impact of fungicides on APases is a topic of debate, with one meta-analysis reporting an increase in ACP activity rather than ALP activity (Riah et al., 2014), possibly due to the predominance of ACP analysis in agricultural soils. Likewise, the effects of insecticides on APases do not exhibit a clear trend. The results found suggest decreases in ACP and ALP activity, followed by recovery in ALP activity within 7 to 30 days after insecticide application (Riah et al., 2014; Mahapatra et al., 2017).

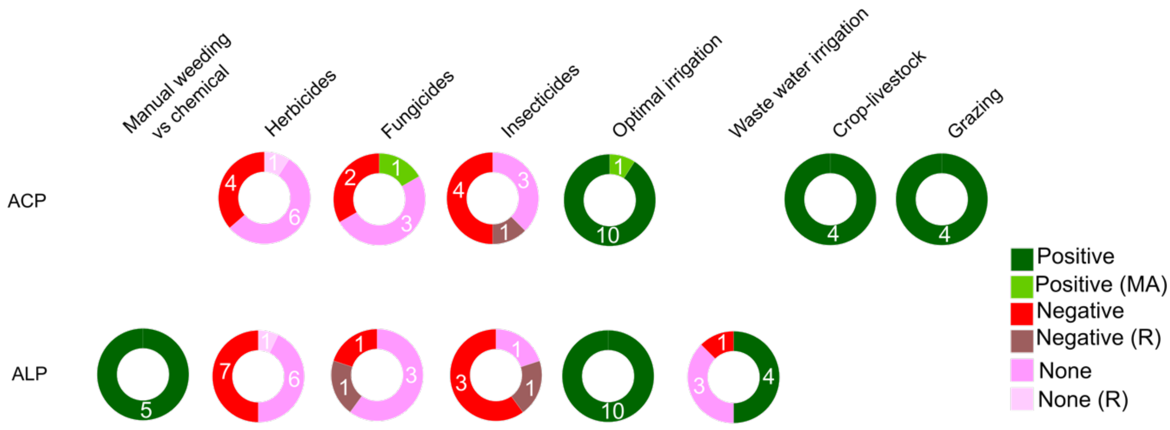

Figure 7. Number of single and meta-analysis/review studies reporting direction of responses of ACP and ALP pest and weed management, irrigation, crop-livestock and grazing management. Factors with fewer or equal than three entries in ACP and ALP response are excluded from the figure as they are considered unrepresentative (e.g., mowing). The number of meta-analyses (MA) and reviews (R) has been counted in order to complement the qualitative analysis based on vote counting.

Weed control plays a crucial role in reducing competition for resources by minimizing non-crop plant abundance. While manual weeding tends to increase APase activity (Figure 7, Table S15), the use of herbicides can result in either negative or negligible impacts on ACP and ALP activity (Riah et al., 2014). Importantly, any adverse effects from herbicide use typically do not persist beyond 30 days after application (Meher et al., 2021). However, cultivating crops in competition with weeds comparably with weeds cultivated alone negatively impacts ACP activity, microbial activity, and inorganic P solubilization (Fialho et al., 2020).

4.4.2.6 Irrigation

Crop irrigation is a practice that involves providing controlled amounts of fresh water or wastewater to sustain and enhance yields in water-scarce regions (Romero-Trigueros et al., 2021). Optimal irrigation levels have been found to positively affect APase activity (Figure 7, Table S16). Irrigated soils have increased availability of soil nutrients, leading to higher demand for P by plants and microbes during plant growth (Sun et al., 2020). Moreover, irrigation strategies can influence P availability, affecting P storage (Zhang et al., 2019) and the abundance of bacteria, which may explain the observed impacts on APases. Research on wastewater irrigation has shown varying effects on ACP and ALP activity, as it affects soil microbial activity and the microbial community (García-Orenes et al., 2015). However, long-term use of wastewater may potentially reduce agricultural crop yield (Kayikcioglu, 2018).

4.4.2.7 Livestock, grazing and mowing management

Livestock can play a significant role in enhancing agroecosystem function (Martins Sousa et al., 2020), and it can be managed within a livestock-only system (pasture) or in combination with crop production (livestock integration). In both cases, the presence of livestock contributes to an increase in soil MBC content and ACP activity (Figure 7, Table S17). Grazing-based pasture management has been linked to various positive effects, including higher soil pH, increased water content, and elevated levels of NO_3^-, NH_4^+, organic matter, and C:N ratios (Galindo et al., 2020). These conditions promote greater APase activity, mostly ACP (Figure 7, Table S17). On the other hand, mowing encourages the growth of plant species with competitive strategies (Catorci et al., 2011), while the contact between cut residues (substrates) and the soil reduces the activity of ALP (Zibilske et al., 2009) (Table S17).

4.4.3 Responses to Soil Pollutants

Soil pollution caused by heavy metals can disrupt biochemical, physiological, and metabolic processes. These pollutants alter nutrient stoichiometry and result in slower P cycling due to an imbalance between litter, soil organic matter, and the elemental composition of microbial biomass (Aponte et al., 2020). Heavy metals have an impact on APase activity (Figure 8, Table S18); negative responses of APase activity due to lead (Pb), chromium (Cr), nickel (Ni), zinc (Zn), cadmium (Cd), copper (Cu), manganese (Mn), arsenic (As), and mercury (Hg) have been observed, while positive responses are reported in one meta-analysis made by Aponte et al., (2020) concerning Cu and Cd. The negative APase responses are attributed to the harmful effects of heavy metals on soil microorganisms (Kunito et al., 2001), while the positive responses may indicate microbial metabolic stimulation resulting from increased levels of metals acting as micronutrients, such as Cu, Mn, cobalt (Co), Zn, and Cr (Mandal et al., 2021). Although heavy metals generally inhibit APase activity, the extent of the response depends on the initial metal composition in the soil, organic matter content, and the inhibition of microbial activity (Calvarro et al., 2014). In soils with high organic matter content, heavy metal impact on APases is relatively lower compared to other enzymes due to the positive association between APase and soil C abundance (De Santiago et al., 2013).

Negative effects on APase activity have been observed following the use of sewage sludge compost with high concentrations of heavy metals such as Pb, As, Cr, Cd, Ba, and Ag (Aponte et al., 2020). Similarly, soil pollution caused by petroleum and nanomaterials (NMs) also negatively affects APase activity, also leading to a decrease in bacterial species richness and diversity (Mitter et al., 2021). The use of NMs as biocides and plant growth promoters influences soil properties and enzyme activity, and a meta-analysis made by Lin et al. (2021) showed that C, Cu, and Ag -NMs result in a decrease in ACP activity, whereas low soil concentrations of Fe-NMs stimulate ACP activity (Table S18).

4.4.4 Impacts of climate change

The rapid global temperature increases, shifts in rainfall patterns, and rising atmospheric CO_2 concentrations that the planet is experiencing are significantly impacting plant stoichiometry and productivity, potentially affecting APase activity (Table S19). Existing meta-analyses have suggested that climate warming could increase ACP activity in agroecosystems and forests (Sun et al., 2020; Meng et al., 2020), primarily due to reduced soil P content (e.g., Olsen P and total soil P) resulting from accelerated plant growth and enhanced plant P acquisition (Sardans et al., 2006). However, another meta-analysis that encompassed grasslands and other natural ecosystems found no correlation between temperature and both APases (Margalef et al., 2021).

The predicted increase in rainfall intensity in some areas under ongoing climate change is likely to lead to higher topsoil nutrient losses, as high soil water availability to plants can elevate groundwater chemistry, including the dissolved content of bicarbonate, sulphate, Cl^- anions, and Na^+, Ca^{2+}, Mg^{2+}, and K^+ cations (Yao et al., 2021). Elevated mean annual precipitation (MAP) levels have been linked to increased ACP and ALP activity (Sun et al., 2020) compared to controls in models of humid grassland soils and irrigated (Ghiloufi and Chaieb, 2021; Morugán-Coronado et al., 2019). Conversely, drier conditions are also expected to become more frequent under climate change in some regions, resulting in reduced demand for available P forms and associated enzyme activity (Sardans and Peñuelas, 2004). APase activity tends to respond negatively to water scarcity and drought in agroecosystems (Figure 9, Table S19), particularly in grasslands and other natural ecosystems under Mediterranean climate conditions known for their seasonal aridity (Sun et al., 2020). However, individual studies focused on temperate pasturelands have reported mixed responses, as changes in precipitation amounts may not significantly alter microbial biomass, allowing soil microbes to adapt to soil drying (Landesman and Dighton, 2010).

APase activity exhibits seasonal variations (Figure 9, Table S19), with higher activity recorded during periods of increased plant growth. In contrast, APase activity tends to be lower during drier cropping periods when human activities in agroecosystems are more pronounced (Jaskulska, 2020).

The influence of anthropogenic CO_2 emissions on APases are not significative but ongoing increases have been linked to enhanced ACP and ALP activities in grasslands and natural ecosystems (Margalef et al., 2021), likely due to elevated microbial activity and increased soil P availability (Dey et al., 2019) (Table S19). However, this is not sufficient to determine the reason why this trend is the way it is.

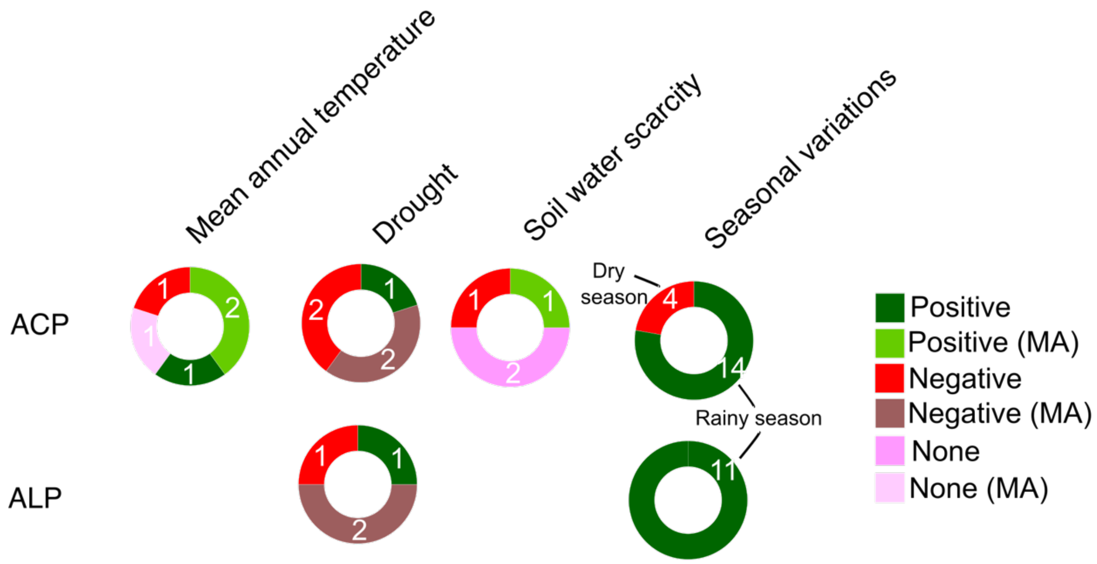

Figure 9. Number of single and meta-analysis studies reporting direction of responses of ACP and ALP to climate change factors. Factors with fewer or equal than three entries in ACP and ALP response are excluded from the figure as they are considered unrepresentative (e.g., mean annual precipitation, soil water availability, CO_2 fertilization). The number of meta-analyses (MA) has been counted in order to complement the qualitative analysis based on vote counting.

4.4.5 Relationship between APases and crop yields

Investigating the potential effects of promoting APase activity in agricultural soils on crop yields is important for addressing global goals of increasing food security and crop productivity. Studies have primarily focused on cereals, although a few other crops have also been examined (Table S20). Positive connections have been observed between APase activity and yields of wheat, maize, barley, beet, fava bean, and lentil. However, the available literature does not show any association between APase activity and tree fruit yields (such as organic plum and orange). Interestingly, a negative relationship has been reported between rice yield and ALP activity, which can be attributed to variations in P availability from inorganic and organic sources, other P-regulating enzymes, and changes in soil pH (Basak et al., 2017). Crop yield is influenced by various soil physicochemical parameters, including N, SOM, and high accumulation of dry matter (de Castro Lopes et al., 2013; Tarafdar and Rao, 1996). Additionally, while crop yields are directly correlated with the amount of plant available P (Moharana and Biswas, 2022) and low soil available P directly affects APase release, there are limited studies that have directly associated APases with crop yield, suggesting that this link needs further research.

4.5 Conclusions

Due to the extensive number of studies evaluated and the results obtained, this systematic review, which is partly quantitative but predominantly qualitative, underscores the significance of APases in driving P uptake in agroecosystems and their role in the global P cycle. Observable changes in APase activity can be attributed to soil biophysicochemical properties, agricultural management practices, environmental pollutants, and climate change factors.

Firstly, microbial abundance, biomass, and activity demonstrate a positive relationship with both ACP and ALP activity. These enzymes are further correlated with pH levels, showing a positive association with soil texture—especially clay content—soil moisture, soil organic C, and available forms of N and P.

Secondly, the activity of ACP and ALP is generally enhanced by management practices promoting soil health. These practices include optimal irrigation, conservation or no-tillage techniques, crop rotation or intercropping, cover crops, and organic fertilization through the use of amendments such as organic manures, vermicompost, green manures, crop residue management, biochar, and biostimulants/biofertilizers containing beneficial bacteria and bacteria and fungi (see Figure 10).

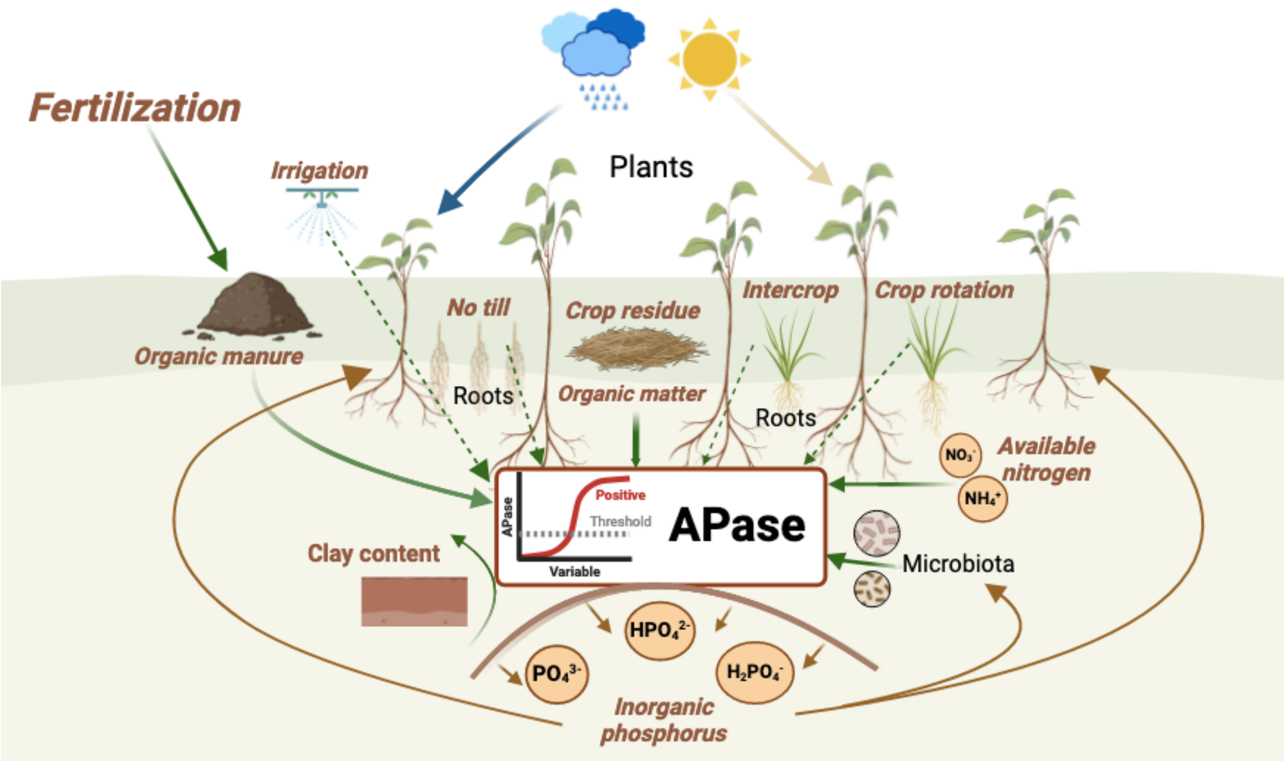

Figure 10. The factors influencing APase activity in belowground environments can be summarized through colour-coded lines and names. Green lines represent the most positive influential factors. The solid lines refer to internal soil processes, the dashed lines correspond to crop management on the soil. When the concentration of inorganic P in the soil is low, plants, roots, and microbiota release APase. The brown lines represent the role of APase activity in providing assimilable P for plant and microbiota uptake. Physicochemical properties, such as soil organic matter, available N, clay content, and management practices like organic manure fertilization, no-till, crop residue utilization, intercropping, and crop rotation, are also depicted in brown as they enhance APase activity. Additionally, climate factors that increase APase activity, including optimal water levels, rainfall (indicated with a cloud) and temperature (indicated with a sun), are also shown.

On the other hand, factors such as soil depth, salinity, pesticide and sewage sludge use, and high concentrations of heavy metals or other pollutants in agricultural soils have a detrimental effect on APase activity. For this reason, the activity of APases is used as an indicator of soil quality in agricultural systems.

Perspectives on Knowledge Gaps

Several knowledge gaps have been identified in this review, such as the relationship between APases and crop productivity, which still remains unclear. However, there seems to be a direct relationship between cereal and legume production with the activity of APases that should be studied, especially when intercropping or crop rotations are used. Reviewing APase responses to crop management practices is problematic due to the diverse and complex nature of agronomic techniques. Thus, the interrelation between P availability, on one hand, and the production and activity of APase on the other hand, exhibits highly nuanced cause-and-effect dynamics. However, it is noteworthy that the adoption of conservative soil practices linked to non-intensive agricultural management holds promise for enhancing the response of APase activity.

The relationship between APases and P has been widely studied, but not the relationship with K, which is also important for plant growth and soil fertility. Plant uptake of P is influenced by the availability of K, which in turn depends on N and C levels. This extremely complex mechanism, involving microorganisms as well, should be experimentally studied, incorporating those strategies that increase enzymatic capacity investment and reduce competition and interference with other organisms.

Moreover, strategies to affect APase activity also involve other soil parameters altered by agricultural practices. For instance, increased CO_3^{2-}, which is carried by water and mobilized between soil horizons and is common in the pH range of agricultural soils, negatively affects the activity of ACP, which is directly linked to plants and consequently may affect their production. Moreover, assessing APase with respect to the availability of nutrients (P or N) in relation to C (e.g., C:P, C:N) would yield valuable information to designate it as a key soil quality variable. These ratios are crucial indicators of soil fertility, microbial activity, and plant nutrient uptake, influencing the overall health and productivity of the ecosystem. The repeated, excessive use of mineral fertilizers in agricultural soils for decades has substantially altered the microbial population adapting to this nutrient excess which directly affects ALP activity mainly released by soil microorganisms. Studies evaluating the response of APases based on soil mesofauna, as well as macrofauna, which regulate soil organic matter transformations and significantly influence nutrient dynamics, are lacking. The activity of these organisms can notably change P availability in active soils and, in parallel, may enhance crop yield.

Ultimately, although the selected studies are too diverse to produce a meaningful summary estimate of the effect of more than two factors, the results demonstrate that there is sufficient data to focus on combined factors that clearly enhance APase activity. The information obtained will enable us to manage agricultural systems to promote the capabilities of plants and associated microorganisms to assimilate nutrients more effectively and rapidly and, at the same time, enhance our understanding of microbial-mediated processes and the dynamics of soil health. The results obtained could guide professional practice on one hand and future research on the other. This approach could achieve a cost-benefit ratio where APases, among other enzymes, would play a determining role.

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4.7 References

Acosta-Martínez, V., Lascano, R., Calderón, F., Booker, J.D., Zobeck, T.M., Upchurch, D.R., 2011. Dryland cropping systems influence the microbial biomass and enzyme activities in a semiarid sandy soil. Biology and Fertility of Soils 47, 655–667. https://doi.org/10.1007/s00374-011-0565-1.

Adetunji, A.T., Lewu, F.B., Mulidzi, R., Ncube, B., 2017. The biological activities of β-glucosidase, phosphatase and urease as soil quality indicators: A review. Journal of Soil Science and Plant Nutrition 17, 794–807. https://doi.org/10.4067/S0718-95162017000300018.

Adetunji, A.T., Ncube, B., Meyer, A.H., Olatunji, O.S., Mulidzi, R., Lewu, F.B., 2021. Soil pH, nitrogen, phosphatase and urease activities in response to cover crop species, termination stage and termination method. Heliyon 7, e05980. https://doi.org/10.1016/j.heliyon.2021.e05980.

Adrover, M., Moyà, G., Vadell, J., 2017. Seasonal and depth variation of soil chemical and biological properties in alfalfa crops irrigated with treated wastewater and saline groundwater. Geoderma 286, 54–63. https://doi.org/10.1016/j.geoderma.2016.10.024.

Ahmed, W., Qaswar, M., Jing, H., Wenjun, D., Geng, S., Kailou, L., Ying, M., Ao, T., Mei, S., Chao, L., Yongmei, X., Ali, S., Normatov, Y., Mehmood, S., Khan, M.N., Huimin, Z., 2020. Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils. Journal of Soils and Sediments 20, 850–861. https://doi.org/10.1007/s11368-019-02468-3.

Alef, K., Nannipieri, P. (Eds.), 1995. 7 - Enzyme activities, in: Methods in Applied Soil Microbiology and Biochemistry. Academic Press, London, pp. 311–373. https://doi.org/10.1016/B978-012513840-6/50022-7.

Allison, S.D., Weintraub, M.N., Gartner, T.B., Waldrop, M.P., 2011. Evolutionary-Economic Principles as Regulators of Soil Enzyme Production and Ecosystem Function, in: Shukla, G., Varma, A. (Eds.), Soil Enzymology. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 229–243. https://doi.org/10.1007/978-3-642-14225-3_12.

Al-Taweel, L.S.J., Jubouri, G.A.A.A.-, 2019. Effect of Agricultural Exploitation on the Activity of Alkaline Phosphatase and Its Kinetic Properties in Some Soils. Al-Qadisiyah Journal for Agriculture Sciences (QJAS) (P-ISSN: 2077-5822, E-ISSN: 2617-1479) 9, 120–135. https://doi.org/10.33794/qjas.vol9.iss1.69.

Angers, D.A., Bissonnette, N., Legere, A., Samson, N., 1993. Microbial and biochemical changes induced by rotation and tillage in a soil under barley production. Canadian Journal of Soil Science 73, 39–50. https://doi.org/10.4141/cjss93-004.

Ansari, M.A., Saha, S., Das, A., Lal, R., Das, B., Choudhury, B.U., Roy, S.S., Sharma, S.K., Singh, I.M., Meitei, C.B., Changloi, K.L., Singh, L.S., Singh, N.A., Saraswat, P.K., Ramakrishna, Y., Singh, D., Hazarika, S., Punitha, P., Sandhu, S.K., Prakash, N., 2021. Energy and carbon budgeting of traditional land use change with groundnut-based cropping system for environmental quality, resilient soil health and farmers income in eastern Indian Himalayas. Journal of Environmental Management 293, 112892. https://doi.org/10.1016/j.jenvman.2021.112892.

Antolín, M.C., Pascual, I., García, C., Polo, A., Sánchez-Díaz, M., 2005. Growth, yield and solute content of barley in soils treated with sewage sludge under semiarid Mediterranean conditions. Field Crops Research 94, 224–237. https://doi.org/10.1016/j.fcr.2005.01.009.

Aparna, K., Rao, D.L.N., Balachandar, D., 2016. Microbial Populations, Activity and Gene Abundance in Tropical Vertisols Under Intensive Chemical Farming. Pedosphere 26, 725–732. https://doi.org/10.1016/S1002-0160(15)60079-0.

Aponte, H., Meli, P., Butler, B., Paolini, J., Matus, F., Merino, C., Cornejo, P., Kuzyakov, Y., 2020. Meta-analysis of heavy metal effects on soil enzyme activities. Science of the Total Environment 737, 139744. https://doi.org/10.1016/j.scitotenv.2020.139744.

Arora, R., Sharma, V., Sharma, S., Maini, A., Dhaliwal, S.S., 2021. Temporal changes in soil biochemical properties with seasons under rainfed land use systems in Shiwalik foothills of northwest India. Agroforestry Systems 95, 1479–1491. https://doi.org/10.1007/s10457-021-00654-2.

Atoloye, I.A., Jacobson, A., Creech, E., Reeve, J., 2021. Variable impact of compost on phosphorus dynamics in organic dryland soils following a one-time application. Soil Science Society of America Journal 85, 1122–1138. https://doi.org/10.1002/saj2.20275.

Balachandar, R., Biruntha, M., Yuvaraj, A., Thangaraj, R., Subbaiya, R., Govarthanan, M., Kumar, P., Karmegam, N., 2021. Earthworm intervened nutrient recovery and greener production of vermicompost from Ipomoea staphylina – An invasive weed with emerging environmental challenges. Chemosphere 263. https://doi.org/10.1016/j.chemosphere.2020.128080.

Balota, E.L., Chaves, J.C.D., 2010. Enzymatic activity and mineralization of carbon and nitrogen in soil cultivated with coffee and green manures. Revista Brasilieria de Ciência do Solo 34, 1573–1583. https://doi.org/10.1590/S0100-06832010000500010.

Balota, E.L., Machineski, O., Truber, P.V., 2011. Soil enzyme activities under pig slurry addition and different tillage systems. Acta Scientiarum. Agronomy 33, 729–737. https://doi.org/10.4025/actasciagron.v33i4.9816.

Bandick, A.K., Dick, R.P., 1999. Field management effects on soil enzyme activities. Soil Biology and Biochemistry 31, 1471–1479. https://doi.org/10.1016/S0038-0717(99)00051-6.

Banerjee, K., Dasgupta, S., Oulkar, D.P., Patil, S.H., Adsule, P.G., 2008. Degradation kinetics of forchlorfenuron in typical grapevine soils of India and its influence on specific soil enzyme activities. Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes 43, 341–349. https://doi.org/10.1080/03601230801941691.

Banerjee, M.R., Burton, D.L., Grant, C.A., 1999. Influence of urea fertilization and urease inhibitor on the size and activity of the soil microbial biomass under conventional and zero tillage at two sites. Canadian Journal of Soil Science 79, 255–263. https://doi.org/10.4141/S97-049.

Barcelos Martins, L.N., de Aguiar Santiago, F.L., Montecchia, M.S., Correa, O.S., Saggin Junior, O.J., Damacena de Souza, E., Barbosa Paulino, H., Carbone Carneiro, M.A., 2019. Biochemical and Biological Properties of Soil from Murundus Wetlands Converted into Agricultural Systems. Revista Brasileira de Ciência do Solo, 43: e0180183. https://doi.org/10.1590/18069657rbcs20180183.

Basak, N., Mandal, B., Datta, A., Mitran, T., Biswas, S., Dhar, D., Badole, S., Saha, B., Hazra, G.C., 2017. Impact of Long-Term Application of Organics, Biological, and Inorganic Fertilizers on Microbial Activities in Rice-Based Cropping System. Communications in Soil Science and Plant Analysis 48, 2390–2401. https://doi.org/10.1080/00103624.2017.1411502.

Bergstrom, D.W., Monreal, C.M., King, D.J., 1998. Sensitivity of Soil Enzyme Activities to Conservation Practices. Soil Science Society of America Journal 62, 1286–1295. https://doi.org/10.2136/sssaj1998.03615995006200050020x.

Bolton, H. Jr., Elliott, L.F., Papendick, R.I., Bezdicek, D.F., 1985. Soil microbial biomass and selected soil enzyme activities: Effect of fertilization and cropping practices. Soil Biology and Biochemistry 17, 297–302. https://doi.org/10.1016/0038-0717(85)90064-1.

Borase, D.N., Nath, C.P., Hazra, K.K., Senthilkumar, M., Singh, S.S., Praharaj, C.S., Singh, U., Kumar, N., 2020. Long-term impact of diversified crop rotations and nutrient management practices on soil microbial functions and soil enzymes activity. Ecological Indicators 114, 106322. https://doi.org/10.1016/j.ecolind.2020.106322.

Brockett, B.F.T., Prescott, C.E., Grayston, S.J., 2012. Soil moisture is the major factor influencing microbial community structure and enzyme activities across seven biogeoclimatic zones in western Canada. Soil Biology and Biochemistry 44, 9–20. https://doi.org/10.1016/j.soilbio.2011.09.003.

Buck, C., Langmaack, M., Schrader, S., 2000. Influence of mulch and soil compaction on earthworm cast properties. Applied Soil Ecology 14, 223–229. https://doi.org/10.1016/S0929-1393(00)00054-8.

Buhler, D.D., 2005. Weed management. Pp. 323–28 in Encyclopedia of Soils in the Environment, edited by D. Hillel. Oxford: Elsevier.

Burns, R.G., 1978. Soil enzymes. Academic Press, London. c.9b01784.Burns, R.G., 1982. Enzyme activity in soil: Location and a possible role in microbial ecology. Soil Biology and Biochemistry 14, 423–427. https://doi.org/10.1016/0038-0717(82)90099-2.

Burns, R.G., 1982. Enzyme activity in soil: Location and a possible role in microbial ecology. Soil Biology and Biochemistry 14, 423–427. https://doi.org/10.1016/0038-0717(82)90099-2.

Burns, R.G., Dick, R.P., 2002. Enzymes in the environment: activity, ecology, and applications (1st ed.). CRC Press. https://doi.org/10.1201/9780203904039.

Calvarro, L.M., Santiago-Martín, A. de, Gómez, J.Q., González-Huecas, C., Quintana, J.R., Vázquez, A., Lafuente, A.L., Fernández, T.M.R., Vera, R.R., 2014. Biological activity in metal-contaminated calcareous agricultural soils: The role of the organic matter composition and the particle size distribution. Environmental Science and Pollution Research 21, 6176–6187. https://doi.org/10.1007/s11356-014-2561-0.

Carlos, F.S., Schaffer, N., Mariot, R.F., Fernandes, R.S., Boechat, C.L., Roesch, L.F.W., Camargo, F.A. de O., 2022. Soybean crop incorporation in irrigated rice cultivation improves nitrogen availability, soil microbial diversity and activity, and growth of ryegrass. Applied Soil Ecology 170. https://doi.org/10.1016/j.apsoil.2021.104313.

Catorci, A., Ottaviani, G., Ballelli, S., Cesaretti, S., 2011. Functional differentiation of central apennine grasslands under mowing and grazing disturbance regimes. Polish Journal of Ecology 59 (1): 115-128.

Cattaneo, F., Gennaro, P.D., Barbanti, L., Giovannini, C., Labra, M., Moreno, B., Benitez, E., Marzadori, C., 2014. Perennial energy cropping systems affect soil enzyme activities and bacterial community structure in a South European agricultural area. Applied Soil Ecology 84, 213–222. https://doi.org/10.1016/j.apsoil.2014.08.003.

Cawley, G.C. 2006. Leave-One-Out Cross-Validation Based Model Selection Criteria for Weighted LS-SVMs, in: The 2006 IEEE International Joint Conference on Neural Network Proceedings. Presented at the The 2006 IEEE International Joint Conference on Neural Network Proceedings, pp. 1661–1668. https://doi.org/10.1109/IJCNN.2006.246634

Chatterjee, D., Nayak, A.K., Mishra, A., Swain, C.K., Kumar, U., Bhaduri, D., Panneerselvam, P., Lal, B., Gautam, P., Pathak, H., 2021. Effect of Long-Term Organic Fertilization in Flooded Rice Soil on Phosphorus Transformation and Phosphate Solubilizing Microorganisms. Journal of Soil Science and Plant Nutrition 21, 1368–1381. https://doi.org/10.1007/s42729-021-00446-8.

Chellappa, J., Sagar, K.L., Sekaran, U., Kumar, S., Sharma, P., 2021. Soil organic carbon, aggregate stability and biochemical activity under tilled and no-tilled agroecosystems. Journal of Agriculture and Food Research 4, 100139. https://doi.org/10.1016/j.jafr.2021.100139.

Chen, S., Cade-Menun, B.J., Bainard, L.D., Luce, M.S., Hu, Y., Chen, Q., 2021. The influence of long-term N and P fertilization on soil P forms and cycling in a wheat/fallow cropping system. Geoderma 404, 115274. https://doi.org/10.1016/j.geoderma.2021.115274.

Choudhary, M., Jat, H.S., Datta, A., Yadav, A.K., Sapkota, T.B., Mondal, S., Meena, R.P., Sharma, P.C., Jat, M.L., 2018. Sustainable intensification influences soil quality, biota, and productivity in cereal-based agroecosystems. Applied Soil Ecology 126, 189–198. https://doi.org/10.1016/j.apsoil.2018.02.027.

Chowdhury, N., Rasid, M.M., 2021. Evaluation of brick kiln operation impact on soil microbial biomass and enzyme activity. Soil Science Annual 72, 1–16. https://doi.org/10.37501/soilsa/132232.

Cross, A.F., Schlesinger, W.H., 1995. A literature review and evaluation of the. Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. Geoderma 64, 197–214. https://doi.org/10.1016/0016-7061(94)00023-4.

Cui, Y., Fang, L., Guo, X., Wang, X., Wang, Y., Zhang, Y., Zhang, X., 2019. Responses of soil bacterial communities, enzyme activities, and nutrients to agricultural-to-natural ecosystem conversion in the Loess Plateau, China. Journal of Soils and Sediments 19, 1427–1440. https://doi.org/10.1007/s11368-018-2110-4.

da Cunha, J.R., Freitas, R. de C.A. de, Souza, D.J. de A.T., Gualberto, A.V.S., Souza, H.A. de, Leite, L.F.C., 2021. Soil biological attributes in monoculture and integrated systems in the cerrado region of Piauí State, Brazil. Acta Scientiarum - Agronomy 43, 1–9. https://doi.org/10.4025/ACTASCIAGRON.V43I1.51814.

de Castro Lopes, A., Gomes de Sousa, D.M., Chaer, G.M., Bueno dos Reis Junior, F., Goedert, W.J., de Carvalho Mendes, I., 2013. Interpretation of microbial soil indicators as a function of crop yield and organic carbon. Soil Science Society of America Journal, 77, 461. http://dx.doi.org/10.2136/sssaj2012.0191.

de Jesus Franco, A., Valadares da Silva, A.P., Silva Souza, A.B., Loverde Oliveira, R., Rodrigues Batista, É., Damacena de Souza, E., Oliveira Silva, A., Carbone Carneiro, M.A., 2020). Plant diversity in integrated crop-livestock systems increases the soil enzymatic activity in the short term. Pesquisa Agropecuária Tropical, 50(). https://doi.org/10.1590/1983-40632020v5064026.

de Santiago-Martín, A., Cheviron, N., Quintana, J.R., González, C., Lafuente, A.L., Mougin, C., 2013. Metal contamination disturbs biochemical and microbial properties of calcareous agricultural soils of the Mediterranean area. Archives of Environmental Contamination and Toxicology 64, 388–398. https://doi.org/10.1007/s00244-012-9842-8.

Dey, S.K., Chakrabarti, B., Purakayastha, T.J., Prasanna, R., Mittal, R., Singh, S.D., Pathak, H., 2019. Interplay of phosphorus doses, cyanobacterial inoculation, and elevated carbon dioxide on yield and phosphorus dynamics in cowpea. Environmental Monitoring and Assessment 191. https://doi.org/10.1007/s10661-019-7378-3.

Dhanker, R., Chaudhary, S., Goyal, S., Kumar, R., 2022. Soil microbial properties and functional diversity in response to sewage sludge amendments. Archives of Agronomy and Soil Science 68, 809–822. https://doi.org/10.1080/03650340.2020.1855328.

Dhull, S., Goyal, S., Kapoor, K., Mundra, M., 2004. Microbial biomass carbon and microbial activities of soils receiving chemical fertilizers and organic amendments. International Journal of Phytoremediation 21, 641–647. https://doi.org/10.1080/08927010400011294.

Dick, R.P., Rasmussen, P.E., Kerle, E.A., 1988. Influence of long-term residue management on soil enzyme activities in relation to soil chemical properties of a wheat-fallow system. Biology and Fertility of Soils 6, 159–164. https://doi.org/10.1007/BF00257667.

Dick, W.A., 1984. Influence of Long-Term Tillage and Crop Rotation Combinations on Soil Enzyme Activities. Soil Science Society of America Journal 48, 569–574. https://doi.org/10.2136/sssaj1984.03615995004800030020x.

Dinesh, R., Ramanathan, G., Singh, H., 1995. Influence of chloride and sulphate ions on soil enzymes. Journal of Agronomy and Crop Science 175, 129–133. https://doi.org/10.1111/j.1439-037X.1995.tb01138.x.

Doran, J.W., 1980. Soil Microbial and Biochemical Changes Associated with Reduced Tillage. Soil Science Society of America Journal 44, 765–771. https://doi.org/10.2136/sssaj1980.03615995004400040022x.

Dou, F., Wright, A.L., Mylavarapu, R.S., Jiang, X., Matocha, J.E., 2016. Soil Enzyme Activities and Organic Matter Composition Affected by 26 Years of Continuous Cropping. Pedosphere 26, 618–625. https://doi.org/10.1016/S1002-0160(15)60070-4.

Dubey, A.N., Chattopadhyaya, N., Mandal, N., 2021. Variation in Soil Microbial Population and Soil Enzymatic Activities Under Zincated Nanoclay Polymer Composites (ZNCPCs), Nano-ZnO and Zn Solubilizers in Rice Rhizosphere. Agricultural Research 10, 21–31. https://doi.org/10.1007/s40003-020-00488-x.

Durrer, A., Gumiere, T., Zagatto, M.R.G., Feiler, H.P., Silva, A.M.M., Longaresi, R.H., Homma, S.K., Cardoso, E.J.B.N., 2021. Organic farming practices change the soil bacteria community, improving soil quality and maize crop yields. PeerJ 9, 1–24. https://doi.org/10.7717/peerj.11985.

Dutta, D., Meena, A.L., Kumar, G.C., Mishra, R.P., Ghasal, P.C., Kumar, Amit, Chaudhary, J., Bhanu, C., Kumar, V., Kumar, Ankur, Tewari, R.B., Panwar, A.S., 2020. Long Term Effect of Organic, Inorganic and Integrated Nutrient Management on Phosphorous Dynamics under Different Cropping Systems of Typic Ustochrept Soil of India. Communications in Soil Science and Plant Analysis 51, 2746–2763. https://doi.org/10.1080/00103624.2020.1849258.

Eichler-Löbermann, B., Zicker, T., Kavka, M., Busch, S., Brandt, C., Stahn, P., Miegel, K., 2021. Mixed cropping of maize or sorghum with legumes as affected by long-term phosphorus management. Field Crops Research 265. https://doi.org/10.1016/j.fcr.2021.108120.

Eivazi, F., Tabatabai, M.A., 1977. Phosphatases in soils. Soil Biology and Biochemistry 9, 167–172. https://doi.org/10.1016/0038-0717(77)90070-0.

Emami, S., Alikhani, H.A., Pourbabaee, A.A., Etesami, H., Sarmadian, F., Motesharezadeh, B., Taghizadeh–Mehrjardi, R., 2022. Performance Evaluation of Phosphate-Solubilizing Fluorescent Pseudomonads in Minimizing Phosphorus Fertilizer Use and Improving Wheat Productivity: a Two-Year Field Study. Journal of Soil Science and Plant Nutrition 22, 1224–1237. https://doi.org/10.1007/s42729-021-00726-3.

European Commission - Joint Research Centre, Institute for Prospective Technological Studies, Rodríguez Cerezo, E., Lusser, M., Comparative regulatory approaches for new plant breading techniques – Workshop proceedings, European Commission, 2010, https://data.europa.eu/doi/10.2779/14571.

Faostat. Comparar datos (2021, 17 September.). Organización de las Naciones Unidas para la alimentación y la Agricultura http://www.fao.org/faostat/es/#compare.

Feng, H., Sekaran, U., Wang, T., Kumar, S., 2021. On-farm assessment of cover cropping effects on soil C and N pools, enzyme activities, and microbial community structure. Journal of Agricultural Science 159, 216–226. https://doi.org/10.1017/S002185962100040X.

Fialho, C.M.T., Silva, A.A., Melo, C.A.D., Costa, M.D., Souza, M.WR., Reis, L.A.C., 2020. Weed interference in soybean crop affects soil microbial activity and biomass. Planta Daninha, 38. https://doi.org/10.1590/s0100-83582020380100046.

Furtak, K., Gawryjołek, K., Gajda, A.M., Gałązka, A., 2017. Effects of maize and winter wheat grown under different cultivation techniques on biological activity of soil. Plant, Soil and Environment 63, 449–454. https://doi.org/10.17221/486/2017-PSE.

Gaind, S., Nain, L., 2007. Chemical and biological properties of wheat soil in response to paddy straw incorporation and its biodegradation by fungal inoculants. Biodegradation 18, 495–503. https://doi.org/10.1007/s10532-006-9082-6.

Gajda, A.M., Przewłoka, B., 2012. Soil biological activity as affected by tillage intensity. International Agrophysics 26, 15–23. https://doi.org/10.2478/v10247-012-0003-0.

Galindo, F.S., Delate, K., Heins, B., Phillips, H., Smith, A., Pagliari, P.H., 2020. Cropping system and rotational grazing effects on soil fertility and enzymatic activity in an integrated organic crop-livestock system. Agronomy 10, 1–18. https://doi.org/10.3390/agronomy10060803.

Gao, Y., Zhou, P., Mao, L., Zhi, Y., Zhang, C., Shi, W., 2010. Effects of plant species coexistence on soil enzyme activities and soil microbial community structure under Cd and Pb combined pollution. Journal of Environmental Sciences 22, 1040–1048. https://doi.org/10.1016/S1001-0742(09)60215-1.

Garcia, C., Hernandez, T., 1996. Influence of salinity on the biological and biochemical activity of a calciorthird soil. Plant and Soil 178, 255–263. https://doi.org/10.1007/bf00011591.

Garcia, C., Roldan, A., Hernandez, T., 1997. Changes in Microbial Activity after Abandonment of Cultivation in a Semiarid Mediterranean Environment. Journal of Environmental Quality 26, 285–292. https://doi.org/10.2134/jeq1997.00472425002600010040x.

García-Orenes, F., Caravaca, F., Morugán-Coronado, A., Roldán, A., 2015. Prolonged irrigation with municipal wastewater promotes a persistent and active soil microbial community in a semiarid agroecosystem. Agricultural Water Management 149, 115–122. https://doi.org/10.1016/j.agwat.2014.10.030.

Garg, S., Bahl, G.S., 2008. Phosphorus availability to maize as influenced by organic manures and fertilizer P associated phosphatase activity in soils. Bioresource Technology 99, 5773–5777. https://doi.org/10.1016/j.biortech.2007.10.063.

Gelsomino, A., Azzellino, A., 2011. Multivariate analysis of soils: microbial biomass, metabolic activity, and bacterial-community structure and their relationships with soil depth and type. Journal of Plant Nutrition and Soil Science 174, 381–394. https://doi.org/10.1002/jpln.200900267.

Ghiloufi, W., Chaieb, M., 2021. Environmental factors controlling vegetation attributes, soil nutrients and hydrolases in South Mediterranean arid grasslands. Ecological Engineering 161, 106155. https://doi.org/10.1016/j.ecoleng.2021.106155.

Ghosh, P., Rathinasabapathi, B., Ma, L.Q., 2015. Phosphorus solubilization and plant growth enhancement by arsenic-resistant bacteria. Chemosphere 134, 1–6. https://doi.org/10.1016/j.chemosphere.2015.03.048.

Gispert, M., Emran, M., Pardini, G., Doni, S., Ceccanti, B., 2013. The impact of land management and abandonment on soil enzymatic activity, glomalin content and aggregate stability. Geoderma 202–203, 51–61. https://doi.org/10.1016/j.geoderma.2013.03.012.

Grafe, M., Kurth, J.K., Panten, K., Raj, A.D., Baum, C., Zimmer, D., Leinweber, P., Schloter, M., Schulz, S., 2021. Effects of different innovative bone char-based P fertilizers on bacteria catalyzing P turnover in agricultural soils. Agriculture, Ecosystems and Environment 314, 107419. https://doi.org/10.1016/j.agee.2021.107419.

Hatti, V., Ramachandrappa, B.K., Sathishand, A., Thimmegowda, M.N., 2018. Soil properties and productivity of rainfed finger millet under conservation tillage and nutrient management in Eastern dry zone of Karnataka. Journal of Environmental Biology 39, 612–624. http://doi.org/10.22438/jeb/39/5/MRN-724.

Honvault, N., Houben, D., Nobile, C., Firmin, S., Lambers, H., Faucon, M.P., 2021. Trade-offs among phosphorus-acquisition root traits of crop species for agroecological intensification. Plant and Soil 461, 137–150. https://doi.org/10.1007/s11104-020-04584-3.

Hoyle, F.C., Murphy, D.V., 2006. Seasonal changes in microbial function and diversity associated with stubble retention versus burning. Australian Journal of Soil Research 44, 407–423. https://doi.org/10.1071/SR05183.

Igalavithana, A.D., Lee, S.S., Niazi, N.K., Lee, Y.H., Kim, K.H., Park, J.H., Moon, D.H., Ok, Y.S., 2017. Assessment of soil health in urban agriculture: Soil enzymes and microbial properties. Sustainability (Switzerland) 9. https://doi.org/10.3390/su9020310.

Inkscape Project, 2020. Inkscape, Available at: https://inkscape.org.

Janes-Bassett, V., Blackwell, M.S.A., Blair, G., Davies, J., Haygarth, P.M., Mezeli, M.M., Stewart, G., 2022. A meta-analysis of phosphatase activity in agricultural settings in response to phosphorus deficiency. Soil Biology and Biochemistry 165. https://doi.org/10.1016/j.soilbio.2021.108537

Jarosch, K.A., Kandeler, E., Frossard, E., Bünemann, E.K., 2019. Is the enzymatic hydrolysis of soil organic phosphorus compounds limited by enzyme or substrate availability?. Soil Biology and Biochemistry 139, 107628. https://doi.org/10.1016/j.soilbio.2019.107628.

Jaskulska, R., 2020. The level of luvisols biochemical activity in midfield shelterbelt and winter triticale (xtriticosecale wittm. ex A. camus) cultivation. Agronomy,10, 1644. https://doi.org/10.3390/agronomy10111644.

Jian, S., Li, J., Chen, J., Wang, G., Mayes, M.A., Dzantor, K.E., Hui, D., Luo, Y., 2016. Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. Soil Biology and Biochemistry 101, 32–43. https://doi.org/10.1016/j.soilbio.2016.07.003.

Jiang, Y., Arafat, Y., Letuma, P., Ali, L., Tayyab, M., Waqas, M., Li, Y., Lin, Weiwei, Lin, S., Lin, Wenxiong, 2019. Restoration of long-term monoculture degraded tea orchard by green and goat manures applications system. Sustainability (Switzerland) 11. https://doi.org/10.3390/su11041011.

Joner, E.J., van Aarle, I.M., Vosatka, M., 2000. Phosphatase activity of extra-radical arbuscular mycorrhizal hyphae: A review. Plant and Soil 226, 199–210. https://doi.org/10.1023/A:1026582207192.

Juma, N.G., Tabatabai, M.A., 1978. Distribution of phosphomonoesterases in soils. Soil Science 126:101-108.

Juma, N.G., Tabatabai, M.A., 1977. Effects of Trace Elements on Phosphatase Activity in Soils. Soil Science Society of America Journal 41, 343–346. https://doi.org/10.2136/sssaj1977.03615995004100020034x.

Juma, N.G., Tabatabai, M.A., 1988. Phosphatase activity in corn and soybean roots: Conditions for assay and effects of metals. Plant Soil 107, 39–47. https://doi.org/10.1007/BF02371542.

Katsalirou, E., Deng, S., Gerakis, A., Nofziger, D.L., 2016. Long-term management effects on soil P, microbial biomass P, and phosphatase activities in prairie soils. European Journal of Soil Biology 76, 61–69. https://doi.org/10.1016/j.ejsobi.2016.07.001.

Kayikcioglu, H.H., 2018. Can treated wastewater be used as an alternative water resource for agricultural irrigation? Changes in soil and plant health after three years of maize cultivation in western anatolia, Turkey. Applied Ecology and Environmental Research 16, 8131–8161. https://doi.org/10.15666/aeer/1606_81318161.

Khan, S.A., Mulvaney, R.L., Ellsworth, T.R., 2014. The potassium paradox: Implications for soil fertility, crop production and human health. Renewable Agriculture and Food Systems 29, 3–27. https://doi.org/10.1017/S1742170513000318.

Kiss, S., Pasca, D., Drägan-Bularda, M., 1998. Enzymology of disturbed soils. Development in soil science 26. Elsevier, Amsterdam.

Kooch, Y., Ehsani, S., Akbarinia, M., 2019. Stoichiometry of microbial indicators shows clearly more soil responses to land cover changes than absolute microbial activities. Ecological Engineering 131, 99–106. https://doi.org/10.1016/j.ecoleng.2019.03.009.

Koper, J., Lemanowicz, J., 2008. Effect of varied mineral nitrogen fertilization on changes in the content of phosphorus in soil and in plant and the activity of soil phosphatases. Ecological Chemistry and Engineering 15, 465–471.

Kroulík, M., Kumhála, F., Hůla, J., Honzík, I., 2009. The evaluation of agricultural machines field trafficking intensity for different soil tillage technologies. Soil and Tillage Research 105, 171–175. https://doi.org/10.1016/j.still.2009.07.004.

Kunito, T., Saeki, K., Goto, S., Hayashi, H., Oyaizu, H., Matsumoto, S., 2001. Copper and zinc fractions affecting microorganisms in long-term sludge-amended soils. Bioresource Technology 79, 135–146. https://doi.org/10.1016/S0960-8524(01)00047-5.

Lago, M. del C.F., Gallego, P.P., Briones, M.J.I., 2019. Intensive cultivation of kiwifruit alters the detrital foodweb and accelerates soil C and N losses. Frontiers in Microbiology 10, 1–10. https://doi.org/10.3389/fmicb.2019.00686.

Landesman, W.J., Dighton, J., 2010. Response of soil microbial communities and the production of plant-available nitrogen to a two-year rainfall manipulation in the New Jersey Pinelands. Soil Biology and Biochemistry 42, 1751–1758. https://doi.org/10.1016/j.soilbio.2010.06.012.

Laxminarayana, K., 2017. Effect of Mycorrhiza, Organic Sources, Lime, Secondary and Micro-nutrients on Soil Microbial Activities and Yield Performance of Yam Bean (Pachyrhizus erosus L.) in Alfisols. Communications in Soil Science and Plant Analysis 48, 186–200. https://doi.org/10.1080/00103624.2016.1254232.

Leirós, M.C., Trasar-Cepeda, C., García-Fernández, F., Gil-Sotres, F., 1999. Defining the validity of a biochemical index of soil quality. Biology and Fertility of Soils 30, 140–146. https://doi.org/10.1007/s003740050600.

Li, C., Veum, K.S., Goyne, K.W., Nunes, M.R., Acosta-Martinez, V., 2021. A chronosequence of soil health under tallgrass prairie reconstruction. Applied Soil Ecology 164. https://doi.org/10.1016/j.apsoil.2021.103939.

Li, K., Wang, C., Zhang, H., Zhang, J., Jiang, R., Feng, G., Liu, X., Zuo, Y., Yuan, H., Zhang, C., Gai, J., Tian, J., Li, H., Sun, Y., Yu, B., 2022. Evaluating the effects of agricultural inputs on the soil quality of smallholdings using improved indices. Catena 209, 105838. https://doi.org/10.1016/j.catena.2021.105838.

Li, Q., Chen, J., Wu, L., Luo, X., Li, N., Arafat, Y., Lin, S., Lin, W., 2018. Belowground interactions impact the soil bacterial community, soil fertility, and crop yield in maize/peanut intercropping systems. International Journal of Molecular Sciences 19. https://doi.org/10.3390/ijms19020622.

Lin, J., Ma, K., Chen, H., Chen, Z., Xing, B., 2022. Influence of different types of nanomaterials on soil enzyme activity: A global meta-analysis. Nano Today 42, 101345. https://doi.org/10.1016/j.nantod.2021.101345.

Liu, L., Zhu, K., Wurzburger, N., Zhang, J., 2020. Relationships between plant diversity and soil microbial diversity vary across taxonomic groups and spatial scales. Ecosphere 11, e02999. https://doi.org/10.1002/ecs2.2999.

Lungmuana, Singh, S.B., Choudhury, B.U., Vanthawmliana, Saha, S., Hnamte, V., 2019. Transforming jhum to plantations: Effect on soil microbiological and biochemical properties in the foot hills of North Eastern Himalayas, India. Catena 177, 84–91. https://doi.org/10.1016/j.catena.2019.02.008.

Madejón, E., Burgos, P., López, R., Cabrera, F., 2003. Agricultural use of three organic residues: Effect on orange production and on properties of a soil of the "Comarca Costa de Huelva" (SW Spain). Nutrient Cycling in Agroecosystems 65, 281–288. https://doi.org/10.1023/A:1022608828694.

Mahapatra, B., Adak, T., Patil, N.K.B., G, G.P.P., Gowda, G.B., Jambhulkar, N.N., Yadav, M.K., Panneerselvam, P., Kumar, U., Munda, S., Jena, M., 2017. Imidacloprid application changes microbial dynamics and enzymes in rice soil. Ecotoxicology and Environmental Safety 144, 123–130. https://doi.org/10.1016/j.ecoenv.2017.06.013.

Mahmood, M., Xu, T., Ahmed, W., Yang, J., Li, J., Mehmood, S., Liu, W., Weng, J., Li, W., 2022. Variability in Soil Parent Materials at Different Development Stages Controlled Phosphorus Fractions and Its Uptake by Maize Crop. Sustainability (Switzerland) 14. https://doi.org/10.3390/su14095048.

Maini, A., Sharma, V., Sharma, S., 2022. Assessment of soil biochemical properties and soil quality index under rainfed land use systems in submontane Punjab, India. Indian Journal of Biochemistry and Biophysics 59, 357–367. https://doi.org/10.56042/ijbb.v59i3.2864.

Makoi, J.H.J.R., Bambara, S., Ndakidemi, P.A., 2010. Rhizosphere phosphatase enzyme activities and secondary metabolites in plants as affected by the supply of Rhizobium, lime and molybdenum in Phaseolus vulgaris L. Australian Journal of Crop Science 4, 590–597. https://www.cropj.com/ndakidemi_4_8_2010_590_597.pdf.

Malhotra, H., Vandana, Sharma, S., Pandey, R., 2018. Phosphorus Nutrition: Plant Growth in Response to Deficiency and Excess, in: Hasanuzzaman, M., Fujita, M., Oku, H., Nahar, K., Hawrylak-Nowak, B. (Eds.), Plant Nutrients and Abiotic Stress Tolerance. Springer Singapore, Singapore, pp. 171–190. https://doi.org/10.1007/978-981-10-9044-8_7.

Mandal, A., Thakur, J.K., Sahu, A., Manna, M.C., Rao, A.S., Sarkar, B., Patra, A.K., 2019. Effects of Bt-cotton on biological properties of Vertisols in central India. Archives of Agronomy and Soil Science 65, 670–685. https://doi.org/10.1080/03650340.2018.1520978.

Mandal, N., Datta, S.C., Dwivedi, B.S., Manjaiah, K.M., Meena, M.C., Bhowmik, A., 2021. Zincated nanoclay polymer composite (ZNCPC): effect on DTPA-Zn, Olsen-P and soil enzymatic activities in rice rhizosphere. Communications in Soil Science and Plant Analysis 52(17), 2032–44. https://doi.org/10.1080/00103624.2021.1908325.

Margalef, O., Sardans, J., Fernández-Martínez, M., Molowny-Horas, R., Janssens, I.A., Ciais, P., Goll, D., Richter, A., Obersteiner, M., Asensio, D., Peñuelas, J., 2017. Global patterns of phosphatase activity in natural soils. Scientific Reports 7, 1337. https://doi.org/10.1038/s41598-017-01418-8.

Margalef, O., Sardans, J., Maspons, J., Molowny-Horas, R., Fernández-Martínez, M., Janssens, I.A., Richter, A., Ciais, P., Obersteiner, M., Peñuelas, J., 2021. The effect of global change on soil phosphatase activity. Global Change Biology 27, 5989–6003. https://doi.org/10.1111/gcb.15832.

Marklein, A.R., Houlton, B.Z., 2012. Nitrogen inputs accelerate phosphorus cycling rates across a wide variety of terrestrial ecosystems. New Phytologist 193, 696–704. https://doi.org/10.1111/j.1469-8137.2011.03967.x.

Martins Sousa, H., Ribeiro Correa, A., de Motta Silva, B., da Silva Oliveira, S., da Silva Campos, D.T., Wruck, F.J., 2020. Dynamics of soil microbiological attributes in integrated crop-livestock systems in the Cerrado-Amozonônia ecotone. Revista Caatinga 33(1), 9–20. https://doi.org/10.1590/1983-21252020v33n102rc.

McLean, J., Gahan, P.B., 1970. The distribution of acid phosphatases and esterases in differentiating roots of Vicia faba. Histochemie 24, 41–49. https://doi.org/10.1007/BF00310002.

Meena, H.M., and Prakasha, H.C., 2021. The impact of biochar, lime and fertilizer on soil acidity and microbiological properties and their relationship with yield of rice and cowpea in an acidic soil of southern India. Journal of Plant Nutrition 45(3), 358–68. https://doi.org/10.1080/01904167.2021.1952225.

Meher, S., Saha, S., Tiwari, N., Panneerselvam, P., Munda, S., Mahapatra, A., Jangde, H.K., 2021. Herbicide-Mediated Effects on Soil Microbes, Enzymes and Yield in Direct Sown Rice. Agricultural Research 10, 592-600. https://doi.org/10.1007/s40003-020-00536-6.

Melero, S., López-Bellido, R.J., López-Bellido, L., Muñoz-Romero, V., Moreno, F., Murillo, J.M., 2011. Long-term effect of tillage, rotation and nitrogen fertiliser on soil quality in a Mediterranean Vertisol. Soil and Tillage Research 114, 97–107. https://doi.org/10.1016/j.still.2011.04.007.

Meng, C., Tian, D., Zeng, H., Li, Z., Chen, H.Y.H., Niu, S., 2020. Global meta-analysis on the responses of soil extracellular enzyme activities to warming. Science of the Total Environment 705, 135992. https://doi.org/10.1016/j.scitotenv.2019.135992.

Miao, F., Li, Y., Cui, S., Jagadamma, S., Yang, G., Zhang, Q., 2019. Soil extracellular enzyme activities under long-term fertilization management in the croplands of China: a meta-analysis. Nutrient Cycling in Agroecosystems 114, 125–138. https://doi.org/10.1007/s10705-019-09991-2.

Mitter, E.K., Germida, J.J., de Freitas, J.R., 2021. Impact of diesel and biodiesel contamination on soil microbial community activity and structure. Scientific Reports 11, 10856. https://doi.org/10.1038/s41598-021-89637-y.

Moharana, P.C., Biswas, D.R., 2022. Phosphorus Delivery Potential in Soil Amended with Rock Phosphate Enriched Composts of Variable Crop Residues under Wheat–Green Gram Cropping Sequence. Communications in Soil Science and Plant Analysis 53, 1000–1017. https://doi.org/10.1080/00103624.2022.2039175.

Monkiedje, A., Spiteller, M., Fotio, D., Sukul, P., 2006. The Effect of Land Use on Soil Health Indicators in Peri-Urban Agriculture in the Humid Forest Zone of Southern Cameroon. Journal of Environmental Quality 35, 2402–2409. https://doi.org/10.2134/jeq2005.0447.

Neal, A.L., Blackwell, M., Akkari, E., Guyomar, C., Clark, I., Hirsch, P.R., 2018. Phylogenetic distribution, biogeography and the effects of land management upon bacterial non-specific Acid phosphatase Gene diversity and abundance. Plant and Soil 427, 175–189. https://doi.org/10.1007/s11104-017-3301-2.

Nedyalkova, K., Donkova, R., Malinov, I., 2020. Acid phosphatase activity under the impact of erosion level in agricultural soils of different type and land use. Bulgarian Journal of Agricultural Science 26, 1217–1222.

Nobile, C., Houben, D., Michel, E., Firmin, S., Lambers, H., Kandeler, E., Faucon, M.P., 2019. Phosphorus-acquisition strategies of canola, wheat and barley in soil amended with sewage sludges. Scientific Reports 9, 1–11. https://doi.org/10.1038/s41598-019-51204-x.

Noronha, F.R., Manikandan, S.K., Nair, V., 2022. Role of coconut shell biochar and earthworm (Eudrilus euginea) in bioremediation and palak spinach (Spinacia oleracea L.) growth in cadmium-contaminated soil. Journal of Environmental Management 302, 114057. https://doi.org/10.1016/j.jenvman.2021.114057.

Odutola O.S., 2018. Introductory Chapter: Relevance of Soil pH to Agriculture, in: Suarau Oshunsanya (Ed.), Soil pH for Nutrient Availability and Crop Performance. IntechOpen, Rijeka, p. Ch. 1. https://doi.org/10.5772/intechopen.82551.

Ojeda, G., Patrício, J., Navajas, H., Comellas, L., Alcañiz, J.M., Ortiz, O., Marks, E., Natal-da-Luz, T., Sousa, J.P., 2013. Effects of nonylphenols on soil microbial activity and water retention. Applied Soil Ecology 64, 77–83. https://doi.org/10.1016/j.apsoil.2012.10.012.

Olsen, S.R. and Sommers, L.E., 1982. Phosphorus. In: Page, A.L., Ed., Methods of soil analysis Part 2 chemical and microbiological properties, American Society of Agronomy, Soil Science Society of America, Madison, 403-430.

Ortiz, J., Faggioli, V.S., Ghio, H., Boccolini, M.F., Ioele, J.P., Tamburrini, P., Garcia, F.O., Gudelj, V., 2020. Long-term impact of fertilization on the structure and functionality of microbial soil community | Impacto a largo plazo de la fertilización sobre la estructura y funcionalidad de la comunidad microbiana del suelo. Ciencia del Suelo 38, 45–55.

Palmer, J., Thorburn, P.J., Biggs, J.S., Dominati, E.J., Probert, M.E., Meier, E.A., Huth, N.I., Dodd, M., Snow, V., Larsen, J.R., Parton, W.J., 2017. Nitrogen Cycling from Increased Soil Organic Carbon Contributes Both Positively and Negatively to Ecosystem Services in Wheat Agro-Ecosystems. Frontiers in Plant Science 8, 731. https://doi.org/10.3389/fpls.2017.00731.

Parihar, C.M., Yadav, M.R., Jat, S.L., Singh, A.K., Kumar, B., Pradhan, S., Chakraborty, D., Jat, M.L., Jat, R.K., Saharawat, Y.S., Yadav, O.P., 2016. Long term effect of conservation agriculture in maize rotations on total organic carbon, physical and biological properties of a sandy loam soil in north-western Indo-Gangetic Plains. Soil and Tillage Research 161, 116–128. https://doi.org/10.1016/j.still.2016.04.001.

Park, Y., Solhtalab, M., Thongsomboon, W., Aristilde, L., 2022. Strategies of organic phosphorus recycling by soil bacteria: acquisition, metabolism, and regulation. Environmental Microbiology Reports 14, 3–24. https://doi.org/10.1111/1758-2229.13040.

Parnell, J.J., Berka, R., Young, H.A., Sturino, J.M., Kang, Y., Barnhart, D.M., DiLeo, M.V., 2016. From the Lab to the Farm: An Industrial Perspective of Plant Beneficial Microorganisms. Frontiers in Plant Science 7. https://doi.org/10.3389/fpls.2016.01110.

Paz-Ferreiro, J., Trasar-Cepeda, C., Leirós, M.C., Seoane, S., Gil-Sotres, F., 2007. Biochemical properties of acid soils under native grassland in a temperate humid zone. New Zealand Journal of Agricultural Research 50, 537–548. https://doi.org/10.1080/00288230709510321.

Peñuelas, J., Poulter, B., Sardans, J., Ciais, P., van der Velde, M., Bopp, L., Boucher, O., Godderis, Y., Hinsinger, P., Llusia, J., Nardin, E., Vicca, S., Obersteiner, M., Janssens, I.A., 2013. Human-induced nitrogen–phosphorus imbalances alter natural and managed ecosystems across the globe. Nature Communications 4, 2934. https://doi.org/10.1038/ncomms3934.

Pokharel, P., Ma, Z., Chang, S.X., 2020. Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: a global meta-analysis. Biochar 2, 65–79. https://doi.org/10.1007/s42773-020-00039-1.

Purnamasari, L., Rostaman, T., Widowati, L.R., Anggria, L., 2021. Comparison of appropriate cation exchange capacity (CEC) extraction methods for soils from several regions of Indonesia. IOP Conference Series: Earth and Environmental Science 648, 012209. https://doi.org/10.1088/1755-1315/648/1/012209.

Ragot, S.A., Kertesz, M.A., Mészáros, É., Frossard, E., Bünemann, E.K., 2016. Soil phoD and phoX alkaline phosphatase gene diversity responds to multiple environmental factors. FEMS Microbiology Ecology 93(1). https://doi.org/10.1093/femsec/fiw212.

Redel, Y.D., Rubio, R., Rouanet, J.L., Borie, F., 2007. Phosphorus bioavailability affected by tillage and crop rotation on a Chilean volcanic derived Ultisol. Geoderma 139, 388–396. https://doi.org/10.1016/j.geoderma.2007.02.018.

Riah, W., Laval, K., Laroche-Ajzenberg, E., Mougin, C., Latour, X., Trinsoutrot-Gattin, I., 2014. Effects of pesticides on soil enzymes: A review. Environmental Chemistry Letters 12, 257–273. https://doi.org/10.1007/s10311-014-0458-2.

Rietz, D.N., Haynes, R.J., 2003. Effects of irrigation-induced salinity and sodicity on soil microbial activity. Soil Biology and Biochemistry 35, 845–854. https://doi.org/10.1016/S0038-0717(03)00125-1.

Riffaldi, R., Saviozzi, A., Levi-Minzi, R., Cardelli, R., 2002. Biochemical properties of a Mediterranean soil as affected by long-term crop management systems. Soil and Tillage Research 67, 109–114. https://doi.org/10.1016/S0167-1987(02)00044-2.

Roldán, A., Salinas-García, J.R., Alguacil, M.M., Caravaca, F., 2007. Soil sustainability indicators following conservation tillage practices under subtropical maize and bean crops. Soil and Tillage Research 93, 273–282. https://doi.org/10.1016/j.still.2006.05.001.

Romero-Trigueros, C., Díaz-López, M., Vivaldi, G.A., Camposeo, S., Nicolás, E., Bastida, F., 2021. Plant and soil microbial community responses to different water management strategies in an

almond crop. Science of the Total Environment 778. https://doi.org/10.1016/j.scitotenv.2021.146148.
Ruiz, J.L., Salas, M.D.C., 2019. Evaluation of organic substrates and microorganisms as bio-fertilisation tool in container crop production. Agronomy 9. https://doi.org/10.3390/agronomy9110705.
Saad, R.F., Kobaissi, A., Echevarria, G., Kidd, P., Calusinska, M., Goux, X., Benizri, E., 2018. Influence of new agromining cropping systems on soil bacterial diversity and the physico-chemical characteristics of an ultramafic soil. Science of the Total Environment 645, 380–392. https://doi.org/10.1016/j.scitotenv.2018.07.106.
Sardans, J., Peñuelas, J., 2004. Increasing drought decreases phosphorus availability in an evergreen Mediterranean forest. Plant and Soil 267, 367–377. https://doi.org/10.1007/s11104-005-0172-8.
Sardans, J., Peñuelas, J., Estiarte, M., 2006. Warming and drought alter soil phosphatase activity and soil P availability in a Mediterranean shrubland. Plant and Soil 289, 227–238. https://doi.org/10.1007/s11104-006-9131-2.
Scaramal da Silva, A. da, Filho, A.C., Nakatani, A.S., Alves, S.J., Andrade, D.S. de, Guimarães, M. de F., 2015. Atributos microbiológicos do solo em sistema de integração. Revista Brasileira de Ciencia do Solo 39, 40–48. https://doi.org/10.1590/01000683rbcs20150185.
Schmidt, G., Laskowski, M., 1961. Phosphate ester cleavage (survey). The Enzymes 3–35.
Sciubba, L., Mazzon, M., Cavani, L., Baldi, E., Toselli, M., Ciavatta, C., Marzadori, C., 2021. Soil response to agricultural land abandonment: A case study of a vineyard in Northern Italy. Agronomy 11. https://doi.org/10.3390/agronomy11091841.
Sepat, S., Behera, U.K., Sharma, A.R., Das, T.K., Bhattacharyya, R., 2014. Productivity, organic carbon and residual soil fertility of Pigeonpea-wheat cropping system under varying tillage and residue management. Proceedings of the National Academy of Sciences India Section B - Biological Sciences 84, 561–571. https://doi.org/10.1007/s40011-014-0359-y.
Sharma, P., Singh, G., Singh, R.P., 2013. Conservation tillage and optimal water supply enhance microbial enzyme (glucosidase, urease and phosphatase) activities in fields under wheat cultivation during various nitrogen management practices. Archives of Agronomy and Soil Science 59, 911–928. https://doi.org/10.1080/03650340.2012.690143.
Sharma, S., Dhaliwal, S.S., 2019. Effect of Sewage Sludge and Rice Straw Compost on Yield, Micronutrient Availability and Soil Quality under Rice–Wheat System. Communications in Soil Science and Plant Analysis 50, 1943–1954. https://doi.org/10.1080/00103624.2019.1648489.
Siddaramappa, R., Wright, R.J., Codling, E.E., Gao, G., McCarty, G.W., 1994. Evaluation of coal combustion byproducts as soil liming materials: their influence on soil pH and enzyme activities. Biology and Fertility of Soils 17, 167–172. https://doi.org/10.1007/BF00336317.

Sigua, G.C., Stone, K.C., Bauer, P.J., Szogi, A.A., 2017. Phosphorus dynamics and phosphatase activity of soils under corn production with supplemental irrigation in humid coastal plain region, USA. Nutrient Cycling in Agroecosystems 109, 249–267. https://doi.org/10.1007/s10705-017-9882-6.

Singh, A., Ghoshal, N., 2013. Impact of herbicide and various soil amendments on soil enzymes activities in a tropical rainfed agroecosystem. European Journal of Soil Biology 54, 56–62. https://doi.org/10.1016/j.ejsobi.2012.10.003.

Singh, G., Bhattacharyya, R., Das, T.K., Sharma, A.R., Ghosh, A., Das, S., Jha, P., 2018. Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo-Gangetic Plains. Soil and Tillage Research 184, 291–300. https://doi.org/10.1016/j.still.2018.08.006.

Singh, S.R., Kundu, D.K., Dey, P., Singh, P., Mahapatra, B.S., 2018. Effect of balanced fertilizers on soil quality and lentil yield in Gangetic alluvial soils of India. Journal of Agricultural Science 156, 225–240. https://doi.org/10.1017/S0021859618000254.

Smith, J.L., Doran, J.W., 1997. Measurement and Use of pH and Electrical Conductivity for Soil Quality Analysis, in: Methods for Assessing Soil Quality, SSSA Special Publications. pp. 169–185. https://doi.org/10.2136/sssaspecpub49.c10.

Soane, B.D., van Ouwerkerk, C., 1994. Chapter 1 - Soil Compaction Problems in World Agriculture, in: Soane, B.D., van Ouwerkerk, C. (Eds.), Developments in Agricultural Engineering. Elsevier, pp. 1–21. https://doi.org/10.1016/B978-0-444-88286-8.50009-X.

Sun, Y., Goll, D.S., Ciais, P., Peng, S., Margalef, O., Asensio, D., Sardans, J., Peñuelas, J., 2020. Spatial Pattern and Environmental Drivers of Acid Phosphatase Activity in Europe. Frontiers in Big Data 2, 1–13. https://doi.org/10.3389/fdata.2019.00051.

Tabatabai, M.A., 1994. Soil Enzymes, in: Methods of Soil Analysis, SSSA Book Series. pp. 775–833. https://doi.org/10.2136/sssabookser5.2.c37.

Tabatabai, M.A., Bremner, J.M., 1969. Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. Soil Biology and Biochemistry 1, 301–307. https://doi.org/10.1016/0038-0717(69)90012-1.

Tao, J., Griffiths, B., Zhang, S., Chen, X., Liu, M., Hu, F., Li, H., 2009. Effects of earthworms on soil enzyme activity in an organic residue amended rice-wheat rotation agro-ecosystem. Applied Soil Ecology 42, 221–226. https://doi.org/10.1016/j.apsoil.2009.04.003.

Tarafdar, J.C., Claassen, N., 1988. Organic phosphorus compounds as a phosphorus source for higher plants through the activity of phosphatases produced by plant roots and microorganisms. Biology and Fertility of Soils 5, 308–312. https://doi.org/10.1007/BF00262137.

Tarafdar, J.C., Rao, A.V., 1996. Contribution of Aspergillus strains to acquisition of phosphorus by wheat (Triticum aestivum L.) and chickpea (Cicer arietinum Linn.) grown in a loamy sand soil. Applied Soil Ecology 3, 109–114. https://doi.org/10.1016/0929-1393(95)00084-4.

Tian, J., Ge, F., Zhang, D., Deng, S., Liu, X., 2021. Roles of Phosphate Solubilizing Microorganisms from Managing Soil Phosphorus Deficiency to Mediating Biogeochemical P Cycle. Biology 10. https://doi.org/10.3390/biology10020158.

Trujillo-Narcía, A., Rivera-Cruz, M.C., Magaña-Aquino, M., Trujillo-Rivera, E.A., 2019. The Burning of Sugarcane Plantation in the Tropics Modifies the Microbial and Enzymatic Processes in Soil and Rhizosphere. Journal of Soil Science and Plant Nutrition 19, 906–919. https://doi.org/10.1007/s42729-019-00089-w.

Truu, M., Truu, J., Ivask, M., 2008. Soil microbiological and biochemical properties for assessing the effect of agricultural management practices in Estonian cultivated soils. European Journal of Soil Biology 44, 231–237. https://doi.org/10.1016/j.ejsobi.2007.12.003.

Tu, C., Ristaino, J.B., Hu, S., 2006. Soil microbial biomass and activity in organic tomato farming systems: Effects of organic inputs and straw mulching. Soil Biology and Biochemistry 38, 247–255. https://doi.org/10.1016/j.soilbio.2005.05.002.

Valarini, P.J., Alvarez, M.C.D., Gascó, J.M., Guerrero, F., Tokeshi, H., 2003. Assessment of soil properties by organic matter and EM-microorganism incorporation. Revista Brasileira de Ciência do Solo 27, 519–525. https://doi.org/10.1590/s0100-06832003000300013.

Vinhal-Freitas, I.C., Correa, G.F., Wendling, B., Bobul'ska, L., Ferreira, A.S., 2017. Soil textural class plays a major role in evaluating the effects of land use on soil quality indicators. Ecological indicators 74, 182–190. https://doi.org/10.1016/j.ecolind.2016.11.020.

Waldrop, M.P., Balser, T.C., Firestone, M.K., 2000. Linking microbial community composition to function in a tropical soil. Soil Biology and Biochemistry 32, 1837–1846. https://doi.org/10.1016/S0038-0717(00)00157-7.

Wang, M., Wu, C., Cheng, Z., Meng, H., Zhang, M., Zhang, H., 2014. Soil chemical property changes in eggplant/garlic relay intercropping systems under continuous cropping. PLoS ONE 9. https://doi.org/10.1371/journal.pone.0111040.

Wang, P., Zhang, J.J., Xia, R.X., Shu, B., Wang, M.Y., Wu, Q.S., Dong, T., 2011. Arbuscular mycorrhiza, rhizospheric microbe populations and soil enzyme activities in citrus orchards under two types of no-tillage soil management. Spanish Journal of Agricultural Research 9, 1307–1318. https://doi.org/10.5424/sjar/20110904-307-10.

Wang, X., Deng, X., Pu, T., Song, C., Yong, T., Yang, F., Sun, X., Liu, W., Yan, Y., Du, J., Liu, J., Su, K., Yang, W., 2017. Contribution of interspecific interactions and phosphorus application to increasing soil phosphorus availability in relay intercropping systems. Field Crops Research 204, 12–22. https://doi.org/10.1016/j.fcr.2016.12.020.

Wang, Y., Huang, Q., Gao, H., Zhang, R., Yang, L., Guo, Y., Li, H., Awasthi, M.K., Li, G., 2021. Long-term cover crops improved soil phosphorus availability in a rain-fed apple orchard. Chemosphere 275, 130093. https://doi.org/10.1016/j.chemosphere.2021.130093.

Wei, K., Chen, Z., Zhu, A., Zhang, J., Chen, L., 2014. Application of ^{31}P NMR spectroscopy in determining phosphatase activities and P composition in soil aggregates influenced by tillage and residue management practices. Soil and Tillage Research 138, 35–43. https://doi.org/10.1016/j.still.2014.01.001.

Weil R.R., Brady N.C., 2016. The Nature and Properties of Soils, 15th Edition, 15th Edition. ed. Pearson Press., Upper Saddle River NJ, 2017.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York. ISBN 978-3-319-24277-4, https://ggplot2.tidyverse.org.

Woźniak, A., Kawecka-Radomska, M., 2016. Crop management effect on chemical and biological properties of soil. International Journal of Plant Production 10, 391–402.

Woźniak, M., Gałazką, A., Siebielec, G., Frąc, M., 2022. Can the Biological Activity of Abandoned Soils Be Changed by the Growth of Paulownia elongata × Paulownia fortunei ? -Preliminary Study on a Young Tree Plantation. Agriculture (Switzerland) 12. https://doi.org/10.3390/agriculture12020128.

Wrage, N., Chapuis-Lardy, L., Isselstein, J., 2010. Phosphorus, Plant Biodiversity and Climate Change, in: Lichtfouse, E. (Ed.), Sociology, Organic Farming, Climate Change and Soil Science. Springer Netherlands, Dordrecht, pp. 147–169. https://doi.org/10.1007/978-90-481-3333-8_6.

Wu, F., Wan, J., Wu, S., Wong, M., 2012. Effects of earthworms and plant growth-promoting rhizobacteria (PGPR) on availability of nitrogen, phosphorus, and potassium in soil. Journal of Plant Nutrition and Soil Science 175, 423–433. https://doi.org/10.1002/jpln.201100022.

Wyszkowska, J., 2002. Effect of Soil Contamination with Treflan 480 EC on Biochemical Properties of Soil. Polish Journal of Environmental Studies 11, 71–77.

Yadav, D., Shivay, Y.S., Singh, Y.V., Sharma, V.K., Bhatia, A., 2019. Water Use and Soil Fertility under Rice–Wheat Cropping System in Response to Green Manuring and Zinc Nutrition. Communications in Soil Science and Plant Analysis 50, 2836–2847. https://doi.org/10.1080/00103624.2019.1686516.

Yang, L., Zhao, F., Chang, Q., Li, T., Li, F., 2015. Effects of vermicomposts on tomato yield and quality and soil fertility in greenhouse under different soil water regimes. Agricultural Water Management 160, 98–105. https://doi.org/10.1016/j.agwat.2015.07.002.

Yang, X., Bao, X., Yang, Y., Zhao, Y., Liang, C., Xie, H., 2019. Comparison of soil phosphorus and phosphatase activity under long-term no-tillage and maize residue management. Plant, Soil and Environment 65, 408–415. https://doi.org/10.17221/307/2019-PSE.

Yao, Y., Dai, Q., Gao, R., Gan, Y., Yi, X., 2021. Effects of rainfall intensity on runoff and nutrient loss of gently sloping farmland in a karst area of SW China. PLoS One 16(3), e0246505. https://doi.org/10.1371/journal.pone.0246505.

Yu, S., He, Z.L., Stoffella, P.J., Calvert, D.V., Yang, X.E., Banks, D.J., Baligar, V.C., 2006. Surface runoff phosphorus (P) loss in relation to phosphatase activity and soil P fractions in Florida sandy soils under citrus production. Soil Biology and Biochemistry 38, 619–628. https://doi.org/10.1016/j.soilbio.2005.02.040.

Zhang, Y., Wang, X., Xu, F., Song, T., Du, H., Gui, Y., Xu, M., Cao, Y., Dang, X., Rensing, C., Zhang, J., Xu, W., 2019. Combining Irrigation Scheme and Phosphorous Application Levels for Grain Yield and Their Impacts on Rhizosphere Microbial Communities of Two Rice Varieties in a Field Trial. Journal of Agricultural and Food Chemistry 67, 10577–10586. https://doi.org/10.1021/acs.jafc.9b03124.

Zhu, J., Li, M., Whelan, M., 2018. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. Science of the Total Environment, 612. https://doi.org/10.1016/j.scitotenv.2017.08.095.

Zibilske, L.M., Bradford, J.M., 2003. Tillage effects on phosphorus mineralization and microbial activity. Soil Science 168, 677–685. https://doi.org/10.1097/01.ss.0000095141.68539.c7.

Zibilske, L.M., Makus, D.J., 2009. Black oat cover crop management effects on soil temperature and biological properties on a Mollisol in Texas, USA. Geoderma 149, 379–385. https://doi.org/10.1016/j.geoderma.2009.01.001.

Zuccarini, P., Sardans, J., Asensio, L., Penuelas, J., 2023. Altered activities of extracellular soil enzymes by the interacting global environmental changes. Global change biology 29, 2067–2091. https://doi.org/10.1111/gcb.16604.

4.8 Supplementary materials Chapter 1

Figure S1. Article search and selection process.

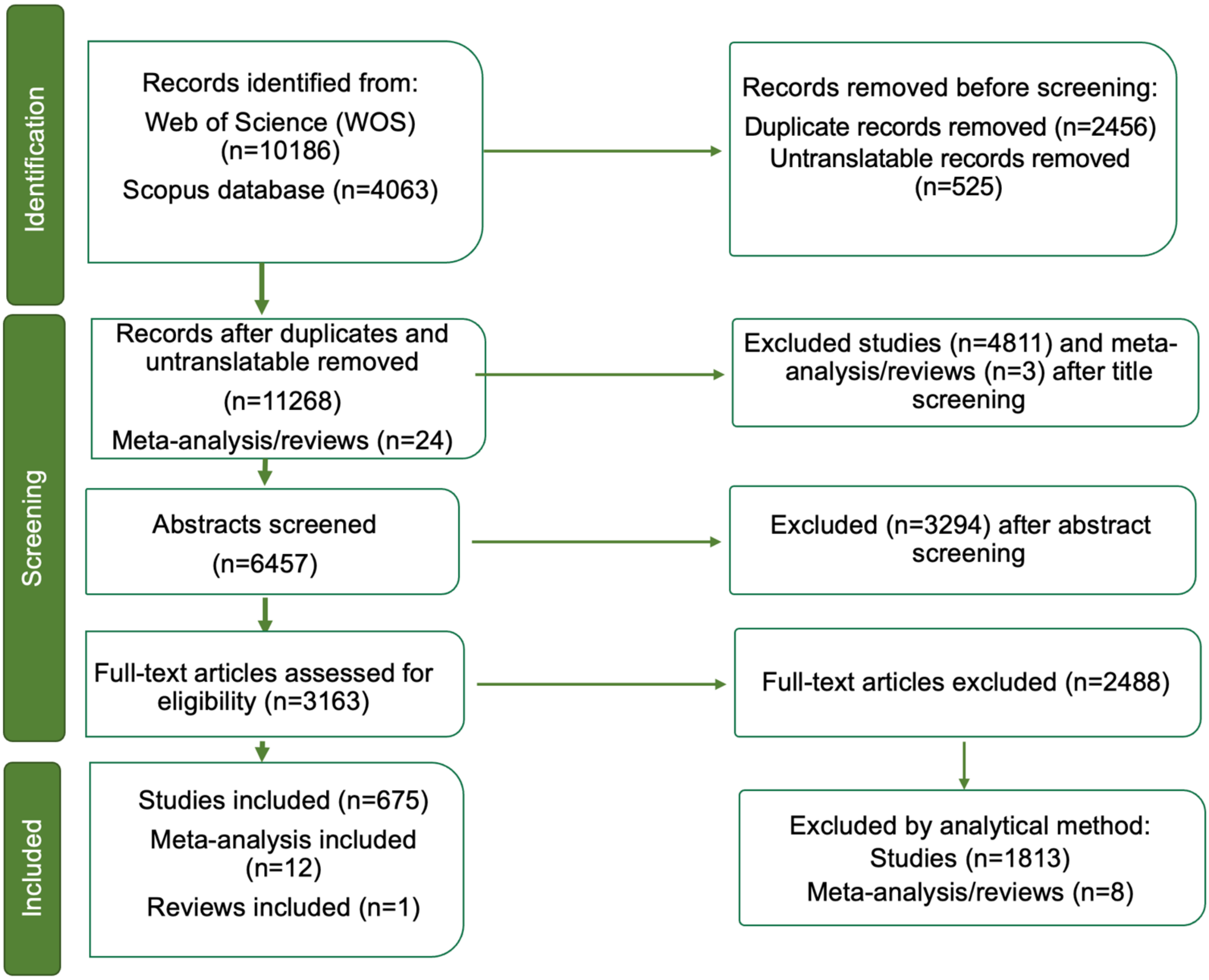

Table S1. Comprehensive overview of meta-analyses and reviews investigating explanatory drivers for phosphatase activity (APase), including the total number of studies, enzyme analysis substrates, and ecosystem types.

Author and Year	Studies	Type	Substrates	Ecosystems
Janes-Bassett et al. (2022)	37	Fertilization	Disodium-p-nitrophenyl phosphate among others	Farmland, grassland
Miao et al. (2019)	85	Fertilization	Disodium-p-nitrophenyl phosphate, 4-MUB-phosphate	Farmland
Jian et al. (2016)	65	Fertilization	Disodium-p-nitrophenyl phosphate, 4-MUB-phosphate	Farmland, grassland, forest, peat
Marklein and Houlton, (2012)	34	Fertilization	Disodium-p-nitrophenyl phosphate among others	Grassland, shrubland, forest, tundra, wetland
Pokharel et al. (2020)	72	Fertilization esp.Biochar	Disodium-p-nitrophenyl phosphate among others	Based on textural classes
Lin et al. (2021)	73	Pollution	Disodium-p-nitrophenyl phosphate among others	Arable land, grassland
Aponte et al. (2020)	46	Pollution	Disodium-p-nitrophenyl phosphate among others	Based on soil (cutivated and uncultivated)
Riah et al. (2014)	47	Pollution	Disodium-p-nitrophenyl phosphate	Agricultural landscapes, microcosms
Margalef et al. (2017)	183	Soil properties/ Climatic	Disodium-p-nitrophenyl phosphate, diso-dium phenyl phosphate, 4-methyl umbelliferyl phosphate	Soil forest, shrublands, grasslands
Margalef et al. (2021)	97	Climatic	Disodium-p-nitrophenyl phosphate, diso-dium phenyl phosphate, 4-methyl umbelliferyl phosphate	Soil forest, shrublands, grasslands
Gao et al. (2020)	79	Climatic	Disodium-p-nitrophenyl phosphate	Cropland, grassland, forest, wetland, shrubland, wasteland, open area,
Meng et al. (2020)	78	Climatic	Disodium-p-nitrophenyl phosphate among others	Farmland, forest, grassland, peatland, shrubland, tundra
Sun et al. (2020)	139	Climatic	Disodium-p-nitrophenyl phosphate, diso-dium phenyl phosphate, 4-methyl umbelliferyl phosphate	Soil forest, shrublands, grasslands

Table S2. Comprehensive overview of meta-analyses and reviews detailing factors influencing phosphatase activity (APase), encompassing number of observations, drivers, variables and acid and alkaline phosphatase (ACP and ALP, respectively) response.

Reference	Number of observations*	Driver	Variable	APase	Response
Jian et al., 2016	16	Fertilization	N	ACP	Positive
Marklein and Houlton, 2012	112	Fertilization	N	ACP, ALP	Positive
Marklein and Houlton, 2012	112	Fertilization	P	ACP, ALP	Positive
Margalef et al., 2021	50	Fertilization	N	ACP, ALP	Positive
Margalef et al., 2021	24	Fertilization	P	ACP, ALP	Negative
Margalef et al., 2021	49	Fertilization	N, P	ACP, ALP	Negative
Janes-Bassett et al., 2022	163	Fertilization	P	Monoesterases (unspecified)	None
Miao et al., 2018	46	Fertilization	Chemical fertilizer (unbalanced application, NPK)	ACP, ALP	Positive
Miao et al., 2018	19	Fertilization	Organic fertilizer (straw residue retention, manure)	ACP, ALP	Positive
Miao et al., 2018	35	Fertilization	Chemical+Organic (NPK+straw, NPK+manure)	ACP, ALP	Positive
Pokharel et al., 2020	37 23	Fertilization	Biochar	ACP ALP	Positive None
Riah et al., 2014	4 5	Pollution	Herbicide	ACP ALP	None None
Riah et al., 2014	4 5	Pollution	Fungicide	ACP ALP	Positive Negative
Reference	**Number of observations***	**Driver**	**Variable**	**APase**	**Response**

Riah et al., 2014	6 8	Pollution	Insecticide	ACP ALP	Negative Positive/ none
Aponte et al., 2020	103 67 103 67	Pollution	Pb, Zn, As Cu, Cd	ACP ALP ACP ALP	Negative Negative Positive Negative
Lin et al., 2021	27 13	Pollution	C, Cu, Ag NMs Fe NMs	ACP ALP ACP ALP	Negative Positive
Sun et al., 2020	139	Climate	MAT MAP	ACP	Positive
Meng et al., 2020	78	Climate	MAT	ACP ALP	Positive
Margalef et al., 2021	13	Climate	MAT	ACP, ALP	None
Margalef et al., 2021	11	Climate	Drought	ACP, ALP	Negative
Margalef et al., 2021	37	Climate	CO_2 fertilization	ACP, ALP	Positive
Gao et al., 2020	97 15	Climate	Drought	ACP ALP	Negative

* When data is accessible, the number of observations evaluating APase activity in cropland, farmland, and grassland is provided.

Tables S3 to S20

Summary and comprehensive tables inclusive of references.

Table S3. Single studies of APase response relationships to soil microbe and fauna factors.

Soil microbe/fauna factor	APase	Response relationship	Vote counting	Study
Total microbe activity	ACP	Positive	9	Boccolini et al., 2019; Bolton et al., 1985; Chellappa et al., 2021; Datta et al., 2021; Nath et al., 2017; Nedunchezhiyan et al., 2018; Radhakrishnan et al., 2022; Stegarescu et al., 2021; Tu C.M., 1995;
	ALP	Positive	4	Datta et al., 2021; Delgado et al., 2012; Nedunchezhiyan et al., 2018; Singh et al., 2022;
Microbe abundance (Bacteria, Actinobacteria, Fungi)	ACP	Positive	11	Carricondo-Martínez et al., 2022; Chen et al., 2018; Chowdhury and Rasid, 2021b; Dolker et al., 2020; Idris and Yuliar, 2021; Li et al., 2002; Meher et al., 2021; Sanchez-Peinado et al., 2009; Swędrzyńska et al., 2013;

				Tarafdar et al., 1989; Yu et al., 2021;
	ALP	Positive	12	Al-Taweel et al., 2019; Firmano et al., 2021; Idris and Yuliar, 2021; Lemanowicz et al., 2016; Li et al., 2017a; Li et al., 2002; Meher et al., 2021; Niewiadomska et al., 2016; Tamilselvi et al., 2015; Tarafdar et al., 1989; Xu et al., 2019; Yu et al., 2021;
Microbial biomass phosphorus content	ACP	Positive	6	Basak and Gajbhiye, 2018; de Jesus Franco et al., 2020; Katsalirou et al., 2016; Moharana et al., 2022; Redel et al., 2011; Turner and Haygarth, 2005;
	ALP	Positive	6	Basak and Gajbhiye, 2018; Hu et al., 2009a; Katsalirou et al., 2016; Moharana et al., 2022; Touhami et al., 2021; Zhou et al., 2022;
Microbial biomass carbon content	ACP	Positive	36	Ansari et al., 2021; Antolín et al., 2005; Arora et al., 2021; Balota et al., 2011b;

	Banerjee et al., 1999; Bhattacharyya et al., 2003; Biswas et al., 2018; Borase et al., 2021; Choudhary et al., 2021; Chowdhury and Rasid, 2021a; Chowdhury and Rasid, 2021b; da Cunha et al., 2021; de Barros et al., 2019; de Castro Lopes et al., 2013; de Jesus Franco et al., 2020; Feng et al., 2021; Furtak et al., 2017; Gelsomino et al., 2011; Hazarika et al., 2009; He et al., 2010; Katsalirou et al., 2016; Li et al., 2012; Liu et al., 2008; Lungmuana et al., 2019; Mahajan et al., 2021; Mandal et al., 2007; Pascual et al., 2007; Rouydel et al., 2021; Roy et al., 2019; Sarkar et al., 2009; Sudhakaran et al., 2019; Tamilselvi et al., 2015; Turner and Haygarth, 2005; Tuti et al., 2020;

			Wei et al., 2017; Woźniak et al., 2022;
	Negative	1	Bera et al., 2016;
ALP	Positive	38	Acosta-Martínez et al., 2004; Acosta-Martínez et al., 2011a; Arora et al., 2021; Bera et al., 2016; Bissonette et al., 2001; Biswas et al., 2018; Borase et al., 2021; Chander et al., 1997; Chaudhary et al., 2015; Choudhary et al., 2021; Dar G., 1996; Dong et al., 2016; Gelsomino et al., 2011; He et al., 2010 Hojati and Nourbakhsh, 2006; Katsalirou et al., 2016; Kaur et al., 2017; Li et al., 2017a; Li et al., 2012; Liu and Zhou, 2017; Lungmuana et al., 2019; Madejón et al., 2007 Mandal et al., 2007 Mbarki et al., 2010 Melero et al., 2007a; Pascual et al., 2007 Rouydel et al., 2021; Roy et al., 2019; Sarkar et al., 2009; Sepat et al., 2014;

				Sudhakaran et al., 2019; Tamilselvi et al., 2015; Tripathi et al., 2007; Tuti et al., 2020; Verma et al., 2016b; Wang et al., 2014a; Wick et al., 1998; Zhao et al., 2009;
Microbial biomass nitrogen content	ACP	Positive	10	Ajwaa et al., 1999; Borase et al., 2021; de Jesus Franco et al., 2020; Furtak et al., 2017; Gelsomino et al., 2011; Katsalirou et al., 2016; Lungmuana et al., 2019; Sarkar et al., 2009; Sudhakaran et al., 2019; Woźniak et al., 2022;
	ALP	Positive	10	Acosta-Martínez et al., 2011a; Borase et al., 2021; Dong et al., 2016; Gelsomino et al., 2011; Katsalirou et al., 2016; Lungmuana et al., 2019; Mandal et al., 2007 Sarkar et al., 2009; Sepat et al., 2014; Sudhakaran et al., 2019;
Microbe diversity (Shannon diversity index)	ACP	Positive	3	Diallo-Diagne et al., 2016; Sun et al., 2018; Woźniak et al., 2022;

	ALP	Positive	2	Cao et al., 2021; Liu et al., 2021a;
phoD gene abundance and richness	ALP	Positive	3	Bi et al., 2020 Gou et al., 2020; Wang et al., 2022c;
Earthworm abundance	ACP	Positive	2	Noronha et al., 2022; Saha et al., 2008a;
		None	1	Wu et al., 2012;
	ALP	Positive	3	Balachandar et al., 2021; Buck et al., 2000; Tao et al., 2009;
		None	1	Stoven and Schnug, 2009;

Table S4. Single and meta-analysis studies of APase response relationships to soil physical properties.

Soil property	APase (single[1] or meta-analysis[2] study)	Response relationship	Vote counting	Study
Depth	ACP[1]	Negative	26	Baligar et al., 2005; Bolton et al., 1993; Cao et al., 2021; de Barros et al., 2019; de Castro Lopes et al., 2021; Denton et al., 2006; Fialho et al., 2008; Firmano et al., 2021; Gelsomino et al., 2011; Guo et al., 2009

				Kahle et al., 2010; Kumar et al., 2021a; Lemanowicz et al., 2016; Rao et al., 1995; Sigua et al., 2017; Tarafdar et al., 1989; Taylor et al., 2002; Tiecher et al., 2012; Trujillo-Narcía et al., 2019; Venkatesan et al., 2006 Wang et al., 2011c; Wang et al., 2012; Yoshioka et al., 2006; Zhang et al., 2016b; Zhong et al., 2015; Zhu et al., 2022;
	ALP[1]	Negative	18	Cao et al., 2021; Caudle et al., 2020; de Barros et al., 2019; Dou et al., 2016; Gelsomino et al., 2011; Guo et al., 2009 Jat et al., 2019; Kumar et al., 2021a; Lalande et al., 2009; Lemanowicz et al., 2016; Mahmood et al., 2022; Melero et al., 2008b; Melero et al., 2011; Rao et al., 1995; Rao et al., 1997; Stehouwer et al., 1993; Tarafdar et al., 1989; Zhang et al., 2018;
Soil moisture	ACP[1]	Positive	5	Gispert et al., 2013;

content				
				Hoyle and Murphy, 2006;
				Lungmuana et al., 2019;
				Omenda et al., 2019;
				Stegarescu et al., 2021;
	ALP[1]	Positive	2	Gangwar et al., 2021;
				Monaci et al., 2022;
		None	1	Wang et al., 2022a;
Clay content	ACP[1]	Positive	10	Acosta-Martínez et al., 2003b;
				Bossio et al., 2005;
				Cycoń et al., 2013;
				Cycoń Piotrowska-Seget, 2015;
				de Castro Lopes et al., 2013;
				Fernández et al., 2008;
				Mejia Guerra et al., 2018;
				Nedyalkova et al., 2020;
				Nedyalkova et al., 2020;
				Sudhakaran et al., 2019;
	ALP[1]	Positive	21	Abdalla and Lager, 2009;
				Acosta-Martínez et al., 2003b;
				Acosta-Martínez et al., 2003a;
				Banerjee et al., 2008;

				Bergstrom and Monreal,1998a; Calvarro et al., 2014; Cycoń et al., 2013; Dar G., 1996; Fernández et al., 2008; Gelsomino et al., 2011; Li et al., 2018c; Łukowski and Dec, 2018; Mahmood et al., 2022; Melero et al., 2007a; Senwo et al., 2007; Stehouwer et al., 1993; Stenberg et al., 1998; Sudhakaran et al., 2019; Tavali et al., 2021; Vekemans et al., 1989; Wyszkowska et al., 2005;
	ACP, ALP[2]	Positive	1	Aponte et al., 2020;
Sand content	ACP[1]	Positive	1	Acosta-Martínez et al., 2003b;
		Negative	3	Fernández-Calviño et al., 2010; Nedyalkova et al., 2020; Woźniak et al., 2022;
	ALP[1]	Positive	3	Acosta-Martínez et al., 2003b;

				Bergstrom and Monreal, 1998a; Wyszkowska et al., 2005;
		Negative	3	Garg and Bahl, 2008; Gelsomino et al., 2011; Łukowski and Dec, 2018;
Microaggregate content (<0.25 mm)	ACP[1]	Negative	1	Wei et al., 2014b;
	ALP[1]	Negative	2	Sharma et al., 2019a; Wei et al., 2014a

Table S5. Single and meta-analysis studies of APase response relationships to soil pH and associated factors.

Soil pH factor	**APase (single[1] or meta-analysis[2] study)**	**Response relationship**	**Vote counting**	**Study**
pH	ACP[1]	Negative at pH >7	50	Acosta-Martínez and Tabatai, 2000; Alvarenga et al., 2008; Bachmann et al., 2014; Balota et al., 2011b; Bera et al., 2016; Bi et al., 2020; Biswas et al., 2018; Borase et al., 2021;

	Caballero Vanegas et al., 2018; Chakrabarti et al., 2000; Chang et al., 2007; Chen et al., 2021a; Dick et al., 2000; Fernández-Calviño et al., 2010 Firmano et al., 2021; Futa et al., 2021; Gaind and Nain, 2015b; Ghiloufi and Chaieb, 2021; Gispert et al., 2013; Gupta et al., 1988; Hu et al., 2019a; Juma and Tabatai, 1988; Katsalirou et al., 2016; Kunito et al., 2001; Laxminarayana K., 2017; Li et al., 2021a; Li et al., 2009; Liu et al., 2008; Martyniuk et al., 2019;

	Masto et al., 2013; Meli et al., 2002; Mullen et al., 1998; Nakas et al., 1987; Nedunchezhiyan et al., 2018; Nedyalkova et al., 2020; Nurulitaa et al., 2016; Ortiz et al., 2020; Pan et al., 2018; Roldán et al., 2007; Singh et al., 2012b; Stege et al., 2009; Sun et al., 2019; Tripathi et al., 2007; Trujillo-Narcía et al., 2019; Turner and Haygarth, 2005; Vanlalveni and Lalfakzuala, 2018; Venkatesan et al., 2006; Wang et al., 2017; Wang et al., 2021c; Woźniak et al., 2022;

	ACP[2]	Negative at pH >7	3	Janes-Bassett et al., 2022; Pokharel et al., 2020; Sun et al., 2020;
	ALP[1]	Positive at pH >7	45	Abdalla and Lager, 2009; Acosta-Martínez and Tabatai, 2000; Bachmann et al., 2014; Basak et al., 2017; Bera et al., 2016; Bi et al., 2020; Biswas et al., 2018; Borase et al., 2021; Caballero Vanegas et al., 2018; Carpenter-Boggs et al., 2003; Chang et al., 2007; Dick et al., 1988; Dick et al., 2000; Dinesh et al., 1998; Firmano et al., 2021; Gelsomino et al., 2011; Graça et al., 2021;

	Guo et al., 2009 Gupta et al., 1988; Katsalirou et al., 2016; Kunito et al., 2001; Laxminarayana K., 2017; Li et al., 2017a; Li et al., 2009; Madejón et al., 2003; Mandal et al., 2018; Melero et al., 2008a Melero et al., 2009; Meli et al., 2002; Monkiedje et al., 2006; Nath et al., 2021; Nedunchezhiyan et al., 2018; Rouydel et al., 2021; Senwo et al., 2007 Shi et al., 2020; Siebielec et al., 2018; Singh et al., 2012b; Singh et al., 2020; Stege et al., 2009; Tavali et al., 2021; Tripathi et al., 2007;

				Truu et al., 2008; Wang et al., 2022c; Wojewódzki et al., 2022; Yu et al., 2021
	ALP[2]	Positive at pH >7	3	Janes-Bassett et al., 2022; Pokharel et al., 2020; Sun et al., 2020;
Cation exchange capacity	ACP[1]	Positive	1	Gonnety et al., 2012;
		Negative	1	Senwo et al., 2007;
	ALP[1]	Positive	1	Gonnety et al., 2012; Senwo et al., 2007;
		Negative	1	Valarini et al., 2003;
Electrical conductivity	ACP[1]	Positive	3	Arora et al., 2021; Liu et al., 2008; Venkatesan et al., 2006;
	ALP[1]	Positive	7	Al-Taweel et al., 2019; Arora et al., 2021; Guo et al., 2009; Melero et al., 2008a; Melero et al., 2009; Monkiedje et al., 2006;

				Singh et al., 2012b;
Chlorine anion content	ACP[1]	Negative	1	Dinesh et al., 1995;
Carbonate content	ACP[1]	Negative	2	Dick et al., 2000; Siddaramappa et al., 1994;
	ALP[1]	Positive	2	Dick et al., 2000; Mahmood et al., 2022;
Iron content	ACP[1]	Positive	1	Maini et al., 2022;
	ALP[1]	Positive	3	Maini et al., 2022; Senwo et al., 2007; Yu et al., 2006;
Exchangeable aluminium content	ACP[1]	Positive	1	Meena et al., 2021;

Table S6. Single studies of APase response relationships to levels of soil salinity.

APase	Response relationship	Vote counting	Study
ACP	Negative	3	Garcia and Hernández, 1996; Rouydel et al., 2021; Sadeghi and Taban, 2021;
ALP	Negative	2	Al-Taweel et al., 2019; Fitriatin et al., 2018;

Table S7. Single and meta-analysis studies of APase response relationships to soil carbon content.

Soil carbon variable	APase (single[1] or meta-analysis[2] study)	Response relationship	Vote counting	Study
Soil organic carbon/matter	ACP[1]	Positive	53	Acosta-Martínez et al., 2003b; Acosta-Martínez et al., 2004; Avila-Salem et al., 2020; Babu et al., 2020; Baligar et al., 2005; Balota et al., 2011b; Bobul'ská et al., 2015; Borase et al., 2021; Butterly et al., 2011; Chang et al., 2007; Chellappa et al., 2021; Chen et al., 2021c; Choudhary et al., 2021; D'Ascoli et al., 2006; de Varennes and Torres, 2011; Eivazi et al., 2003;

	Evald et al., 2021; Fernández-Calviño et al., 2010; Gaind and Singh, 2016; Green et al., 2007; Hazarika et al., 2009; Katsalirou et al., 2016; Laxminarayana K., 2017; Li et al., 2021a; Lungmuana et al., 2019; Mahajan et al., 2021; Maini et al., 2022; McCallister et al., 2002; Monkiedje et al., 2006; Mullen et al., 1998; Omenda et al., 2019; Pan et al., 2018; Ramdas et al., 2016; Rietz and Haynes, 2003; Roy et al., 2019; Sangma et al., 2016; Šarapatka et al.,

				2004; Sarkar et al., 2020; Sharma et al., 2013a; Sharma et al., 2019a; Singh et al., 2018b; Singh et al., 2021; Siwik-Ziomek et al., 2014; Soon et al., 2000; Sudhakaran et al., 2019; Tarafdar et al., 1989; Truu et al., 2008; Tuti et al., 2020; Venkatesan et al., 2006; Wang et al., 2011b; Wei et al., 2017; Yu et al., 2006; Zuazo et al., 2020;
	ACP[2]	Positive	1	Sun et al., 2020;
	ALP[1]	Positive	47	Acosta-Martínez et al., 2003b; Acosta-Martínez et al., 2004; Arora et al., 2021; Bhattachayya et al., 2008;

	Blaise and Rao, 2004; Bobul'ská et al., 2015; Borase et al., 2020; Borase et al., 2021; Cao et al., 2022; Cattaneo et al., 2014; Chang et al., 2007; Chocano et al., 2016; Choudhary et al., 2018c; Choudhary et al., 2021; Cui et al., 2015; Eivazi et al., 2003; Gaind and Singh, 2016; Gangwar et al., 2021; Ghosh et al., 2019; Laxminarayana K., 2017; Li et al., 2017b; Liu et al., 2017; Łukowski and Dec, 2018; Lungmuana et al., 2019; Madejón et al., 2007; Maini et al., 2022;

				Melero et al., 2006; Mullen et al., 1998; Rietz and Haynes, 2003; Roy et al., 2019; Sepat et al., 2014; Sharma et al., 2015; Sharma et al., 2019a; Shi et al., 2020; Singh et al., 2018b; Singh et al., 2021; Siwik-Ziomek et al., 2014; Sudhakaran et al., 2019; Tarafdar et al., 1989; Truu et al., 2008; Tuti et al., 2020; Vekemans et al., 1989; Verma et al., 2016a; Wang et al., 2011b; Yu et al., 2006; Yu et al., 2021; Zhao et al., 2009;
	ALP[2]	Positive	1	Pokharel et al., 2020;
Total organic carbon	ACP[1]	Positive	10	Borase et al., 2021;

			da Silva Xavier et al., 2020;
			Franco-Otero et al., 2012;
			Futa et al., 2021;
			Gelsomino et al., 2011;
			Kobierski and Lemanowicz, 2016;
			Kobierski et al., 2017;
			Liu et al., 2008;
			Sarkar et al., 2009;
			Tiecher et al., 2017;
	Negative	1	Wojewódzki et al., 2022;
ALP[1]	Positive	11	Bera et al., 2016;
			Borase et al., 2021;
			Futa et al., 2021;
			Guo et al., 2009;
			Kobierski and Lemanowicz, 2016;
			Melero et al., 2007b;
			Melero et al., 2008a;
			Melero et al., 2009;
			Melero Sánchez et al., 2008;
			Sarkar et al., 2009;
			Sharma et al., 2019b;

Dissolved organic carbon	ACP[1]	Positive	3	Basak and Gajbhiye, 2018; Franco-Otero et al., 2012; Hazarika et al., 2009;
	ALP[1]	Positive	5	Basak and Gajbhiye, 2018; Calvarro et al., 2014; Madejón et al., 2007; Sharma et al., 2019b; Wojewódzki et al., 2022;

Table S8. Single and meta-analysis studies of APase response relationships to soil content of nitrogen forms and soil carbon:nitrogen ratios.

Nitrogen form/ratio	APase (single[1] or meta-analysis[2] study)	Response relationship	Vote counting	Study
Nitrate nitrogen	ACP[1]	Positive	1	Roy et al., 2019;
		Negative	2	Schaller K., 2003; Wang et al., 2021c;
	ALP[1]	Positive	1	Roy et al., 2019;
		Negative	1	Verma et al., 2016a;
		None	2	Adrover et al., 2017; Wang et al., 2022b;
Ammonium	ACP[1]	Positive	2	Liu et al., 2008;

nitrogen				Roy et al., 2019;
		None	1	Wang et al., 2013a;
	ALP[1]	Positive	2	Roy et al., 2019; Monkiedje et al., 2006;
		None	1	Wang et al., 2022a;
Total nitrogen (Kjeldahl method)	ACP[1]	Positive	15	Baligar et al., 2005; Chen et al., 2021b; Chen et al., 2021a; Fernández-Calviño et al., 2010; Gelsomino et al., 2011; Green et al., 2007; Katsalirou et al., 2016; Laxminarayana K., 2017; Li et al., 2021a; Mandal et al., 2007; Qaswar et al., 2019; Sudhakaran et al., 2019; Tamilselvi et al., 2015; Turner and Haygarth, 2005;

			Wang et al., 2011b;
	Negative	1	Wojewódzki et al., 2022;
ACP[2]	Positive	1	Sun et al., 2020;
ALP[1]	Positive	18	Acosta-Martínez et al., 2004;
			Cattaneo et al., 2014;
			Dinesh et al., 1998;
			Gelsomino et al., 2011;
			Guo et al., 2009;
			Katsalirou et al., 2016;
			Laxminarayana K., 2017;
			Li et al., 2017a;
			Liu et al., 2017;
			Mandal et al., 2007;
			Melero et al., 2007b;
			Melero Sánchez et al., 2008;
			Shi et al., 2020;
			Tan et al., 2014;
			Truu et al., 2008;
			Vekemans et al., 1989;

				Wang et al., 2011b; Wojewódzki et al., 2022;
Soil carbon:nitrogen ratio	ACP[1]	Positive	1	Liu et al., 2008;
	ALP[1]	Positive	1	Singh and Ghoshal, 2013;

Table S9. Single and meta-analysis studies of APase response relationships to soil content of phosphorus forms and carbon:phosphorus ratios.

Phosphorus form/ratio	**APase (single[1] or meta-analysis[2] study)**	**Response relationship**	**Vote counting**	**Study**
Labile inorganic phosphorus (Pi)	ACP[1]	Negative	10	Alves et al., 2021; Arruda et al., 2018; Castillo et al., 2017; Gao et al., 2016; Ohm et al., 2017; Romanya et al., 2017; Schoebitz et al., 2020; Simanca Fontalvo and Cuervo Andrade, 2018; Tarafdar and Claassen, 1988; Teng et al., 2013;
	ALP[1]	Negative	5	Fereidooni et al.,

				2013; Mahmood et al., 2022; Niewiadomska et al., 2020a; Recena et al., 2015; Simanca Fontalvo and Cuervo Andrade, 2018;
Soil solution phosphorus	ACP[1]	Positive	23	Arora et al., 2021; Atoloye et al., 2021; Babu et al., 2020; Futa et al., 2021; Guo et al., 2009; Kamh et al., 1999; Kobierski and Lemanowicz, 2016; Kobierski et al., 2017; Laxminarayana K., 2017; Li et al., 2018a; Liu et al., 2008; Lungmuana et al., 2019; Mahajan et al., 2021; Maini et al., 2022; Nedunchezhiyan et al., 2018; Ortiz et al., 2020;

			Qaswar et al., 2019;
			Sharma et al., 2019a;
			Sharpley et al., 1995;
			Singh et al., 2012a;
			Tarafdar et al., 1989;
			Yuan et al., 2022;
			Zhong et al., 2007;
	Negative	1	Saha et al., 2008a;
	None	3	Koczorski et al., 2021;
			Waldrop et al., 2000;
			Wojewódzki et al., 2022;
ALP[1]	Positive	16	Arora et al., 2021;
			Futa et al., 2021;
			Garg and Bahl, 2008;
			Guo et al., 2021;
			Kobierski and Lemanowicz, 2016;
			Laxminarayana K., 2017;
			Liu et al., 2017;
			Lungmuana et al., 2019;
			Maini et al., 2022;
			Sharma et al., 2019a;
			Tarafdar et al., 1989;
			Verma et al., 2016a;

				Wang et al., 2021a; Wang et al., 2021b; Wojewódzki et al., 2022; Zhao et al., 2009;
		Negative	2	Madejón et al., 2003; Saha et al., 2008a;
		None	2	Koczorski et al., 2021; Wang et al., 2022a;
Olsen phosphorus	ACP[1]	Positive	7	Basak et al., 2017; Basak and Gajbhiye, 2018; Moharana et al., 2022; Roy et al., 2019; Singh et al., 2018b; Yin et al., 2021; Zhang et al., 2019a;
	ACP[1]	Negative	1	Wang et al., 2021c;
	ACP[2]	Negative	1	Sun et al., 2020;
	ALP[1]	Positive	8	Atoloye et al., 2021; Basak and Gajbhiye, 2018; Melero et al., 2007b; Melero Sánchez et al., 2008; Moharana et al., 2022;

		Negative	4	Roy et al., 2019; Sharma et al., 2015; Singh et al., 2018b; Fraser et al., 2015; Katsalirou et al., 2016; Soni et al., 2021; Yu et al., 2006;
Organic phosphorus	ACP[1]	Positive	6	Moharana et al., 2022; Silva et al., 2015; Tarafdar et al., 1989; Turner and Haygarth, 2005; Wang et al., 2011c; Wei et al., 2021;
	ALP[1]	Positive	5	Dey et al., 2019; Guo et al., 2009; Moharana et al., 2022; Recena et al., 2015; Tarafdar et al., 1989;
Labile organic phosphorus (Po)	ACP[1]	Negative	3	Kamh et al., 1999; Wang et al., 2022b; Wu et al., 2012;
	ACP[2]	Negative	1	Sun et al., 2020;
	ALP[1]	Negative	1	de Santiago-Martín et al., 2013;

Soil carbon: phosphorus ratio	ACP[1]	Positive	1	Li et al., 2021a;

Table S10. Single studies of APase response relationships to soil available potassium content.

APase	Response relationship	Vote counting	Study
ACP	Positive	6	Arora et al., 2021; Koczorski et al., 2021; Laxminarayana K., 2017; Mahajan et al., 2021; Nedunchezhiyan et al., 2018; Venkatesan et al., 2006;
ALP	Positive	6	Arora et al., 2021; Koczorski et al., 2021; Laxminarayana K., 2017; Roy et al., 2019; Sharma et al., 2019a; Tan et al., 2014;

Table S11. Single and meta-analysis studies of APase response relationships to land use change.

Land use	APase (single[1] or meta-analysis[2] study)	Response relationship	Vote counting	Study
Ungrazed grassland, meadow, pasture	ACP[1]	Positive	25	Acosta-Martínez et al., 2008;
				Avila-Salem et al., 2020; Carlos et al., 2022; Chen et al., 2004; Damian et al., 2021; Gonnety et al., 2012; Graça et al., 2021; Izquierdo et al., 2003; Katsalirou et al., 2016; Kremer and Li, 2003; Lebrun et al., 2012; Li et al., 2017b; Notaro et al., 2018; Ohm et al., 2017; Pan et al., 2018; Pankhurst et al., 1995; Paz-Ferreiro et al., 2009; Raiesi F., 2007 Reardon et al., 2016; Šarapatka et al., 2004; Serri et al., 2018; Shi et al., 2013; Silvestro et al., 2017; Tiecher et al., 2012; Vinhal-Freitas et al., 2017;

	ALP[1]	Positive	13	Acosta-Martínez et al., 2008; Cattaneo et al., 2014; Cui et al., 2019; Dong et al., 2016; Gonnety et al., 2012; Graça et al., 2021; Katsalirou et al., 2016; Kremer and Li, 2003; Lebrun et al., 2012; Notaro et al., 2018; Ohm et al., 2017; Raiesi F., 2007; Saviozzi et al., 2001;
Revegetation				
Natural vegetation	ACP[1]	Positive	1	Aon and Colaneri, 2001;
Non cultivated	ACP[1]	Positive	1	Dick et al., 1994
Recolonization trees	ACP[1]	Positive	1	Garcia et al., 1997;
Reconstruction prairie	ACP[1]	Positive	1	García-Orenes et al., 2010;
Spontaneous recovery	ACP[1]	Positive	3	Li et al., 2021a; Lungmuana et al., 2019; Sciubba et al., 2021;
Plant invasion	ACP, ALP[2]	Positive	1	Margalef et al., 2021;
Forest clearance for cropland	ACP[1]	Negative	11	Barcelos Martins et al., 2019; Caravaca et al., 2002; de Oliveira Silva et al., 2019; Dormaar and Willms, 2000; Garcia et al., 1997;

				Guo et al., 2009 Hernández-Vigoa et al., 2018 Katsalirou et al., 2016; Leirós et al., 1999; Raiesi F., 2007; Serri et al., 2018;
	ALP[1]	Negative	3	Guo et al., 2009; Katsalirou et al., 2016; Raiesi F., 2007
Afforestation	ACP[1]	Positive	10	Arora et al., 2021; Brackin et al., 2014; Figueira da Silva et al., 2020; Garcia et al., 1997; Kooch et al., 2019; Li et al., 2021a; Martins Sousa et al., 2020; Nurulitaa et al., 2016; Singh et al., 2012a; Ventura et al., 2021;
	ALP[1]	Positive	7	Arora et al., 2021; Cui et al., 2019; Dilly O., 1999; Lungmuana et al., 2019; Neha et al., 2020; Tarafdar et al., 1989; Zhang et al., 2015;

Table S12. Single studies of APase response relationships to crop rotation composition and cover cropping.

Crop rotation type/property	APase	Response relationship	Vote counting	Study
Crop rotation	ACP	Positive	14	Alvey et al., 2001; Chen et al., 2018; Eichler-Löbermann et al., 2021; Ferreras et al., 2009; He et al., 2010; Inal et al., 2007; Jain et al., 2018; Koczorski et al., 2021; Nayyar et al., 2009 Qaswar et al., 2019; Redel et al., 2011; Siwik-Ziomek et al., 2014; Woźniak and Kawecka-Radomska, 2016; Yu et al., 2021;
	ALP	Positive	13	Acosta-Martínez et al., 2003a; Acosta-Martínez et al., 2011a; Alvey et al., 2001; Borase et al., 2020; Eichler-Löbermann et al., 2021; Gou et al., 2020; Habig and Swanepoel, 2018;

					He et al., 2010 Jain et al., 2018; Koczorski et al., 2021; Saad et al., 2018; Siwik-Ziomek et al., 2014; Yu et al., 2021;
	Cereal-legumes	ACP	Positive	2	Eichler-Löbermann et al., 2021; Nath et al., 2021;
		ALP	Positive	2	Eichler-Löbermann et al., 2021; Nath et al., 2021;
	Cereal-based	ACP	Positive	4	Acosta-Martínez et al., 2003b; Chen et al., 2021a; Datta et al., 2021; Dick et al., 1988;
		ALP	Positive	7	Acosta-Martínez et al., 2003b; Choudharyet al., 2018b; Datta et al., 2021; Dick et al., 1988; Gajda and Martyniuk, 2005; Wick et al., 1998; Zhang et al., 2018;
Cover crops		ACP	Positive	13	Adetunji et al., 2021; Boccolini et al., 2019; Chavarría et al., 2016; Cui et al., 2015;

				de Castro Lopes et al., 2021; Feng et al., 2021; Mullen et al., 1998; Pérez Brandan et al., 2017; Ramos et al., 2011; Ramos et al., 2010; Stegarescu et al., 2021; Takeda et al., 2009; Ventura et al., 2021;
	ALP	Positive	8	Cui et al., 2015; Feng et al., 2021; Hai-Ming et al., 2014; Melero et al., 2007a; Mullen et al., 1998; Niewiadomska et al., 2020b; Thapa et al., 2021; Wang et al., 2021b;
Intercropping	ACP	Positive	4	Balota et al., 2010; Gunes et al., 2007; Koczorski et al., 2021; Roohi et al., 2020;
	ALP	Positive	3	Koczorski et al., 2021; Roohi et al., 2020; Li et al., 2021b;
Intercropping+fertilization	ACP	Positive	1	Rezaei-Chiyaneh et al., 2021;
	ALP	Positive	3	Pittarello et al., 2021;

				Rezaei-Chiyaneh et al., 2021; Wang et al., 2014b;
Intercropping with legumes	ACP	Positive	2	Balota et al., 2010; Lo Presti et al., 2021;
Wheat vs maize/rice	ACP	Positive	2	Furtak et al., 2017; Masto et al., 2006;
	ALP	Positive	3	Furtak et al., 2017; Masto et al., 2006; Tao et al., 2009;
Legumes vs wheat/rice	ACP	Positive	11	Ansari et al., 2021; Aparna et al., 2016; Borase et al., 2021; Gunes et al., 2007 Kumar et al., 2017; Li et al., 2021b; Lo Presti et al., 2021; Nuruzzaman et al., 2006; Ohm et al., 2017; Raghurama et al., 2022; Singh et al., 2021;
	ALP	Positive	7	Acosta-Martínez et al., 2004; Aparna et al., 2016; Borase et al., 2021; Datta et al., 2021; Kumar et al., 2017; Singh et al., 2021; Yu et al., 2021;
Horticulture vs maize	ACP	Positive	4	Avila-Salem et al., 2020; Lago et al., 2019;

				Maini et al., 2022; Monkiedje et al., 2006;
	ALP	Positive	2	Maini et al., 2022; Monkiedje et al., 2006;
Barley vs horticulture	ACP	Positive	1	Moreno et al., 1998;
Monoculture maize vs others	ACP	Positive	8	Bossio et al., 2005; Dora et al., 2006; Fialho et al., 2008; Mankolo et al., 2006; Roohi et al., 2020; Savin et al., 2009; Serafim et al., 2019; Wang et al., 2017;
	ALP	Positive	4	Bossio et al., 2005; Dora et al., 2006; Roohi et al., 2020; Savin et al., 2009;
Monoculture lupine vs others	ACP	Positive	4	Lo Presti et al., 2021; Redel et al., 2007; Schoebitz et al., 2020; Touhami et al., 2021;
	ALP	Positive	2	Touhami et al., 2021; Wyszkowska et al., 2019;
Monoculture sorghum vs others	ACP	Positive	2	Alvey et al., 2001; Neal et al., 2021;
	ALP	Positive	2	Dou et al., 2016;

				Neal et al., 2021;
Monoculture transgenic cotton vs cotton	ACP	Positive	2	Beura and Rakshit, 2013; Sarkar et al., 2009;
	ALP	Positive	3	Beura and Rakshit, 2013; Mandal et al., 2018; Sarkar et al., 2009;
Monoculture transgenic rice vs rice	ACP	None	2	Zhaolei et al., 2017; Wei et al., 2012

Table S13. Single studies of response relationships of APase to tillage practices.

Tillage practice	APase	Response relationship	Vote counting	Study
Conventional tillage vs others	ACP	Positive	4	Acosta-Martínez et al., 2003b; de Varennes and Torres, 2011; Niewiadomska et al., 2016; Woźniak, A., 2019;
		Negative	8	Balota et al., 2004; Balota et al., 2011a; Bini et al., 2014; Carter et al., 2007 Farhangi-Abriz et al., 2021; Jaskulska R., 2020a; Peixoto et al., 2010 Swędrzyńska et al., 2013;
	ALP	Positive	4	Acosta-Martínez et al., 2003a;

				Acosta-Martínez et al., 2003b; Niewiadomska et al., 2016; Soni et al., 2021;
		Negative	3	Balota et al., 2004; Jaskulska R., 2020a; Niewiadomska et al., 2020b;
Reduced tillage vs conventional tillage	ACP	Positive	5	Farhangi-Abriz et al., 2021; Gajda and Przewłoka, 2012; Jaskulska R., 2020a; Ventura et al., 2021; Woźniak and Kawecka-Radomska, 2016;
	ALP	Positive	2	Madejón et al., 2007 Zibilske and Bradford, 2003;
No till vs others	ACP	Positive	24	Balota et al., 2004; Balota et al., 2011a; Barcelos Martins et al., 2019; Caballero Vanegas et al., 2018; Campbell et al., 1989; Chellappa et al., 2021; Eivazi et al., 2003; Green et al., 2007; Hatti et al., 2018; Hazarika et al., 2009; Hu et al., 2019b; Kumar et al., 2017; Mina et al., 2008

				Nath et al., 2017; Omidi et al., 2008 Peixoto et al., 2020 Redel et al., 2011; Roldán et al., 2007; Sepat et al., 2014; Silvestro et al., 2017; Ventura et al., 2021; Wang et al., 2011a; Wang et al., 2011b; Yang et al., 2019;
	ALP	Positive	21	Acosta-Martinez et al., 2011a; Balota et al., 2004; Bergstrom et al., 1998b; Caballero Vanegas et al., 2018; Carpenter-Boggs et al., 2003; Choudhary et al., 2018a; Habig and Swanepoel, 2018; Kumar et al., 2017; Melero et al., 2011; Mina et al., 2008 Naragund et al., 2020; Omidi et al., 2008 Parihar et al., 2016; Parihar et al., 2016; Sepat et al., 2014; Shahane et al., 2020; Singh et al., 2022; Wang et al., 2011b; Wei et al., 2014b;

				Xomphoutheb et al., 2020; Yang et al., 2019;
No till + residue retention vs others	ACP	Positive	9	Ahmed et al., 2019; Bini et al., 2014; Chellappa et al., 2021; Malobane et al., 2020; Rabary et al., 2008 Redel et al., 2007; Redel et al., 2011; Wang et al., 2011a; Cao et al., 2021;
	ALP	Positive	1	Wei et al., 2014a;
No till with depth vs others	ACP	Positive	5	Dick W.A., 1984; Doran J.W., 1980; Green et al., 2007; Kumar et al., 2017; Wang et al., 2011a;
	ALP	Positive	6	Angers et al., 1993; Dick W.A., 1984; Kharia et al., 2017; Kumar et al., 2017; Parihar et al., 2020; Shi et al., 2012;

Table S14. Single and meta-analysis studies of APase response relationships to types of inorganic and organic fertilization and rates.

APase (single[1] or meta-analysis[2] study)	Response relationship	Vote counting	Fertilization type	Study
ACP[1]	Positive	3	Liming	Bardgett and Leemans, 1995; Meena et al., 2021; Shi et al., 2019a;
	Negative	2		Makoi et al., 2010 Siddaramappa et al., 1994;
ALP[1]	Positive	3		Acosta-Martínez and Tabatai, 2000; Firmano et al., 2021; Lalande et al., 2009;
	Negative	1		Makoi et al., 2010
ACP[1]	Positive	13	Inorganic fertilizer (general)	Ajwaa et al., 1999; Bardgett and Leemans, 1995; Bi et al., 2018; Bi et al., 2020; Choudhary et al., 2021; de Castro Lopes et al., 2013; Futa et al., 2021; Gaind and Singh, 2016; Damian et al., 2021; Ning et al., 2017; Prasanthi et al., 2019; Rezaei-Chiyaneh et al., 2021;

	Negative	1		Verdenelli et al., 2013; Aparnad et al., 2016;
ALP[1]	Positive	16		Ajwaa et al., 1999; Aparna et al., 2016; Bi et al., 2018; Bi et al., 2020 Biswas et al., 2021; Choudhary et al., 2021; Dhull et al., 2004; Futa et al., 2021; Goyal et al., 1999; Jain et al., 2018; Joshi et al., 2021; Kumar et al., 2021b; Liu et al., 2010; Manna et al., 2005; Prasanthi et al., 2019; Rezaei-Chiyaneh et al., 2021;
	Negative	1		Wang et al., 2022a;
ACP, ALP[2]	Positive	1		Miao et al., 2019;
ACP[1]	Positive	8	Inorganic nitrogen	Bardgett and Leemans,1995; Dick et al., 1988; Guan et al., 2011; Johnson et al., 1998; Kohler et al., 2007; Menge and Field, 2007; Sarma and Gogoi, 2017; Siwik-Ziomek et al., 2014;
	Negative	8		Arruda et al., 2018; Chen et al., 2021a; Koper and Lemanowicz, 2008; Mullen et al., 1998; Rakshit et al., 2016;

				Siwik-Ziomek et al., 2014; Sun et al., 2020; Wang et al., 2021c;
ACP[2]	Positive	1		Jian et al., 2016;
ALP[1]	Positive	2		Liu et al., 2017; Siwik-Ziomek et al., 2014;
	Negative	4		Manna et al., 2005; Moreno-Cornejo et al., 2017; Rakshit et al., 2016; Siwik-Ziomek et al., 2014;
ACP, ALP[2]	Positive	2		Margalef et al., 2021; Marklein and Houlton, 2012;
ACP[1]	Negative	8	Inorganic phosphorus	de Castro Lopes et al., 2013; Gispert et al., 2013; Khandare et al., 2020; Li et al., 2021a; Liang and Elsgaard, 2021; Lo Presti et al., 2021; Silva et al., 2015; Wang et al., 2021c;
	None	3		Guan et al., 2013; Radersma and Grierson, 2004; Randall et al., 2020;
ALP[1]	Negative	2		Khandare et al., 2020; Svensson et al., 2001;
	None	4		Emami et al., 2022; Shi et al., 2012; Shi et al., 2020; Trabelsi et al., 2017;
ACP[2], ALP[2]	Negative	2		Margalef et al., 2021;

	None	1		Marklein and Houlton, 2012; Janes-Bassett et al., 2022;
ACP[1]	Positive	39	Organic fertilizers	Atoloye et al., 2021; Banik et al., 2006; Basak et al., 2017; Bobul'ská et al., 2015; Caballero Vanegas et al., 2018; Carricondo-Martínez et al., 2022; Chang et al., 2007; Chatterjee et al., 2021; Chen et al., 2003; Chen et al., 2021a; Cicatelli et al., 2014; Dutta et al., 2020; Efthimiadou et al., 2010; Eichler-Löbermann et al., 2021; Gaind and Singh, 2015a; García-Ruiz et al., 2008; García-Ruiz et al., 2012; Guan et al., 2011; Haynes and Williams, 1999; Jiang et al., 2019; Lalande et al., 2003; Martínez et al., 2018; Moharana et al., 2022; Monokrousos et al., 2006; Moreno et al., 1998; Pajares et al., 2009; Pramanik et al., 2017;

				Prasanthi et al., 2019; Radhakrishnan et al., 2022; Rao et al., 1997; Ros et al., 2007; Sarkar et al., 2020; Sharma et al., 2013b; Simanca Fontalvo and Cuervo Andrade, 2018; Singh et al., 2015; Singh et al., 2020; Sudhakaran et al., 2019; Tejada et al., 2006; Tuti et al., 2020;
ALP[1]	Positive	43		Adeleke et al., 2021; Aher et al., 2019; Akmal et al., 2019b; Atoloye et al., 2021; Basak et al., 2017; Blaise and Rao, 2004; Bobul'ská et al., 2015; Brennan and Acosta-Martinez, 2019; Caballero Vanegas et al., 2018; Chang et al., 2007; Chatterjee et al., 2021; Dhull et al., 2004; Durrer et al., 2021; Dutta et al., 2020; Efthimiadou et al., 2010; Eichler-Löbermann et al., 2021; Fereidooni et al., 2013; Gaind and Singh, 2016; García-Ruiz et al., 2008;

				Gigliotti et al., 2001; Krey et al., 2011; Kumar et al., 2021a; Meena et al., 2016; Melero et al., 2006; Melero et al., 2007a; Melero Sanchez et al., 2008; Melero et al., 2008a; Melero et al., 2008b; Moharana et al., 2022; Monokrousos et al., 2006; Okur et al., 2006; Pandey and Pandey, 2009 Prasanthi et al., 2019; Ram et al., 2019; Ramanandan et al., 2020; Rao et al., 1997; Sharma et al., 2013b; Singh et al., 2020; Sudhakaran et al., 2019; Tavali et al., 2021; Tejada and Gonzalez, 2007; Tejada and González, 2009; Truu et al., 2008;
ACP, ALP[2]	Positive	1		Miao et al., 2019;
ACP[1]	Positive	22	Manure	Acosta-Martinez et al., 2011b; Ali et al., 2019; Antonious C.F., 2009; Balota et al., 2014; Bhambure et al., 2018; Chakrabarti et al., 2000;

				Diallo-Diagne et al., 2016; Dick et al., 1988; Dinesh et al., 2012; Dora et al., 2006; Gopinath et al., 2009; Hazarika et al., 2021; Kobierski et al., 2017; Kuziemska et al., 2020; Li et al., 2012; Mahajan et al., 2021; Mani et al., 2020; Martyniuk et al., 2019; Romanya et al., 2017; Saha et al., 2008a; Tiecher et al., 2017; Xu et al., 2019;
ALP[1]	Positive	29		Antonious C.F., 2009; Böhme et al., 2005; Chaudhary et al., 2015; Delgado et al., 2012; Dick et al., 1988; Dora et al., 2006; Fereidooni et al., 2013; Fraser et al., 2015; Gaind and Nain, 2010; Garg and Bahl, 2008; Gopinath et al., 2009; Hojati and Nourbakhsh, 2006; Kobierski et al., 2017; Kumar et al., 2021b; Langer and Klimanek, 2006; Li et al., 2012; Liu and Zhou, 2017; Liu et al., 2010;

				Mani et al., 2020; Manna et al., 2007; Pandey et al., 2008; Qin et al., 2020; Ramesh et al., 2009; Saha et al., 2008a; Saha et al., 2008b; Shi et al., 2019b; Wang et al., 2012; Yang et al., 2018; Zhao et al., 2009;
ACP[1]	Positive	26	Manure + mineral fertilizer	Alguacil et al., 2003; Ali et al., 2019; Bera et al., 2016; Bhatt et al., 2016; Billah et al., 2020; Biswas et al., 2018; Cao et al., 2022; Choudhary et al., 2021; Damian et al., 2021; Dinesh et al., 2012; Elbl et al., 2019; Gagnon et al., 1999; Hatti et al., 2018; Jiang et al., 2019; Laxminarayana K., 2017; Masto et al., 2006; Meshram et al., 2016; Moro et al., 2021; Omenda et al., 2019; Qaswar et al., 2020; Roohi et al., 2020; Saha et al., 2019; Shao et al., 2014;

				Singh et al., 2015; Singh et al., 2018b; Wei et al., 2017;
ALP[1]	Positive	26		Akmal et al., 2019a; Bera et al., 2016; Bhatt et al., 2016; Biswas et al., 2018; Cao et al., 2022; Choudhary et al., 2021; Colvan et al., 2001; Gagnon et al., 1999; Goyal et al., 1999; Guo et al., 2021; Jia et al., 2018; Kaur et al., 2017; Laxminarayana K., 2017; Mandal et al., 2007; Manna et al., 2007; Masto et al., 2006; Meshram et al., 2016; Roohi et al., 2020; Saha et al., 2019; Sharma et al., 2015; Singh et al., 2020; Singh et al., 2018b; Wei et al., 2017; Wyszkowska and Wyszkowski, 2010; Xu et al., 2018; Zhao et al., 2009;
ACP, ALP[2]	Positive	1		Miao et al., 2019;
ACP[1]	Positive	1	Organic phosphorus	Guan et al., 2013;
ALP[1]	Positive	3		Durrer et al., 2021; Shi et al., 2021; Verma et al., 2021;

ACP[1]	Positive	7	Vermicompost	Aechra et al., 2021; Das et al., 2021; Hazarika et al., 2021; Ruiz and Salas, 2019; Saha et al., 2008a; Tejada and Benítez, 2011; Zhang et al., 2020;
ALP[1]	Positive	6		Becagli et al., 2022; Das et al., 2021; Dubey et al., 2020; Nisha et al., 2019; Tejada and González, 2009; Zhang et al., 2020;
ACP[1]	Positive	11	Biostimulant/biofertilizer (±microorganisms)	Aechra et al., 2021; Bana et al., 2022a; Bana et al., 2022b; Dubey et al., 2021; Firmano et al., 2021; Fitriatin et al., 2021; García-Martínez et al., 2010; Khandare et al., 2020; Kowalska et al., 2017; Sadeghi and Taban, 2021; Sharma et al., 2013a;
ALP[1]	Positive	11		Bana et al., 2022a; Bana et al., 2022b; Chaudhary et al., 2021; Chaudhary et al., 2022; Dubey et al., 2021;

				Firmano et al., 2021; Guo et al., 2021; Kaur et al., 2017; Khandare et al., 2020; Kowalska et al., 2017; Niewiadomska et al., 2020a;
ACP[1]	Positive	5	Biowaste fertilizer	El-Bassi et al., 2021; Krey et al., 2011; Rajashekhara and Siddaramappa, 2008; Romero et al., 2005; Tejada et al., 2006;
ALP[1]	Positive	6		Emmerling et al., 2010; Hashimoto et al., 2009 Mbarki et al., 2010; Meli et al., 2007; Piotrowska et al., 2006; Tejada et al., 2007;
ACP[1]	Positive	6	Sludge	Bhattacharyya et al., 2001; Gagnon et al., 1999; Gagnon et al., 2003; Moreira et al., 2017; Pascual et al., 2007 Siebielec et al., 2018;
	None	1		Alvarenga et al., 2008
ALP[1]	Positive	15		Carbonell et al., 2009; Dhanker et al., 2020; Dhanker et al., 2021; Frąc M., 2011; Ghosh et al., 2019; Lakhdar et al., 2011; Liu et al., 2020; Meena et al., 2016;

				Meena et al., 2018; N'Dayegamiye et al., 2006; Pascual et al., 2007; Roy et al., 2019; Siebielec et al., 2018; Tavali et al., 2021; Xie et al., 2011;
ACP[1]	Positive	2	Green manure	Pérez Brandan et al., 2017; Zhaolei et al., 2017;
ALP[1]	Positive	1		Janaki et al., 2021;
ACP[1]	Positive	1	Green manure + fertilizer	Bolton et al., 1985;
	None	3		Elfstrand et al., 2007a; Elfstrand et al., 2007b; Onkum and Teamkao, 2020;
ALP[1]	Positive	1		Dhull et al., 2004;
ACP[1]	Positive	8	Crop residue management	Chatterjee et al., 2021; Nath et al., 2017; Nath et al., 2021; Qaswar et al., 2020; Sepat et al., 2014; Sharma et al., 2019a; Singh et al., 2018; Yang et al., 2019;
	Negative	1		Peruccci et al., 1985;
ALP[1]	Positive	22		Chatterjee et al., 2021; Choudhary et al., 2018a; Gaind and Nain, 2007; Galvez et al., 2012; Hai-Ming et al., 2014; Hazra et al., 2021; Jat et al., 2020;

				Khan et al., 2022; Melero et al., 2006; Melero et al., 2009; Moreno-Cornejo et al., 2017; Nath et al., 2021; Peruccci et al., 1985; Pooniya et al., 2022; Sepat et al., 2014; Sharma et al., 2019a; Singh et al., 2018; Tao et al., 2009; Tejada et al., 2009; Ullah et al., 2020; Wei et al., 2014a; Yang et al., 2019;
ACP[1]	Positive	3	Straw residues	Arun et al., 2020; Cao et al., 2022; Wei et al., 2021;
ALP[1]	Positive	7		Arun et al., 2020; Cao et al., 2022; Cui et al., 2022; Singh and Sharma, 2020; Singh et al., 2022; Ullah et al., 2018a; Zhang et al., 2016a;
ACP[1]	Positive	5	Mulching	Arun et al., 2020; Balota et al., 2004; Benítez et al., 2000; da Silva Xavier et al., 2020; Zhu et al., 2022;
	None	1		Jain et al., 2018;
ALP[1]	Positive	5		Arun et al., 2020; Balota et al., 2004; Buck et al., 2000;

				Rao et al., 1997;
				Wang et al., 2014a;
	None	1		Jain et al., 2018;
ACP[1]	Positive	7	Biochar	Akmal et al., 2019a;
				Akmal et al., 2019b;
				Egamberdieva et al., 2019;
				El-Bassi et al., 2021;
				Noronha et al., 2022;
				Salam et al., 2019;
				Wojewódzki et al., 2022;
	Negative	1		Yuan et al., 2022;
ALP[1]	Positive	14		Ali et al., 2017;
				Azeem et al., 2021;
				Becagli et al., 2022;
				Becagli et al., 2022;
				Du et al., 2014;
				Dubey et al., 2020;
				Guo et al., 2021;
				Jabborova et al., 2021;
				Khan et al., 2022;
				Masto et al., 2013;
				Saha et al., 2019;
				Wojewódzki et al., 2022;
				Yao et al., 2021;
				Zhu et al., 2017;
ALP[2]	Positive	1		Pokharel et al., 2020;
ACP[1]	Negative	3	Burning	Dick et al., 1988;
				Hoyle and Murphy, 2006;
				Trujillo-Narcía et al., 2019;
ALP[1]	Negative	3		Ajwaa et al., 1999;
				Peruccci et al., 1984;
				Perucci et al., 2007;

ACP[1]	Positive	7	Phosphate solubilizing bacteria	Aechra et al., 2021; Chatterjee et al., 2021; Khandare et al., 2020; Khuong et al., 2018; Krey et al., 2011; Liu et al., 2021b; Pareek et al., 2019;
ALP[1]	Positive	9		Basak et al., 2017; Biswas et al., 2021; Chatterjee et al., 2021; Chaudhary et al., 2022; Gaind and Nain, 2007; Khandare et al., 2020; Krey et al., 2011; Naragund et al., 2020; Pareek et al., 2019;
ACP[1]	Positive	11	Plant beneficial bacteria	Benbrik et al., 2021; Bhambure et al., 2018; Billah et al., 2020; de Cássia et al., 2018; Gospodarek et al., 2021; Idris and Yuliar, 2021; Rajeela et al., 2017; Madhaiyan et al., 2009 Mercl et al., 2020; Rouydel et al., 2021; Verma et al., 2016b;
	Negative	2		de Barros et al., 2019; Makoi et al., 2010
	None	1		Ruiz and Salas, 2019;
ALP[1]	Positive	16		Ali et al., 2017; Benbrik et al., 2021; Chaudhary et al., 2021;

				Cui et al., 2015;
				de Cássia et al., 2018;
				Dubey et al., 2021;
				Emami et al., 2022;
				Idris and Yuliar, 2021;
				Kohler et al., 2007;
				Manjunath et al., 2016;
				Nakas et al., 1987;
				Omara et al., 2017;
				Rouydel et al., 2021;
				Schoebitz et al., 2019;
				Valarini et al., 2003;
				Verma et al., 2016b;
	Negative	2		Makoi et al., 2010;
				Mercl et al., 2020;
ACP[1]	Positive	17	Arbuscular mycorrhizal fungi	de Barros et al., 2019;
				Ferreira-Vilela et al., 2014;
				Hu et al., 2019b;
				Hu et al., 2019a;
				Kim et al., 2002;
				Laxminarayana K., 2017;
				Manjunath et al., 2016;
				Nakas et al., 1987;
				Sales et al., 2021;
				Sharma et al., 2013a;
				Tarafdar and Rao, 1996;
				Tarafdar and Gharu, 2006;
				Turan V., 2021;
				Wang et al., 2013c;
				Yadav et al., 2007;
				Yin et al., 2021;
				Zhang et al., 2019b;

	None	2	Wakelin et al., 2007; Izaguirre-Mayoral et al., 2000;
ALP[1]	Positive	8	Chatterjee et al., 2021; de Barros et al., 2019; Gaind and Nain, 2007; Kohler et al., 2008; Laxminarayana K., 2017; Tarafdar and Rao, 1996; Tarafdar and Gharu, 2006; Yadav et al., 2007;
ALP[1]	None	1	Wakelin et al., 2007;

Table S15. Single studies and reviews of APase response relationships to weed and pest management practices.

Management practice	APase (single study[1] or review[2])	Response relationship	Vote counting	Study
Manual weeding vs chemical	ACP[1]	Positive	3	Bhatt et al., 2016; Majumdar et al., 2010; Nedunchezhiyan et al., 2018;
	ALP[1]	Positive	5	Bhatt et al., 2016; Majumdar et al., 2010 Nedunchezhiyan et al., 2018; Ullah et al., 2018b; Ullah et al., 2020;
Herbicides	ACP[1]	Negative	4	Carter et al., 2007; Cycoń et al., 2013; Savin et al., 2009; Wyszkowska J., 2002;

		None	6	Arya et al., 2018; Majumdar et al., 2010 Meher et al., 2021; Pozo et al., 1994; Sofo et al., 2012; Tomkiel et al., 2018;
	ALP[1]	Negative	7	Cycoń et al., 2013; Rasool et al., 2014; Saha et al., 2016; Savin et al., 2009; Singh and Gohshal, 2013; Sofo et al., 2012; Wyszkowska J., 2002;
		None	6	Majumdar et al., 2010; Meher et al., 2021; Nivelle et al., 2018; Pozo et al., 1994; Tejada et al., 2017; Tomkiel et al., 2018;
	ACP, ALP[2]	None	1	Riah et al., 2014;
Fungicides	ACP[1]	Negative	2	Chen et al., 2001; Wang et al., 2022c;
		None	3	Ntalli et al., 2019b; Pozo et al., 1995; Singh N., 2005;
	ACP[2]	Positive		Riah et al., 2014;
	ALP[1]	Negative	1	Ntalli et al., 2019a;
		None	3	Baćmaga et al., 2019; Pozo et al., 1995; Wang et al., 2022c;
	ALP[2]	Negative		Riah et al., 2014;
Insecticides	ACP[1]	Negative	4	Dinesh et al., 1995; García-Martínez et al., 2010; Megharaj et al., 1999;

		None	3	Tu C.M., 1995; Megharaj et al., 1999; Racke et al., 1996; Tu C.M., 1995;
	ACP[2]	Negative	1	Riah et al., 2014;
	ALP[1]	Recovery with time	3	Cycoń Piotrowska-Seget, 2015; Mahapatra et al., 2017; Pandey et al., 2006;
		None	1	Racke et al., 1996;
	ALP[2]	Recovery with time	1	Riah et al., 2014;

S16. Single and meta-analysis studies of APase response relationships to irrigation practice.

Irrigation practice	**APase (single[1] or meta-analysis[2] study)**	**Response relationship**	**Vote counting**	**Study**
Optimal irrigation	ACP[1]	Positive	10	D'Ascoli et al., 2006; George et al., 2013; He et al., 2010; Li et al., 2017a; Pascual et al., 2007; Sharma et al., 2013b; Wang et al., 2013c; Zhang et al., 2019a; Zhang et al., 2021; Zhong et al., 2007;
	ACP[2]	Positive	1	Sun et al., 2020;
	ALP[1]	Positive	10	Abdalla and Lager, 2009; George et al., 2013; He et al., 2010; Jia et al., 2018;

				Kumar et al., 2021b; Li et al., 2018c; Pascual et al., 2007; Romero-Trigueros et al., 2021; Sharma et al., 2013b; Tan et al., 2009;
Waste water irrigation	ACP[1]	Positive	1	Meli et al., 2002;
		Negative	1	Masto et al., 2008
		None	1	Santos et al., 2016;
	ALP[1]	Positive	4	Bhattachayya et al., 2008; García-Orenes et al., 2015; Lal et al., 2015; Meli et al., 2002;
		Negative	1	Masto et al., 2008
		None	3	Adrover et al., 2007; Adrover et al., 2017; Kayikcioglu H.H., 2018;

Table S17. Single studies of APase response relationships to livestock, grazing and mowing management.

Management type	APase	Response relationship	Vote counting	Study
Crop-livestock	ACP	Positive	5	de Jesus Franco et al., 2020; Izquierdo et al., 2003; Damian et al., 2021; Martins Sousa et al., 2020; Silva et al., 2015;
Grazing	ACP	Positive	4	Bardgett and Leemans, 1995;

				George et al., 2013; Ramos et al., 2011; Ramos et al., 2010;
	ALP	Positive	2	Galindo et al., 2020; George et al., 2013;
Mowing	ALP	Negative	1	Zibilske and Makus, 2009;

Table S18. Single and meta-analysis studies of APase response relationships to soil pollutant content.

Pollutant	APase (single[1] or meta-analysis[2] study)	Response relationship	Vote counting	Study
Heavy metals				
Lead	ACP[1]	Negative	5	Bartkowiak et al., 2021; Chowdhury and Rasid, 2021b; Lemanowicz et al., 2016; Li et al., 2009; Papa et al., 2009
	ALP[1]	Negative	5	Bartkowiak et al., 2021; Bhattachayya et al., 2008 Calvarro et al., 2014; de Santiago-Martín et al., 2013; Lemanowicz et al., 2016;
Chromium	ACP[1]	Negative	3	Bartkowiak et al., 2021; Chowdhury and Rasid, 2021a; Wyszkowska et al., 2001;
	ALP[1]	Negative	2	Bartkowiak et al., 2021; Wyszkowska et al., 2001;
Nickel	ACP[1]	Negative	2	Antonious C.F., 2009; Lemanowicz et al., 2016;

	ALP[1]	Negative	4	Antonious C.F., 2009; Lemanowicz et al., 2016; Pandey and Pandey, 2009; Wyszkowska et al., 2005;
Zinc	ACP[1]	Positive Negative	1 4	Mandal et al., 2021; Chowdhury and Rasid, 2021a; Lemanowicz et al., 2016; Li et al., 2018d; Ros et al., 2008
	ALP[1]	Positive Negative	1 7	Mandal et al., 2021; Calvarro et al., 2014; de Santiago-Martín et al., 2013; Fernández et al., 2014; Lemanowicz et al., 2016; Liu et al., 2020; Łukowski and Dec, 2018; Pandey and Pandey, 2009;
Cadmium	ACP[1]	Negative	2	Chowdhury and Rasid, 2021b; Li et al., 2009;
	ACP[2]	Positive	1	Aponte et al., 2020;
	ALP[1]	Positive Negative	1 4	Ogunkunle et al., 2020; Calvarro et al., 2014; Dar G., 1996; de Santiago-Martín et al., 2013; Pandey and Pandey, 2009;
Copper	ACP[1]	Positive Negative	1 8	Belyaeva et al., 2005; Bartkowiak et al., 2021; Dewey et al., 2012; Fernández-Calviño et al., 2010 Lebrun et al., 2012; Lemanowicz et al., 2016;

				Li et al., 2009; Papa et al., 2009 Ros et al., 2008
	ACP[2]	Positive	1	Aponte et al., 2020;
	ALP[1]	Negative	7	Bartkowiak et al., 2021; Bhattachayya et al., 2008 Calvarro et al., 2014; de Santiago-Martín et al., 2013; Kuziemska et al., 2020; Lemanowicz et al., 2016; Pandey and Pandey, 2009;
Manganese	ACP[1]	Negative	2	Li et al., 2009; Ros et al., 2008
Arsenic	ACP[1]	Negative	1	Garg and Cheema, 2021;
	ALP	Negative	1	Garg and Cheema, 2021;
Mercury	ACP[2]	Negative	1	Aponte et al., 2020;
	ALP[1]	Negative	1	Casucci et al., 2003;
	ALP[2]	Negative	1	Aponte et al., 2020;
Sewage sludge compost	ACP[1]	Negative	3	Antolín et al., 2005; Kunito et al., 2001; Moreno et al., 1998;
	ALP[1]	Negative	5	Dar G., 1996; Fernández et al., 2014; Kunito et al., 2001; Stoven and Schnug, 2009; Wang et al., 2021b;
Petroleum diesel	ACP[1]	Negative	2	Wyszkowska et al., 2002; Wyszkowska and Wyszkowski, 2010;
	ALP[1]	Negative	4	Gospodarek et al., 2021; Serrano et al., 2009; Wyszkowska et al., 2002;

				Wyszkowska and Wyszkowski, 2010;
Nanomaterials				
Carbon, copper, silver	ACP[2]	Negative	1	Lin et al., 2021;
Iron	ACP[2]	Positive	1	Lin et al., 2021;

Table S19. Single and meta-analysis studies of APase responses to the increase of different climate change variables.

Variable	APase (single[1] or meta-analysis[2] study)	Response relationship	Vote counting	Study
Mean annual temperature	ACP[1]	Positive	1	Ghiloufi and Chaieb, 2021;
		Negative	1	Chen et al., 2021b;
	ACP[2]	Positive	2	Sun et al., 2020; Meng et al., 2020;
	ALP[1]	Negative	1	Wang et al., 2021a;
	ACP, ALP[2]	None	1	Margalef et al., 2021;
Mean annual precipitation	ACP[1]	Positive	1	Ghiloufi and Chaieb, 2021;
	ACP[2]	Positive	1	Sun et al., 2020;
	ALP[1]	Positive	2	Habig and Swanepoel, 2015; Morugán-Coronado et al., 2019;
Drought	ACP[1]	Positive	1	Caballero Vanegas et al., 2018;
		Negative	2	Gunes et al., 2007 Egamberdieva et al., 2019;

	ALP[1]	Positive Negative	1 1	Caballero Vanegas et al., 2018; Egamberdieva et al., 2019;
	ACP, ALP[2]	Negative	2	Gou et al., 2020; Margalef et al., 2021;
Soil water scarcity	ACP[1]	Negative None	1 2	Ghiloufi and Chaieb, 2021; Mazzuchelli et al., 2020; Zago et al., 2018;
	ACP, ALP[2]	Negative	1	Gou et al., 2020;
Soil water availability	ACP[1]	Positive	2	Figueira da Silva et al., 2020; Izquierdo et al., 2003;
	ALP[1]	Positive	2	Fraser et al., 2015; Jabborova et al., 2021;
Seasonal variations				
Rainy season	ACP[1]	Positive	14	Arora et al., 2021; Bachmann et al., 2014; Bolton et al., 1985; Carlos et al., 2022; Dormaar and Willms, 2000; Elfstrand et al., 2007b; García-Ruiz et al., 2009; Jaskulska et al., 2020b;

				Koper and Lemanowicz, 2008; Li et al., 2021a; Mejia Guerra et al., 2018; Mina et al., 2008 Silvestro et al., 2017; Singh et al., 2012a;
	ALP[1]	Positive	11	Angers et al., 1993; Arora et al., 2021; Bachmann et al., 2014; Du et al., 2014; Efthimiadou et al., 2010; Koper and Lemanowicz, 2008; Łukowski and Dec, 2018; Meli et al., 2002; Neha et al., 2020; Okur et al., 2006; Shi et al., 2020;
Dry season	ACP[1]	Negative	4	Bolton et al., 1985; Hoyle and Murphy, 2006; McCallister et al., 2002; Tiecher et al., 2012;
CO_2 fertilization	ALP[1]	Positive	1	Dey et al., 2019;
	ACP, ALP[2]	Positive	1	Margalef et al., 2021;

Table S20. Single studies of crop yield responses to APase activity.

Crop	APase	Response relationship	Vote counting	Study
Wheat	ACP	Positive	1	Moharana et al., 2022;
	ALP	Positive	4	Borase et al., 2020; Furtak et al., 2017; Mandal et al., 2007; Moharana et al., 2022;
Organic Wheat	ACP	Positive	1	Dick et al., 1988;
	ALP	Positive	2	Sharma et al., 2015; Tejada and Gonzalez, 2007;
Maize	ACP	Positive	1	Wei et al., 2021;
	ALP	Positive	2	Furtak et al., 2017; Zhou et al., 2022;
Organic winter barley	ACP	Positive	1	Antolín et al., 2005;
Organic beet	ACP	Positive	1	Roy et al., 2019;
	ALP	Positive	1	Roy et al., 2019;
Rice	ACP	Positive	1	Zhang et al., 2019a;
	ALP	Negative	1	Basak et al., 2017;
Organic lentil	ALP	Positive	1	Singh et al., 2018b;
Broad bean	ACP	Positive	1	Gao et al., 2016;
Organic plum	ALP	None	1	Chocano et al., 2016;
Organic orange	ALP	None	1	Madejón et al., 2003;

References

Alves, G.S., Bertini, S.C.B., Barbosa, B.B., Pimentel, J.P., Junior, V.A.R., Mendes, G. de O., Azevedo, L.C.B., 2021. Fungal endophytes inoculation improves soil nutrient availability, arbuscular mycorrhizal colonization and common bean growth. Rhizosphere 18. https://doi.org/10.1016/j.rhisph.2021.100330.

Alvey, S., Bagayoko, M., Neumann, G., Buerkert, A., 2001. Cereal/legume rotations affect chemical properties and biological activities in two West African soils. Plant and Soil 231, 45–54. https://doi.org/10.1023/A:1010386800937.

Angers, D.A., Bissonnette, N., Legere, A., Samson, N., 1993. Microbial and biochemical changes induced by rotation and tillage in a soil under barley production. Canadian Journal of Soil Science 73, 39–50. https://doi.org/10.4141/cjss93-004.

Ansari, M.A., Saha, S., Das, A., Lal, R., Das, B., Choudhury, B.U., Roy, S.S., Sharma, S.K., Singh, I.M., Meitei, C.B., Changloi, K.L., Singh, L.S., Singh, N.A., Saraswat, P.K., Ramakrishna, Y., Singh, D., Hazarika, S., Punitha, P., Sandhu, S.K., Prakash, N., 2021. Energy and carbon budgeting of traditional land use change with groundnut based cropping system for environmental quality, resilient soil health and farmers income in eastern Indian Himalayas. Journal of Environmental Management 293, 112892. https://doi.org/10.1016/j.jenvman.2021.112892.

Abdalla M. A., and Langer, U., 2009. Soil enzymes activities in irrigated and rain-fed vertisols of the Semi-Arid tropics of Sudan. International Journal of Soil Science, 5, 226-238. http://dx.doi.org/10.3923/ijss.2009.67.79.

Acosta-Martínez, V., and Tabatabai, M.A., 2000. Enzyme activities in a limed agricultural soil. Biology and Fertility of Soils 31, 85–91. https://doi.org/10.1007/s003740050628.

Acosta-Martínez, V., Zobeck, T.M., Gill, T.E., Kennedy, A.C., 2003a. Enzyme activities and microbial community structure in semiarid agricultural soils. Biology and Fertility of Soils 38, 216–227. https://doi.org/10.1007/s00374-003-0626-1.

Acosta-Martínez, V., Klose, S., Zobeck, T.M., 2003b. Enzyme activities in semiarid soils under conservation reserve program, native rangeland, and cropland. Journal of Plant Nutrition and Soil Science 166, 699–707. https://doi.org/10.1002/jpln.200321215.

Acosta-Martínez, V., Upchurch, D.R., Schubert, A.M., Porter, D., Wheeler, T., 2004. Early impacts of cotton and peanut cropping systems on selected soil chemical, physical, microbiological and biochemical properties. Biology and Fertility of Soils 40, 44–54. https://doi.org/10.1007/s00374-004-0745-3.

Acosta-Martinez, V., Acosta-Mercado, D., Sotomayor-Ramirez, D., Cruz-Rodriguez, L., 2008. Microbial communities and enzymatic activities under different management in semiarid soils. APPLIED SOIL ECOLOGY 38, 249–260. https://doi.org/10.1016/j.apsoil.2007.10.012.

Acosta-Martínez, V., Lascano, R., Calderón, F., Booker, J.D., Zobeck, T.M., Upchurch, D.R., 2011a. Dryland cropping systems influence the microbial biomass and enzyme activities in a semiarid sandy soil. Biology and Fertility of Soils 47, 655–667. https://doi.org/10.1007/s00374-011-0565-1.

Acosta-Martinez, V., Mikha, M.M., Sistani, K.R., Stahlman, P.W., Benjamin, J.G., Vigil, M.F., Erickson, R., 2011a. Multi-location study of soil enzyme activities as affected by types and rates of manure application and tillage practices. Agriculture (Switzerland) 1, 4–21. https://doi.org/10.3390/agriculture1010004.

Adeleke, K.A., Atoloye, I.A., Creech, J.E., Dai, X., Reeve, J.R., 2021. Nutritive and non-nutritive effects of compost on organic dryland wheat in Utah. Agronomy Journal 113, 3518–3531. https://doi.org/10.1002/agj2.20698.

Adetunji, A.T., Ncube, B., Meyer, A.H., Olatunji, O.S., Mulidzi, R., Lewu, F.B., 2021. Soil pH, nitrogen, phosphatase and urease activities in response to cover crop species, termination stage and termination method. Heliyon 7, e05980. https://doi.org/10.1016/j.heliyon.2021.e05980.

Adrover M., Farrús E., Moyà G. , Vadell J., 2007. Chemical properties and biological activity in soils of Mallorca following twenty years of treated wastewater irrigation. Applied Soil Ecology, 37, 41-138. https://doi.org/10.1016/j.jenvman.2010.08.017.

Adrover, M., Moyà, G., Vadell, J., 2017. Seasonal and depth variation of soil chemical and biological properties in alfalfa crops irrigated with treated wastewater and saline groundwater. Geoderma 286, 54–63. https://doi.org/10.1016/j.geoderma.2016.10.024.

Aechra S., Meena R.H., Meena S.C., Mundra S.L., Lakhawat S.S., Mordia A., Jat G., 2021. Soil microbial dynamics and enzyme activities as influenced by biofertilizers and split application of vermicompost in rhizosphere of wheat (Triticum aestivum. L.). Journal of Environmental Biology 42: 1370-1378.

Aher, S.B., Lakaria, B.L.A.L., Singh, A.B., Kaleshananda, S., Ramana, S., Ramesh, K., Thakur, J.K., Rajput, P.S., Yashona, D.S., 2019. Effect of organic sources of nutrients on performance of soybean (Glycine max). Indian Journal of Agricultural Sciences 89, 1787–1791.

Ahmed, W., Qaswar, M., Jing, H., Wenjun, D., Geng, S., Kailou, L., Ying, M., Ao, T., Mei, S., Chao, L., Yongmei, X., Ali, S., Normatov, Y., Mehmood, S., Khan, M.N., Huimin, Z., 2019. Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils. Journal of Soils and Sediments 20, 850–861. https://doi.org/10.1007/s11368-019-02468-3.

Ajwa, H.A., Dell, C.J., Rice, C.W., 1999. Changes in enzyme activities and microbial biomass of tallgrass prairie soil as related to burning and nitrogen fertilization. Soil Biology and Biochemistry 31, 769–777. https://doi.org/10.1016/S0038-0717(98)00177-1.

Akmal, M., Gondal, T.A., Khan, K.S., Hussain, Q., Ahmad, M., Abbas, M.S., Rafa, H.U., Khosa, S.A., 2019a. Impact of biochar prepared from leaves of Populous euphratica on soil microbial activity and mung bean (Vigna radiata) growth. Arabian Journal of Geosciences 12. https://doi.org/10.1007/s12517-019-4724-2.

Akmal, M., Maqbool, Z., Khan, K.S., Hussain, Q., Ijaz, S.S., Iqbal, M., Aziz, I., Hussain, A., Abbas, M.S., Rafa, H.U., 2019b. Integrated use of biochar and compost to improve soil microbial activity, nutrient availability, and plant growth in arid soil. Arabian Journal of Geosciences 12. https://doi.org/10.1007/s12517-019-4414-0.

Al-Taweel, L.S.J., Jubouri, G.A.A.A., 2019. Effect of Agricultural Exploitation on the Activity of Alkaline Phosphatase and Its Kinetic Properties in Some Soils. Al-Qadisiyah Journal For Agriculture Sciences (QJAS) (P-ISSN: 2077-5822 , E-ISSN: 2617-1479) 9, 120–135. https://doi.org/10.33794/qjas.vol9.iss1.69.

Alguacil, M.M., Caravaca, F., Azcón, R., Pera, J., Díaz, G., Roldán, A., 2003. Improvements in soil quality and performance of mycorrhizal <I>Cistus albidus</I> L. seedlings resulting from addition of microbially treated sugar beet residue to a degraded semiarid Mediterranean soil. Soil Use and Management 19, 277–283. https://doi.org/10.1079/sum2003206.

Ali, A., Guo, D., Mahar, A., Wang, P., Ma, F., Shen, F., Li, R., Zhang, Z., 2017. Phytoextraction of toxic trace elements by Sorghum bicolor inoculated with Streptomyces pactum (Act12) in contaminated soils. Ecotoxicology and Environmental Safety 139, 202–209. https://doi.org/10.1016/j.ecoenv.2017.01.036.

Ali, W., Nadeem, M., Ashiq, W., Zaeem, M., Gilani, S.S.M., Rajabi-Khamseh, S., Pham, T.H., Kavanagh, V., Thomas, R., Cheema, M., 2019. The effects of organic and inorganic phosphorus amendments on the biochemical attributes and active microbial population of agriculture podzols following silage corn cultivation in boreal climate. Scientific Reports 9, 1–17. https://doi.org/10.1038/s41598-019-53906-8.

Alvarenga, P., Palma, P., Gonçalves, A.P., Baião, N., Fernandes, R.M., Varennes, A. de, Vallini, G., Duarte, E., Cunha-Queda, A.C., 2008. Assessment of chemical, biochemical and ecotoxicological aspects in a mine soil amended with sludge of either urban or industrial origin. Chemosphere 72, 1774–1781. https://doi.org/10.1016/j.chemosphere.2008.04.042.

Antolín, M.C., Pascual, I., García, C., Polo, A., Sánchez-Díaz, M., 2005. Growth, yield and solute content of barley in soils treated with sewage sludge under semiarid Mediterranean conditions. Field Crops Research 94, 224–237. https://doi.org/10.1016/j.fcr.2005.01.009.

Antonious, G.F., 2009. Enzyme activities and heavy metals concentration in soil amended with sewage sludge. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering 44, 1019–1024. https://doi.org/10.1080/10934520902996971.

Aon, M.A., and Colaneri, A.C., 2001. II. Temporal and spatial evolution of enzymatic activities and physico-chemical properties in an agricultural soil. Applied Soil Ecology 18, 255–270. https://doi.org/10.1016/S0929-1393(01)00161-5.

Aparna, K., Rao, D.L.N., Balachandar, D., 2016. Microbial Populations, Activity and Gene Abundance in Tropical Vertisols Under Intensive Chemical Farming. Pedosphere 26, 725–732. https://doi.org/10.1016/S1002-0160(15)60079-0.

Aponte, H., Meli, P., Butler, B., Paolini, J., Matus, F., Merino, C., Cornejo, P., Kuzyakov, Y., 2020. Meta-analysis of heavy metal effects on soil enzyme activities. Science of the Total Environment 737, 139744. https://doi.org/10.1016/j.scitotenv.2020.139744.

Arora, R., Sharma, V., Sharma, S., Maini, A., Dhaliwal, S.S., 2021. Temporal changes in soil biochemical properties with seasons under rainfed land use systems in Shiwalik foothills of northwest India. Agroforestry Systems 95, 1479–1491. https://doi.org/10.1007/s10457-021-00654-2.

Arruda, B., Dall'orsoletta, D.J., Heidemann, J.C., Gatiboni, L.C., 2018. Phosphorus dynamics in the rhizosphere of two wheat cultivars in a soil with high organic matter content. Archives of Agronomy and Soil Science 64, 1011–1020. https://doi.org/10.1080/03650340.2017.1407028.

Arun, T., Sridevi, S., Rani, K.R., 2020. Soil Hydrothermal Regimes, Biological Activity and Nutrient Availability under Various Mulches and Weed Management Practices in Tomato. International Research Journal of Pure and Applied Chemistry 21, 40–48. https://doi.org/10.9734/irjpac/2020/v21i1730264.

Arya, S.R., Syriac, E.K., Aparna, B., 2018. Enzyme dynamics and organic carbon status of soil as influenced by flucetosulfuron in wet seeded rice. Journal of Tropical Agriculture 56, 1–8.

Atoloye, I.A., Jacobson, A., Creech, E., Reeve, J., 2021. Variable impact of compost on phosphorus dynamics in organic dryland soils following a one-time application. Soil Science Society of America Journal 85, 1122–1138. https://doi.org/10.1002/saj2.20275.

Avila-Salem, M.E., Montesdeoca, F., Orellana, M., Pacheco, K., Alvarado, S., Becerra, N., Marín, C., Borie, F., Aguilera, P., Cornejo, P., 2020. Soil Biological Properties and Arbuscular Mycorrhizal Fungal Communities of Representative Crops Established in the Andean Region from Ecuadorian Highlands. Journal of Soil Science and Plant Nutrition 20, 2156–2163. https://doi.org/10.1007/s42729-020-00283-1.

Azeem, M., Ali, A., Jeyasundar, P.G.S.A., Li, Y., Abdelrahman, H., Latif, A., Li, R., Basta, N., Li, G., Shaheen, S.M., Rinklebe, J., Zhang, Z., 2021. Bone-derived biochar improved soil quality and reduced Cd and Zn phytoavailability in a multi-metal contaminated mining soil. Environmental Pollution 277. https://doi.org/10.1016/j.envpol.2021.116800.

Babu, S., Singh, R., Avasthe, R.K., Yadav, G.S., Das, A., Singh, V.K., Mohapatra, K.P., Rathore, S.S., Chandra, P., Kumar, A., 2020. Impact of land configuration and organic nutrient management on productivity, quality and soil properties under baby corn in Eastern Himalayas. Scientific Reports 10, 1–14. https://doi.org/10.1038/s41598-020-73072-6.

Bachmann, S., Gropp, M., Eichler-Löbermann, B., 2014. Phosphorus availability and soil microbial activity in a 3 year field experiment amended with digested dairy slurry. Biomass and Bioenergy 70, 429–439. https://doi.org/10.1016/j.biombioe.2014.08.004.

Baćmaga, M., Kucharski, J., Wyszkowska, J., 2019. Microbiological and biochemical properties of soil polluted with a mixture of spiroxamine, tebuconazole, and triadimenol under the cultivation of Triticum aestivum L. Environmental Monitoring and Assessment 191. https://doi.org/10.1007/s10661-019-7539-4.

Balachandar, R., Biruntha, M., Yuvaraj, A., Thangaraj, R., Subbaiya, R., Govarthanan, M., Kumar, P., Karmegam, N., 2021. Earthworm intervened nutrient recovery and greener production of vermicompost from Ipomoea staphylina – An invasive weed with emerging environmental challenges. Chemosphere 263. https://doi.org/10.1016/j.chemosphere.2020.128080.

Baligar, V.C., Wright, R.J., Hern, J.L., 2005. Enzyme activities in soil influenced by levels of applied sulfur and phosphorus. Communications in Soil Science and Plant Analysis 36, 1727–1735. https://doi.org/10.1081/CSS-200062431.

Balota, E.L., Kanashiro, M., Filho, A.C., Andrade, D.S., Dick, R.P., 2004. Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agro-ecosystems. Brazilian Journal of Microbiology 35, 300–306. https://doi.org/10.1590/S1517-83822004000300006.

Balota E. L., Chaves D., César J., 2010. Enzymatic activity and mineralization of carbon and nitrogen in soil cultivated with coffee and green manures. Rev. Bras. Ciênc. Solo.2010;34(5):1573-83. https://doi.org/10.1590/S0100-06832010000500010.

Balota, E.L., Machineski, O., Truber, P.V., 2011a. Soil enzyme activities under pig slurry addition and different tillage systems. Acta Scientiarum. Agronomy 33, 729–737. https://doi.org/10.4025/actasciagron.v33i4.9816.

Balota, E.L., Machineski, O., Truber, P.V., Antonio, P., Auler, M., 2011b. Effect of tillage systems and permanent groundcover intercropped with orange trees on soil enzyme activities. Brazilian Archives of Biology and Technology 54, 221–228.

Balota, E.L., Machineski, O., Hamid, K.I.A., Yada, I.F.U., Barbosa, G.M.C., Nakatani, A.S., Coyne, M.S., 2014. Soil microbial properties after long-term swine slurry application to conventional and no-tillage systems in Brazil. Science of the Total Environment 490, 397–404. https://doi.org/10.1016/j.scitotenv.2014.05.019.

Bana, R.S., Grover, M., Kumar, V., Jat, G.S., Kuri, B.R., Singh, D., Kumar, H., Bamboriya, S.D., 2022a. Multi-micronutrient foliar fertilization in eggplant under diverse fertility scenarios: Effects on productivity, nutrient biofortification and soil microbial activity. Scientia Horticulturae 294, 110781. https://doi.org/10.1016/j.scienta.2021.110781.

Bana, R.S., Jat, G.S., Grover, M., Bamboriya, S.D., Singh, D., Bansal, R., Choudhary, A.K., Kumar, V., Laing, A.M., Godara, S., Bana, R.C., Kumar, H., Kuri, B.R., Yadav, A., Singh, T., 2022b. Foliar nutrient supplementation with micronutrient-embedded fertilizer increases biofortification, soil biological activity and productivity of eggplant. Scientific Reports 12, 1–16. https://doi.org/10.1038/s41598-022-09247-0.

Banerjee, M.R., Burton, D.L., Grant, C.A., 1999. Influence of urea fertilization and urease inhibitor on the size and activity of the soil microbial biomass under conventional and zero tillage at two sites. Canadian Journal of Soil Science 79, 255–263. https://doi.org/10.4141/S97-049.

Banerjee, K., Dasgupta, S., Oulkar, D.P., Patil, S.H., Adsule, P.G., 2008. Degradation kinetics of forchlorfenuron in typical grapevine soils of India and its influence on specific soil enzyme activities. Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes 43, 341–349. https://doi.org/10.1080/03601230801941691.

Banik, P., Ghosal, P.K., Sasmal, T.K., Bhattacharya, S., Sarkar, B.K., Bagchi, D.K., 2006. Effect of organic and inorganic nutrients for soil quality conservation and yield of rainfed low land rice in sub-tropical plateau region. Journal of Agronomy and Crop Science 192, 331–343. https://doi.org/10.1111/j.1439-037X.2006.00219.x.

Barcelos Martins L.N., de Aguiar Santiago F.L., Montecchia M.S., Correa O.S., Saggin Junior O.J., Damacena de Souza E., Barbosa Paulino H., Carbone Carneiro M.A., 2019. 'Biochemical and Biological Properties of Soil from Murundus Wetlands Converted into Agricultural Systems'. Revista Brasileira de Ciencia do Solo, 43 :e0180183. https://doi.org/10.1590/18069657rbcs20180183.

Bardgett, R.D., and Leemans, D.K., 1995. The short-term effects of cessation of fertiliser applications, liming, and grazing on microbial biomass and activity in a reseeded upland grassland soil. Biology and Fertility of Soils 19, 148–154. https://doi.org/10.1007/BF00336151.

Bartkowiak, A., Dąbkowska-Naskręt, H., Lemanowicz, J., Siwik-Ziomek, A., 2021. Assessment of physicochemical and biochemical factors of urban street dust. Environment Protection Engineering 43: 155-164. https://api.semanticscholar.org/CorpusID:204912358.

Basak, N., Mandal, B., Datta, A., Mitran, T., Biswas, S., Dhar, D., Badole, S., Saha, B., Hazra, G.C., 2017. Impact of Long-Term Application of Organics, Biological, and

Inorganic Fertilizers on Microbial Activities in Rice-Based Cropping System. Communications in Soil Science and Plant Analysis 48, 2390–2401. https://doi.org/10.1080/00103624.2017.1411502.

Basak, B.B., and Gajbhiye, N.A., 2018. Phosphorus enriched organic fertilizer, an effective P source for improving yield and bioactive principle of Senna (Cassia angustifolia Vhal.). Industrial Crops and Products 115, 208–213. https://doi.org/10.1016/j.indcrop.2018.02.026.

Baziramakenga, R., Simard, R.R., Lalande, R., 2001. Effect of de-inking paper sludge compost application on soil chemical and biological properties. Canadian Journal of Soil Science 81, 561–575. https://doi.org/10.4141/S00-063.

Becagli, M., Arduini, I., Cardelli, R., 2022. Using Biochar and Vermiwash to Improve Biological Activities of Soil. Agriculture (Switzerland) 12. https://doi.org/10.3390/agriculture12020178.

Belyaeva, O.N., Haynes, R.J., Birukova, O.A., 2005. Barley yield and soil microbial and enzyme activities as affected by contamination of two soils with lead, zinc or copper. Biology and Fertility of Soils 41, 85–94. https://doi.org/10.1007/s00374-004-0820-9.

Benbrik, B., Elabed, A., Iraqui, M., Ghachtouli, N.E., Douira, A., Amir, S., Filali-Maltouf, A., Abed, S.E., Modafar, C.E., Ibnsouda-Koraichi, S., 2021. A phosphocompost amendment enriched with PGPR consortium enhancing plants growth in deficient soil. Communications in Soil Science and Plant Analysis 52, 1236–1247. https://doi.org/10.1080/00103624.2021.1879121.

Benítez, E., Melgar, R., Sainz, H., Gómez, M., Nogales, R., 2000. Enzyme activities in the rhizosphere of pepper (Capsicum annuum, L.) grown with olive cake mulches. Soil Biology and Biochemistry 32, 1829–1835. https://doi.org/10.1016/S0038-0717(00)00156-5.

Bera, T., Collins, H.P., Alva, A.K., Purakayastha, T.J., Patra, A.K., 2016. Biochar and manure effluent effects on soil biochemical properties under corn production. Applied Soil Ecology 107, 360–367. https://doi.org/10.1016/j.apsoil.2016.07.011.

Bergstrom, D.W., and Monreal, C.M., 1998a. Increased soil enzyme activities under two row crops. Soil Science Society of America Journal 62, 1295–1301. https://doi.org/10.2136/sssaj1998.03615995006200050021x.

Bergstrom, D.W., Monreal, C.M., King, D.J., 1998b. Sensitivity of Soil Enzyme Activities to Conservation Practices. Soil Science Society of America Journal 62, 1286–1295. https://doi.org/10.2136/sssaj1998.03615995006200050020x.

Beura, K., and Rakshit, A., 2013. Bt cotton influencing enzymatic activities under varied soils. Open Journal of Ecology 03, 505–509. https://doi.org/10.4236/oje.2013.38059.

Bhambure, A.B., Mahajan, G.R., Kerkar, S., 2018. Salt Tolerant Bacterial Inoculants as Promoters of Rice Growth and Microbial Activity in Coastal Saline Soil. Proceedings of the National Academy of Sciences India Section B - Biological Sciences 88, 1531–1538. https://doi.org/10.1007/s40011-017-0901-9.

Bhatt, B., Chandra, R., Ram, S., Pareek, N., 2016. Long-term effects of fertilization and manuring on productivity and soil biological properties under rice (Oryza sativa)–wheat (Triticum aestivum) sequence in Mollisols. Archives of Agronomy and Soil Science 62, 1109–1122. https://doi.org/10.1080/03650340.2015.1125471.

Bhattacharyya, P., Pal, R., Chakraborty, A., Chakrabarti, K., 2001. Microbial biomass and activity in a laterite soil amended with municipal solid waste compost. Journal of Agronomy and Crop Science 187, 207–211. https://doi.org/10.1046/j.1439-037x.2001.00517.x.

Bhattacharyya, P., Chakrabarti, K., Chakraborty, A., 2003. Residual effect of municipal solid waste compost on microbial biomass and activities in mustard growing soil: Restwirkung von müllkompost auf die mikrobielle biomasse und mikrobielle aktivitaten in boden mit senfbewuchs. Archives of Agronomy and Soil Science 49, 585–592. https://doi.org/10.1080/03650340310001615147.

Bhattacharyya, P., Tripathy, S., Chakrabarti, K., Chakraborty, A., Banik, P., 2008. Fractionation and bioavailability of metals and their impacts on microbial properties in sewage irrigated soil. Chemosphere 72, 543–550. https://doi.org/10.1016/j.chemosphere.2008.03.035.

Bi, Q.F., Zheng, B.X., Lin, X.Y., Li, K.J., Liu, X.P., Hao, X.L., Zhang, H., Zhang, J.B., Jaisi, D.P., Zhu, Y.G., 2018. The microbial cycling of phosphorus on long-term fertilized soil: Insights from phosphate oxygen isotope ratios. Chemical Geology 483, 56–64. https://doi.org/10.1016/j.chemgeo.2018.02.013.

Bi, Q.F., Li, K.J., Zheng, B.X., Liu, X.P., Li, H.Z., Jin, B.J., Ding, K., Yang, X.R., Lin, X.Y., Zhu, Y.G., 2020. Partial replacement of inorganic phosphorus (P) by organic manure reshapes phosphate mobilizing bacterial community and promotes P bioavailability in a paddy soil. Science of the Total Environment 703, 134977. https://doi.org/10.1016/j.scitotenv.2019.134977.

Billah, M., Khan, M., Bano, A., Nisa, S., Hussain, A., Dawar, K.M., Munir, A., Khan, K., 2020. Rock Phosphate-Enriched Compost in Combination with Rhizobacteria ; a cost-effective Source for Better Soil Health and Wheat. Agronomy 10.

Bini, D., Santos, C.A.D., Bernal, L.P.T., Andrade, G., Nogueira, M.A., 2014. Identifying indicators of C and N cycling in a clayey Ultisol under different tillage and uses in winter. Applied Soil Ecology 76, 95–101. https://doi.org/10.1016/j.apsoil.2013.12.015.

Bissonnette, N., Angers, D.A., Simard, R.R., Lafond, J., 2001. Interactive effects of management practices on water-stable aggregation and organic matter of a Humic Gleysol. Canadian Journal of Soil Science 81, 545–551. https://doi.org/10.4141/S00-078.

Biswas S., Kundu D.K., Mazumdar S.P., Saha A.R., Majumdar B., Ghorai A.K., Ghosh D., Yadav A.N., Saxena A.K., 2018. Study on the activity and diversity of bacteria in a New Gangetic alluvial soil (Eutrocrept) under rice-wheat- jute cropping system. Journal of environmental biology,39: 379-386. http://doi.org/10.22438/jeb/39/3/MRN-523.

Biswas, S.S., Biswas, D.R., Purakayastha, T.J., Sarkar, A., Kumar, R., Das, T.K., Barman, M., Pabbi, S., Ghosh, A., Pal, R., 2021. Residual effect of rock-phosphate and PSB on rice yield and soil properties. Indian Journal of Agricultural sciences 91, 440–444.

Blaise, D., and Rao, M. R. K., 2004. Glucosidase and Alkaline Phosphatase Activity as Affected by Organic and Modern Method of Cotton (Gossypium Hirsutum) Cultivation of the Rainfed Vertisols’. Indian Journal of Agricultural Sciences 74(5):276–78.

Bobuľská, L., Fazekašová, D., Angelovičová, L., Kotorová, D., 2015. Impact of ecological and conventional farming systems on chemical and biological soil quality indices in a cold mountain climate in Slovakia. Biological Agriculture and Horticulture 31, 205–218. https://doi.org/10.1080/01448765.2014.1002537.

Boccolini, M.F., Cazorla, C.R., Galantini, J.A., Belluccini, P.A., Baigorria, T., 2019. Cultivos de cobertura disminuyen el impacto ambiental mejorando propiedades biológicas del suelo y el rendimiento de los cultivos. Revista de Investigaciones Agropecuarias 45, 412–425.

Böhme, L., Langer, U., Böhme, F., 2005. Microbial biomass, enzyme activities and microbial community structure in two European long-term field experiments. Agriculture, Ecosystems and Environment 109, 141–152. https://doi.org/10.1016/j.agee.2005.01.017.

Bolton JR, H., Elliott, L.F., Papendick, R.I., Bezdicek, D.F., 1985. Soil microbial biomass and selected soil enzyme activities: effect of fertilization and cropping practices.. Soil Biol. Biochem, 17, 297-302. http://dx.doi.org/10.1007/BF00257821.

Bolton, H., Smith, J.L., Link, S.O., 1993. Soil microbial biomass and activity of a disturbed and undisturbed shrub-steppe ecosystem. Soil Biology and Biochemistry 25, 545–552. https://doi.org/10.1016/0038-0717(93)90192-E.

Borase, D.N., Nath, C.P., Hazra, K.K., Senthilkumar, M., Singh, S.S., Praharaj, C.S., Singh, U., Kumar, N., 2020. Long-term impact of diversified crop rotations and nutrient management practices on soil microbial functions and soil enzymes activity. Ecological Indicators 114, 106322. https://doi.org/10.1016/j.ecolind.2020.106322.

Borase, D.N., Murugeasn, S., Nath, C.P., Hazra, K.K., Singh, S.S., Kumar, N., Singh, U., Praharaj, C.S., 2021. Long-term impact of grain legumes and nutrient management practices on soil microbial activity and biochemical properties. Archives of Agronomy and Soil Science 67, 2015–2032. https://doi.org/10.1080/03650340.2020.1819532.

Bossio, D.A., Girvan, M.S., Verchot, L., Bullimore, J., Borelli, T., Albrecht, A., Scow, K.M., Ball, A.S., Pretty, J.N., Osborn, A.M., 2005. Soil microbial community response to land use change in an agricultural landscape of western Kenya. Microbial Ecology 49, 50–62. https://doi.org/10.1007/s00248-003-0209-6.

Brackin, R., Robinson, N., Lakshmanan, P., Schmidt, S., 2014. Soil microbial responses to labile carbon input differ in adjacent sugarcane and forest soils. Soil Research 52, 307–316. https://doi.org/10.1071/SR13276.

Brennan, E.B., and Acosta-Martinez, V., 2019. Cover Crops and Compost Influence Soil Enzymes during Six Years of Tillage-Intensive, Organic Vegetable Production. Soil Science Society of America Journal 83, 624–637. https://doi.org/10.2136/sssaj2017.12.0412.

Buck, C., Langmaack, M., Schrader, S., 2000. Influence of mulch and soil compaction on earthworm cast properties. Applied Soil Ecology 14, 223–229. https://doi.org/10.1016/S0929-1393(00)00054-8.

Butterly, C.R., McNeill, A.M., Baldock, J.A., Marschner, P., 2011. Changes in water content of two agricultural soils does not alter labile P and C pools. Plant and Soil 348, 185–201. https://doi.org/10.1007/s11104-011-0931-7.

Caballero Vanegas J.J., Mejía Zambrano K.B., Avellaneda-Torres L.M., 2018. Effect of ecological and conventional managements on soil enzymatic activities in coffee agroecosystems. Pesquisa Agropecuaria Tropical, Goiânia, 48 (4): 420-428. https://doi.org/10.1590/1983-40632018v4852373.

Calvarro, L.M., Santiago-Martín, A. de, Gómez, J.Q., González-Huecas, C., Quintana, J.R., Vázquez, A., Lafuente, A.L., Fernández, T.M.R., Vera, R.R., 2014. Biological activity in metal-contaminated calcareous agricultural soils: The role of the organic matter composition and the particle size distribution. Environmental Science and Pollution Research 21, 6176–6187. https://doi.org/10.1007/s11356-014-2561-0.

Campbell, C.A., Biederbeck, V.O., Schnitzer, M., Selles, F., Zentner, R.P., 1989. Effect of 6 Years of Zero Tillage and N Fertilizer Management on Changes in Soil Quality of an Orthic Brown Chernozem in Southwestern Saskatchewan. Soil & Tillage Research, 14, 39-52. http://dx.doi.org/10.1016/0167-1987(89)90019-6.

Cao, N., Zhi, M., Zhao, W., Pang, J., Hu, W., Zhou, Z., Meng, Y., 2021. Straw retention combined with phosphorus fertilizer promotes soil phosphorus availability by enhancing soil P-related enzymes and the abundance of phoC and phoD genes. Soil and Tillage Research 220, 105390. https://doi.org/10.1016/j.still.2022.105390.

Cao, Q., Li, G., Yang, F., Kong, F., Cui, Z., Jiang, X., Lu, Y., Zhang, E., 2022. Eleven-year mulching and tillage practices alter the soil quality and bacterial community composition in Northeast China. Archives of Agronomy and Soil Science 68, 1274–1289. https://doi.org/10.1080/03650340.2021.1890719.

Caravaca, F., Masciandaro, G., Ceccanti, B., 2002. Land use in relation to soil chemical and biochemical properties in a semiarid Mediterranean environment. Soil and Tillage Research 68, 23–30. https://doi.org/10.1016/S0167-1987(02)00080-6.

Carbonell, G., Pro, J., Gómez, N., Babín, M.M., Fernández, C., Alonso, E., Tarazona, J.V., 2009. Sewage sludge applied to agricultural soil: Ecotoxicological effects on representative soil organisms. Ecotoxicology and Environmental Safety 72, 1309–1319. https://doi.org/10.1016/j.ecoenv.2009.01.007.

Carlos, F.S., Schaffer, N., Mariot, R.F., Fernandes, R.S., Boechat, C.L., Roesch, L.F.W., Camargo, F.A. de O., 2022. Soybean crop incorporation in irrigated rice cultivation improves nitrogen availability, soil microbial diversity and activity, and growth of ryegrass. Applied Soil Ecology 170. https://doi.org/10.1016/j.apsoil.2021.104313.

Carpenter-Boggs, L., Stahl, P.D., Lindstrom, M.J., Schumacher, T.E., 2003. Soil microbial properties under permanent grass, conventional tillage, and no-fill management in South Dakota. Soil and Tillage Research 71, 15–23. https://doi.org/10.1016/S0167-1987(02)00158-7.

Carricondo-Martínez, I., Falcone, D., Berti, F., Orsini, F., Salas-Sanjuan, M.D.C., 2022. Use of Agro-Waste as a Source of Crop Nutrients in Intensive Horticulture System. Agronomy 12, 1–12. https://doi.org/10.3390/agronomy12020447.

Carter, M.R., Sanderson, J.B., Holmstrom, D.A., Ivany, J.A., DeHaan, K.R., 2007. Influence of conservation tillage and glyphosate on soil structure and organic carbon fractions through the cycle of a 3-year potato rotation in Atlantic Canada. Soil and Tillage Research 93, 206–221. https://doi.org/10.1016/j.still.2006.04.004.

Castillo, C., Montoya, Á., Borie, F., 2017. Efecto de pre-cultivos hospederos y no hospederos en el crecimiento y propágulos micorricicos de trigo en Andisol e Inceptisol de Chile. Chilean Journal of Agricultural and Animal Sciences 33, 252–262. https://doi.org/10.4067/s0719-38902017005000703.

Casucci, C., Okeke, B.C., Frankenberger, W.T., 2003. Effects of mercury on microbial biomass and enzyme activities in soil. Biological Trace Element Research 94, 179–191. https://doi.org/10.1385/BTER:94:2:179.

Cattaneo, F., Gennaro, P.D., Barbanti, L., Giovannini, C., Labra, M., Moreno, B., Benitez, E., Marzadori, C., 2014. Perennial energy cropping systems affect soil enzyme activities and bacterial community structure in a South European agricultural area. Applied Soil Ecology 84, 213–222. https://doi.org/10.1016/j.apsoil.2014.08.003.

Caudle, C., Osmond, D., Heitman, J., Ricker, M., Miller, G., Wills, S., 2020. Comparison of soil health metrics for a Cecil soil in the North Carolina Piedmont. Soil Science Society of America Journal 84, 978–993. https://doi.org/10.1002/saj2.20075.

Chakrabarti, K., Sarkar, B., Chakraborty, A., Banik, P., Bagchi, D.K., 2000. Organic recycling for soil quality conservation in a sub-tropical plateau region. Journal of Agronomy and Crop Science 184, 137–142. https://doi.org/10.1046/j.1439-037X.2000.00352.x.

Chander, K., Goyal, S., Mundra, M.C., Kapoor, K.K., 1997. Organic matter, microbial biomass and enzyme activity of soils under different crop rotations in the tropics. Biology and Fertility of Soils 24, 306–310. https://doi.org/10.1007/s003740050248.

Chang, E.-H., Chung, R.-S., Tsai, Y.-H., 2007. Effect of different application rates of organic fertilizer on soil enzyme activity and microbial population: Original article. Soil Science and Plant Nutrition 53, 132–140. https://doi.org/10.1111/j.1747-0765.2007.00122.x.

Chatterjee, D., Nayak, A.K., Mishra, A., Swain, C.K., Kumar, U., Bhaduri, D., Panneerselvam, P., Lal, B., Gautam, P., Pathak, H., 2021. Effect of Long-Term Organic Fertilization in Flooded Rice Soil on Phosphorus Transformation and Phosphate Solubilizing Microorganisms. Journal of Soil Science and Plant Nutrition 21, 1368–1381. https://doi.org/10.1007/s42729-021-00446-8.

Chaudhary, D.R., Gautam, R.K., Ghosh, A., Chikara, J., Jha, B., 2015. Effect of Nitrogen Management on Soil Microbial Community and Enzymatic Activities in Jatropha curcas L. Plantation. Clean - Soil, Air, Water 43, 1058–1065. https://doi.org/10.1002/clen.201400357.

Chaudhary, P., Sharma, A., Chaudhary, A., Khati, P., Gangola, S., Maithani, D., 2021. Illumina based high throughput analysis of microbial diversity of maize rhizosphere treated with nanocompounds and Bacillus sp. Applied Soil Ecology 159. https://doi.org/10.1016/j.apsoil.2020.103836.

Chaudhary, P., Chaudhary, A., Bhatt, P., Kumar, G., Khatoon, H., Rani, A., Kumar, S., Sharma, A., 2022. Assessment of Soil Health Indicators Under the Influence of Nanocompounds and Bacillus spp. in Field Condition. Frontiers in Environmental Science 9, 1–11. https://doi.org/10.3389/fenvs.2021.769871.

Chavarría, D.N., Verdenelli, R.A., Serri, D.L., Restovich, S.B., Andriulo, A.E., Meriles, J.M., Vargas-Gil, S., 2016. Effect of cover crops on microbial community structure and related enzyme activities and macronutrient availability. European Journal of Soil Biology 76, 74–82. https://doi.org/10.1016/j.ejsobi.2016.07.002.

Chellappa, J., Sagar, K.L., Sekaran, U., Kumar, S., Sharma, P., 2021. Soil organic carbon, aggregate stability and biochemical activity under tilled and no-tilled agroecosystems. Journal of Agriculture and Food Research 4, 100139. https://doi.org/10.1016/j.jafr.2021.100139.

Chen, S.-K., Edwards, C.A., Subler, S., 2001. A microcosm approach for evaluating the effects of the fungicides benomyl and captan on soil ecological processes and plant growth. Applied Soil Ecology 18, 69–82. https://doi.org/10.1016/S0929-1393(01)00135-4.

Chen, S.-K., Edwards, C.A., Subler, S., 2003. The influence of two agricultural biostimulants on nitrogen transformations, microbial activity, and plant growth in soil microcosms. Soil Biology and Biochemistry 35, 9–19. https://doi.org/10.1016/S0038-0717(02)00209-2.

Chen, C.R., Condron, L.M., Davis, M.R., Sherlock, R.R., 2004. Effects of plant species on microbial biomass phosphorus and phosphatase activity in a range of grassland soils. Biology and Fertility of Soils 40, 313–322. https://doi.org/10.1007/s00374-004-0781-z.

Chen, S., Qi, G., Luo, T., Zhang, H., Jiang, Q., Wang, R., Zhao, X., 2018. Continuous-cropping tobacco caused variance of chemical properties and structure of bacterial network in soils. Land Degradation and Development 29, 4106–4120. https://doi.org/10.1002/ldr.3167.

Chen, S., Cade-Menun, B.J., Bainard, L.D., Luce, M.S., Hu, Y., Chen, Q., 2021a. The influence of long-term N and P fertilization on soil P forms and cycling in a wheat/fallow cropping system. Geoderma 404, 115274. https://doi.org/10.1016/j.geoderma.2021.115274.

Chen, Y.P., Tsai, C.F., Hameed, A., Chang, Y.J., Young, C.C., 2021b. Agricultural management and cultivation period alter soil enzymatic activity and bacterial diversity in litchi (Litchi chinensis Sonn.) orchards. Botanical Studies 62. https://doi.org/10.1186/s40529-021-00322-9.

Chen, Y.P., Tsai, C.F., Rekha, P.D., Ghate, S.D., Huang, H.Y., Hsu, Y.H., Liaw, L.L., Young, C.C., 2021c. Agricultural management practices influence the soil enzyme activity and bacterial community structure in tea plantations. Botanical Studies 62. https://doi.org/10.1186/s40529-021-00314-9.

Chocano, C., García, C., González, D., Aguilar, J.M. de, Hernández, T., 2016. Organic plum cultivation in the Mediterranean region: The medium-term effect of five different organic soil management practices on crop production and microbiological soil quality.

Agriculture, Ecosystems and Environment 221, 60–70. https://doi.org/10.1016/j.agee.2016.01.031.

Choudhary, M., Sharma, P.C., Jat, H.S., McDonald, A., Jat, M.L., Choudhary, S., Garg, N., 2018a. Soil biological properties and fungal diversity under conservation agriculture in indo-gangetic plains of india. Journal of Soil Science and Plant Nutrition 18, 1142–1156. https://doi.org/10.4067/S0718-95162018005003201.

Choudhary, M., Jat, H.S., Datta, A., Yadav, A.K., Sapkota, T.B., Mondal, S., Meena, R.P., Sharma, P.C., Jat, M.L., 2018b. Sustainable intensification influences soil quality, biota, and productivity in cereal-based agroecosystems. Applied Soil Ecology 126, 189–198. https://doi.org/10.1016/j.apsoil.2018.02.027.

Choudhary, M., Datta, A., Jat, H.S., Yadav, A.K., Gathala, M.K., Sapkota, T.B., Das, A.K., Sharma, P.C., Jat, M.L., Singh, R., Ladha, J.K., 2018c. Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. Geoderma 313, 193–204. https://doi.org/10.1016/j.geoderma.2017.10.041.

Choudhary, M., Meena, V.S., Panday, S.C., Mondal, T., Yadav, R.P., Mishra, P.K., Bisht, J.K., Pattanayak, A., 2021. Long-term effects of organic manure and inorganic fertilization on biological soil quality indicators of soybean-wheat rotation in the Indian mid-Himalaya. Applied Soil Ecology 157, 103754. https://doi.org/10.1016/j.apsoil.2020.103754.

Chowdhury, N., and Rasid, M.M., 2021a. Heavy metal concentrations and its impact on soil microbial and enzyme activities in agricultural lands around ship yards in Chattogram, Bangladesh. Soil Science Annual 72, 1–21. https://doi.org/10.37501/soilsa/135994.

Chowdhury, N. and Rasid, M.M., 2021b. Evaluation of brick kiln operation impact on soil microbial biomass and enzyme activity. Soil Science Annual 72, 1–16. https://doi.org/10.37501/soilsa/132232.

Cicatelli, A., Baldantoni, D., Iovieno, P., Carotenuto, M., Alfani, A., Feis, I.D., Castiglione, S., 2014. Genetically biodiverse potato cultivars grown on a suitable agricultural soil under compost amendment or mineral fertilization: Yield, quality, genetic and epigenetic variations, soil properties. Science of the Total Environment 493, 1025–1035. https://doi.org/10.1016/j.scitotenv.2014.05.122.

Colvan, S.R., Syers, J.K., O'Donnell, A.G., 2001. Effect of long-term fertiliser use on acid and alkaline phosphomonoesterase and phosphodiesterase activities in managed grassland. Biology and Fertility of Soils 34, 258–263. https://doi.org/10.1007/s003740100411.

Cui, H., Zhou, Y., Gu, Z., Zhu, H., Fu, S., Yao, Q., 2015. The combined effects of cover crops and symbiotic microbes on phosphatase gene and organic phosphorus hydrolysis in subtropical orchard soils. Soil Biology and Biochemistry 82, 119–126. https://doi.org/10.1016/j.soilbio.2015.01.003.

Cui, Y., Fang, L., Guo, X., Wang, X., Wang, Y., Zhang, Y., Zhang, X., 2019. Responses of soil bacterial communities, enzyme activities, and nutrients to agricultural-to-natural ecosystem conversion in the Loess Plateau, China. Journal of Soils and Sediments 19, 1427–1440. https://doi.org/10.1007/s11368-018-2110-4.

Cui, H., Luo, Y., Chen, J., Jin, M., Li, Y., Wang, Z., 2022. Straw return strategies to improve soil properties and crop productivity in a winter wheat-summer maize cropping system. European Journal of Agronomy 133, 126436. https://doi.org/10.1016/j.eja.2021.126436.

Cycoń, M., Wójcik, M., Borymski, S., Piotrowska-Seget, Z., 2013. Short-term effects of the herbicide napropamide on the activity and structure of the soil microbial community assessed by the multi-approach analysis. Applied Soil Ecology 66, 8–18. https://doi.org/10.1016/j.apsoil.2013.01.014.

Cycoń, M., and Piotrowska-Seget, Z., 2015. Biochemical and microbial soil functioning after application of the insecticide imidacloprid. Journal of Environmental Sciences (China) 27, 147–158. https://doi.org/10.1016/j.jes.2014.05.034.

D'Ascoli, R., Rao, M.A., Adamo, P., Renella, G., Landi, L., Rutigliano, F.A., Terribile, F., Gianfreda, L., 2006. Impact of river overflowing on trace element contamination of volcanic soils in south Italy: Part II. Soil biological and biochemical properties in relation to trace element speciation. Environmental Pollution 144, 317–326. https://doi.org/10.1016/j.envpol.2005.11.017.

da Cunha, J.R., de Cassia de Freitas, R., de Almeida Taveres Souza, D.J., Santana Gualberto, A.V., de Souza, H.A., Carvalho Leite, L.F., 2021. Soil Biological Attributes in Monoculture and Integrated Systems in the Cerrado Region of Piaui State, Brazil. ACTA SCIENTIARUM-AGRONOMY 43. https://doi.org/10.4025/actasciagron.v43i1.51814.

da Silva Xavier F.A., da Silva Pereira B.L, de Almeida Souza E., Borges A.L, Ferreira Coelho E., 2020. Irrigation Systems, Fertigation and Mulch: Effects on the Physical, Chemical and Biological Attributes of the Soil with Banana Crop in Northeastern Brazil. Communications in soil science and plant analysis, 51 (20): 2592–2605. https://doi.org/10.1080/00103624.2020.1845359.

Damian, J.M., Matos, E. da S., Pedreira, B.C. e, Carvalho, P.C. de F., Souza, A.J. de, Andreote, F.D., Premazzi, L.M., Cerri, C.E.P., 2021. Pastureland intensification and diversification in Brazil mediate soil bacterial community structure changes and soil C accumulation. Applied Soil Ecology 160. https://doi.org/10.1016/j.apsoil.2020.103858.

Dar, G., 1996. Effects of cadmium and sewage-sludge on soil microbial biomass and enzyme activities. Bioresource Technology 56Using Sm, 2–3.

Das, S.K., Ghosh, G.K., Avasthe, R., Choudhury, B.U., Mishra, V.K., Kundu, M.C., Roy, A., Mondal, T., Lama, A., Dhakre, D.S., 2021. Organic nutrient sources and biochar technology on microbial biomass carbon and soil enzyme activity in maize-black gram cropping system. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-021-01625-4.

Datta, A., Choudhary, M., Jat, H.S., Sharma, P.C., Kakraliya, S.K., Dixit, B., Jat, M.L., 2021. Climate smart agriculture influences soil enzymes activity under cereal-based systems of north-west india. Journal of the Indian Society of Soil Science 69, 86–95. https://doi.org/10.5958/0974-0228.2021.00024.4.

de Barros J.A, Valente De Medeiros E., Paes Da Costa D., Pereira Duda G., Romualdo De Sousa Lima J., Dos Santos U.J, Celso Dantas A. Antonino, Hammecker C., 2019. Human disturbance affects enzyme activity, microbial biomass and organic carbon in tropical dry sub-humid pasture and forest soils.. Archives of Agronomy and Soil Science, 66(4): 458–472. https://doi.org/10.1080/03650340.2019.1622095.

de Cássia M., Moraes H d S., Valente de Medeiros E., da Silva de Andrade D., Dias de Lima L., da Silva Santos I.C., Pereira Martins Filho A., 2018. Microbial biomass and enzymatic activities in sandy soil cultivated with lettuce inocualted with plant growth promoters.. Revista Caatinga, 31(4): 860-870. http://dx.doi.org/10.1590/1983-21252018v31n408rc.

de Castro Lopes, A., Gomes de Sousa, D. M., Chaer, G. M., Bueno dos Reis Junior, Fá., Goedert, W. J., de Carvalho Mendes, I., 2013. Interpretation of Microbial Soil Indicators as a Function of Crop Yield and Organic Carbon. Soil Science Society of America Journal, 77, 461. http://dx.doi.org/10.2136/sssaj2012.0191.

de Castro Lopes, A.A., Bogiani, J.C., de Figueiredo, C.C., dos Reis Junior, F.B., de Sousa, D.M.G., Malaquias, J.V., de Carvalho Mendes, I., 2021.Enzyme activities in a sandy soil of Western Bahia under cotton production systems: short-term effects, temporal variability, and the FERTBIO sample concept. Brazilian Journal of Microbiology, 52: 2193-2204. https://doi.org/10.1007/s42770-021-00606-z.

de Jesus Franco A., Valadares da Silva A.P., Silva Souza A.B., Loverde Oliveira R., Rodrigues Batista E., Damacena de Souza E., Oliveira Silva A., Carbone Carneiro M.A., 2020. Plant diversity in integrated crop-livestock systems increases the soil enzymatic activity in the short term. Pesquisa Agropecuaria Tropical, Goiânia, 50: 1-11. https://doi.org/10.1590/1983-40632020v5064026.

de Oliveira Silva, E., Valente de Medeiros E., Pereira Duda G., Lira Junior M.A., Brossard M., Braga de Oliveira J., dos Santos U.J., Hammecker C., 2019. Seasonal Effect of Land Use Type on Soil Absolute and Specific Enzyme Activities in a Brazilian Semi-Arid Region. Catena 172:397–407. https://doi.org/10.1016/j.catena.2018.09.007.

de Santiago-Martín, A., Cheviron N., Quintana J.R., González C., Lafuente A.L., Mougin C., 2013. Metal Contamination Disturbs Biochemical and Microbial Properties of Calcareous Agricultural Soils of the Mediterranean Area. Archives of Environmental Contamination and Toxicology 64(3):388–98. https://doi.org/10.1007/s00244-012-9842-8.

de Varennes, A., and Torres M.O., 2011. Post-Fallow Tillage and Crop Effects on Soil Enzymes and Other Indicators. Soil Use and Management 27(1):18–27. https://doi.org/10.1111/j.1475-2743.2010.00307.x.

Delgado, M., Rodríguez, C., Martín, J.V., Imperial, R.M. de, Alonso, F., 2012. Environmental assay on the effect of poultry manure application on soil organisms in agroecosystems. Science of the Total Environment 416, 532–535. https://doi.org/10.1016/j.scitotenv.2011.11.047.

Denton, M.D., Sasse, C., Tibbett, M., Ryan, M.H., 2006. Root distributions of Australian herbaceous perennial legumes in response to phosphorus placement. Functional Plant Biology 33, 1091–1102. https://doi.org/10.1071/FP06176.

Dewey, K.A., Gaw, S.K., Northcott, G.L., Lauren, D.R., Hackenburg, S., 2012. The effects of copper on microbial activity and the degradation of atrazine and indoxacarb in a New Zealand soil. Soil Biology and Biochemistry 52, 64–74. https://doi.org/10.1016/j.soilbio.2012.04.009.

Dey, S.K., Chakrabarti, B., Purakayastha, T.J., Prasanna, R., Mittal, R., Singh, S.D., Pathak, H., 2019. Interplay of phosphorus doses, cyanobacterial inoculation, and elevated carbon dioxide on yield and phosphorus dynamics in cowpea. Environmental Monitoring and Assessment 191. https://doi.org/10.1007/s10661-019-7378-3.

Dhanker, R., Chaudhary, S., Goyal, S., Garg, V.K., 2020. Influence of urban sewage sludge amendment on agricultural soil parameters. Environmental Technology and Innovation 23, 101642. https://doi.org/10.1016/j.eti.2021.101642.

Dhanker, R., Chaudhary, S., Goyal, S., Kumar, R., 2021. Soil microbial properties and functional diversity in response to sewage sludge amendments. Archives of Agronomy and Soil Science 68, 809–822. https://doi.org/10.1080/03650340.2020.1855328.

Dhull, S., Goyal, S., Kapoor, K., Mundra, M., 2004. Microbial biomass carbon and microbial activities of soils receiving chemical fertilizers and organic amendments. International Journal of Phytoremediation 21, 641–647. https://doi.org/10.1080/08927010400011294.

Diallo-Diagne, N.H., Assigbetse, K., Sall, S., Masse, D., Bonzi, M., Ndoye, I., Chotte, J.L., 2016. Response of Soil Microbial Properties to Long-Term Application of Organic and Inorganic Amendments in a Tropical Soil (Saria, Burkina Faso). Open Journal of Soil Science 06, 21–33. https://doi.org/10.4236/ojss.2016.62003.

Dick, R.P., Rasmussen, P.E., Kerle, E.A., 1988. Influence of long-term residue management on soil enzyme activities in relation to soil chemical properties of a wheat-fallow system. Biology and Fertility of Soils 6, 159–164. https://doi.org/10.1007/BF00257667.

Dick, R.P., Sandor, J.A., Eash, N.S., 1994. Soil enzyme activities after 1500 years of terrace agriculture in the Colca Valley, Peru. Agriculture, Ecosystems and Environment 50, 123–131. https://doi.org/10.1016/0167-8809(94)90131-7.

Dick, W.A., 1984. Influence of Long-Term Tillage and Crop Rotation Combinations on Soil Enzyme Activities. Soil Science Society of America Journal 48, 569–574. https://doi.org/10.2136/sssaj1984.03615995004800030020x.

Dick, W.A., Cheng, L., Wang, P., 2000. Soil acid and alkaline phosphatase activity as pH adjustment indicators. Soil Biology and Biochemistry 32, 1915–1919. https://doi.org/10.1016/S0038-0717(00)00166-8.

Dilly, O., 1999. Nitrogen and phosphorus requirement of the microbiota in soils of the Bornhoved Lake district. Plant and Soil 212, 175–183.

Dinesh, R., Ramanathan, G., Singh, H., 1995. Influence of chloride and sulphate ions on soil enzymes. Journal of Agronomy and Crop Science 175, 129–133. https://doi.org/10.1111/j.1439-037X.1995.tb01138.x.

Dinesh, R., Dubey, R.P., Prasad, G.S., 1998. Soil microbial biomass and enzyme activities as influenced by organic manure incorporation into soils of a rice-rice system. Journal of Agronomy and Crop Science 181, 173–178. https://doi.org/10.1111/j.1439-037X.1998.tb00414.x.

Dinesh, R., Srinivasan, V., Hamza, S., Manjusha, A., Kumar, P.S., 2012. Short-term effects of nutrient management regimes on biochemical and microbial properties in soils under rainfed ginger (Zingiber officinale Rosc.). Geoderma 173–174, 192–198. https://doi.org/10.1016/j.geoderma.2011.12.025.

Dolker, T., Mukherjee, A., Agrawal, S.B., Agrawal, M., 2020. Responses of a semi-natural grassland community of tropical region to elevated ozone: An assessment of soil dynamics and biomass accumulation. Science of The Total Environment 718, 137141. https://doi.org/10.1016/j.scitotenv.2020.137141.

Dong, W.H., Zhang, S., Rao, X., Liu, C.A., 2016. Newly-reclaimed alfalfa forage land improved soil properties comparison to farmland in wheat-maize cropping systems at the margins of oases. Ecological Engineering 94, 57–64. https://doi.org/10.1016/j.ecoleng.2016.05.056.

Dora, S.A., Domu, C.N., Maria, Ş., 2006. Soil Enzyme Activities Under Crop Rotations Systems in a Brown Luvic Soil. Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agriculture 62(0):2–7. https://doi.org//10.15835/buasvmcn-agr:1578.

Doran, J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage.. Soil Sci Soc Am J, 44, 765-771.

Dormaar, J.F., and Willms, W.D., 2000. Rangeland management impacts on soil biological indicators in southern Alberta. Journal of Range Management 53, 233–238. https://doi.org/10.2307/4003289.

Dou, F., Wright A. L., Mylavaparu R. S., Jiang X., Matocha J. E., 2016. Soil Enzyme Activities and Organic Matter Composition Affected by 26 Years of Continuous Cropping. Pedosphere 26(5):618–25. https://doi.org/10.1016/S1002-0160(15)60070-4.

Du, Z., Wang, Y., Huang, J., Lu, N., Liu, X., Lou, Y., Zhang, Q., 2014. Consecutive biochar application alters soil enzyme activities in the winter wheat-growing season. Soil Science 179, 75–83. https://doi.org/10.1097/SS.0000000000000050.

Dubey, A.N., Chattopadhyaya, N., Mandal, N., 2021. Variation in Soil Microbial Population and Soil Enzymatic Activities Under Zincated Nanoclay Polymer Composites (ZNCPCs), Nano-ZnO and Zn Solubilizers in Rice Rhizosphere. Agricultural Research 10, 21–31. https://doi.org/10.1007/s40003-020-00488-x.

Dubey, R.K., Dubey, P.K., Chaurasia, R., Singh, H.B., Abhilash, P.C., 2020. Sustainable agronomic practices for enhancing the soil quality and yield of Cicer arietinum L. under diverse agroecosystems. Journal of Environmental Management 262, 110284. https://doi.org/10.1016/j.jenvman.2020.110284.

Durrer, A., Gumiere, T., Zagatto, M.R.G., Feiler, H.P., Silva, A.M.M., Longaresi, R.H., Homma, S.K., Cardoso, E.J.B.N., 2021. Organic farming practices change the soil bacteria community, improving soil quality and maize crop yields. PeerJ 9, 1–24. https://doi.org/10.7717/peerj.11985.

Dutta, D., Meena, A.L., Kumar, G.C., Mishra, R.P., Ghasal, P.C., Kumar, Amit, Chaudhary, J., Bhanu, C., Kumar, V., Kumar, Ankur, Tewari, R.B., Panwar, A.S., 2020. Long Term Effect of Organic, Inorganic and Integrated Nutrient Management on Phosphorous Dynamics under Different Cropping Systems of Typic Ustochrept Soil of India. Communications in Soil Science and Plant Analysis 51, 2746–2763. https://doi.org/10.1080/00103624.2020.1849258.

Efthimiadou, E., Papatheodorou, E.M., Monokrousos, N., Stamou, G.P., 2010. Changes of soil chemical, microbiological, and enzymatic variables in relation to management regime and the duration of organic farming in Phaseolus vulgaris. Journal of Biological Research 14, 151–159.

Egamberdieva, D., Li, L., Ma, H., Wirth, S., Bellingrath-Kimura, S.D., 2019. Soil amendment with different maize biochars improves chickpea growth under different moisture levels by improving symbiotic performance with mesorhizobium ciceri and soil biochemical properties to varying degrees. Frontiers in Microbiology 10, 1–14. https://doi.org/10.3389/fmicb.2019.02423.

Eichler-Löbermann, B., Zicker, T., Kavka, M., Busch, S., Brandt, C., Stahn, P., Miegel, K., 2021. Mixed cropping of maize or sorghum with legumes as affected by long-term phosphorus management. Field Crops Research 265. https://doi.org/10.1016/j.fcr.2021.108120.

Eivazi, F., Bayan, M.R., Schmidt, K., 2003. Select soil enzyme activities in the historic Sanborn Field as affected by long-term cropping systems. Communications in Soil Science and Plant Analysis 34, 2259–2275. https://doi.org/10.1081/CSS-120024062.

El-Bassi, L., Azzaz, A.A., Jellali, S., Akrout, H., Marks, E.A.N., Ghimbeu, C.M., Jeguirim, M., 2021. Application of olive mill waste-based biochars in agriculture: Impact on soil properties, enzymatic activities and tomato growth. Science of the Total Environment 755, 142531. https://doi.org/10.1016/j.scitotenv.2020.142531.

Elbl, J., Maková, J., Javoreková, S., Medo, J., Kintl, A., Lošák, T., Lukas, V., 2019. Response of microbial activities in soil to various organic and mineral amendments as an indicator of soil quality. Agronomy 9. https://doi.org/10.3390/agronomy9090485.

Elfstrand, S., Båth, B., Mårtensson, A., 2007a. Influence of various forms of green manure amendment on soil microbial community composition, enzyme activity and nutrient levels in leek. Applied Soil Ecology 36, 70–82. https://doi.org/10.1016/j.apsoil.2006.11.001.

Elfstrand, S., Hedlund, K., Mårtensson, A., 2007b. Soil enzyme activities, microbial community composition and function after 47 years of continuous green manuring. Applied Soil Ecology 35, 610–621. https://doi.org/10.1016/j.apsoil.2006.09.011.

Emami, S., Alikhani, H.A., Pourbabaee, A.A., Etesami, H., Sarmadian, F., Motesharezadeh, B., Taghizadeh–Mehrjardi, R., 2022. Performance Evaluation of Phosphate-Solubilizing Fluorescent Pseudomonads in Minimizing Phosphorus Fertilizer Use and Improving Wheat Productivity: a Two-Year Field Study. Journal of Soil Science and Plant Nutrition 22, 1224–1237. https://doi.org/10.1007/s42729-021-00726-3.

Emmerling, C., Udelhoven, T., Schneider, R., 2010. Long-lasting impact of biowaste-compost application in agriculture on soil-quality parameters in three different crop-rotation systems. Journal of Plant Nutrition and Soil Science 173, 391–398. https://doi.org/10.1002/jpln.200900348.

Evald, A., Melo, V.F., Rocha, P.R.R., Cordeiro, A.C.C., Maia, S.D.S., Espindola, I.D.C., 2021. Soil attributes under different water management systems of rice paddies in the amazonian savanna of brazil. Revista Caatinga 34, 640–649. https://doi.org/10.1590/1983-21252021v34n316rc.

Farhangi-Abriz, S., Ghassemi-Golezani, K., Torabian, S., 2021. A short-term study of soil microbial activities and soybean productivity under tillage systems with low soil organic matter. Applied Soil Ecology 168, 104122. https://doi.org/10.1016/j.apsoil.2021.104122.

Feng, H., Sekaran, U., Wang, T., Kumar, S., 2021. On-farm assessment of cover cropping effects on soil C and N pools, enzyme activities, and microbial community structure. Journal of Agricultural Science 159, 216–226. https://doi.org/10.1017/S002185962100040X.

Fereidooni, M., Raiesi, F., Fallah, S., 2013. Ecological restoration of soil respiration, microbial biomass and enzyme activities through broiler litter application in a calcareous soil cropped with silage maize. Ecological Engineering 58, 266–277. https://doi.org/10.1016/j.ecoleng.2013.06.032.

Fernández-Calviño, D., Soler-Rovira, P., Polo, A., Díaz-Raviña, M., Arias-Estévez, M., Plaza, C., 2010. Enzyme activities in vineyard soils long-term treated with copper-based fungicides. Soil Biology and Biochemistry 42, 2119–2127. https://doi.org/10.1016/j.soilbio.2010.08.007.

Fernández, L.A., Sagardoy, M.A., Gómez, M.A., 2008. Pampeana Norte Del Área Sojera Argentina Study of Acid and Alkaline Phosphatase in Soils of the Pampean North. Ciencia del Suelo 26, 35–40.

Fernández, M.D., Alonso-Blázquez, M.N., García-Gómez, C., Babin, M., 2014. Evaluation of zinc oxide nanoparticle toxicity in sludge products applied to agricultural soil using multispecies soil systems. Science of the Total Environment 497–498, 688–696. https://doi.org/10.1016/j.scitotenv.2014.07.085.

Ferreira-Vilela, LA., Saggin Júnior, O.J., Paulino, H.B., Siqueira, J.O., Santos, V.L.S., Carneiro, M.A.C., 2014. Arbuscular mycorrhizal fungus in microbial activity and aggregation of a cerrado Oxisol in crop sequence.. Ciênc. Agrotec Lavras, 38, 34-42. http://dx.doi.org/10.1590/S0100-06832012000100006.

Ferreras, L., Toresani, S., Bonel, B., Fernández, E., Bacigaluppo, S., Faggioli, V., BeltráN, C., 2009. Parámetros químicos y biológicos como indicadores de calidad del suelo en diferentes manejos. Ciencia del Suelo 27, 103–114.

Fialho, J.S., Gomes, V.F.F., de Oliveira, T.S., da Silva Jr, J.M.T., 2008. Indicadores da qualidade do solo, em sistema de rotação, na Chapada do Apodi-CE.. Revista Ciência Agronômica, 39, 353-361. https://www.redalyc.org/articulo.oa?id=195317435001.

Figueira da Silva C., Pereira M.G., Gaia Gomes J.H., Fontes M.A., Ribeiro da Silva E.M., 2020. Enzyme Activity, Glomalin, and Soil Organic Carbon in Agroforestry Systems.. Floresta e Ambiente,27: 1-9. https://doi.org/10.1590/2179-8087.071617.

Firmano, R.F., Colzato, M., Bossolani, J.W., Colnago, L.A., Martin-Neto, L., Alleoni, L.R.F., 2021. Long-term lime and phosphogypsum broadcast affects phosphorus cycling in a tropical Oxisol cultivated with soybean under no-till. Nutrient Cycling in Agroecosystems 120, 307–324. https://doi.org/10.1007/s10705-021-10151-8.

Fitriatin, B.N., Khumairah, F.H., Setiawati, M.R., Suryatmana, P., Hindersah, R., Herdiyantoro, A.N.D., Simarmata, T., 2018. Evaluation of biofertilizer consortium on rice at different salinity levels. Asian Journal of Microbiology, Biotechnology and Environmental Sciences 20, 1102–1105.

Fitriatin, B.N., Amanda, A.P., Kamaluddin, N.N., Khumairah, F.H., Sofyan, E.T., Yuniarti, A., Turmuktini, T., 2021. Some soil biological and chemical properties as affected by biofertilizers and organic ameliorants application on paddy rice. Eurasian Journal of Soil Science 10, 105–110. https://doi.org/10.18393/ejss.829695.

Frąc, M., 2011. Agricultural utilisation of dairy sewage sludge: Its effect on enzymatic activity and microorganisms of the soil environment. African Journal of Microbiology Research 5, 1755–1762. https://doi.org/10.5897/ajmr10.707.

Franco-Otero, V.G., Soler-Rovira, P., Hernández, D., López-de-Sá, E.G., Plaza, C., 2012. Short-term effects of organic municipal wastes on wheat yield, microbial biomass, microbial activity, and chemical properties of soil. Biology and Fertility of Soils 48, 205–216. https://doi.org/10.1007/s00374-011-0620-y.

Fraser, T., Lynch, D.H., Entz, M.H., Dunfield, K.E., 2015. Linking alkaline phosphatase activity with bacterial phoD gene abundance in soil from a long-term management trial. Geoderma 257–258, 115–122. https://doi.org/10.1016/j.geoderma.2014.10.016.

Frazão, J.J., Benites, V. de M., Ribeiro, J.V.S., Pierobon, V.M., Lavres, J., 2019. Agronomic effectiveness of a granular poultry litter-derived organomineral phosphate fertilizer in tropical soils: Soil phosphorus fractionation and plant responses. Geoderma 337, 582–593. https://doi.org/10.1016/j.geoderma.2018.10.003.

Furtak, K., Gawryjołek, K., Gajda, A.M., Gałązka, A., 2017. Effects of maize and winter wheat grown under different cultivation techniques on biological activity of soil. Plant, Soil and Environment 63, 449–454. https://doi.org/10.17221/486/2017-PSE.

Futa, B., Kraska, P., Andruszczak, S., Gierasimiuk, P., Jaroszuk-Sierocińska, M., 2021. Impact of subsurface application of compound mineral fertilizer on soil enzymatic activity under reduced tillage. Agronomy 11, 1–20. https://doi.org/10.3390/agronomy11112213.

Gagnon, B., Lalande, R., Simard, R.R., Roy, M., 1999. Soil enzyme activities following paper sludge addition in a winter cabbage-sweet corn rotation. Canadian Journal of Soil Science 80, 91–97. https://doi.org/10.4141/S99-033.

Gagnon, B., Simard, R.R., Lalande, R., Lafond, J., 2003. Improvement of soil properties and fruit yield of native lowbush blueberry by papermill sludge addition. Canadian Journal of Soil Science 83, 1–9. https://doi.org/10.4141/S02-011.

Gaind, S., and Nain, L., 2007. Chemical and biological properties of wheat soil in response to paddy straw incorporation and its biodegradation by fungal inoculants. Biodegradation 18, 495–503. https://doi.org/10.1007/s10532-006-9082-6.

Gaind, S., and Nain, L., 2010. Exploration of composted cereal waste and poultry manure for soil restoration. Bioresource Technology 101, 2996–3003. https://doi.org/10.1016/j.biortech.2009.12.016.

Gaind, S., and Singh, Y.V., 2015a. Soil organic phosphorus fractions in response to long-term fertilization with composted manures under rice–wheat cropping system. Journal of Plant Nutrition 39, 1336–1347. https://doi.org/10.1080/01904167.2015.1086795.

Gaind, S., and Nain, L., 2015b. Soil–Phosphorus Mobilization Potential of Phytate Mineralizing Fungi. Journal of Plant Nutrition 38, 2159–2175. https://doi.org/10.1080/01904167.2015.1014561.

Gaind, S., and Singh, Y.V., 2016. Short-Term Impact of Organic Fertilization and Seasonal Variations on Enzymes and Microbial Indices Under Rice–Wheat Rotation. Clean - Soil, Air, Water 44, 1396–1404. https://doi.org/10.1002/clen.201500946.

Gajda, A., and Martyniuk, S., 2005. Microbial biomass C and N and activity of enzymes in soil under winter wheat grown in different crop management systems. Polish Journal of Environmental Studies 14, 159–163.

Gajda, A.M., Przewłoka, B., 2012. Soil biological activity as affected by tillage intensity. International Agrophysics 26, 15–23. https://doi.org/10.2478/v10247-012-0003-0.

Galindo, F.S., Delate, K., Heins, B., Phillips, H., Smith, A., Pagliari, P.H., 2020. Cropping system and rotational grazing effects on soil fertility and enzymatic activity in an integrated organic crop-livestock system. Agronomy 10, 1–18. https://doi.org/10.3390/agronomy10060803.

Galvez, A., Sinicco, T., Cayuela, M.L., Mingorance, M.D., Fornasier, F., Mondini, C., 2012. Short term effects of bioenergy by-products on soil C and N dynamics, nutrient availability and biochemical properties. Agriculture, Ecosystems and Environment 160, 3–14. https://doi.org/10.1016/j.agee.2011.06.015.

Gangwar, R.K., Makadi, M., Demeter, I., Tancsics, A., Cserhati, M., Varbiro, G., Singh, J., Csorba, A., Fuchs, M., Micheli, E., Szegi, T., 2021. Comparing Soil Chemical and Biological Properties of Salt Affected Soils under Different Land Use Practices in Hungary and India. EURASIAN SOIL SCIENCE 54, 1007–1018. https://doi.org/10.1134/S1064229321070048.

Gao, X., Shi, D., Lv, A., Wang, S., Yuan, S., Zhou, P., An, Y., 2016. Increase phosphorus availability from the use of alfalfa (Medicago sativa L) green manure in rice (Oryza sativa L.) agroecosystem. Scientific Reports 6, 1–13. https://doi.org/10.1038/srep36981.

García-Martínez, A.M., Tejada, M., Díaz, A.I., Rodríguez-Morgado, B., Bautista, J., Parrado, J., 2010. Enzymatic vegetable organic extracts as soil biochemical biostimulants and atrazine extenders. Journal of Agricultural and Food Chemistry 58, 9697–9704. https://doi.org/10.1021/jf101289n.

García-Orenes, F., Guerrero, C., Roldán, A., Mataix-Solera, J., Cerdà, A., Campoy, M., Zornoza, R., Bárcenas, G., Caravaca, F., 2010. Soil microbial biomass and activity under different agricultural management systems in a semiarid Mediterranean agroecosystem. Soil and Tillage Research 109, 110–115. https://doi.org/10.1016/j.still.2010.05.005.

García-Orenes, F., Caravaca, F., Morugán-Coronado, A., Roldán, A., 2015. Prolonged irrigation with municipal wastewater promotes a persistent and active soil microbial community in a semiarid agroecosystem. Agricultural Water Management 149, 115–122. https://doi.org/10.1016/j.agwat.2014.10.030.

García-Ruiz, R., Ochoa, V., Viñegla, B., Hinojosa, M.B., Peña-Santiago, R., Liébanas, G., Linares, J.C., Carreira, J.A., 2009. Soil enzymes, nematode community and selected physico-chemical properties as soil quality indicators in organic and conventional olive oil farming: Influence of seasonality and site features. Applied Soil Ecology 41, 305–314. https://doi.org/10.1016/j.apsoil.2008.12.004.

García-Ruiz, R., Ochoa, V., Hinojosa, M.B., Carreira, J.A., 2008. Suitability of enzyme activities for the monitoring of soil quality improvement in organic agricultural systems. Soil Biology and Biochemistry 40, 2137–2145. https://doi.org/10.1016/j.soilbio.2008.03.023.

García-Ruiz, R; Ochoa, M V; Hinojosa, M B; Gómez-Muñoz, B., 2012. Improved soil quality after 16 years of olive mill pomace application in olive oil groves. Agronomy for Sustainable Development, 32:803–810. https://doi.org/10.1007/s13593-011-0080-7.

Garcia, C., Roldan, A., Hernandez, T., 1997. Changes in Microbial Activity after Abandonment of Cultivation in a Semiarid Mediterranean Environment. Journal of Environmental Quality 26, 285–292. https://doi.org/10.2134/jeq1997.00472425002600010040x.

Garcia, C., and Hernandez, T., 1996. Influence of salinity on the biological and biochemical activity of a calciorthird soil. Plant and Soil 178, 255–263. https://doi.org/10.1007/bf00011591.

Garg, N., and Cheema, A., 2021. Relative roles of Arbuscular Mycorrhizae in establishing a correlation between soil properties, carbohydrate utilization and yield in Cicer arietinum L. under As stress. Ecotoxicology and Environmental Safety 207, 111196. https://doi.org/10.1016/j.ecoenv.2020.111196.

Garg, S., Bahl, G.S., 2008. Phosphorus availability to maize as influenced by organic manures and fertilizer P associated phosphatase activity in soils. Bioresource Technology 99, 5773–5777. https://doi.org/10.1016/j.biortech.2007.10.063.

Gelsomino, A., Azzellino, A., 2011. Multivariate analysis of soils: microbial biomass, metabolic activity, and bacterial-community structure and their relationships with soil depth and type. Journal of Plant Nutrition and Soil Science 174, 381–394. https://doi.org/10.1002/jpln.200900267.

George, S., Wright, D.L., Marois, J.J., 2013. Impact of grazing on soil properties and cotton yield in an integrated crop-livestock system. Soil and Tillage Research 132, 47–55. https://doi.org/10.1016/j.still.2013.05.004.

Ghiloufi, W., and Chaieb, M., 2021. Environmental factors controlling vegetation attributes, soil nutrients and hydrolases in South Mediterranean arid grasslands. Ecological Engineering 161, 106155. https://doi.org/10.1016/j.ecoleng.2021.106155.

Ghosh, A., Kumar, S., Manna, M.C.C., Singh, A.K.A.K., Sharma, P., Sarkar, A., Saha, M., Bhattacharyya, R., Misra, S., Biswas, S.S.S., Biswas, D.R., Gautam, K., Kumar, R.V.V., Biswas, D.R., Gautam, K., Kumar, R.V.V., 2019. Long-term in situ moisture conservation in horti-pasture system improves biological health of degraded land. Journal of Environmental Management 248. https://doi.org/10.1016/j.jenvman.2019.109339.

Gigliotti, G., Giusquiani, P.L., Businelli, D., 2001. A long-term chemical and infrared spectroscopy study on a soil amended with municipal sewage sludge. Agronomie 21, 169–178. https://doi.org/10.1051/agro:2001115.

Gispert, M., Emran, M., Pardini, G., Doni, S., Ceccanti, B., 2013. The impact of land management and abandonment on soil enzymatic activity, glomalin content and aggregate stability. Geoderma 202–203, 51–61. https://doi.org/10.1016/j.geoderma.2013.03.012.

Gong, X., Zhang, Z., Wang, H., 2021. Effects of Gleditsia sinensis pod powder, coconut shell biochar and rice husk biochar as additives on bacterial communities and compost quality during vermicomposting of pig manure and wheat straw. Journal of Environmental Management 295, 113136. https://doi.org/10.1016/j.jenvman.2021.113136.

Gonnety, J.T., Assemien, E.F.L., Guei, A.M., N'Dri, A.A., Djina, Y., Kone, A.W., Tondoh, J.E., 2012. Effect of land-use types on soil enzymatic activities and chemical properties in semi-deciduous forest areas of Central-West Cote d'Ivoire. Biotechnologie Agronomie Societe Et Environnement 16, 478–485.

Gopinath, K.A., Saha, S., Mina, B.L., Pande, H., Kumar, N., Srivastva, A.K., Gupta, H.S., 2009. Yield potential of garden pea (Pisum sativum L.) varieties, and soil properties under organic and integrated nutrient management systems. Archives of Agronomy and Soil Science 55, 157–167. https://doi.org/10.1080/03650340802382207.

Gospodarek, J., Rusin, M., Barczyk, G., Nadgórska-Socha, A., 2021. The effect of petroleum-derived substances and their bioremediation on soil enzymatic activity and soil invertebrates. Agronomy 11. https://doi.org/10.3390/agronomy11010080.

Gou, X., Cai, Y., Wang, C., Li, B., Zhang, R., Zhang, Y., Tang, X., Chen, Q., Shen, J., Deng, J., Zhou, X., 2020. Effects of different long-term cropping systems on phoD-harboring bacterial community in red soils. Journal of Soils and Sediments 21, 376–387. https://doi.org/10.1007/s11368-020-02749-2.

Goyal, S., Chander, K., Mundra, M.C., Kapoor, K.K., 1999. Influence of inorganic fertilizers and organic amendments on soil organic matter and soil microbial properties under tropical conditions. Biology and Fertility of Soils 29, 196–200. https://doi.org/10.1007/s003740050544.

Graça, J., Daly, K., Bondi, G., Ikoyi, I., Crispie, F., Cabrera-Rubio, R., Cotter, P.D., Schmalenberger, A., 2021. Drainage class and soil phosphorus availability shape microbial communities in Irish grasslands. European Journal of Soil Biology 104, 103297. https://doi.org/10.1016/j.ejsobi.2021.103297.

Green, V.S., Stott, D.E., Cruz, J.C., Curi, N., 2007. Tillage impacts on soil biological activity and aggregation in a Brazilian Cerrado Oxisol. Soil and Tillage Research 92, 114–121. https://doi.org/10.1016/j.still.2006.01.004.

Guan, G., Tu, S.-X., Yang, J.-C., Zhang, J.-F., Yang, L., 2011. A Field Study on Effects of Nitrogen Fertilization Modes on Nutrient Uptake, Crop Yield and Soil Biological

Properties in Rice-Wheat Rotation System. Agricultural Sciences in China 10, 1254–1261. https://doi.org/10.1016/S1671-2927(11)60117-X.

Guan, G., Tu, S., Li, H., Yang, J., Zhang, J., Wen, S., Yang, L., 2013. Phosphorus Fertilization Modes Affect Crop Yield, Nutrient Uptake, and Soil Biological Properties in the Rice-Wheat Cropping System. Soil Science Society of America Journal 77, 166–172. https://doi.org/10.2136/sssaj2011.0324.

Gunes, A., Inal, A., Adak, M.S., Alpaslan, M., Bagci, E.G., Erol, T., Pilbeam, D.J., 2007. Mineral nutrition of wheat, chickpea and lentil as affected by mixed cropping and soil moisture. Nutrient Cycling in Agroecosystems 78, 83–96. https://doi.org/10.1007/s10705-006-9075-1.

Guo, D., Ali, A., Zhang, Z., 2021. Streptomyces pactum and sulfur mediated the rhizosphere microhabitats of potherb mustard after a phytoextraction trial. Environmental Pollution 281, 116968. https://doi.org/10.1016/j.envpol.2021.116968.

Guo, Y.J., Ni, Y., Han, J.G., 2009. The Influence of Land Use Change on Chemical and Biological Properties of Steppe Soils in Northern China. Arid Land Research and Management 23, 197–212. https://doi.org/10.1080/15324980903028553.

Gupta, V.V.S.R., Lawrence, J.R., Germida, J.J., 1988. Impact of elemental sulfur fertilization on agricultural soils. I. Effects on microbial biomass and enzyme activities. Canadian Journal of Soil Science 68, 463–473. https://doi.org/10.4141/cjss88-045.

Habig, J., and Swanepoel, C., 2015. Effects of conservation agriculture and fertilization on soil microbial diversity and activity. Environments - MDPI 2, 358–384. https://doi.org/10.3390/environments2030358.

Habig, J., Labuschagne, J., Marais, M., Swart, A., Claassens, S., 2018. The effect of a medic-wheat rotational system and contrasting degrees of soil disturbance on nematode functional groups and soil microbial communities. Agriculture, Ecosystems and Environment 268, 103–114. https://doi.org/10.1016/j.agee.2018.09.013.

Hai-Ming, T., Xao-Ping, X., Wen-Guang, T., Ye-Chum, T., Ye-Chun, L., Ke, W., Guang-Li, Y., 2014 . Effects of Winter Cover Crops Residue Returning on Soil Enzyme Activities and Soil Microbial Community in Double-Cropping Rice Fields.. PLOS ONE, 9: e100443. http://dx.doi.orgjournal.pone.0100443.

Hashimoto, Y., Matsufuru, H., Takaoka, M., Tanida, H., Sato, T., 2009. Impacts of Chemical Amendment and Plant Growth on Lead Speciation and Enzyme Activities in a Shooting Range Soil: An X-ray Absorption Fine Structure Investigation. Journal of Environmental Quality 38, 1420–1428. https://doi.org/10.2134/jeq2008.0427.

Hatti V., Ramachandrappa B.K., Mudalagiriyappa, Sathish A., Thimmegowda M.N., 2018. Soil properties and productivity of rainfed finger millet under conservation tillage and nutrient management in Eastern dry zone of Karnataka. Journal of Environmental Biology, 19: 612-624. http://doi.org/10.22438/jeb/39/5/MRN-724.

Haynes, R.J., and Williams, P.H., 1999. Influence of stock camping behaviour on the soil microbiological and biochemical properties of grazed pastoral soils. Biology and Fertility of Soils 28, 253–258. https://doi.org/10.1007/s003740050490.

Hazarika, S., Parkinson, R., Bol, R., Dixon, L., Russell, P., Donovan, S., Allen, D., 2009. Effect of tillage system and straw management on organic matter dynamics. Agronomy for Sustainable Development 29, 525–533. https://doi.org/10.1051/agro/2009024.

Hazarika, S., Sohliya, B., Thakuria, D., Kataki, S., Rangappa, K., 2021. Influence of organic amendments on acidic soil responsive crop groundnut (Arachis hypogaea L.). Environmental Progress and Sustainable Energy 40. https://doi.org/10.1002/ep.13592.

Hazra, K.K., Swain, D.K., Singh, S.S., 2021. The potential of crop residue recycling for sustainable phosphorus management in non-flooded rice-lentil system in alkaline soil. Soil and Tillage Research 213, 105147. https://doi.org/10.1016/j.still.2021.105147.

He, Z., Honeycutt, C.W., Griffin, T.S., Larkin, R.P., Olanya, M., Halloran, J.M., 2010. Increases of soil phosphatase and urease activities in potato fields by cropping rotation practices. Journal of Food, Agriculture and Environment 8, 1112–1117.

Hernández-Vigoa, G., Cabrera-Dávila, G. de la C., Izquierdo-Brito, I., Socarrás-Rivero, A.A., Hernández-Martínez, L., Sánchez-Rendón, J.A., 2018. Edaphic indicators after the conversion of a grassland area into agroecological systems. Pastos y Forrajes 41, 3–12.

Hojati, S., and Nourbakhsh, F., 2006. Enzyme activities and microbial biomass carbon in a soil amended with organic and inorganic fertilizers. Journal of Agronomy, 5, 563-579. http://dx.doi.org/10.3923/ja.2006.563.569.

Hoyle, F.C., and Murphy, D.V., 2006. Seasonal changes in microbial function and diversity associated with stubble retention versus burning. Australian Journal of Soil Research 44, 407–423. https://doi.org/10.1071/SR05183.

Hu, J., Lin, X., Wang, J., Dai, J., Cui, X., Chen, R., Zhang, J., 2009. Arbuscular mycorrhizal fungus enhances crop yield and P-uptake of maize (Zea mays L.): A field case study on a sandy loam soil as affected by long-term P-deficiency fertilization. Soil Biology and Biochemistry 41, 2460–2465. https://doi.org/10.1016/j.soilbio.2009.09.002.

Hu, J., Cui, X., Wang, J., Lin, X., 2019a. The non-simultaneous enhancement of phosphorus acquisition and mobilization respond to enhanced arbuscular mycorrhization on Maize (Zea mays L.). Microorganisms 7, 1–13. https://doi.org/10.3390/microorganisms7120651.

Hu, J., Li, M., Liu, H., Zhao, Q., Lin, X., 2019b. Intercropping with sweet corn (Zea mays L. var. rugosa Bonaf.) expands P acquisition channels of chili pepper (Capsicum annuum L.) via arbuscular mycorrhizal hyphal networks. Journal of Soils and Sediments 19, 1632–1639. https://doi.org/10.1007/s11368-018-2198-6.

Idris, I., and Yuliar, Y., 2021. Potential application of Bacillus amyloliquefaciens EB13 inoculant for improving soil fertility and Citrus sinensis growth. Asian Journal of Agriculture and Biology 2022, 1–7. https://doi.org/10.35495/AJAB.2021.02.069.

Inal, A., Gunes, A., Zhang, F., Cakmak, I., 2007. Peanut/maize intercropping induced changes in rhizosphere and nutrient concentrations in shoots. Plant Physiology and Biochemistry 45, 350–356. https://doi.org/10.1016/j.plaphy.2007.03.016.

Izaguirre-Mayoral, M.L., Carballo, O., Carreño, L., Mejia, M.G.D., 2000. Effects of arbuscular mycorrhizal inoculation on growth, yield, nitrogen, and phosphorus nutrition of nodulating bean varieties in two soil substrates of contrasting fertility. Journal of Plant Nutrition 23, 1117–1133. https://doi.org/10.1080/01904160009382086.

Izquierdo, I., Caravaca, F., Alguacil, M.M., Roldán, A., 2003. Changes in physical and biological soil quality indicators in a troipical crop system (Havana, Cuba) in response to different agroecological management practices. Environmental Management, 32, 639-645. http://dx.doi.org/10.1007/s00267-003-3034-2.

Jabborova, D., Annapurna, K., Al-Sadi, A.M., Alharbi, S.A., Datta, R., Zuan, A.T.K., 2021. Biochar and Arbuscular mycorrhizal fungi mediated enhanced drought tolerance in Okra (Abelmoschus esculentus) plant growth, root morphological traits and physiological properties. Saudi Journal of Biological Sciences 28, 5490–5499. https://doi.org/10.1016/j.sjbs.2021.08.016.

Jain, N.K., Jat, R.A., Yadav, R.S., Bhaduri, D., Meena, H.N., 2018. Polythene mulching and fertigation in peanut (Arachis hypogaea): Effect on crop productivity, quality, water productivity and economic profitability. Indian Journal of Agricultural Sciences 88, 1168–1178.

Janaki, P., Alagesan, A., Ejilane, J., Nithila, S., Balasubramaniam, P., Santhy, P., 2021. Effect of soil and crop management practices on sodicity stress alleviation and rice productivity under water scarce condition. Journal of Applied and Natural Science 13, 1238–1248. https://doi.org/10.31018/jans.v13i4.2930.

Janes-Bassett, V., Blackwell, M.S.A., Blair, G., Davies, J., Haygarth, P.M., Mezeli, M.M., Stewart, G., 2022. A meta-analysis of phosphatase activity in agricultural settings in response to phosphorus deficiency. Soil Biology and Biochemistry 165, 108537. https://doi.org/10.1016/j.soilbio.2021.108537.

Jaskulska R. 2020a. The Level of Luvisols Biochemical Activity in Midfield Shelterbelt and Winter Triticale (xTriticosecale Wittm. ex A. Camus) Cultivation. Agronomy,10: 1644. https://doi.org/10.3390/agronomy10111644.

Jaskulska, I., Romaneckas, K., Jaskulski, D., Gałęzewski, L., Breza-Boruta, B., Dębska, B., Lemanowicz, J., 2020. Soil properties after eight years of the use of strip-till one-pass technology. Agronomy 10, 1–16. https://doi.org/10.3390/agronomy10101596.

Jat, H.S., Datta, A., Choudhary, M., Sharma, P.C., Yadav, A.K., Choudhary, V., Gathala, M.K., Jat, M.L., McDonald, A., 2019. Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. Catena 181, 104059. https://doi.org/10.1016/j.catena.2019.05.005.

Jat, H.S., Choudhary, M., Datta, A., Yadav, A.K., Meena, M.D., Devi, R., Gathala, M.K., Jat, M.L., McDonald, A., Sharma, P.C., 2020. Temporal changes in soil microbial properties and nutrient dynamics under climate smart agriculture practices. Soil and Tillage Research 199, 104595. https://doi.org/10.1016/j.still.2020.104595.

Jia, Q., Kamran, M., Ali, S., Sun, L., Zhang, P., Ren, X., Jia, Z., 2018. Deficit irrigation and fertilization strategies to improve soil quality and alfalfa yield in arid and semi-arid areas of northern China. PeerJ 2018, 1–21. https://doi.org/10.7717/peerj.4410.

Jian, S., Li, J., Chen, J., Wang, G., Mayes, M.A., Dzantor, K.E., Hui, D., Luo, Y., 2016. Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. Soil Biology and Biochemistry 101, 32–43. https://doi.org/10.1016/j.soilbio.2016.07.003.

Jiang, Y., Arafat, Y., Letuma, P., Ali, L., Tayyab, M., Waqas, M., Li, Y., Lin, Weiwei, Lin, S., Lin, Wenxiong, 2019. Restoration of long-term monoculture degraded tea orchard by green and goat manures applications system. Sustainability (Switzerland) 11. https://doi.org/10.3390/su11041011.

Johnson, D., Leake, J.R., Lee, J.A., Campbell, C.D., 1998. Changes in soil microbial biomass and microbial activities in response to 7 years simulated pollutant nitrogen deposition on a heathland and two grasslands. Environmental Pollution 103, 239–250. https://doi.org/10.1016/S0269-7491(98)00115-8.

Joshi, E., Vyas, A.K., Dhar, S., Dass, A., Sasode, D.S., Prajapati, K., Jinger, D., Singhal, V., Gupta, G., Prasad, D., 2021. Soil microbial biomass carbon and soil enzymatic activity under nutrient omission plot technique in maize (Zea mays)–wheat (triticum aestivum) cropping system. Indian Journal of Agronomy 66, 170–179.

Juma, N.G., and Tabatabai, M.A., 1988. Comparison of kinetic and thermodynamic parameters of phosphomonoesterases of soils and of corn and soybean roots. Soil Biology and Biochemistry 20, 533–539. https://doi.org/10.1016/0038-0717(88)90069-7.

Damian, J.M., da Silva Matos, E., e Pedreira, B.C., de Faccio Carvalho, P.C., de Souza, A.J., Andreote, F.D., Premazzi, L.M., Cerri, C.E.P., 2021. Pastureland intensification and diversification in Brazil mediate soil bacterial community structure changes and soil C accumulation. Applied Soil Ecology 160, 103858. https://doi.org/10.1016/j.apsoil.2020.103858.

Kahle, P., Baum, C., Boelcke, B., Kohl, J., Ulrich, R., 2010. Vertical distribution of soil properties under short-rotation forestry in Northern Germany. Journal of Plant Nutrition and Soil Science 173, 737–746. https://doi.org/10.1002/jpln.200900230.

Kamh, M., Horst, W.J., Amer, F., Mostafa, H., Maier, P., 1999. Mobilization of soil and fertilizer phosphate by cover crops. Plant and Soil 211, 19–27. https://doi.org/10.1023/A:1004543716488.

Katsalirou, E., Deng, S., Gerakis, A., Nofziger, D.L., 2016. Long-term management effects on soil P, microbial biomass P, and phosphatase activities in prairie soils. European Journal of Soil Biology 76, 61–69. https://doi.org/10.1016/j.ejsobi.2016.07.001.

Kaur, H., Gosal, S.K., Walia, S.S., 2017. Synergistic effect of organic, inorganic and biofertilizers on soil microbial activities in rhizospheric soil of green pea. Annual Research and Review in Biology 12, 1–11. https://doi.org/10.9734/ARRB/2017/32509.

Kayikcioglu, H.H., 2018. Can treated wastewater be used as an alternative water resource for agricultural irrigation? Changes in soil and plant health after three years of maize cultivation in western anatolia, Turkey. Applied Ecology and Environmental Research 16, 8131–8161. https://doi.org/10.15666/aeer/1606_81318161.

Rajeela, T.H.K., Gopal, M., Gupta, A., Bhat, R., Thomas, G.V., 2017. Cross-compatibility evaluation of plant growth promoting rhizobacteria of coconut and cocoa on yield and rhizosphere properties of vegetable crops. Biocatalysis and Agricultural Biotechnology 9, 67–73. https://doi.org/10.1016/j.bcab.2016.11.006.

Khan, M.N., Huang, J., shah, A., Li, D., Daba, N.A., Han, T., Du, J., Qaswar, M., Anthonio, C.K., Sial, T.A., Haseeb, A., Zhang, L., Xu, Y., He, Z., Zhang, H., Núñez-Delgado, A., 2022. Mitigation of greenhouse gas emissions from a red acidic soil by using magnesium-modified wheat straw biochar. Environmental Research 203. https://doi.org/10.1016/j.envres.2021.111879.

Khandare, R.N., Chandra, R., Pareek, N., Raverkar, K.P., 2020. Carrier-based and liquid bioinoculants of Azotobacter and PSB saved chemical fertilizers in wheat (Triticum aestivum L.) and enhanced soil biological properties in Mollisols. Journal of Plant Nutrition 43, 36–50. https://doi.org/10.1080/01904167.2019.1659333.

Kharia, S., Thind, H., Sharma, S., Sidhu, H., Jat, M., Singh, Y., 2017. Tillage and Rice Straw Management Affect Soil Enzyme Activities and Chemical Properties after Three Years of Conservation Agriculture Based Rice-wheat System in North-Western India. International Journal of Plant & Soil Science 15, 1–13. https://doi.org/10.9734/ijpss/2017/33494.

Khuong, N.Q., Kantachote, D., Onthong, J., Xuan, L.N.T., Sukhoom, A., 2018. Enhancement of rice growth and yield in actual acid sulfate soils by potent acid-resistant Rhodopseudomonas palustris strains for producing safe rice. Plant and Soil 429, 483–501. https://doi.org/10.1007/s11104-018-3705-7.

Kim, K.Y., Cho, Y.S., Sohn, B.K., Park, R.D., Shim, J.H., Jung, S.J., Kim, Y.W., Seong, K.Y., 2002. Cold-storage of mixed inoculum of Glomus intraradices enhances root colonization, phosphorus status and growth of hot pepper. Plant and Soil 238, 267–272. https://doi.org/10.1023/A:1014474617170.

Kobierski, M., and Lemanowicz, J., 2016. Activity of phosphomonoesterases and the content of phosphorus in the eroded Luvisols of orchard and arable soils. Scientific Review Engineering and Environmental Sciences 25, 323–332.

Kobierski, M., Bartkowiak, A., Lemanowicz, J., Piekarczyk, M., 2017. Impact of poultry manure fertilization on chemical and biochemical properties of soils. Plant, Soil and Environment 63, 558–563. https://doi.org/10.17221/668/2017-PSE.

Koczorski, P., Furtado, B., Hrynkiewicz, K., Breezmann, M., Weih, M., Baum, C., 2021. Site-effects dominate the plant availability of nutrients under salix species during the first cutting cycle. Forests 12. https://doi.org/10.3390/f12091226.

Kohler, J., Caravaca, F., Carrasco, L., Roldán, A., 2007. Interactions between a plant growth-promoting rhizobacterium, an AM fungus and a phosphate-solubilising fungus in the rhizosphere of Lactuca sativa. Applied Soil Ecology 35, 480–487. https://doi.org/10.1016/j.apsoil.2006.10.006.

Kohler, J., Tortosa, G., Cegarra, J., Caravaca, F., Roldán, A., 2008. Impact of DOM from composted “alperujo” on soil structure, AM fungi, microbial activity and growth of Medicago sativa. Waste Management 28, 1423–1431. https://doi.org/10.1016/j.wasman.2007.05.008.

Kooch, Y., Ehsani, S., Akbarinia, M., 2019. Stoichiometry of microbial indicators shows clearly more soil responses to land cover changes than absolute microbial activities. Ecological Engineering 131, 99–106. https://doi.org/10.1016/j.ecoleng.2019.03.009.

Koper, J., and Lemanowicz, J., 2008. Effect of varied mineral nitrogen fertilization on changes in the content of phosphorus in soil and in plant and the activity of soil phosphatases. Ecol. Chem. Eng. S 15, 465–471.

Kowalska, J., Niewiadomska, A., Głuchowska, K., Kaczmarek, D., 2017. Impact of fertilizers on soil properties in the case of solanum tuberosum L. During conversion to organic farming. Applied Ecology and Environmental Research 15, 369–383. https://doi.org/10.15666/aeer/1504_369383.

Kremer, R.J., and Li, J., 2003. Developing weed-suppressive soils through improved soil quality management. Soil and Tillage Research 72, 193–202. https://doi.org/10.1016/S0167-1987(03)00088-6.

Krey, T., Caus, M., Baum, C., Ruppel, S., Eichler-Löbermann, B., 2011. Interactive effects of plant growth-promoting rhizobacteria and organic fertilization on P nutrition of Zea mays L. and Brassica napus L. Journal of Plant Nutrition and Soil Science 174, 602–613. https://doi.org/10.1002/jpln.200900349.

Kumar, B., Dhar, S., Paul, S., Paramesh, V., Dass, A., Upadhyay, P.K., Kumar, A., Abdelmohsen, S.A.M., Alkallas, F.H., El-Abedin, T.K.Z., Elansary, H.O., Abdelbacki, A.M.M., 2021a. Microbial biomass carbon, activity of soil enzymes, nutrient availability, root growth, and total biomass production in wheat cultivars under variable irrigation and nutrient management. Agronomy 11, 1–16. https://doi.org/10.3390/agronomy11040669.

Kumar, G., Suman, A., Lal, S., Ram, R.A., Bhatt, P., Pandey, G., Chaudhary, P., Rajan, S., 2021b. Bacterial structure and dynamics in mango (Mangifera indica) orchards after long term organic and conventional treatments under subtropical ecosystem. Scientific Reports 11, 1–13. https://doi.org/10.1038/s41598-021-00112-0.

Kumar, R., Shambhavi, S., Beura, K., Kumar, S., Singh, R.G., 2017. Soil microbial budgeting as influenced by contrasting tillage and crop diversification under rice based cropping systems in Inseptisol of Bihar. Journal of Pure and Applied Microbiology 11, 539–547. https://doi.org/10.22207/JPAM.11.1.71.

Kunito, T., Saeki, K., Goto, S., Hayashi, H., Oyaizu, H., Matsumoto, S., 2001. Copper and zinc fractions affecting microorganisms in long-term sludge-amended soils. Bioresource Technology 79, 135–146. https://doi.org/10.1016/S0960-8524(01)00047-5.

Kuziemska, B., Wysokiński, A., Klej, P., 2020. Effect of different zinc doses and organic fertilization on soil's enzymatic activity. Journal of Elementology 25, 1089–1099. https://doi.org/10.5601/jelem.2020.25.1.1927.

Lago, M. del C.F., Gallego, P.P., Briones, M.J.I., 2019. Intensive cultivation of kiwifruit alters the detrital foodweb and accelerates soil C and N losses. Frontiers in Microbiology 10, 1–10. https://doi.org/10.3389/fmicb.2019.00686.

Lagomarsino, A., Moscatelli, M.C., Tizio, A.D., Mancinelli, R., Grego, S., Marinari, S., 2009. Soil biochemical indicators as a tool to assess the short-term impact of agricultural management on changes in organic C in a Mediterranean environment. Ecological Indicators 9, 518–527. https://doi.org/10.1016/j.ecolind.2008.07.003.

Lakhdar, A., Scelza, R., Achiba, W.B., Scotti, R., Rao, M.A., Jedidi, N., Abdelly, C., Gianfreda, L., 2011. Effect of municipal solid waste compost and sewage sludge on enzymatic activities and wheat yield in a clayey-loamy soil. Soil Science 176, 15–21. https://doi.org/10.1097/SS.0b013e3182028d8a.

Lal, K., Minhas, P.S., Yadav, R.K., 2015. Long-term impact of wastewater irrigation and nutrient rates II.Nutrient balance, nitrate leaching and soil properties underperi-urban cropping systems.. Agricultural Water Management,156, 110-117. http://dx.doi.org/10.1016/j.agwat.2015.04.001.

Lalande, R., Gagnon, B., Simard, R.R., 2003. Papermill biosolid and hog manure compost affect short-term biological activity and crop yield of a sandy soil. Canadian Journal of Soil Science 83, 353–362. https://doi.org/10.4141/S03-004.

Lalande, R., Gagnon, B., Royer, I., 2009. Impact of natural or industrial liming materials on soil properties and microbial activity. Canadian Journal of Soil Science 89, 209–222. https://doi.org/10.4141/CJSS08015.

Langer, U., and Klimanek, E.M., 2006. Soil microbial diversity of four German long-term field experiments. Archives of Agronomy and Soil Science 52, 507–523. https://doi.org/10.1080/03650340600915554.

Laxminarayana, K., 2017. Effect of Mycorrhiza, Organic Sources, Lime, Secondary and Micro-nutrients on Soil Microbial Activities and Yield Performance of Yam Bean (Pachyrhizus erosus L.) in Alfisols. Communications in Soil Science and Plant Analysis 48, 186–200. https://doi.org/10.1080/00103624.2016.1254232.

Lebrun, J.D., Trinsoutrot-Gattin, I., Vinceslas-Akpa, M., Bailleul, C., Brault, A., Mougin, C., Laval, K., 2012. Assessing impacts of copper on soil enzyme activities in regard to their natural spatiotemporal variation under long-term different land uses. Soil Biology and Biochemistry 49, 150–156. https://doi.org/10.1016/j.soilbio.2012.02.027.

Leirós, M.C., Trasar-Cepeda, C., García-Fernández, F., Gil-Sotres, F., 1999. Defining the validity of a biochemical index of soil quality. Biology and Fertility of Soils 30, 140–146. https://doi.org/10.1007/s003740050600.

Lemanowicz, J., Bartkowiak, A., Breza-Boruta, B., 2016. Changes in phosphorus content, phosphatase activity and some physicochemical and microbiological parameters of soil within the range of impact of illegal dumping sites in Bydgoszcz (Poland). Environmental Earth Sciences 75, 1–14. https://doi.org/10.1007/s12665-015-5162-4.

Li, C.H., Ma, B.L., Zhang, T.Q., 2002. Soil bulk density effects on soil microbial populations and enzyme activities during the growth of maize (Zea mays L.) planted in large pots under field exposure. Canadian Journal of Soil Science 82, 147–154. https://doi.org/10.4141/S01-026.

Li, Z., Jin, Z., Li, Q., 2017a. Changes in land use and their effects on soil properties in Huixian karst wetland system. Polish Journal of Environmental Studies 26, 699–707. https://doi.org/10.15244/pjoes/65360.

Li, B., Chen, Y., Liang, W. zhen, Mu, L., Bridges, W.C., Jacobson, A.R., Darnault, C.J.G., 2017b. Influence of cerium oxide nanoparticles on the soil enzyme activities in a soil-grass microcosm system. Geoderma 299, 54–62. https://doi.org/10.1016/j.geoderma.2017.03.027.

Li, C., Veum, K.S., Goyne, K.W., Nunes, M.R., Acosta-Martinez, V., 2021a. A chronosequence of soil health under tallgrass prairie reconstruction. Applied soil ecology 164. https://doi.org/10.1016/j.apsoil.2021.103939.

Li, C., Hoffland, E., Werf, W. van der, Zhang, J., Li, H., Sun, J., Zhang, F., Kuyper, T.W., 2021b. Complementarity and facilitation with respect to P acquisition do not drive overyielding by intercropping. FIELD CROPS RESEARCH 265. https://doi.org/10.1016/j.fcr.2021.108127.

Li, Q., Chen, J., Wu, L., Luo, X., Li, N., Arafat, Y., Lin, S., Lin, W., 2018a. Belowground interactions impact the soil bacterial community, soil fertility, and crop yield in maize/peanut intercropping systems. International Journal of Molecular Sciences 19. https://doi.org/10.3390/ijms19020622.

Li, J., Liu, L., Zhang, C., Chen, C., Lu, G., Xiong, J., Yang, H., 2018b. Effects of crop type on soil microbial properties in the cropland of the jianghan plain of China. Plant, Soil and Environment 64, 421–426. https://doi.org/10.17221/283/2018-PSE.

Li, J., Xu, Y., 2018. Effects of clay combined with moisture management on Cd immobilization and fertility index of polluted rice field. Ecotoxicology and Environmental Safety 158, 182–186. https://doi.org/10.1016/j.ecoenv.2018.04.031.

Li, Qiang, Hu, Q., Zhang, C., Jin, Z., 2018. Effects of Pb, Cd, Zn, and Cu on soil enzyme activity and soil properties related to agricultural land-use practices in karst area contaminated by Pb-Zn tailings. Polish Journal of Environmental Studies 27, 2623–2632. https://doi.org/10.15244/pjoes/81213.

Li, X.H., Han, X.Z., Li, H.B., Song, C., Yan, J., Liang, Y., 2012. Soil chemical and biological properties affected by 21-year application of composted manure with chemical fertilizers in a Chinese mollisol. Canadian Journal of Soil Science 92, 419–428. https://doi.org/10.4141/CJSS2010-046.

Li, Y.T., Rouland, C., Benedetti, M., Li, F. bai, Pando, A., Lavelle, P., Dai, J., 2009. Microbial biomass, enzyme and mineralization activity in relation to soil organic C, N and P turnover influenced by acid metal stress. Soil Biology and Biochemistry 41, 969–977. https://doi.org/10.1016/j.soilbio.2009.01.021.

Liang, Z., and Elsgaard, L., 2021. Nitrous oxide fluxes from long-term limed soils following P and glucose addition: Nonlinear response to liming rates and interaction from added P. Science of the Total Environment 797, 148933. https://doi.org/10.1016/j.scitotenv.2021.148933.

Lin, J., Ma, K., Chen, H., Chen, Z., Xing, B., 2021. Influence of different types of nanomaterials on soil enzyme activity: A global meta-analysis. Nano Today 42, 101345. https://doi.org/10.1016/j.nantod.2021.101345.

Liu, C.-A., and Zhou, L.-M., 2017. Soil organic carbon sequestration and fertility response to newly-built terraces with organic manure and mineral fertilizer in a semi-arid environment. Soil and Tillage Research 172, 39–47. https://doi.org/10.1016/j.still.2017.05.003.

Liu, E., Yan, C., Mei, X., He, W., Bing, S.H., Ding, L., Liu, Q., Liu, S., Fan, T., 2010. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. Geoderma 158, 173–180. https://doi.org/10.1016/j.geoderma.2010.04.029.

Liu, X. M., Li Q., Liang W.J., Jiang Y., 2008. Distribution of soil enzyme activities and microbial biomass along a latitudinal gradient in farmlands of songliao plain, Northeast China. Pedosphere 18(4):431–40. https://doi.org/10.1016/S1002-0160(08)60034-X.

Liu, Y.M., Cao, W.Q., Chen, X.X., Yu, B.G., Lang, M., Chen, X.P., Zou, C.Q., 2020. The responses of soil enzyme activities, microbial biomass and microbial community structure to nine years of varied zinc application rates. Science of the Total Environment 737, 140245. https://doi.org/10.1016/j.scitotenv.2020.140245.

Liu, Z., Bai, J., Qin, H., Sun, D., Li, M., Hu, J., Lin, X., 2021a. Application of rice straw and horse manure coameliorated soil arbuscular mycorrhizal fungal community: Impacts on structure and diversity in a degraded field in Eastern China. Land Degradation and Development 32, 2595–2605. https://doi.org/10.1002/ldr.3927.

Liu, C., Wang, Q.W., Jin, Y., Tang, J., Lin, F., Olatunji, O.A., 2021b. Perennial cover crop biomass contributes to regulating soil P availability more than rhizosphere P-mobilizing capacity in rubber-based agroforestry systems. Geoderma 401, 115218. https://doi.org/10.1016/j.geoderma.2021.115218.

Lo Presti, E., Badagliacca G., Romeo M., Monti M., 2021. Does legume root exudation facilitate itself P uptake in intercropped wheat? Journal of Soil Science and Plant Nutrition 21(4):3269–83. https://doi.org/10.1007/s42729-021-00605-x.

Łukowski, A., and Dec, D., 2018. Influence of Zn, Cd, and Cu fractions on enzymatic activity of arable soils. Environmental Monitoring and Assessment 190. https://doi.org/10.1007/s10661-018-6651-1.

Lungmuana, Singh, S.B., Choudhury, B.U., Vanthawmliana, Saha, S., Hnamte, V., 2019. Transforming jhum to plantations: Effect on soil microbiological and biochemical properties in the foot hills of North Eastern Himalayas, India. Catena 177, 84–91. https://doi.org/10.1016/j.catena.2019.02.008.

Madejón, E., Moreno, F., Murillo, J.M., Pelegrín, F., 2007. Soil biochemical response to long-term conservation tillage under semi-arid Mediterranean conditions. Soil and Tillage Research 94, 346–352. https://doi.org/10.1016/j.still.2006.08.010.

Madejón, E., Burgos, P., López, R., Cabrera, F., 2003. Agricultural use of three organic residues: effect on orange production and on properties of a soil of the 'Comarca Costa de Huelva' (SW Spain). Nutrient Cycling in Agroecosystems 65(3):281–88. https://doi.org/10.1023/A:1022608828694.

Madhaiyan, M., Poonguzhali, S., Kang, B.G., Lee, Y.J., Chung, J.B., Sa, T.M., 2010. Effect of co-inoculation of methylotrophic Methylobacterium oryzae with Azospirillum brasilense and Burkholderia pyrrocinia on the growth and nutrient uptake of tomato, red pepper and rice. Plant and Soil 328, 71–82. https://doi.org/10.1007/s11104-009-0083-1.

Mahajan, Gopal R., Manjunath, B.L., Morajkar, S., Desai, A., Das, B., Paramesh, V., 2021. Long-Term Effect of Various Organic and Inorganic Nutrient Sources on Rice Yield and Soil Quality in West Coast India Using Suitable Indexing Techniques. Communications in Soil Science and Plant Analysis 52, 1819–1833. https://doi.org/10.1080/00103624.2021.1900221.

Mahapatra, B., Adak, T., Patil, N.K.B., G, G.P.P., Gowda, G.B., Jambhulkar, N.N., Yadav, M.K., Panneerselvam, P., Kumar, U., Munda, S., Jena, M., 2017. Imidacloprid application changes microbial dynamics and enzymes in rice soil. Ecotoxicology and Environmental Safety 144, 123–130. https://doi.org/10.1016/j.ecoenv.2017.06.013.

Mahmood, M., Xu, T., Ahmed, W., Yang, J., Li, J., Mehmood, S., Liu, W., Weng, J., Li, W., 2022. Variability in Soil Parent Materials at Different Development Stages Controlled Phosphorus Fractions and Its Uptake by Maize Crop. Sustainability (Switzerland) 14. https://doi.org/10.3390/su14095048.

Maini, A., Sharma, V., Sharma, S., 2022. Assessment of soil biochemical properties and soil quality index under rainfed land use systems in submontane Punjab, India. Indian

Journal of Biochemistry and Biophysics 59, 357–367. https://doi.org/10.56042/ijbb.v59i3.28641.
Majumdar, B., Saha, A.R., Sarkar, S., Maji, B., Mahapatra, B.S., 2010. Effect of herbicides and fungicides application on fibre yield and nutrient uptake by jute (Corchorus olitorius), residual nutrient status and soil quality. Indian Journal of Agricultural Sciences 80, 878–883.
Makoi, J.H.J.R., Bambara, S., Ndakidemi, P.A., 2010. Rhizosphere phosphatase enzyme activities and secondary metabolites in plants as affected by the supply of Rhizobium, lime and molybdenum in Phaseolus vulgaris L. Australian Journal of Crop Science 4, 590–597.
Malobane, M.E., Nciizah, A.D., Nyambo, P., Mudau, F.N., Wakindiki, I.I.C., 2020. Microbial biomass carbon and enzyme activities as influenced by tillage, crop rotation and residue management in a sweet sorghum cropping system in marginal soils of South Africa. Heliyon 6, e05513. https://doi.org/10.1016/j.heliyon.2020.e05513.
Mandal, A., Patra, A.K., Singh, D., Swarup, A., Masto, R.E., 2007. Effect of long-term application of manure and fertilizer on biological and biochemical activities in soil during crop development stages. Bioresource Technology 98, 3585–3592. https://doi.org/10.1016/j.biortech.2006.11.027.
Mandal, A., Thakur, J.K., Sahu, A., Manna, M.C., Rao, A.S., Sarkar, B., Patra, A.K., 2018. Effects of Bt-cotton on biological properties of Vertisols in central India. Archives of Agronomy and Soil Science 65, 670–685. https://doi.org/10.1080/03650340.2018.1520978.
Mandal, N., Datta, S.C., Dwivedi, B.S., Manjaiah, K.M., Meena, M.C., Bhowmik, A., 2021. Zincated Nanoclay Polymer Composite (ZNCPC): Effect on DTPA-Zn, Olsen-P and Soil Enzymatic Activities in Rice Rhizosphere. Communications in Soil Science and Plant Analysis 52, 2032–2044. https://doi.org/10.1080/00103624.2021.1908325.
Mani, S., Avudainayagam S., Boomiraj K., Sethupathi N., 2020. Effect of nutrient management on d15N, d13C isotopes and enzyme activities in higher altitude agricultural soils, India. Geomicrobiology Journal 38(2):174–80. https://doi.org/10.1080/01490451.2020.1822469.
Manjunath, M., Kanchan, A., Ranjan, K., Venkatachalam, S., Prasanna, R., Ramakrishnan, B., Hossain, F., Nain, L., Shivay, Y.S., Rai, A.B., Singh, B., 2016. Beneficial cyanobacteria and eubacteria synergistically enhance bioavailability of soil nutrients and yield of okra. Heliyon 2. https://doi.org/10.1016/j.heliyon.2016.e00066.
Mankolo, R.N., Senwo, Z.N., Ranatunga, T.D., Tazisong, I.A., 2006. Phosphorus partitioning and phosphatase activity along topographic gradients of an ggricultural

watershed cropped with corn and soybean. Journal of Sustainable Agriculture 28, 131–143. https://doi.org/10.1300/J064v28n02_10.

Manna, M.C., Rao, A.S., Ganguly, T.K., 2007. Effect of fertilizer P and farmyard manure on bioavailable P as influenced by rhizosphere microbial activities in soybean-wheat rotation. Journal of Sustainable Agriculture 29, 149–166. https://doi.org/10.1300/J064v29n03_12.

Manna, M.C., Swarup, A., Wanjari, R.H., Ravankar, H.N., Mishra, B., Saha, M.N., Singh, Y.V., Sahi, D.K., Sarap, P.A., 2005. Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. Field Crops Research 93, 264–280. https://doi.org/10.1016/j.fcr.2004.10.006.

Margalef, O., Sardans, J., Fernández-Martínez, M., Molowny-Horas, R., Janssens, I.A., Ciais, P., Goll, D., Richter, A., Obersteiner, M., Asensio, D., Peñuelas, J., 2017. Global patterns of phosphatase activity in natural soils. Scientific Reports 7, 1337. https://doi.org/10.1038/s41598-017-01418-8.

Margalef, O., Sardans, J., Maspons, J., Molowny-Horas, R., Fernández-Martínez, M., Janssens, I.A., Richter, A., Ciais, P., Obersteiner, M., Peñuelas, J., 2021. The effect of global change on soil phosphatase activity. Global Change Biology 27, 5989–6003. https://doi.org/10.1111/gcb.15832.

Marklein, A.R., and Houlton, B.Z., 2012. Nitrogen inputs accelerate phosphorus cycling rates across a wide variety of terrestrial ecosystems. New Phytologist 193, 696–704. https://doi.org/10.1111/j.1469-8137.2011.03967.x.

Martínez, M.M., Ortega, R., Janssens, M., Fincheira, P., 2018. Use of organic amendments in table grape: Effect on plant root system and soil quality indicators. Journal of Soil Science and Plant Nutrition 18, 100–112. https://doi.org/10.4067/S0718-95162018005000501.

Martins Sousa, H., Ribeiro Correa A., de Motta Silva B., da Silva Oliveira S., da Silva Campos D.T., Wruck F.J., 2020. Dynamics of soil microbiological attributes in integrated crop-livestock systems in the cerrado-amozonônia ecotone. Revista Caatinga 33(1):9–20. https://doi.org/10.1590/1983-21252020v33n102rc.

Martyniuk, S., Pikuła, D., Kozieł, M., 2019. Soil properties and productivity in two long-term crop rotations differing with respect to organic matter management on an Albic Luvisol. Scientific Reports 9, 1–9. https://doi.org/10.1038/s41598-018-37087-4.

Masto, R.E., Chhonkar, P.K., Singh, D., Patra, A.K., 2006. Changes in soil biological and biochemical characteristics in a long-term field trial on a sub-tropical Inceptisol. Soil Biology and Biochemistry 38, 1577–1582. https://doi.org/10.1016/j.soilbio.2005.11.012.

Masto, R.E., Chhonkar, P.K., Singh, D., Patra, A.K., 2008. Changes in soil quality indicators under long-term sewage irrigation in a sub-tropical environment. Environmental Geology 56, 1237–1243. https://doi.org/10.1007/s00254-008-1223-2.

Masto, R.E., Ansari, M.A., George, J., Selvi, V.A., Ram, L.C., 2013. Co-application of biochar and lignite fly ash on soil nutrients and biological parameters at different crop growth stages of Zea mays. Ecological Engineering 58, 314–322. https://doi.org/10.1016/j.ecoleng.2013.07.011.

Mazzuchelli, R. de C.L., Araujo, A.S.F. de, Moro, E., Araujo, F.F. de, 2020. Changes in Soil Properties and Crop Yield as a Function of Early Desiccation of Pastures. Journal of Soil Science and Plant Nutrition 20, 840–848. https://doi.org/10.1007/s42729-019-00169-x.

Mbarki, S., Labidi, N., Talbi, O., Jdidi, N., Abdelly, C., Pascual, J.A., 2010. Ameliorative Effect of Municipal Solid Waste Compost on the Biological Quality Of Mediterranean Salt Lake Soil. Compost Science and Utilization 18, 242–248. https://doi.org/10.1080/1065657X.2010.10736962.

McCallister, D.L., Bahadir, M.A., Blumenthal, J.M., 2002. Phosphorus partitioning and phosphatase activity in semi-arid region soils under increasing crop growth intensity. Soil Science 167, 616–624. https://doi.org/10.1097/00010694-200209000-00006.

Meena, H.M., Prakasha, H.C., 2021. The impact of biochar, lime and fertilizer on soil acidity and microbiological properties and their relationship with yield of rice and cowpea in an acidic soil of Southern India. Journal of Plant Nutrition 45, 358–368. https://doi.org/10.1080/01904167.2021.1952225.

Meena, M.D., Joshi, P.K., Jat, H.S., Chinchmalatpure, A.R., Narjary, B., Sheoran, P., Sharma, D.K., 2016. Changes in biological and chemical properties of saline soil amended with municipal solid waste compost and chemical fertilizers in a mustard-pearl millet cropping system. Catena 140, 1–8. https://doi.org/10.1016/j.catena.2016.01.009.

Meena, M.D., Narjary, B., Sheoran, P., Jat, H.S., Joshi, P.K., Chinchmalatpure, A.R., Yadav, G., Yadav, R.K., Meena, M.K., 2018. Changes of phosphorus fractions in saline soil amended with municipal solid waste compost and mineral fertilizers in a mustard-pearl millet cropping system. Catena 160, 32–40. https://doi.org/10.1016/j.catena.2017.09.002.

Megharaj, M., Singleton, I., Kookana, R., Naidu, R., 1999. Persistence and effects of fenamiphos on native algal populations and enzymatic activities in soil. Soil Biology and Biochemistry 31, 1549–1553. https://doi.org/10.1016/S0038-0717(99)00078-4.

Meher, S., Saha, S., Tiwari, N., Panneerselvam, P., Munda, S., Mahapatra, A., Jangde, H.K., 2021. Herbicide-Mediated Effects on Soil Microbes, Enzymes and Yield in Direct

Sown Rice. Agricultural Research 10, 592–600. https://doi.org/10.1007/s40003-020-00536-6.

Mejia Guerra P.A., Salas Sanjúan MdC., López M.J., 2018. Evaluation of physicochemical properties and enzymatic activity of organic substrates during four crop cycles in soilless containers.. Food Science & Nutrition, 6(8): 2066-2078. https://doi.org/10.1002/fsn3.757.

Melero, S., Porras, J.C.R., Herencia, J.F., Madejon, E., 2006. Chemical and biochemical properties in a silty loam soil under conventional and organic management. Soil and Tillage Research 90, 162–170. https://doi.org/10.1016/j.still.2005.08.016.

Melero, S., Madejón, E., Herencia, J.F., Ruiz, J.C., 2007a. Biochemical properties of two different textured soils (loam and clay) after the addition of two different composts during conversion to organic farming. Spanish Journal of Agricultural Research 5, 593–604. https://doi.org/10.5424/sjar/2007054-281.

Melero, S., Madejón, E., Ruiz, J.C., Herencia, J.F., 2007b. Chemical and biochemical properties of a clay soil under dryland agriculture system as affected by organic fertilization. European Journal of Agronomy 26, 327–334. https://doi.org/10.1016/j.eja.2006.11.004.

Melero, S., Vanderlinden, K., Ruiz, J.C., Madejon, E., 2008a. Long-term effect on soil biochemical status of a Vertisol under conservation tillage system in semi-arid Mediterranean conditions. European Journal of Soil Biology 44, 437–442. https://doi.org/10.1016/j.ejsobi.2008.06.003.

Melero, S., Madejón, E., Herencia, J.F., Ruiz, J.C., 2008b. Effect of implementing organic farming on chemical and biochemical properties of an irrigated loam soil. Agronomy Journal 100, 136–144. https://doi.org/10.2134/agronj2007.0087.

Melero Sanchez, S., Madejón, E., Herencia, J. F., Porras, J. C. R., 2008. Long-term study of properties of a xerofluvent of the Guadalquivir River Valley under organic fertilization. Agronomy journal, 100 (3): 611-618. https://doi.org/10.2134/agronj2006.0317.

Melero, S., Vanderlinden, K., Ruiz, J.C., Madejn, E., 2009. Soil biochemical response after 23 years of direct drilling under a dryland agriculture system in southwest Spain. Journal of Agricultural Science 147, 9–15. https://doi.org/10.1017/S0021859608008204.

Melero, S., López-Bellido, R.J., López-Bellido, L., Muñoz-Romero, V., Moreno, F., Murillo, J.M., 2011. Long-term effect of tillage, rotation and nitrogen fertiliser on soil quality in a Mediterranean Vertisol. Soil and Tillage Research 114, 97–107. https://doi.org/10.1016/j.still.2011.04.007.

Meli, S.M., Baglieri, A., Porto, M., Belligno, A., Gennari, M., 2007. Chemical and microbiological aspects of soil amended with citrus pulp. Journal of Sustainable Agriculture 30, 53–66. https://doi.org/10.1300/J064v30n04_05.

Meli, S., Porto, M., Belligno, A., Bufo, S.A., Mazzatura, A., Scopa, A., 2002. Influence of irrigation with lagooned urban wastewater on chemical and microbiological soil parameters in a citrus orchard under Mediterranean condition. Science of the Total Environment 285, 69–77. https://doi.org/10.1016/S0048-9697(01)00896-8.

Meng, C., Tian, D., Zeng, H., Li, Z., Chen, H.Y.H., Niu, S., 2020. Global meta-analysis on the responses of soil extracellular enzyme activities to warming. Science of the Total Environment 705, 135992. https://doi.org/10.1016/j.scitotenv.2019.135992.

Menge, D.N.L., and Field, C.B., 2007. Simulated global changes alter phosphorus demand in annual grassland. Global Change Biology 13, 2582–2591. https://doi.org/10.1111/j.1365-2486.2007.01456.x.

Mercl, F., García-Sánchez, M., Kulhánek, M., Košnář, Z., Száková, J., Tlustoš, P., 2020. Improved phosphorus fertilisation efficiency of wood ash by fungal strains Penicillium sp. PK112 and Trichoderma harzianum OMG08 on acidic soil. Applied Soil Ecology 147. https://doi.org/10.1016/j.apsoil.2019.09.010.

Meshram, N.A., Ismail, S., Patil, V.D., 2016. Long-term effect of organic manuring and inorganic fertilization on humus fractionation, microbial community and enzymes assay in vertisol. Journal of Pure and Applied Microbiology 10, 139–150.

Miao, F., Li, Y., Cui, S., Jagadamma, S., Yang, G., Zhang, Q., 2019. Soil extracellular enzyme activities under long-term fertilization management in the croplands of China: a meta-analysis. Nutr Cycl Agroecosyst 114, 125–138. https://doi.org/10.1007/s10705-019-09991-2.

Mina, B.L., Saha, S., Kumar, N., Srivastva, A.K., Gupta, H.S., 2008. Changes in soil nutrient content and enzymatic activity under conventional and zero-tillage practices in an Indian sandy clay loam soil. Nutrient Cycling in Agroecosystems 82, 273–281. https://doi.org/10.1007/s10705-008-9189-8.

Moharana, P.C., Biswas, D.R., 2022. Phosphorus Delivery Potential in Soil Amended with Rock Phosphate Enriched Composts of Variable Crop Residues under Wheat–Green Gram Cropping Sequence. Communications in Soil Science and Plant Analysis 53, 1000–1017. https://doi.org/10.1080/00103624.2022.2039175.

Monaci, E., Angeletti, C., Casucci, C., Vischetti, C., 2022. Nitrogen release from pelletized poultry fertilizer in two soils: influence of soil moisture and microbial biomass. Revista Brasileira de Ciencia do Solo 46, 1–13. https://doi.org/10.36783/18069657rbcs20210101.

Monkiedje, A., Spiteller, M., Fotio, D., Sukul, P., 2006. The Effect of Land Use on Soil Health Indicators in Peri-Urban Agriculture in the Humid Forest Zone of Southern Cameroon. Journal of Environmental Quality 35, 2402–2409. https://doi.org/10.2134/jeq2005.0447.

Monokrousos, N., Papatheodorou, E.M., Diamantopoulos, J.D., Stamou, G.P., 2006. Soil quality variables in organically and conventionally cultivated field sites. Soil Biology and Biochemistry 38, 1282–1289. https://doi.org/10.1016/j.soilbio.2005.09.023.

Moreira, R.S., Chiba, M.K., Nunes, S.B., Maria, I.C.D., 2017. Air-drying pretreatment effect on soil enzymatic activity. Plant, Soil and Environment 63, 29–33. https://doi.org/10.17221/656/2016-PSE.

Moreno-Cornejo, J., Caballero-Lajarín, A., Faz, Á., Zornoza, R., 2017. Pepper crop residues and chemical fertilizers effect on soil fertility, yield and nutritional status in a crop of Brassica oleracea. Journal of Soil Science and Plant Nutrition 17, 648–661. https://doi.org/10.4067/S0718-95162017000300008.

Moreno, J.L., García, C., Hernández, T., 1998. Changes in organic matter and enzymatic activity of an agricultural soil amended with metal-contaminated sewage sludge compost. Communications in Soil Science and Plant Analysis 29, 2247–2262. https://doi.org/10.1080/00103629809370108.

Moro, H., Park, H.D., Kunito, T., 2021. Organic phosphorus substantially contributes to crop plant nutrition in soils with low phosphorus availability. Agronomy 11. https://doi.org/10.3390/agronomy11050903.

Morugán-Coronado, A., García-Orenes, F., McMillan, M., Pereg, L., 2019. The effect of moisture on soil microbial properties and nitrogen cyclers in Mediterranean sweet orange orchards under organic and inorganic fertilization. Science of the Total Environment 655, 158–167. https://doi.org/10.1016/j.scitotenv.2018.11.174.

Mullen, M.D., Melhorn, C.G., Tyler, D.D., Duck, B.N., 1998. Biological and biochemical soil properties in no-till corn with different cover crops. Journal of Soil and Water Conservation 53, 219–224.

N'Dayegamiye, A., 2006. Mixed paper mill sludge effects on corn yield, nitrogen efficiency, and soil properties. Agronomy Journal 98, 1471–1478. https://doi.org/10.2134/agronj2005.0339.

Nakas, J.P., Gould, W.D., Klein, D.A., 1987. Origin and expression of phosphatase activity in a semi-arid grassland soil. Soil Biology and Biochemistry 19, 13–18. https://doi.org/10.1016/0038-0717(87)90118-0.

Naragund, R., Singh, Y.V., Jaiswal, P., Bana, R.S., Choudhary, A.K., 2020. Influence of Crop Establishment Practices and Microbial Inoculants on Nodulation of Summer

Green Gram (Vigna radiata) and Soil Quality Parameters. Legume Research 45, 646–651. https://doi.org/10.18805/LR-4246.

Nath, C.P., Das, T.K., Bhattacharyya, R., Pathak, H., Paul, S., Chakraborty, D., Hazra, K.K., 2017. Nitrogen Effects on Productivity and Soil Properties in Conventional and Zero Tilled Wheat with Different Residue Management. Proceedings of the National Academy of Sciences India Section B - Biological Sciences 89, 123–135. https://doi.org/10.1007/s40011-017-0919-z.

Nath, C.P., Kumar, N., Das, K., Hazra, K.K., Praharaj, C.S., Singh, N.P., 2021. Impact of variable tillage based residue management and legume based cropping for seven years on enzymes activity, soil quality index and crop productivity in rice ecology. Environmental and Sustainability Indicators 10, 100107. https://doi.org/10.1016/j.indic.2021.100107.

Nayyar, A., Hamel, C., Lafond, G., Gossen, B.D., Hanson, K., Germida, J., 2009. Soil microbial quality associated with yield reduction in continuous-pea. Applied Soil Ecology 43, 115–121. https://doi.org/10.1016/j.apsoil.2009.06.008.

Neal, A.L., McLaren, T., Campolino, M.L., Hughes, D., Coelho, A.M., Lana, U.G.D.P., Gomes, E.A., Sousa, S.M.D., 2021. Crop type exerts greater influence upon rhizosphere phosphohydrolase gene abundance and phylogenetic diversity than phosphorus fertilization. FEMS Microbiology Ecology 97. https://doi.org/10.1093/femsec/fiab033.

Nedunchezhiyan, M., Laxminarayana, K., Chauhan, V.B.S., 2018. Soil Microbial Activities and Yield of Elephant Foot Yam as Influenced by Weed Management Practices in Alfisols. International Journal of Vegetable Science 24, 583–596. https://doi.org/10.1080/19315260.2018.1454567.

Nedyalkova, K., Donkova, R., Malinov, I., 2020. Acid phosphatase activity under the impact of erosion level in agricultural soils of different type and land use. Bulgarian Journal of Agricultural Science 26, 1217–1222.

Neha, Bhople, B.S., Sharma, S., 2020. Seasonal variation of rhizospheric soil properties under different land use systems at lower shivalik foothills of Punjab, India. Agroforestry Systems 94, 1959–1976. https://doi.org/10.1007/s10457-020-00512-7.

Niewiadomska, A., Gaj, R., Przybył, J., Budka, A., Mioduszewska, N., Wolna-Maruwka, A., 2016. Analysis of microbial parameters of soil in different tillage systems under sugar beets (Beta vulgaris L.). Polish Journal of Environmental Studies 25, 1803–1811. https://doi.org/10.15244/pjoes/62644.

Niewiadomska, A., Majchrzak, L., Borowiak, K., Wolna-Maruwka, A., Waraczewska, Z., Budka, A., Gaj, R., 2020a. The influence of tillage and cover cropping on soil microbial parameters and spring wheat physiology. Agronomy 10. https://doi.org/10.3390/agronomy10020200.

Niewiadomska, A., Sulewska, H., Wolna-Maruwka, A., Ratajczak, K., Waraczewska, Z., Budka, A., 2020b. The influence of bio-stimulants and foliar fertilizers on yield, plant features, and the level of soil biochemical activity in white lupine (Lupinus albus L.) cultivation. Agronomy 10. https://doi.org/10.3390/agronomy10010150.

Ning, C. C., Gao P.D., Wang B.Q., Lin W.P., Jiang N.H., Cai K.Z., 2017. Impacts of chemical fertilizer reduction and organic amendments supplementation on soil nutrient, enzyme activity and heavy metal content. Journal of Integrative Agriculture 16(8):1819–31. https://doi.org/10.1016/S2095-3119(16)61476-4.

Nisha, Walia, M., Batra, N., Gera, R., Goyal, S., 2019. Impact of management practices on soil microbial properties under wheat-cluster bean cropping system. Legume Research 42, 565–571. https://doi.org/10.18805/LR-3908.

Nivelle, E., Verzeaux, J., Chabot, A., Roger, D., Chesnais, Q., Ameline, A., Lacoux, J., Nava-Saucedo, J.E., Tétu, T., Catterou, M., 2018. Effects of glyphosate application and nitrogen fertilization on the soil and the consequences on aboveground and belowground interactions. Geoderma 311, 45–57. https://doi.org/10.1016/j.geoderma.2017.10.002.

Noronha, F.R., Manikandan, S.K., Nair, V., 2022. Role of coconut shell biochar and earthworm (Eudrilus euginea) in bioremediation and palak spinach (Spinacia oleracea L.) growth in cadmium-contaminated soil. Journal of Environmental Management 302, 114057. https://doi.org/10.1016/j.jenvman.2021.114057.

Notaro, K.A., Medeiros, E.V. de, Duda, G.P., Moreira, K.A., Barros, J.A. de, Santos, U.J. dos, Lima, J.R. de S., Moraes, W. da S., 2018. Enzymatic activity, microbial biomass, and organic carbon of entisols from brazilian tropical dry forest and annual and perennial crops. Chilean Journal of Agricultural Research 78, 68–77. https://doi.org/10.4067/S0718-58392018000100068.

Ntalli, N., Tsiafouli, M.A., Tzani, K., Mavridi, O., Oplos, C., Menkissoglu-Spiroudi, U., Monokrousos, N., 2019a. Whey: The soil bio-community enhancer that selectively controls root-knot nematodes. Plants 8, 1–15. https://doi.org/10.3390/plants8110445.

Ntalli, N., Zioga, D., D, M.A., M, E.P., Menkissoglu-Spiroudi, U., Monokrousos, N., 2019b. Anise, parsley and rocket as nematicidal soil amendments and their impact on non-target soil organisms. Applied Soil Ecology 143, 17–25. https://doi.org/10.1016/j.apsoil.2019.05.024.

Nurulita, Y., Adetutu, E.M., Gunawan, H., Zul, D., Ball, A.S., 2016. Restoration of tropical peat soils: The application of soil microbiology for monitoring the success of the restoration process. Agriculture, Ecosystems and Environment 216, 293–303. https://doi.org/10.1016/j.agee.2015.09.031.

Nuruzzaman, M., Lambers, H., Bolland, M.D.A., Veneklaas, E.J., 2006. Distribution of carboxylates and acid phosphatase and depletion of different phosphorus fractions in the rhizosphere of a cereal and three grain legumes. Plant and Soil 281, 109–120. https://doi.org/10.1007/s11104-005-3936-2.

Ogunkunle, C.O., Falade, F.O., Oyedeji, B.J., Akande, F.O., Vishwakarma, V., Alagarsamy, K., Ramachandran, D., Fatoba, P.O., 2021. Short-Term Aging of Pod-Derived Biochar Reduces Soil Cadmium Mobility and Ameliorates Cadmium Toxicity to Soil Enzymes and Tomato. Environmental Toxicology and Chemistry 40, 3306–3316. https://doi.org/10.1002/etc.4958.

Ohm, M., Paulsen, H.M., Moos, J.H., Eichler-Löbermann, B., 2017. Long-term negative phosphorus budgets in organic crop rotations deplete plant-available phosphorus from soil. Agronomy for Sustainable Development 37. https://doi.org/10.1007/s13593-017-0425-y.

Okur, N., Göçmez, S., Tüzel, Y., 2006. Effect of organic manure application and solarization on soil microbial biomass and enzyme activities under greenhouse conditions. Biological Agriculture and Horticulture 23, 305–320. https://doi.org/10.1080/01448765.2006.9755331.

Omara, A.E.-D., Hauka, F., Afify, A., El-Din, M.N., Kassem, M., 2017. The role of some PGPR strains to biocontrol rhizoctonia solani in soybean and enhancement the Growth Dynamics and Seed Yield. Environment, Biodiversity and Soil Security 1, 47–59.

Omenda, J.A., Ngetich, K.F., Kiboi, M.N., Mucheru-Muna, M.W., Mugendi, D.N., 2019. Soil organic carbon and acid phosphatase enzyme activity response to phosphate rock and organic inputs in acidic soils of central highlands of Kenya in Maize. International Journal of Plant & Soil Science 30, 1–13. https://doi.org/10.9734/ijpss/2019/v30i230169.

Omidi, H., Tahmasebi, Z., Torabi, H., Miransari, M., 2008. Soil enzymatic activities and available P and Zn as affected by tillage practices, canola (Brassica napus L.) cultivars and planting dates. European Journal of Soil Biology 44, 443–450. https://doi.org/10.1016/j.ejsobi.2008.05.002.

Onkum, P., and Teamkao, P., 2020. Soil microbial activities in Alfisol with different green manure application. International Journal of Agricultural Technology 16, 319–328.

Ortiz, J., Faggioli, V.S., Ghio, H., Boccolini, M.F., Ioele, J.P., Tamburrini, P., Garcia, F.O., Gudelj, V., 2020. Long-term impact of fertilization on the structure and functionality of microbial soil community | Impacto a largo plazo de la fertilización sobre la estructura y funcionalidad de la comunidad microbiana del suelo. Ciencia del Suelo 38, 45–55.

Pajares, S., Gallardo, J.F., Masciandaro, G., Ceccanti, B., Marinari, S., Etchevers, J.D., 2009. Biochemical indicators of carbon dynamic in an Acrisol cultivated under different management practices in the central Mexican highlands. Soil and Tillage Research 105, 156–163. https://doi.org/10.1016/j.still.2009.07.002.

Pan, F., Zhang, W., Liang, Y., Liu, S., Wang, K., 2018. Increased associated effects of topography and litter and soil nutrients on soil enzyme activities and microbial biomass along vegetation successions in karst ecosystem, southwestern China. Environmental Science and Pollution Research 25, 16979–16990. https://doi.org/10.1007/s11356-018-1673-3.

Pandey, S., Singh, D.K., 2006. Soil dehydrogenase, phosphomonoesterase and arginine deaminase activities in an insecticide treated groundnut (Arachis hypogaea L.) field. Chemosphere 63, 869–880. https://doi.org/10.1016/j.chemosphere.2005.07.053.

Pandey, J., Pandey, U., Shubhashish, K., Pandey, R., 2008. Inter-species variations in soil fertility stability in organic farm. Plant Archives 8, 61–63.

Pandey, J., and Pandey, U., 2009. Atmospheric deposition and heavy metal contamination in an organic farming system in a seasonally dry tropical region of India. Journal of Sustainable Agriculture 33, 361–378. https://doi.org/10.1080/10440040902834954.

Pankhurst, C.E., Hawke, B.G., McDonald, H.J., Kirkby, C.A., Buckerfield, J.C., Michelsen, P., O’Brien, K.A., Gupta, V.V.S.R., Doube, B.M., 1995. Evaluation of Soil Biological Properties as Potential Bioindicators of Soil Health. Australian Journal of Experimental Agriculture 35, 1015–1028. https://doi.org/10.1071/EA9951015.

Papa, S., Bartoli, G., Pellegrino, A., Fioretto, A., 2009. Microbial activities and trace element contents in an urban soil. Environmental Monitoring and Assessment 165, 193–203. https://doi.org/10.1007/s10661-009-0938-1.

Pareek N., Ramesh Chandra N., Raverkar, K.P., 2019. Effect of Rhizobium and PGPR Inoculation in Mungbean on Productivity and Soil Properties in Mungbean-Wheat Sequence. Journal of the Indian Society of Soil Science (2019) 67 (4): 458-464. https://doi.org/10.5958/0974-0228.2019.00050.1.

Parihar, C.M., Yadav, M.R., Jat, S.L., Singh, A.K., Kumar, B., Pradhan, S., Chakraborty, D., Jat, M.L., Jat, R.K., Saharawat, Y.S., Yadav, O.P., 2016. Long term effect of conservation agriculture in maize rotations on total organic carbon, physical and biological properties of a sandy loam soil in north-western Indo-Gangetic Plains. Soil and Tillage Research 161, 116–128. https://doi.org/10.1016/j.still.2016.04.001.

Parihar, C.M., Singh, A.K., Jat, S.L., Dey, A., Nayak, H.S., Mandal, B.N., Saharawat, Y.S., Jat, M.L., Yadav, O.P., 2020. Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal-based system. Soil and Tillage Research 202, 104653. https://doi.org/10.1016/j.still.2020.104653.

Pascual, I., Antolín, M.C., García, C., Polo, A., Sánchez-Díaz, M., 2007. Effect of water deficit on microbial characteristics in soil amended with sewage sludge or inorganic fertilizer under laboratory conditions. Bioresource Technology 98, 29–37. https://doi.org/10.1016/j.biortech.2005.11.026.

Paz-Ferreiro, J., Trasar-Cepeda, C., Leirós, M.C., Seoane, S., Gil-Sotres, F., 2009. Biochemical properties in managed grassland soils in a temperate humid zone: Modifications of soil quality as a consequence of intensive grassland use. Biology and Fertility of Soils 45, 711–722. https://doi.org/10.1007/s00374-009-0382-y.

Peixoto, R.S., Chaer, G.M., Franco, N., Junior, F.B.R., Mendes, I.C., Rosado, A.S., 2010. A decade of land use contributes to changes in the chemistry, biochemistry and bacterial community structures of soils in the Cerrado. Antonie van Leeuwenhoek, International Journal of General and Molecular Microbiology 98, 403–413. https://doi.org/10.1007/s10482-010-9454-0.

Pérez Brandan C., Chavarría D., Huidobro Meriles J.M., Pérez Brandan C.,Vargas Gil S., 2017. Influence of a tropical grass (Brachiaria brizantha cv. Mulato) as cover crop on soil biochemical properties in a degraded agricultural soil. European Journal of Soil Biology, 83: 84–90. https://doi.org/10.1016/j.ejsobi.2017.10.009.

Peruccci P., Scarponi L., Businelli M., 1984. Enzyme activities in a clay-loam soil amended with various crop residues.. Plant and Soil 81, 345-351. https://doi.org/10.1007/BF02323049.

Perucci, P., Scarponi, L., 1985. Effect of different treatments with crop residues on soil phosphatase activity. Biology and Fertility of Soils 1, 111–115. https://doi.org/10.1007/BF00255138.

Perucci, P., Monaci, E., Onofri, A., Vischetti, C., Casucci, C., 2007. Changes in physico-chemical and biochemical parameters of soil following addition of wood ash: A field experiment. European Journal of Agronomy 28, 155–161. https://doi.org/10.1016/j.eja.2007.06.005.

Piotrowska, A., Iamarino, G., Rao, M.A., Gianfreda, L., 2006. Short-term effects of olive mill waste water (OMW) on chemical and biochemical properties of a semiarid Mediterranean soil. Soil Biology and Biochemistry 38, 600–610. https://doi.org/10.1016/j.soilbio.2005.06.012.

Pittarello, M., Ferro, N.D., Chiarini, F., Morari, F., Carletti, P., 2021. Influence of tillage and crop rotations in organic and conventional farming systems on soil organic matter, bulk density and enzymatic activities in a short-term field experiment. Agronomy 11. https://doi.org/10.3390/agronomy11040724.

Pokharel, P., Ma, Z., Chang, S.X., 2020. Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: a global meta-analysis. Biochar 2, 65–79. https://doi.org/10.1007/s42773-020-00039-1.

Pooniya, V., Zhiipao, R.R., Biswakarma, N., Kumar, D., Shivay, Y.S., Babu, S., Das, K., Choudhary, A.K., Swarnalakshmi, K., Jat, R.D., Choudhary, R.L., Ram, H., Khokhar, M.K., Mukri, G., Lakhena, K.K., Puniya, M.M., Jat, R., Muralikrishnan, L., Singh, A.K., Lama, A., 2022. Conservation agriculture based integrated crop management sustains productivity and economic profitability along with soil properties of the maize-wheat rotation. Scientific Reports 12, 1–13. https://doi.org/10.1038/s41598-022-05962-w.

Pozo, C., Salmeron, V., Rodelas, B., Martinez-Toledo, M.V., Gonzalez-Lopez, J., 1994. Effects of the herbicide alachlor on soil microbial activities. Ecotoxicology 3, 4–10. https://doi.org/10.1007/BF00121384.

Pozo, C., Salmeron, V., Rodelas, B., Martinez-Toledo, M.V., Gonzalez-Lopez, J., 1995. Effects of the fungicides maneb and mancozeb on soil enzyme activities. Toxicological & Environmental Chemistry 52, 243–248. https://doi.org/10.1080/02772249509358265.

Pramanik, P., Safique, S., Jahan, A., Bhagat, R.M., 2017. Humic substrates application in diluted form enhanced availability of phosphorus (P) and its uptake by tea bushes in the tea-growing soil of Northeast India. Journal of Plant Nutrition 40, 2841–2849. https://doi.org/10.1080/01904167.2017.1383420.

Prasanthi, G., Kumar, N.G., Raghu, S., Srinivasa, N., Gurumurthy, H., 2019. Study on the effect of different levels of organic and inorganic fertilizers on microbial enzymes and soil mesofauna in soybean ecosystem. Legume Research 42, 233–237. https://doi.org/10.18805/LR-3850.

Pupin, B., Freddi, O. da S., Nahas, E., 2009. Microbial alterations of the soil influenced by induced compaction. Revista Brasileira de Ciencia do Solo 33, 1207–1213. https://doi.org/10.1590/s0100-06832009000500014.

Qaswar, M., Jing, H., Ahmed, W., Dongchu, L., Shujun, L., Ali, S., Kailou, L., Yongmei, X., Lu, Z., Lisheng, L., Jusheng, G., Huimin, Z., 2019. Long-term green manure rotations improve soil biochemical properties, yield sustainability and nutrient balances in acidic paddy soil under a rice-based cropping system. Agronomy 9. https://doi.org/10.3390/agronomy9120780.

Qaswar, M., Chai, R., Ahmed, W., Jing, H., Han, T., Liu, K., Ye, X., Xu, Y., Anthonio, C.K., Zhang, H., 2020. Partial substitution of chemical fertilizers with organic amendments increased rice yield by changing phosphorus fractions and improving phosphatase activities in fluvo-aquic soil. Journal of Soils and Sediments 20, 1285–1296. https://doi.org/10.1007/s11368-019-02476-3.

Qin, X., Guo, S., Zhai, L., Pan, J., Khoshnevisan, B., Wu, S., Wang, H., Yang, B., Ji, J., Liu, H., 2020. How long-term excessive manure application affects soil phosphorous species and risk of phosphorous loss in fluvo-aquic soil. Environmental Pollution 266, 115304. https://doi.org/10.1016/j.envpol.2020.115304.

Rabary, B., Sall, S., Letourmy, P., Husson, O., Ralambofetra, E., Moussa, N., Chotte, J.L., 2008. Effects of living mulches or residue amendments on soil microbial properties in direct seeded cropping systems of Madagascar. Applied Soil Ecology 39, 236–243. https://doi.org/10.1016/j.apsoil.2007.12.012.

Racke, K.D., Steele, K.P., Yoder, R.N., Dick, W.A., Avidov, E., 1996. Factors Affecting the Hydrolytic Degradation of Chlorpyrifos in Soil. Journal of Agricultural and Food Chemistry 44, 1582–1592. https://doi.org/10.1021/jf9506141.

Radersma, S., and Grierson, P.F., 2004. Phosphorus mobilization in agroforestry: Organic anions, phosphatase activity and phosphorus fractions in the rhizosphere. Plant and Soil 259, 209–219. https://doi.org/10.1023/B:PLSO.0000020970.40167.40.

Radhakrishnan, A.R.S., Suja, G., Sreekumar, J., 2022. How sustainable is organic management in cassava? Evidences from yield, soil quality, energetics and economics in the humid tropics of South India. Scientia Horticulturae 293, 110723. https://doi.org/10.1016/j.scienta.2021.110723.

Raghurama, M., Sankaran, M., 2022. Invasive nitrogen-fixing plants increase nitrogen availability and cycling rates in a montane tropical grassland. PLANT ECOLOGY 223, 13–26. https://doi.org/10.1007/s11258-021-01188-4.

Raiesi, F., 2007. The conversion of overgrazed pastures to almond orchards and alfalfa cropping systems may favor microbial indicators of soil quality in Central Iran. Agriculture, Ecosystems and Environment 121, 309–318. https://doi.org/10.1016/j.agee.2006.11.002.

Rajashekhara R.B.K., and Siddaramappa R., 2008. Evaluation of soil quality parameters in a tropical paddy soil amended with rice residues and tree litters. European Journal of Soil Biology, 44 (3): 334-340. https://doi.org/10.1016/j.ejsobi.2008.04.002.

Rakshit, R., Patra, A.K., Purakayastha, T.J., Singh, R.D., Dhar, S., Pathak, H., Das, A., 2016. Effect of super-optimal levels of fertilizers on soil enzymatic activities during growth stages of wheat crop on an Inceptisol. Journal of Applied and Natural Science 8, 1398–1403. https://doi.org/10.31018/jans.v8i3.972.

Ram, R.A., Singha, A., Singh, V.K., 2019. Improvement in yield and fruit quality of mango (Mangifera indica) with organic amendments. Indian Journal of Agricultural Sciences 89, 1429–1433.

Ramanandan, L.G., Swaroop, N., David, A.A., Thomas, T., 2020. Effectiveness of Organics with Nitrogen Levels and Bio-fertilizers on Soil Chemico-biological Properties of Wheat (Triticum aestivum L.) Crop [Cv.PBW-343] in Inseptisol. Asian Journal of Soil Science and Plant Nutrition 6, 30–50. https://doi.org/10.9734/ajsspn/2020/v6i230084.

Ramdas, M.G., Manjunath, B.L., Pratap, S.N., Ramesh, R., Verma, R.R., Marutrao, L.A., Ruenna, D., Natasha, B., Rahul, K., 2017. Effect of organic and inorganic sources of nutrients on soil microbial activity and soil organic carbon build-up under rice in west coast of India. Archives of Agronomy and Soil Science 63, 414–426. https://doi.org/10.1080/03650340.2016.1213813.

Ramesh, P., Panwar, N.R., Singh, A.B., Ramana, S., Rao, A.S., 2009. Impact of organic-manure combinations on the productivity and soil quality in different cropping systems in central India. Journal of Plant Nutrition and Soil Science 172, 577–585. https://doi.org/10.1002/jpln.200700281.

Ramos, M.E., Benítez, E., García, P.A., Robles, A.B., 2010. Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: Effects on soil quality. Applied Soil Ecology 44, 6–14. https://doi.org/10.1016/j.apsoil.2009.08.005.

Ramos, M.E., Robles, A.B., Sánchez-Navarro, A., González-Rebollar, J.L., 2011. Soil responses to different management practices in rainfed orchards in semiarid environments. Soil and Tillage Research 112, 85–91. https://doi.org/10.1016/j.still.2010.11.007.

Randall, K.C., Brennan, F., Clipson, N., Creamer, R.E., Griffiths, B.S., Storey, S., Doyle, E., 2020. An Assessment of Climate Induced Increase in Soil Water Availability for Soil Bacterial Communities Exposed to Long-Term Differential Phosphorus Fertilization. Frontiers in Microbiology 11, 1–14. https://doi.org/10.3389/fmicb.2020.00682.

Rao, A.V., Tarafdar, J.C., Sharma, S.K., Kumar, P., Aggarwal, R.K., 1995. Influence of cropping systems on soil biochemical properties in an arid rain-fed environment. Journal of Arid Environments 31, 237–244. https://doi.org/10.1006/jare.1995.0063.

Rao, A.V., Singh, K.C., Gupta, J.P., 1997. Ley farming—an alternate farming system for sustainability in the indian arid zone. Arid Soil Research and Rehabilitation 11, 201–210. https://doi.org/10.1080/15324989709381472.

Rasool, N., Reshi, Z.A., Shah, M.A., 2014. Effect of butachlor (G) on soil enzyme activity. European Journal of Soil Biology 61, 94–100. https://doi.org/10.1016/j.ejsobi.2014.02.002.

Reardon, C.L., Wuest, S.B., 2016. Soil amendments yield persisting effects on the microbial communities-a 7-year study. Applied Soil Ecology 101, 107–116. https://doi.org/10.1016/j.apsoil.2015.12.013.

Recena, R., Torrent, J., Campillo, M.C. del, Delgado, A., 2015. Accuracy of Olsen P to assess plant P uptake in relation to soil properties and P forms. Agronomy for Sustainable Development 35, 1571–1579. https://doi.org/10.1007/s13593-015-0332-z.

Redel, Y.D., Rubio, R., Rouanet, J.L., Borie, F., 2007. Phosphorus bioavailability affected by tillage and crop rotation on a Chilean volcanic derived Ultisol. Geoderma 139, 388–396. https://doi.org/10.1016/j.geoderma.2007.02.018.

Redel, Y.D., Escudey, M., Alvear, M., Conrad, J., Borie, F., 2011. Effects of tillage and crop rotation on chemical phosphorus forms and some related biological activities in a Chilean Ultisol. Soil Use and Management 27, 221–228. https://doi.org/10.1111/j.1475-2743.2011.00334.x.

Rezaei-Chiyaneh, E., Amirnia, R., Chiyaneh, S.F., Maggi, F., Barin, M., Razavi, B.S., 2021. Improvement of dragonhead (Dracocephalum moldavica L.) yield quality through a coupled intercropping system and vermicompost application along with maintenance of soil microbial activity. Land Degradation and Development 32, 2833–2848. https://doi.org/10.1002/ldr.3957.

Riah, W., Laval, K., Laroche-Ajzenberg, E., Mougin, C., Latour, X., Trinsoutrot-Gattin, I., 2014. Effects of pesticides on soil enzymes: A review. Environmental Chemistry Letters 12, 257–273. https://doi.org/10.1007/s10311-014-0458-2.

Rietz, D.N., and Haynes, R.J., 2003. Effects of irrigation-induced salinity and sodicity on soil microbial activity. Soil Biology and Biochemistry 35, 845–854. https://doi.org/10.1016/S0038-0717(03)00125-1.

Roldán, A., Salinas-García, J.R., Alguacil, M.M., Caravaca, F., 2007. Soil sustainability indicators following conservation tillage practices under subtropical maize and bean crops. Soil and Tillage Research 93, 273–282. https://doi.org/10.1016/j.still.2006.05.001.

Romanya J., Blanco-Moreno J. M., Sans F. X., 2017. Phosphorus mobilization in low-P arable soils may involve soil organic C depletion. Soil Biology & Biochemistry 113: 250e259. http://dx.doi.org/10.1016/j.soilbio.2017.06.015.

Romero-Trigueros, C., Díaz-López, M., Vivaldi, G.A., Camposeo, S., Nicolás, E., Bastida, F., 2021. Plant and soil microbial community responses to different water management strategies in an almond crop. Science of the Total Environment 778. https://doi.org/10.1016/j.scitotenv.2021.146148.

Romero, E., Benítez, E., Nogales, R., 2005. Suitability of wastes from olive-oil industry for initial reclamation of a Pb/Zn mine tailing. Water, Air, and Soil Pollution 165, 153–165. https://doi.org/10.1007/s11270-005-4638-3.

Roohi, M., Arif, M.S., Yasmeen, T., Riaz, M., Rizwan, M., Shahzad, S.M., Ali, S., Bragazza, L., 2020. Effects of cropping system and fertilization regime on soil phosphorous are mediated by rhizosphere-microbial processes in a semi-arid agroecosystem. Journal of Environmental Management 271, 111033. https://doi.org/10.1016/j.jenvman.2020.111033.

Ros, M., García, C., Hernandez, M.T., 2007. Evaluation of different pig slurry composts as fertilizer of horticultural crops: Effects on selected chemical and microbial properties. Renewable Agriculture and Food Systems 22, 307–315. https://doi.org/10.1017/S1742170507001913.

Ros, M., Garcia, C., Hernandez, M.T., Lacasa, A., Fernandez, P., Pascual, J.A., 2008. Effects of biosolarization as methyl bromide alternative for Meloidogyne incognita control on quality of soil under pepper. Biology and Fertility of Soils 45, 37–44. https://doi.org/10.1007/s00374-008-0307-1.

Rouydel, Z., Barin, M., Rasouli-Sadaghiani, M.H., Khezri, M., Vetukuri, R.R., Kushwaha, S., 2021. Harnessing the potential of symbiotic endophytic fungi and plant growth-promoting rhizobacteria to enhance soil quality in saline soils. Processes 9. https://doi.org/10.3390/pr9101810.

Roy, T., Biswas, D.R.R., Ghosh, A., Patra, A.K.K., Singh, R.D.D., Sarkar, A., Biswas, S.S.S., 2019. Dynamics of culturable microbial fraction in an Inceptisol under short-term amendment with municipal sludge from different sources. Applied Soil Ecology 136, 116–121. https://doi.org/10.1016/j.apsoil.2018.12.024.

Ruiz, J.L., and Salas, M.D.C., 2019. Evaluation of organic substrates and microorganisms as bio-fertilisation tool in container crop production. Agronomy 9. https://doi.org/10.3390/agronomy9110705.

Saad, R.F., Kobaissi, A., Echevarria, G., Kidd, P., Calusinska, M., Goux, X., Benizri, E., 2018. Influence of new agromining cropping systems on soil bacterial diversity and the physico-chemical characteristics of an ultramafic soil. Science of the Total Environment 645, 380–392. https://doi.org/10.1016/j.scitotenv.2018.07.106.

Sadeghi, H., and Taban, A., 2021. Crushed maize seeds enhance soil biological activity and salt tolerance in caper (Capparis spinosa L.). Industrial Crops and Products 160, 113103. https://doi.org/10.1016/j.indcrop.2020.113103.

Saha, A., Bhaduri, D., Pipariya, A., Jain, N.K., 2016. Influence of imazethapyr and quizalofop-p-ethyl application on microbial biomass and enzymatic activity in peanut grown soil. Environmental Science and Pollution Research 23, 23758–23771. https://doi.org/10.1007/s11356-016-7553-9.

Saha, A., Basak, B.B., Gajbhiye, N.A., Kalariya, K.A., Manivel, P., 2019. Sustainable fertilization through co-application of biochar and chemical fertilizers improves yield, quality of Andrographis paniculata and soil health. Industrial Crops and Products 140, 111607. https://doi.org/10.1016/j.indcrop.2019.111607.

Saha, S., Mina, B.L., Gopinath, K.A., Kundu, S., Gupta, H.S., 2008a. Relative changes in phosphatase activities as influenced by source and application rate of organic composts in field crops. Bioresource Technology 99, 1750–1757. https://doi.org/10.1016/j.biortech.2007.03.049.

Saha, S., Mina, B.L., Gopinath, K.A., Kundu, S., Gupta, H.S., 2008b. Organic amendments affect biochemical properties of a subtemperate soil of the Indian Himalayas. Nutrient Cycling in Agroecosystems 80, 233–242. https://doi.org/10.1007/s10705-007-9139-x.

Salam, A., Bashir, S., Khan, I., Hussain, Q., Gao, R., Hu, H., 2019. Biochar induced Pb and Cu immobilization, phytoavailability attenuation in Chinese cabbage, and improved biochemical properties in naturally co-contaminated soil. Journal of Soils and Sediments 19, 2381–2392. https://doi.org/10.1007/s11368-019-02250-5.

Sales, F.R., Silva, A.O., Sales, L.R., Rodrigues, T.L., Moreira, F.M. de S., Carneiro, M.A.C., 2021. Native Arbuscular Mycorrhizal Fungi Exhibit Biotechnological Potential in Improvement of Soil Biochemical Quality and in Increasing Yield in Sugarcane Cultivars. Sugar Tech 23, 1235–1246. https://doi.org/10.1007/s12355-021-01016-z.

Sánchez-Peinado, M. del M., Rodelas, B., Martínez-Toledo, M.V., González-López, J., Pozo, C., 2009. Response of soil enzymes to Linear Alkylbenzene Sulfonate (LAS) addition in soil microcosms. Soil Biology and Biochemistry 41, 69–76. https://doi.org/10.1016/j.soilbio.2008.09.019.

Sangma, C.B.K., Thakuria, D., Biam, D.E.D., 2016. Rice ecosystems in hill agriculture: Effect on soil biological pools of carbon, nitrogen and phosphorus. Journal of the Indian Society of Soil Science 64, 391–401. https://doi.org/10.5958/0974-0228.2016.00051.7.

Santos, E.S., Abreu, M.M., Macías, F., de Varennes, A., 2016. Chemical quality of leachates and enzymatic activities in Technosols with gossan and sulfide wastes from the São Domingos mine. Journal of Soils and Sediments, 16, 1366–1382. https://doi.org/10.1007/s11368-015-1068-8.

Šarapatka, B., Dudová, L., Kršková, M., 2004. Effect of pH and phosphate supply on acid phosphatase activity in cereal roots. Biologia - Section Botany 59, 127–131.

Sarkar, B., Patra, A.K., Purakayastha, T.J., Megharaj, M., 2009. Assessment of biological and biochemical indicators in soil under transgenic Bt and non-Bt cotton crop in a sub-tropical environment. Environmental Monitoring and Assessment 156, 595–604. https://doi.org/10.1007/s10661-008-0508-y.

Sarkar, I.U.I.U.I.U., Jahan, A., Naher, U.A.U.A., Iqbal, M., Mamun, A.A., Biswas, J.C.J.C.J.C., Islam, R., 2020. Organic and inorganic amendment of wetland paddy soil for five years: effects on phosphorus fraction dynamics. Journal of Crop Improvement 34, 875–896. https://doi.org/10.1080/15427528.2020.1784343.

Sarma, B., and Gogoi, N., 2017. Nitrogen Management for Sustainable Soil Organic Carbon Increase in Inceptisols Under Wheat Cultivation. Communications in Soil Science and Plant Analysis 48, 1428–1437. https://doi.org/10.1080/00103624.2017.1373785.

Savin, M.C., Purcell, L.C., Daigh, A., Manfredini, A., 2009. Response of mycorrhizal infection to glyphosate applications and P fertilization in glyphosate-tolerant soybean, Maize, and Cotton. Journal of Plant Nutrition 32, 1702–1717. https://doi.org/10.1080/01904160903150941.

Saviozzi, A., Levi-Minzi, R., Cardelli, R., Riffaldi, R., 2001. A comparison of soil quality in adjacent cultivated, forest and native grassland soils. Plant and Soil 233, 251–259. https://doi.org/10.1023/A:1010526209076.

Schaller, K., 2003. Green manuring as a tool to improve physical and chemical soil properties, prevent erosion as well as conserving essential plant nutrients. Bulletinul USAMV-CN 59:188–93.

Schoebitz, M., López, M.D., Serri, H., Aravena, V., Zagal, E., Roldán, A., 2019. Characterization of Bioactive Compounds in Blueberry and Their Impact on Soil Properties in Response to Plant Biostimulants. Communications in Soil Science and Plant Analysis 50, 2482–2494. https://doi.org/10.1080/00103624.2019.1667374.

Schoebitz, M., Castillo, D., Jorquera, M., Roldan, A., 2020. Responses of microbiological soil properties to intercropping at different planting densities in an acidic Andisol. Agronomy 10. https://doi.org/10.3390/agronomy10060781.

Sciubba, L., Mazzon, M., Cavani, L., Baldi, E., Toselli, M., Ciavatta, C., Marzadori, C., 2021. Soil response to agricultural land abandonment: A case study of a vineyard in Northern Italy. Agronomy 11. https://doi.org/10.3390/agronomy11091841.

Senwo, Z.N., Ranatunga, T.D., Tazisong, I.A., Taylor, R.W., He, Z., 2007. Phosphatase activity of Ultisols and relationship to soil fertility indices. Journal of Food, Agriculture and Environment 5, 262–266.

Sepat, S., Behera, U.K., Sharma, A.R., Das, T.K., Bhattacharyya, R., 2014. Productivity, organic carbon and residual soil fertility of Pigeonpea-wheat cropping system under varying tillage and residue management. Proceedings of the National Academy of Sciences India Section B - Biological Sciences 84, 561–571. https://doi.org/10.1007/s40011-014-0359-y.

Serafim, M.E., Zeviani, W.M., Ono, F.B., Neves, L.G., Silva, B.M., Lal, R., 2019. Reference values and soil quality in areas of high soybean yield in Cerrado region, Brazil. Soil and Tillage Research 195. https://doi.org/10.1016/j.still.2019.104362.

Serrano, A., Tejada, M., Gallego, M., Gonzalez, J.L., 2009. Evaluation of soil biological activity after a diesel fuel spill. Science of the Total Environment 407, 4056–4061. https://doi.org/10.1016/j.scitotenv.2009.03.017.

Serri D.L., Boccolini M., Oberto R., Chavarría D., Bustos N., Vettorello C., Apezteguía H., Miranda J., Alvarez C., Galarza C., Chiófalo S., Manrique M., Sueldo R., Fernández Belmonte M.C., Mattalia L., Cholaky C., Vargas Gil S., 2018. Efecto de la agriculturación sobre la calidad biológica del suelo. Ciencia del Suelo (Argentina),36(2): 92-104. https://dialnet.unirioja.es/servlet/articulo?codigo=6978782.

Shahane, A.A., Shivay, Y.S., Prasanna, R., 2020. Enhancing phosphorus and iron nutrition of wheat through crop establishment techniques and microbial inoculations in conjunction with fertilization. Soil Science and Plant Nutrition 66, 763–771. https://doi.org/10.1080/00380768.2020.1799692.

Shao, X. hua, Zheng, J. wei, 2014. Soil organic carbon, black carbon, and enzyme activity under long-term fertilization. Journal of Integrative Agriculture 13, 517–524. https://doi.org/10.1016/S2095-3119(13)60707-8.

Sharma, R.C., Sarkar, S., Das, D., Banik, P., 2013a. Impact Assessment of Arbuscular Mycorrhiza Azospirillum and Chemical Fertilizer Application on Soil Health and Ecology. Communications in Soil Science and Plant Analysis 44, 1116–1126. https://doi.org/10.1080/00103624.2012.750335.

Sharma, P., Singh, G., Singh, R.P., 2013b. Conservation tillage and optimal water supply enhance microbial enzyme (glucosidase, urease and phosphatase) activities in fields under wheat cultivation during various nitrogen management practices. Archives of Agronomy and Soil Science 59, 911–928. https://doi.org/10.1080/03650340.2012.690143.

Sharma, S., Thind, H.S., Singh, Y., Singh, V., Singh, B., 2015. Soil enzyme activities with biomass ashes and phosphorus fertilization to rice–wheat cropping system in the Indo-Gangetic plains of India. Nutrient Cycling in Agroecosystems 101, 391–400. https://doi.org/10.1007/s10705-015-9684-7.

Sharma, S., Dhaliwal, S.S., 2019a. Effect of Sewage Sludge and Rice Straw Compost on Yield, Micronutrient Availability and Soil Quality under Rice–Wheat System. Communications in Soil Science and Plant Analysis 50, 1943–1954. https://doi.org/10.1080/00103624.2019.1648489.

Sharma, S., Vashisht, M., Singh, Y., Thind, H.S., 2019b. Soil carbon pools and enzyme activities in aggregate size fractions after seven years of conservation agriculture in a rice-wheat system. Crop and Pasture Science 70, 473–485. https://doi.org/10.1071/CP19013.

Sharpley, A.N., Robinson, J.S., Smith, S.J., 1995. Bioavailable phosphorus dynamics in agricultural soils and effects on water quality. Geoderma 67, 1–15. https://doi.org/10.1016/0016-7061(94)00027-8.

Shi, Y., Lalande, R., Ziadi, N., Sheng, M., Hu, Z., 2012. An assessment of the soil microbial status after 17 years of tillage and mineral P fertilization management. Applied Soil Ecology 62, 14–23. https://doi.org/10.1016/j.apsoil.2012.07.004.

Shi, X.M., Li, X.G., Li, C.T., Zhao, Y., Shang, Z.H., Ma, Q., 2013. Grazing exclusion decreases soil organic C storage at an alpine grassland of the Qinghai-Tibetan Plateau. Ecological Engineering 57, 183–187. https://doi.org/10.1016/j.ecoleng.2013.04.032.

Shi, L., Guo, Z., Liang, F., Xiao, X., Peng, C., Zeng, P., Feng, W., Ran, H., 2019a. Effect of liming with various water regimes on both immobilization of cadmium and improvement of bacterial communities in contaminated paddy: A field experiment. International Journal of Environmental Research and Public Health 16. https://doi.org/10.3390/ijerph16030498.

Shi, S., Tian, L., Nasir, F., Bahadur, A., Batool, A., Luo, S., Yang, F., Wang, Z., Tian, C., 2019b. Response of microbial communities and enzyme activities to amendments in saline-alkaline soils. Applied Soil Ecology 135, 16–24. https://doi.org/10.1016/j.apsoil.2018.11.003.

Shi, Y., Ziadi, N., Hamel, C., Bélanger, G., Abdi, D., Lajeunesse, J., Lafond, J., Lalande, R., Shang, J., 2020. Soil microbial biomass, activity and community structure as affected by mineral phosphorus fertilization in grasslands. Applied Soil Ecology 146, 103391. https://doi.org/10.1016/j.apsoil.2019.103391.

Shi, J., Gong, J., Baoyin, T., Luo, Q., Zhai, Z., Zhu, C., Yang, B., Wang, B., Zhang, Z., Li, X., 2021. Short-term phosphorus addition increases soil respiration by promoting gross ecosystem production and litter decomposition in a typical temperate grassland in northern China. CATENA 197, 104952. https://doi.org/10.1016/j.catena.2020.104952.

Siddaramappa, R., Wright, R.J., Codling, E.E., Gao, G., McCarty, G.W., 1994. Evaluation of coal combustion byproducts as soil liming materials: their influence on soil pH and enzyme activities. Biology and Fertility of Soils 17, 167–172. https://doi.org/10.1007/BF00336317.

Siebielec, G., Siebielec, S., Lipski, D., 2018. Long-term impact of sewage sludge, digestate and mineral fertilizers on plant yield and soil biological activity. Journal of Cleaner Production 187, 372–379. https://doi.org/10.1016/j.jclepro.2018.03.245.

Sigua, G.C., Stone, K.C., Bauer, P.J., Szogi, A.A., 2017. Phosphorus dynamics and phosphatase activity of soils under corn production with supplemental irrigation in humid coastal plain region, USA. Nutrient Cycling in Agroecosystems 109, 249–267. https://doi.org/10.1007/s10705-017-9882-6.

Silva, A.S. da, Filho, A.C., Nakatani, A.S., Alves, S.J., Andrade, D.S. de, Guimarães, M. de F., 2015. Atributos microbiológicos do solo em sistema de integração. Revista Brasileira de Ciencia do Solo 39, 40–48. https://doi.org/10.1590/01000683rbcs20150185.

Silvestro, L.B., Biganzoli, F., Forjan, H., Albanesi, A., Arambarri, A.M., Manso, L., Moreno, M.V., 2017. Mollisol: Biological characterization under zero tillage with different crops sequences. Journal of Agricultural Science and Technology 19, 245–257.

Simanca Fontalvo R. M., and Cuervo Andrade J. L., 2018. Effect of organic amendments and sulfur on chemical and biological properties of a sodic soil Efeito de corretivos orgânicos e enxofre nas propriedades químicas e biológicas de um solo sódico. Spanish journal of soil science (SJSS) (2018) 8 (3): 347-362. https://doi.org/10.3232/SJSS.2018.V8.N3.04.

Singh, N., 2005. Factors affecting triadimefon degradation in soils. Journal of Agricultural and Food Chemistry 53, 70–75. https://doi.org/10.1021/jf048884j.

Singh, A., and Ghoshal, N., 2013. Impact of herbicide and various soil amendments on soil enzymes activities in a tropical rainfed agroecosystem. European Journal of Soil Biology 54, 56–62. https://doi.org/10.1016/j.ejsobi.2012.10.003.

Singh, K., Pandey, V.C., Singh, B., Singh, R.R., 2012. Ecological restoration of degraded sodic lands through afforestation and cropping. Ecological Engineering 43, 70–80. https://doi.org/10.1016/j.ecoleng.2012.02.029.

Singh, K., Singh, B., Singh, R.R., 2012. Changes in physico-chemical, microbial and enzymatic activities during restoration of degraded sodic land: Ecological suitability of mixed forest over monoculture plantation. Catena 96, 57–67. https://doi.org/10.1016/j.catena.2012.04.007.

Singh, S.R., Kundu, D.K., Tripathi, M.K., Dey, P., Saha, A.R., Kumar, M., Singh, I., Mahapatra, B.S., 2015. Impact of balanced fertilization on nutrient acquisition, fibre yield of jute and soil quality in New Gangetic alluvial soils of India. Applied Soil Ecology 92, 24–34. https://doi.org/10.1016/j.apsoil.2015.03.007.

Singh, G., Bhattacharyya, R., Das, T.K., Sharma, A.R., Ghosh, A., Das, S., Jha, P., 2018a. Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo-Gangetic Plains. Soil and Tillage Research 184, 291–300. https://doi.org/10.1016/j.still.2018.08.006.

Singh, S.R., Kundu, D.K., Dey, P., Singh, P., Mahapatra, B.S., 2018b. Effect of balanced fertilizers on soil quality and lentil yield in Gangetic alluvial soils of India. Journal of Agricultural Science 156, 225–240. https://doi.org/10.1017/S0021859618000254.

Singh, C., Rakshit, R., Das, A., Bharti, P., 2020. Interpretations of Elemental and Microbial Phosphorus Indicators to Understand P Availability in Soils Under Rice–Wheat Cropping System. Agricultural Research 9, 329–339. https://doi.org/10.1007/s40003-019-00439-1.

Singh, S., and Sharma, S., 2020. Temporal changes in rhizosphere biological soil quality indicators of wheat in response to nitrogen and straw incorporation. Tropical Ecology 61, 328–344. https://doi.org/10.1007/s42965-020-00092-8.

Singh, S.R., Yadav, P., Singh, D., Bahadur, L., Singh, S.P., Yadav, A.S., Mishra, A., Yadav, P.P.S., Kumar, S., 2021. Impact of different cropping systems on the land nutrient index, microbial diversity, and soil quality. Land Degradation and Development 32, 3973–3991. https://doi.org/10.1002/ldr.3863.

Singh, G., Bhattacharyya, R., Dhaked, B.S., Das, T.K., 2022. Soil aggregation, glomalin and enzyme activities under conservation tilled rice-wheat system in the Indo-Gangetic Plains. Soil and Tillage Research 217, 105272. https://doi.org/10.1016/j.still.2021.105272.

Siwik-Ziomek, A., Lemanowicz, J., 2014. The content of carbon, nitrogen, phosphorus and sulphur in soil against the activity of selected hydrolases as affected by crop rotation and fertilisation. Zemdirbyste 101, 367–372. https://doi.org/10.13080/z-a.2014.101.046.

Sofo, A., Scopa, A., Dumontet, S., Mazzatura, A., Pasquale, V., 2012. Toxic effects of four sulphonylureas herbicides on soil microbial biomass. Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes 47, 653–659. https://doi.org/10.1080/03601234.2012.669205.

Soni, P.G., Basak, N., Rai, A.K., Sundha, P., Narjary, B., Kumar, P., Yadav, G., Kumar, S., Yadav, R.K., 2021. Deficit saline water irrigation under reduced tillage and residue mulch improves soil health in sorghum-wheat cropping system in semi-arid region. Scientific Reports 11, 1–13. https://doi.org/10.1038/s41598-020-80364-4.

Soon, Y.K., Rice, W.A., Arshad, M.A., Mills, P., 2000. Effect of pipeline installation on crop yield and some biological properties of boreal soils. Canadian Journal of Soil Science 80, 483–488. https://doi.org/10.4141/S99-096.

Stegarescu, G., Reintam, E., Tõnutare, T., 2021. Cover crop residues effect on soil structural stability and phosphatase activity. Acta Agriculturae Scandinavica Section B: Soil and Plant Science 71, 992–1005. https://doi.org/10.1080/09064710.2021.1973083.

Stege, P.W., Messina, G.A., Bianchi, G., Olsina, R.A., Raba, J., 2009. Determination of arylsulphatase and phosphatase enzyme activities in soil using screen-printed electrodes modified with multi-walled carbon nanotubes. Soil Biology and Biochemistry 41, 2444–2452. https://doi.org/10.1016/j.soilbio.2009.08.024.

Stehouwer, R.C., Dick, W.A., Traina, S.J., 1993. Characteristics of earthworm burrow lining affecting atrazine sorption. Journal of Environmental Quality 22, 181–185. https://doi.org/10.2134/jeq1993.00472425002200010024x.

Stenberg, B., Pell, M., Torstensson, L., 1998. Integrated evaluation of variation in biological, chemical and physical soil properties. Ambio 27, 9–15.

Stoven, K., and Schnug, E., 2009. Long term effects of heavy metal enriched sewage sludge disposal in agriculture on soil biota. Landbauforschung Volkenrode 59, 131–138.

Sudhakaran, M., Ramamoorthy, D., Savitha, V., Kirubakaran, N., 2019. Soil Enzyme Activities and Their Relationship with Soil Physico-Chemical Properties and Oxide Minerals in Coastal Agroecosystem of Puducherry. Geomicrobiology Journal 36, 452–459. https://doi.org/10.1080/01490451.2019.1570396.

Sun, J., Zou, L., Li, W., Yang, J., Wang, Y., Xia, Q., Peng, M., 2018. Rhizosphere soil properties and banana Fusarium wilt suppression influenced by combined chemical and organic fertilizations. Agriculture, Ecosystems and Environment 254, 60–68. https://doi.org/10.1016/j.agee.2017.10.010.

Sun, B., Gao, Y., Wu, X., Ma, H., Zheng, C., Wang, X., Zhang, H., Li, Z., Yang, H., 2019. The relative contributions of pH, organic anions, and phosphatase to rhizosphere soil phosphorus mobilization and crop phosphorus uptake in maize/alfalfa polyculture. Plant and Soil 447, 117–133. https://doi.org/10.1007/s11104-019-04110-0.

Sun, Y., Goll, D.S., Ciais, P., Peng, S., Margalef, O., Asensio, D., Sardans, J., Peñuelas, J., 2020. Spatial Pattern and Environmental Drivers of Acid Phosphatase Activity in Europe. Frontiers in Big Data 2, 1–13. https://doi.org/10.3389/fdata.2019.00051.

Svensson, K., Pell, M., 2001. Soil microbial tests for discriminating between different cropping systems and fertiliser regimes. Biology and Fertility of Soils 33, 91–99. https://doi.org/10.1007/s003740000292.

Swedrzyńska, D., Małecka, I., Blecharczyk, A., Swedrzyński, A., Starzyk, J., 2013. Effects of various long-term tillage systems on some chemical and biological properties of soil. Polish Journal of Environmental Studies 22, 1835–1844.

Takeda, M., Nakamoto, T., Miyazawa, K., Murayama, T., Okada, H., 2009. Phosphorus availability and soil biological activity in an Andosol under compost application and winter cover cropping. Applied Soil Ecology 42, 86–95. https://doi.org/10.1016/j.apsoil.2009.02.003.

Tamilselvi, S.M., Chinnadurai, C., Ilamurugu, K., Arulmozhiselvan, K., Balachandar, D., 2015. Effect of long-term nutrient managements on biological and biochemical properties of semi-arid tropical alfisol during maize crop development stages. Ecological Indicators 48, 76–87. https://doi.org/10.1016/j.ecolind.2014.08.001.

Tan, J.L., Kang Y.H., 2009. Changes in Soil Properties Under the Influences of Cropping and Drip Irrigation During the Reclamation of Severe Salt-Affected Soils. Agricultural Sciences in China 8(10):1228–37. https://doi.org/10.1016/S1671-2927(08)60333-8.

Tan, X., Xie, B., Wang, J., He, W., Wang, X., Wei, G., 2014. County-scale spatial distribution of soil enzyme activities and enzyme activity indices in agricultural land: Implications for soil quality assessment. Scientific World Journal 2014. https://doi.org/10.1155/2014/535768.

Tao, J., Griffiths, B., Zhang, S., Chen, X., Liu, M., Hu, F., Li, H., 2009. Effects of earthworms on soil enzyme activity in an organic residue amended rice-wheat rotation agro-ecosystem. Applied Soil Ecology 42, 221–226. https://doi.org/10.1016/j.apsoil.2009.04.003.

Tarafdar, J.C., and Claassen, N., 1988. Organic phosphorus compounds as a phosphorus source for higher plants through the activity of phosphatases produced by plant roots and microorganisms. Biology and Fertility of Soils 5, 308–312. https://doi.org/10.1007/BF00262137.

Tarafdar, J.C., Kiran, B., Rao, A.V., 1989. Phosphatase activity and distribution of phosphorus in arid soil profiles under different land use patterns. Journal of Arid Environments 16, 29–34. https://doi.org/10.1016/s0140-1963(18)31044-9.

Tarafdar, J.C., and Rao, A.V., 1996. Contribution of Aspergillus strains to acquisition of phosphorus by wheat (Triticum aestivum L.) and chick pea (Cicer arietinum Linn.) grown in a loamy sand soil. Applied Soil Ecology 3, 109–114. https://doi.org/10.1016/0929-1393(95)00084-4.

Tarafdar, J.C., and Gharu, A., 2006. Mobilization of organic and poorly soluble phosphates by Chaetomium globosum. Applied Soil Ecology 32, 273–283. https://doi.org/10.1016/j.apsoil.2005.08.005.

Tavali, I.E., Orman, S., Ozgur, A., Uz, I., Sulaman, S., 2021. Monitoring the changes in the microbial dynamics of calcareous soil with the amendment of stabilized and dried sewage sludge in mediterranean region of turkey. Polish Journal of Environmental Studies 30, 5263–5271. https://doi.org/10.15244/pjoes/135613.

Taylor, J.P., Wilson, B., Mills, M.S., Burns, R.G., 2002. Comparison of microbial numbers and enzymatic activities in surface soils and subsoils using various techniques. Soil Biology and Biochemistry 34, 387–401. https://doi.org/10.1016/S0038-0717(01)00199-7.

Tejada, M., Garcia, C., Gonzalez, J.L., Hernandez, M.T., 2006. Organic Amendment Based on Fresh and Composted Beet Vinasse. Soil Science Society of America Journal 70, 900–908. https://doi.org/10.2136/sssaj2005.0271.

Tejada, M., and Gonzalez, J.L., 2007. Application of different organic wastes on soil properties and wheat yield. Agronomy Journal 99, 1597–1606. https://doi.org/10.2134/agronj2007.0019.

Tejada, M., Moreno, J.L., Hernandez, M.T., Garcia, C., 2007. Application of two beet vinasse forms in soil restoration: Effects on soil properties in an arid environment in southern Spain. Agriculture, Ecosystems and Environment 119, 289–298. https://doi.org/10.1016/j.agee.2006.07.019.

Tejada, M., and González, J.L., 2009. Application of two vermicomposts on a rice crop: Effects on soil biological properties and rice quality and yield. Agronomy Journal 101, 336–344. https://doi.org/10.2134/agronj2008.0211.

Tejada, M., Hernandez, M.T., Garcia, C., 2009. Soil restoration using composted plant residues: Effects on soil properties. Soil and Tillage Research 102, 109–117. https://doi.org/10.1016/j.still.2008.08.004.

Tejada, M., and Benítez, C., 2011. Organic amendment based on vermicompost and compost: Differences on soil properties and maize yield. Waste Management and Research 29, 1185–1196. https://doi.org/10.1177/0734242X10383622.

Tejada, M., Morillo, E., Gómez, I., Madrid, F., Undabeytia, T., 2017. Effect of controlled release formulations of diuron and alachlor herbicides on the biochemical activity of agricultural soils. Journal of Hazardous Materials 322, 334–347. https://doi.org/10.1016/j.jhazmat.2016.10.002.

Teng, W., Deng, Y., Chen, X.-P., Xu, X.-F., Chen, R.-Y., Lv, Y., Zhao, Y.-Y., Zhao, X.-Q., He, X., Li, B., Zhang, F.-S., Li, Z.-S., 2013. Characterization of root response to phosphorus supply from morphology to gene analysis in field-grown wheat. Journal of Experimental Botany 64, 1403–1411. https://doi.org/10.1093/jxb/ert023.

Thapa, V.R., Ghimire, R., Acosta-Martínez, V., Marsalis, M.A., Schipanski, M.E., 2021. Cover crop biomass and species composition affect soil microbial community structure and enzyme activities in semiarid cropping systems. Applied Soil Ecology 157. https://doi.org/10.1016/j.apsoil.2020.103735.

Tiecher, T., Santos, D.R. dos, Calegari, A., 2012. Soil organic phosphorus forms under different soil management systems and winter crops, in a long term experiment. Soil and Tillage Research 124, 57–67. https://doi.org/10.1016/j.still.2012.05.001.

Tiecher, T., Tiecher, T.L., Mallmann, F.J.K., Zafar, M., Ceretta, C.A., Lourenzi, C.R., Brunetto, G., Gatiboni, L.C., Santos, D.R. dos, 2017. Chemical, biological, and biochemical parameters of the soil P cycle after Long-Term pig slurry application in No-Tillage system. Revista Brasileira de Ciencia do Solo 41, 1–16. https://doi.org/10.1590/18069657rbcs20170037.

Tomkiel, M., Baćmaga, M., Borowik, A., Wyszkowska, J., Kucharski, J., 2018. The sensitivity of soil enzymes, microorganisms and spring wheat to soil contamination with carfentrazone-ethyl. Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes 53, 97–107. https://doi.org/10.1080/03601234.2017.1387475.

Touhami, D., Condron, L.M., McDowell, R.W., 2021. Plant Species Rather than Elevated Atmospheric CO2 Impact Rhizosphere Properties and Phosphorus Fractions in a Phosphorus-Deficient Soil. Journal of Soil Science and Plant Nutrition 21, 622–636. https://doi.org/10.1007/s42729-020-00388-7.

Trabelsi, D., Cherni, A., Zineb, A.B., Dhane, S.F., Mhamdi, R., 2017. Fertilization of Phaseolus vulgaris with the Tunisian rock phosphate affects richness and structure of rhizosphere bacterial communities. Applied Soil Ecology 114, 1–8. https://doi.org/10.1016/j.apsoil.2016.11.014.

Tripathi, S., Chakraborty, A., Chakrabarti, K., Bandyopadhyay, B.K., 2007. Enzyme activities and microbial biomass in coastal soils of India. Soil Biology and Biochemistry 39, 2840–2848. https://doi.org/10.1016/j.soilbio.2007.05.027.

Trujillo-Narcía, A., Rivera-Cruz, M.C., Magaña-Aquino, M., Trujillo-Rivera, E.A., 2019. The Burning of Sugarcane Plantation in the Tropics Modifies the Microbial and Enzymatic Processes in Soil and Rhizosphere. Journal of Soil Science and Plant Nutrition 19, 906–919. https://doi.org/10.1007/s42729-019-00089-w.

Truu, M., Truu, J., Ivask, M., 2008. Soil microbiological and biochemical properties for assessing the effect of agricultural management practices in Estonian cultivated soils.

European Journal of Soil Biology 44, 231–237. https://doi.org/10.1016/j.ejsobi.2007.12.003.

Tu, C.M., 1995. Effect of five insecticides on microbial and enzymatic activities in sandy soil. Journal of Environmental Science and Health, Part B 30, 289–306. https://doi.org/10.1080/03601239509372940.

Turan, V., 2021. Calcite in combination with olive pulp biochar reduces Ni mobility in soil and its distribution in chili plant. International Journal of Phytoremediation 24, 166–176. https://doi.org/10.1080/15226514.2021.1929826.

Turner, B.L., and Haygarth, P.M., 2005. Phosphatase activity in temperate pasture soils: Potential regulation of labile organic phosphorus turnover by phosphodiesterase activity. Science of the Total Environment 344, 27–36. https://doi.org/10.1016/j.scitotenv.2005.02.003.

Tuti, M.D., Pal, R.S., Mahanta, D., Pandey, B.M., Bisht, J.K., 2020. Soil Chemical and Biological Activities under Vegetable Intensive Colocasia-based Cropping System in Indian Sub-Himalayas. Communications in Soil Science and Plant Analysis 51, 948–962. https://doi.org/10.1080/00103624.2020.1744623.

Ullah, Rehmat, Mehdi, S.M., Khan, K.S.U., Sheikh, A.A., Sulistyowati, E., Saud, M., 2018a. Mineralization of organic residues, dynamics of microbial biomass and enzyme activities in an Aridisol and Alfisol soil under rain-fed dry farming. Agritropica: Journal of Agricultural Sciences 1, 25–36. https://doi.org/10.31186/j.agritropica.1.1.25-36.

Ullah, R., Aslam, Z., Khaliq, A., Zahir, Z.A., 2018b. Sunflower residue incorporation suppresses weeds, enhances soil properties and seed yield of spring-planted mung bean. Planta Daninha 36, 1–14. https://doi.org/10.1590/S0100-83582018360100057.

Ullah, R., Aslam, Z., Maitah, M., Zaman, Q.U., Bashir, S., Hassan, W., Chen, Z., 2020. Sustainable weed control and enhancing nutrient use efficiency in crops through brassica (Brassica compestris l.) allelopathy. Sustainability (Switzerland) 12, 1–17. https://doi.org/10.3390/su12145763.

Valarini, P.J., Alvarez, M.C.D., Gascó, J.M., Guerrero, F., Tokeshi, H., 2003. Assessment of soil properties by organic matter and EM-microorganism incorporation. Revista Brasileira de Ciência do Solo 27, 519–525. https://doi.org/10.1590/s0100-06832003000300013.

Vanlalveni, C., and Lalfakzuala, R., 2018. Effect of seasonal variation on soil enzymes activity and fertility of soil in paddy fields of North Vanlaiphai, Mizoram, India. Science Vision 18, 70–73. https://doi.org/10.33493/scivis.18.02.04.

Vekemans, X., Godden, B., Penninckx, M.J., 1989. Factor analysis of the relationships between several physico-chemical and microbiological characteristics of some

Belgian agricultural soils. Soil Biology and Biochemistry 21, 53–58. https://doi.org/10.1016/0038-0717(89)90010-2.

Venkatesan, S., Senthurpandian, V.K., 2006. Comparison of enzyme activity with depth under tea plantations and forested sites in south India. Geoderma 137, 212–216. https://doi.org/10.1016/j.geoderma.2006.08.011.

Ventura, B.S., Meyer, E., Souza, M., Vieira, A.S., Scarsanella, J.D.A., Comin, J.J., Lovato, P.E., 2021. Soil phosphorus availability and uptake by mycorrhizal and non-mycorrhizal plants in an onion no-tillage system. Ciencia Rural 51. https://doi.org/10.1590/0103-8478cr20200839.

Verdenelli, R.A., Conforto, C.B., Pérez-Brandán, C., Chavarría, D., Rovea, A., Vargas-Gil, S., Meriles, J.M., 2013. Integrated multivariate analysis of selected soil microbial properties and their relationships with mineral fertilization management in a conservation agriculture system. Acta Agriculturae Scandinavica Section B: Soil and Plant Science 63, 623–632. https://doi.org/10.1080/09064710.2013.837193.

Verma, S.K., Pankaj, U., Khan, K., Singh, R., Verma, R.K., 2016a. Bioinoculants and Vermicompost Improve Ocimum basilicum Yield and Soil Health in a Sustainable Production System. Clean - Soil, Air, Water 44, 686–693. https://doi.org/10.1002/clen.201400639.

Verma, S., Adak, A., Prasanna, R., Dhar, S., Choudhary, H., Nain, L., Shivay, Y.S., 2016b. Microbial priming elicits improved plant growth promotion and nutrient uptake in pea. Israel Journal of Plant Sciences 63, 191–207. https://doi.org/10.1080/07929978.2016.1200352.

Verma, R.K., Shivay, Y.S., Prasanna, R., Choudhary, M., Ghasal, P.C., 2021. Nutrient management options modulating soil physico-chemical and biological properties under direct-seeded rice-based cropping systems. Archives of Agronomy and Soil Science 67, 1783–1798. https://doi.org/10.1080/03650340.2020.1808627.

Vinhal-Freitas, I.C., Correa, G.F., Wendling, B., Bobul'ska, L., Ferreira, A.S., 2017. Soil textural class plays a major role in evaluating the effects of land use on soil quality indicators. Ecological Indicators 74, 182–190. https://doi.org/10.1016/j.ecolind.2016.11.020.

Wakelin, S.A., Gupta, V.V.S.R., Harvey, P.R., Ryder, M.H., 2007. The effect of Penicillium fungi on plant growth and phosphorus mobilization in neutral to alkaline soils from southern Australia. Can. J. Microbiol. 53, 106–115. https://doi.org/10.1139/w06-109.

Waldrop, M.P., Balser, T.C., Firestone, M.K., 2000. Linking microbial community composition to function in a tropical soil. Soil Biology and Biochemistry 32, 1837–1846. https://doi.org/10.1016/S0038-0717(00)00157-7.

Wang, F.Y., Tong, R.J., Shi, Z.Y., Xu, X.F., He, X.H., 2011a. Inoculations with Arbuscular mycorrhizal fungi increase vegetable yields and decrease phoxim concentrations in carrot and green onion and their soils. PLoS ONE 6. https://doi.org/10.1371/journal.pone.0016949.

Wang, J.B., Chen, Z.H., Chen, L.J., Zhu, A.N., Wu, Z.J., 2011b. Surface soil phosphorus and phosphatase activities affected by tillage and crop residue input amounts. Plant, Soil and Environment 57, 251–257. https://doi.org/10.17221/437/2010-pse.

Wang, P., Zhang, J.J., Xia, R.X., Shu, B., Wang, M.Y., Wu, Q.S., Dong, T., 2011c. Arbuscular mycorrhiza, rhizospheric microbe populations and soil enzyme activities in citrus orchards under two types of no-tillage soil management. Spanish Journal of Agricultural Research 9, 1307–1318. https://doi.org/10.5424/sjar/20110904-307-10.

Wang, S., Liang, X., Chen, Y., Luo, Q., Liang, W., Li, S., Huang, C., Li, Z., Wan, L., Li, W., Li, W., Shao, X., 2012. Phosphorus loss potential and phosphatase activity under phosphorus fertilization in long-term paddy wetland agroecosystems. Soil Science Society of America Journal 76, 161–167. https://doi.org/10.2136/sssaj2011.0078.

Wang, F., Jiang, R., Kertesz, M.A., Zhang, F., Feng, G., 2013a. Arbuscular mycorrhizal fungal hyphae mediating acidification can promote phytate mineralization in the hyphosphere of maize (zea mays L.). Soil Biology and Biochemistry 65, 69–74. https://doi.org/10.1016/j.soilbio.2013.05.010.

Wang, L., Cai, K., Chen, Y., Wang, G., 2013b. Silicon-mediated tomato resistance against Ralstonia solanacearum is associated with modification of soil microbial community structure and activity. Biological Trace Element Research 152, 275–283. https://doi.org/10.1007/s12011-013-9611-1.

Wang, Y., Chi, S. yun, Ning, T. yuan, Tian, S. zhong, Li, Z. jia, 2013c. Coupling Effects of Irrigation and Phosphorus Fertilizer Applications on Phosphorus Uptake and Use Efficiency of Winter Wheat. Journal of Integrative Agriculture 12, 263–272. https://doi.org/10.1016/S2095-3119(13)60225-7.

Wang, M., Wu, C., Cheng, Z., Meng, H., Zhang, M., Zhang, H., 2014a. Soil chemical property changes in eggplant/garlic relay intercropping systems under continuous cropping. PLoS ONE 9. https://doi.org/10.1371/journal.pone.0111040.

Wang, Y.P., Li, X.G., Hai, L., Siddique, K.H.M., Gan, Y., Li, F.M., 2014b. Film fully-mulched ridge-furrow cropping affects soil biochemical properties and maize nutrient uptake in a rainfed semi-arid environment. Soil Science and Plant Nutrition 60, 486–498. https://doi.org/10.1080/00380768.2014.909709.

Wang, X., Deng, X., Pu, T., Song, C., Yong, T., Yang, F., Sun, X., Liu, W., Yan, Y., Du, J., Liu, J., Su, K., Yang, W., 2017. Contribution of interspecific interactions and phosphorus application to increasing soil phosphorus availability in relay intercropping systems. Field Crops Research 204, 12–22. https://doi.org/10.1016/j.fcr.2016.12.020.

Wang, F., Tang, J., Li, Z., Xiang, J., Wang, L., Tian, L., Jiang, L., Luo, Y., Hou, E., Shao, X., 2021a. Warming reduces the production of a major annual forage crop on the Tibetan Plateau. Science of the Total Environment 798, 149211. https://doi.org/10.1016/j.scitotenv.2021.149211.

Wang, Y., Huang, Q., Gao, H., Zhang, R., Yang, L., Guo, Y., Li, H., Awasthi, M.K., Li, G., 2021b. Long-term cover crops improved soil phosphorus availability in a rain-fed apple orchard. Chemosphere 275, 130093. https://doi.org/10.1016/j.chemosphere.2021.130093.

Wang, Y., Huang, C., Liu, M., Yuan, L., 2021c. Long-term application of manure reduced nutrient leaching under heavy N deposition. Nutrient Cycling in Agroecosystems 4. https://doi.org/10.1007/s10705-020-10107-4.

Wang, M., Wu, Y., Zhao, J., Liu, Y., Chen, Z., Tang, Z., Tian, W., Xi, Y., Zhang, J., 2022a. Long-term fertilization lowers the alkaline phosphatase activity by impacting the phoD-harboring bacterial community in rice-winter wheat rotation system. Science of the Total Environment 821. https://doi.org/10.1016/j.scitotenv.2022.153406.

Wang, W., Li, Y., Guan, P., Chang, L., Zhu, X., Zhang, P., Wu, D., 2022b. How do climate warming affect soil aggregate stability and aggregate-associated phosphorus storage under natural restoration? Geoderma 420, 115891. https://doi.org/10.1016/j.geoderma.2022.115891.

Wang, Y., Yang, X., Xu, M., Geissen, V., 2022c. Variations of soil phosphatase activity and phosphorus fractions in ginger fields exposed to different years of chloropicrin fumigation. Journal of Soils and Sediments 22, 1372–1384. https://doi.org/10.1007/s11368-022-03135-w.

Wei, M., Tan, F., Zhu, H., Cheng, K., Wu, X., Wang, J., Zhao, K., Tang, X., 2012. Impact of Bt-transgenic rice (SHK601) on soil ecosystems in the rhizosphere during crop development. Plant, Soil and Environment 58, 217–223.

Wei, K., Chen, Z., Zhu, A., Zhang, J., Chen, L., 2014a. Application of 31P NMR spectroscopy in determining phosphatase activities and P composition in soil aggregates influenced by tillage and residue management practices. Soil and Tillage Research 138, 35–43. https://doi.org/10.1016/j.still.2014.01.001.

Wei, K., Chen, Z.H., Zhang, X.P., Liang, W.J., Chen, L.J., 2014b. Tillage effects on phosphorus composition and phosphatase activities in soil aggregates. Geoderma 217–218, 37–44. https://doi.org/10.1016/j.geoderma.2013.11.002.

Wei, K., Bao, H., Huang, S., Chen, L., 2017. Effects of long-term fertilization on available P, P composition and phosphatase activities in soil from the Huang-Huai-Hai Plain of

China. Agriculture, Ecosystems and Environment 237, 134–142. https://doi.org/10.1016/j.agee.2016.12.030.

Wei, K., Chen, Z., Jiang, N., Zhang, Y., Feng, J., Tian, J., Chen, X., Lou, C., Chen, L., 2021. Effects of mineral phosphorus fertilizer reduction and maize straw incorporation on soil phosphorus availability, acid phosphatase activity, and maize grain yield in northeast China. Archives of Agronomy and Soil Science 67, 66–78. https://doi.org/10.1080/03650340.2020.1714031.

Wick, B.; Kühne, R. F.; Vlek, P. L. G., 1998. Soil microbiological parameters as indicators of soil quality under improved fallow management systems in south-western Nigeria. Plant and Soil, 202, 97-107. http://dx.doi.org/10.1023/A:1004305615397.

Wojewódzki, P., Lemanowicz, J., Debska, B., Haddad, S.A., 2022. Soil Enzyme Activity Response under the Amendment of Different Types of Biochar. Agronomy 12, 1–14. https://doi.org/10.3390/agronomy12030569.

Woźniak, A., and Kawecka-Radomska, M., 2016. Crop management effect on chemical and biological properties of soil. International Journal of Plant Production 10, 391–402.

Woźniak, A., 2019. Chemical properties and enzyme activity of soil as affected by tillage system and previous crop. Agriculture (Switzerland) 9. https://doi.org/10.3390/agriculture9120262.

Woźniak, M., Gałazką, A., Siebielec, G., Frąc, M., 2022. Can the Biological Activity of Abandoned Soils Be Changed by the Growth of Paulownia elongata × Paulownia fortune? Preliminary study on a young tree plantation. Agriculture (Switzerland) 12. https://doi.org/10.3390/agriculture12020128.

Wu, F., Wan, J., Wu, S., Wong, M., 2012. Effects of earthworms and plant growth-promoting rhizobacteria (PGPR) on availability of nitrogen, phosphorus, and potassium in soil. Journal of Plant Nutrition and Soil Science 175, 423–433. https://doi.org/10.1002/jpln.201100022.

Wyszkowska, J., Kucharski, J., Jastrzebska, E., Hłasko, A., 2001. The Biological Properties of Soil as Influenced by Chromium Contamination. Polish Journal of Environmental Studies 10, 37–42.

Wyszkowska, J., 2002. Effect of Soil Contamination with Treflan 480 EC on Biochemical Properties of Soil. Polish Journal of Environmental Studies 11, 71–77.

Wyszkowska, J., Kucharski, J., Waldowska, E., 2002. The influence of diesel oil contamination on soil microorganisms and oat growth. Rostlinna Vyroba 48, 51–57. https://doi.org/10.17221/4359-pse.

Wyszkowska J., Kucharski J., Boros E., 2005. Effect of nickel contamination on soil enzymatic activities. Plant, Soil and Environment: 51: 523-531. https://doi.org/10.17221/3627-PSE.

Wyszkowska, J., and Wyszkowski, M., 2010. Activity of soil dehydrogenases, urease, and acid and alkaline phosphatases in soil polluted with petroleum. Journal of Toxicology and Environmental Health - Part A: Current Issues 73, 1202–1210. https://doi.org/10.1080/15287394.2010.492004.

Wyszkowska, J., Borowik, A., Olszewski, J., Kucharski, J., 2019. Soil Bacterial Community and Soil Enzyme Activity. Diversity 11.

Xie, C., Tang, J., Zhao, J., Wu, D., Xu, X., 2011. Comparison of phosphorus fractions and alkaline phosphatase activity in sludge, soils, and sediments. Journal of Soils and Sediments 11, 1432–1439. https://doi.org/10.1007/s11368-011-0429-1.

Xomphoutheb, T., Jiao, S., Guo, X., Mabagala, F.S., Sui, B., Wang, H., Zhao, L., Zhao, X., 2020. The effect of tillage systems on phosphorus distribution and forms in rhizosphere and non-rhizosphere soil under maize (Zea mays L.) in Northeast China. Scientific Reports 10, 1–9. https://doi.org/10.1038/s41598-020-63567-7.

Xu, L., Yi, M., Yi, H., Guo, E., Zhang, A., 2018. Manure and mineral fertilization change enzyme activity and bacterial community in millet rhizosphere soils. World Journal of Microbiology and Biotechnology 34, 0. https://doi.org/10.1007/s11274-017-2394-3.

Xu, L., Han, Y., Yi, M., Yi, H., Guo, E., Zhang, A., 2019. Shift of millet rhizosphere bacterial community during the maturation of parent soil revealed by 16S rDNA high-throughput sequencing. Applied Soil Ecology 135, 157–165. https://doi.org/10.1016/j.apsoil.2018.12.004.

Yadav, B.K., Tarafdar, J.C., 2007. Ability of Emericella rugulosa to mobilize unavailable P compounds during Pearl millet [Pennisetum glaucum (L.) R. Br.] crop under arid condition. Indian Journal of Microbiology 47, 57–63. https://doi.org/10.1007/s12088-007-0011-0.

Yang, L., Bian, X., Yang, R., Zhou, C., Tang, B., 2018. Assessment of organic amendments for improving coastal saline soil. Land Degradation and Development 29, 3204–3211. https://doi.org/10.1002/ldr.3027.

Yang, X., Bao, X., Yang, Y., Zhao, Y., Liang, C., Xie, H., 2019. Comparison of soil phosphorus and phosphatase activity under long-term no-tillage and maize residue management. Plant, Soil and Environment 65, 408–415. https://doi.org/10.17221/307/2019-PSE.

Yao, T., Zhang, W., Gulaqa, A., Cui, Y., Zhou, Y., Weng, W., Wang, X., Liu, Q., Jin, F., 2021. Effects of Peanut Shell Biochar on Soil Nutrients, Soil Enzyme Activity, and Rice

Yield in Heavily Saline-Sodic Paddy Field. Journal of Soil Science and Plant Nutrition 21, 655–664. https://doi.org/10.1007/s42729-020-00390-z.

Yin, J., Sui, Z.-M., Huang, J.-G., 2021. Mobilization of soil inorganic phosphorus and stimulation of crop phosphorus uptake and growth induced by Ceriporia lacerata HG2011. Geoderma 383. https://doi.org/10.1016/j.geoderma.2020.114690.

Yoshioka I.C., Sánchez De Prager M., Bolaños B M.M., 2006. Actividad de fosfatasas ácida y alcalina en suelo cultivado con plátano en tres sistemas de manejo. Acta Agronómica (2006) 55:1-8. https://revistas.unal.edu.co/index.php/acta_agronomica/article/view/211.

Yu, S., He, Z.L., Stoffella, P.J., Calvert, D.V., Yang, X.E., Banks, D.J., Baligar, V.C., 2006. Surface runoff phosphorus (P) loss in relation to phosphatase activity and soil P fractions in Florida sandy soils under citrus production. Soil Biology and Biochemistry 38, 619–628. https://doi.org/10.1016/j.soilbio.2005.02.040.

Yu, H., Wang, F., Shao, M., Huang, L., Xie, Y., Xu, Y., Kong, L., 2021. Effects of Rotations With Legume on Soil Functional Microbial Communities Involved in Phosphorus Transformation. Frontiers in Microbiology 12. https://doi.org/10.3389/fmicb.2021.661100.

Yuan, J., Wang, L., Wang, S., Wang, Y., Wang, H., Chen, H., Zhu, W., 2018. The use of biologically based phosphorus fractions to evaluate soil P availability in reduced P-input paddy soils. Soil Use and Management 34, 326–334. https://doi.org/10.1111/sum.12430.

Yuan, J., Wang, Y., Zhao, X., Chen, H., Chen, G., Wang, S., 2022. Seven years of biochar amendment has a negligible effect on soil available P and a progressive effect on organic C in paddy soils. Biochar 4, 1–13. https://doi.org/10.1007/s42773-021-00127-w.

Zago, L.M.S., Moreira, A.K.O., Silva-Neto, C.M., Nabout, J.C., Ferreira, M.E., Caramori, S.S., 2018. Biochemical activity in Brazilian Cerrado soils is differentially affected by perennial and annual crops. Australian Journal of Crop Science 12, 235–242. https://doi.org/10.21475/ajcs.18.12.02.pne716.

Zhang, W., Zhao, J., Pan, F., Li, D., Chen, H., Wang, K., 2015. Changes in nitrogen and phosphorus limitation during secondary succession in a karst region in southwest China. Plant and Soil 391, 77–91. https://doi.org/10.1007/s11104-015-2406-8.

Zhang, J., Bo, G., Zhang, Z., Kong, F., Wang, Y., Shen, G., 2016a. Effects of straw incorporation on soil nutrients, enzymes, and aggregate stability in tobacco fields of China. Sustainability (Switzerland) 8, 1–12. https://doi.org/10.3390/su8080710.

Zhang, Y., Hu, M., Liang, H., Wang, X., Wang, Z., Jiang, Z., Li, X., 2016b. The effects of sugar beet rinse water irrigation on the soil enzyme activities. Toxicological and

Environmental Chemistry 98, 419–428. https://doi.org/10.1080/02772248.2015.1123485.

Zhang, L., Wang, J., Fu, G., Zhao, Y., 2018. Rotary tillage in rotation with plowing tillage improves soil properties and crop yield in a wheat-maize cropping system. PLoS ONE 13, 1–16. https://doi.org/10.1371/journal.pone.0198193.

Zhang, Yu, Hu, J., Bai, J., Qin, H., Wang, Junhua, Wang, Jingwei, Lin, X., 2019a. Intercropping with sunflower and inoculation with arbuscular mycorrhizal fungi promotes growth of garlic chive in metal-contaminated soil at a WEEE-recycling site. Ecotoxicology and Environmental Safety 167, 376–384. https://doi.org/10.1016/j.ecoenv.2018.10.046.

Zhang, Y., Wang, X., Xu, F., Song, T., Du, H., Gui, Y., Xu, M., Cao, Y., Dang, X., Rensing, C., Zhang, J., Xu, W., 2019b. Combining Irrigation Scheme and Phosphorous Application Levels for Grain Yield and Their Impacts on Rhizosphere Microbial Communities of Two Rice Varieties in a Field Trial. Journal of Agricultural and Food Chemistry 67, 10577–10586. https://doi.org/10.1021/acs.jafc.9b03124.

Zhang, Z.J., Wang, X.Z., Wang, H., Huang, E., Sheng, J.L., Zhou, L.Q., Jin, W.Z., 2020. Housefly Larvae (Musca domestica) Vermicompost on Soil Biochemical Features for a Chrysanthemum (Chrysanthemum morifolium) Farm. Communications in Soil Science and Plant Analysis 51, 1315–1330. https://doi.org/10.1080/00103624.2020.1763389.

Zhang, Y., Finn, D., Bhattacharyya, R., Dennis, P.G., Doolette, A.L., Smernik, R.J., Dalal, R.C., Meyer, G., Lombi, E., Klysubun, W., Jones, A.R., Wang, P., Menzies, N.W., Kopittke, P.M., 2021. Long-term changes in land use influence phosphorus concentrations, speciation, and cycling within subtropical soils. GEODERMA 393. https://doi.org/10.1016/j.geoderma.2021.115010.

Zhao, Y., Wang, P., Li, J., Chen, Y., Ying, X., Liu, S., 2009. The effects of two organic manures on soil properties and crop yields on a temperate calcareous soil under a wheat-maize cropping system. European Journal of Agronomy 31, 36–42. https://doi.org/10.1016/j.eja.2009.03.001.

Zhaolei, L., Naishun, B., Jun, C., Xueping, C., Manqiu, X., Feng, W., Zhiping, S., Changming, F., 2017. Effects of long-term cultivation of transgenic Bt rice (Kefeng-6) on soil microbial functioning and C cycling. Scientific Reports 7, 1–13. https://doi.org/10.1038/s41598-017-04997-8.

Zhong, W.-H., Cai, Z.-C., Zhang, H., 2007. Effects of Long-Term Application of Inorganic Fertilizers on Biochemical Properties of a Rice-Planting Red Soil. Pedosphere 17, 419–428. https://doi.org/10.1016/s1002-0160(07)60051-4.

Zhong, S., Zeng, H., Jin, Z., 2015. Soil Microbiological and Biochemical Properties as Affected by Different Long-Term Banana-Based Rotations in the Tropics. Pedosphere 25, 868–877. https://doi.org/10.1016/S1002-0160(15)30067-9.

Zhou, L., Xu S.T., Monreal C.M., Mclaughlin N.B., Zhao B.P., Liu J.H., Hao, G.C., 2022. Bentonite-Humic Acid Improves Soil Organic Carbon, Microbial Biomass, Enzyme Activities and Grain Quality in a Sandy Soil Cropped to Maize (Zea Mays L.) in a Semi-Arid Region. Journal of Integrative Agriculture 21(1):208–21. https://doi.org/10.1016/S2095-3119(20)63574-2.

Zhu, L. xia, Xiao, Q., Cheng, H. yan, Shi, B. jie, Shen, Y. fang, Li, S. qing, 2017. Seasonal dynamics of soil microbial activity after biochar addition in a dryland maize field in North-Western China. Ecological Engineering 104, 141–149. https://doi.org/10.1016/j.ecoleng.2017.04.026.

Zhu, Z., Qian, J., Zhang, Y., Zhang, H., Dai, H., Zhang, Z., Miao, M., Jiang, J., 2022. Taro (Colocasia esculenta (L.) Schott) Yields and Soil Chemical Properties Were Improved by Row-Surface Straw Mulching. Agronomy 12. https://doi.org/10.3390/agronomy12030645.

Zibilske, L.M., and Bradford, J.M., 2003. Tillage effects on phosphorus mineralization and microbial activity. Soil Science 168, 677–685. https://doi.org/10.1097/01.ss.0000095141.68539.c7.

Zibilske, L.M., and Makus, D.J., 2009. Black oat cover crop management effects on soil temperature and biological properties on a Mollisol in Texas, USA. Geoderma 149, 379–385. https://doi.org/10.1016/j.geoderma.2009.01.001.

5. Chapter 2

Research article

Effect of climate, crop, and management on soil phosphatase activity in croplands: a global investigation and relationships with crop yield

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5.1 Abstract

Agricultural and livestock production cover more than a third of the Earth's land surface and are crucial to food supply. Soil extracellular enzymes play an important role in the transformation of elements and compounds in soil, particularly acid (ACP) and alkaline (ALP) phosphatases (both, APase). These enzymes have a vital role in releasing phosphorus (P) from organic matter. However, the effect of climate variables and agro-ecosystem management on APase activity in croplands remains unclear, as does its eventual relationship with agricultural productivity. Therefore, we compiled a global database of APase activity in croplands (between 1977 and 2022) and we globally analyzed 5876 observations across 474 papers to study climate variables, crop family, and management effects on ACP and ALP activity, and their relationship with yield. ACP activity is reduced by higher temperatures ($p<0.001$) and lower rainfall ($p=0.002$). There was an interaction effect of temperature and precipitation on ALP activity ($p=0.046$), with the negative effect of temperature being stronger with high precipitation, and low precipitation showing low ALP activity levels at any temperature. The crop family greatly influenced APase activity ($p<0.001$). Management practices affected ACP and ALP activity differently; ACP activity was positively influenced by organic fertilization combined with, crop rotation or irrigation by an average of 15,63% and 30,67%, respectively. ALP activity was mainly positively influenced by the interaction of two different factors: organic and inorganic-organic fertilization and reduced or zero tillage. Further understanding of soil enzyme mechanisms would aid global food security and yield. As ACP activity doubles from 100 to 200 mg pNP $kg^{-1}h^{-1}$, the crop yield increases by more than two-fold, an outcome not demonstrated in croplands until now. These results enhance yield potential by promoting APase activity, considering climate variables and agro-ecosystem management, and improving cost-benefit ratios for sustainable crop growth.

Keywords: phosphomonoesterases; arable land*;* management*;* species*,* climate*;* yield

5.2 Introduction

Agricultural and livestock production covers approximately 5 billion hectares (38%) of the Earth's land surface, with around 66% of that consisting of livestock-grazed grasslands and 33% being cropland (Faostat, 2021). Ensuring the appropriate balance between food safety, food security and economic, social, and environmental sustainability is crucial (Vågsholm et al., 2020). Food security is a complex issue that requires as much attention to increasing environmental sustainability as to raising productivity (Garnett et al., 2013). Agricultural productivity is linked to environmental damages due to the physical impacts caused by its management. Cropland soils experience more intensive human disturbance and receive lower inputs of plant residues, root exudates and senescent leaves compared to soils in natural and semi-natural ecosystems (Riffaldi et al., 2002). This human activity negatively impacts the soil biological and biochemical properties, leading to a decline in phosphorus (P) and carbon (C) cycling (Cui et al., 2019). Cropland soils generally have lower soil organic C and microbial biomass C compared to natural soils (Martins et al., 2019), with diminished global activity of extracellular enzymes as a result (Carlos et al., 2022). Phosphorus is an essential element for plant growth and the imbalanced human-induced inputs of nitrogen (N) and P are also affecting the functioning of ecosystems and croplands (Peñuelas et al., 2013). Intensively farmed areas can suffer P losses by water erosion (Panagos et al., 2022) due to fertilization addition and cause P pollution to nearby water bodies (Del Rossi et al., 2023).

In agricultural soils, the amount of P available to plants in soil solution is very low, seldom exceeding about 0.01% of the total P in the soil (Weil and Brady 2016). The mechanisms governing composition, timing, spatial distribution and quantity in response to environmental changes have been explored elsewhere (Allison et al., 2010; Zuccarini et al., 2023), emphasizing the pivotal role of soil enzymes in biogeochemical cycles and ecosystem responses to global change drivers. Phosphomonoesterases or phosphatases are a group of relatively non-specific phosphohydrolases that can cleave the phosphate group from organic compounds, especially from dissolved organic P, making P available for plant uptake (Weil and Brady 2016). Within this group, soil acid phosphatase (ACP; EC 3.1.3.2) and soil alkaline phosphatase (ALP; EC 3.1.3.1) are the predominant forms across a wide range of soil pH conditions (Eivazi and Tabatabai, 1977). In particular, ACP and ALP enzymes, collectively referred to as APase, has been extensively studied in natural and agricultural soils. This is evident from numerous meta-analyses published on the subject (Janes-Bassett et al., 2022; Miao et al., 2019; Yuan et al., 2023), as well as from a recent review (Campdelacreu Rocabruna et al., 2024). APase play an important role in bringing nutrient supply more closely in line with nutrient demand (Allison et al., 2010). According to their optimum pH, soil ACP has been found in animals such as earthworms, microbial and plant cells, and soil ALP has been found in microorganisms and animals (Alef and Nannipieri, 1995). Due to the challenge of extracting enzymes from soils and their tendency to lose integrity, soil enzymes are characterized by measuring their activity under stringent conditions (e.g., temperature, pH buffer, and substrate concentration). As a result, ACP and ALP activity assays measure potential activity rather than in situ activity (Dick et al., 1997). Furthermore, according to Burns (1982) enzymes catalysing the measured reaction can be associated with active microbial cells or debris, resting cells like bacterial spores, released as truly extracellular enzymes, present as enzyme-substrate complexes, or free extracellular enzymes. They can also be stabilized by association with surface-reactive particles or entrapped by humic matter.

APase activity is known to be indirectly affected by climatic factors. For instance, an increase in temperature without significant changes in water availability can induce accelerated plant growth (Sardans et al., 2006), while an increase in drought can lead to a reduction in the soil's macronutrient demand (Sardans and Peñuelas, 2004), positively or negatively affecting APase activity, respectively. Furthermore, different responses have been observed depending on the type of cereals (Furtak et al., 2017) but when compared with legumes, APase activity is higher in the latter (Aparna et al., 2016; Borase et al., 2021; Singh et al., 2021). Additionally, APase assessed in vegetables exhibited higher activity compared to cereals or forest land (Monkiedje et al., 2006), indicating the importance of the species identity in response of P demand. On the other hand, there are indications that APase activity is enhanced under conservation agriculture practices such as crop rotation (Eichler-Löbermann et al., 2021), cover cropping (Feng et al., 2021), and no till practices (Yang et al., 2019). Regarding nutrient input, the APase activity tends to respond positively when soil receives inorganic fertilization (Choudhary et al., 2021), organic fertilization (Chatterjee et al., 2021), or a combination of both types of fertilization (Cao et al., 2022). However, despite these findings, there remains a significant gap in understanding how agricultural practices and climate can also collectively affect APase activity on a global scale within croplands. Addressing this gap constitutes the primary aim of our study. Namely, it is crucial to assess the global effects on ACP and ALP activity under agroecological management concerning crop species choice and rotation, soil tillage, and soil fertilization. Understanding these effects is important for establishing a link with crop yields, as changes in APase activity due to management could lead to either beneficial or detrimental shifts in crop productivity or quality.

To assess the effects of climate, crop and management on ACP and ALP activity in croplands, as well as their relationship with yield, a global analysis was conducted with the aim of testing the following hypotheses:

i) ACP and ALP activity is higher in regions with a warm and wet climate due to enhanced plant production and microbial activity.

ii) Strong species-specific effects on APase activity are expected, particularly in legumes, as N-fixing plants are typically P-limited.

iii) The activity of both enzymes will increase under management practices promoting soil health (e.g., conservation techniques such as reduced or zero tillage, crop rotation, cover crops, and organic fertilization).

iv) Crop yields are positively influenced by ACP and ALP activity.

5.3 Materials and methods

5.3.1 Literature search and data collection

Using the Web of Science and Scopus databases, a bibliographic search was carried out, including research papers published from 1977 to mid 2022. We carried out a search using different combinations of the terms: “phosphatase* AND soil AND agriculture”, “phosphatase* AND soil AND agricultural”, “phosphatase* AND soil AND crop”, and “phosphatase* AND soil AND arable” in the title, abstract or keywords. In total, 16,123 records were initially identified for subsequent screening.

In order to maintain quality control, we applied the subsequent criteria for selecting studies: i) only published papers were considered (data from book chapters, congress proceedings or posters were discarded); ii) for comparability purposes studies were only selected if para-nitrophenyl phosphate (pNPP) was used as a substrate to quantify the APase activity, and whether pH 6.5 and pH 11 were used for ACP and ALP assessment, respectively, with temperature set at 37ºC, incubation time of 60 minutes, soil samples collected at a depth ranging from 0 to 20 centimetres, and the units expressed or recalculated to mg pNP kg-1 h-1, following the method described by (Tabatabai and Bremner, 1969) and the additional improvements by Eivazi and Tabatabai (1977) and Tabatabai (1994); iii) only field studies conducted on arable land with a single crop were included (studies in managed grasslands, timber tree plantations, and intercropping were excluded) and when soil APase activity was experimentally assessed during the crop development; iv) APase activity had to be evaluated alongside other parameters from bulk soil (studies focusing on rhizosphere soil, root surface, and in culture mediums were discarded). A PRISMA flow diagram showing the procedures used to select studies for analysis is detailed in Figure S1.

To be included in the final database, studies were required to ensure that the experiment described in the reported study integrated georeferencing, buffer pH, incubation temperature and duration, and soil depth. If the studies included elevation and climate data, specifically mean annual precipitation (MAP) and mean annual temperature (MAT), such information was also recorded. As additional considerations, winter fallow was not considered a true fallow, as it should last a minimum of a year in a rotation scheme or many if permanent. Moreover, fallow for short periods and the use of green manures or cover crops were registered as crop rotations. Furthermore, we only considered the actual soil property values for each treatment. If these values were provided solely for the control plots, they were exclusively utilized for determining the APase activity values in those plots (except for permanent properties such as texture that were used for all the treatments). When a study included several experiments at different sites or different ecosystem types, we considered them to be independent observations. Consequently, all selected data may originate from both the control groups and the treatment groups.

In total, we generated a dataset with 5,876 observations (3,517 individual observations of ACP activity and 2,359 individual observations of ALP activity) reported in 474 published papers (see supplemental information for the list of references).

All data were directly extracted from tables and supplementary materials of the published papers. When only available in graphical form, data were retrieved using a web-based plot digitizer (WebPlotDigitizer version 4.6). In instances where latitude or longitude information was not provided in the paper, we estimated approximate latitude and longitude coordinates by geocoding the location site names in Google Earth 6.2. When MAT and MAP values were unavailable in the study, were obtained from the WorldClim database (Hijmans et al., 2005) with a spatial resolution of around 1 km at the equator while missing elevations were sourced from Google Earth, utilizing the geographic coordinates of the site.

To compare the effects of different drivers to ACP and ALP activity as dependent variables, the database was grouped according to four approaches for inclusion as explanatory variables into the statistical model (see Supplementary Material Table S1). First, we explored the influence of climate using only MAT and MAP as predictors. As a result of this data grouping, the number of observations for ACP and ALP activity is 3,104 and 2,105 respectively. Second, we investigated the importance of crop species, grouping them by taxonomical affiliation at the family level (Amaranthaceae, Amaryllidaceae, Anacardiaceae, Apiaceae, Araceae, Arecaceae, Asparagaceae, Asteraceae, Brassicaceae, Caryophyllaceae, Cucurbitaceae, Ericaceae, Euphorbiaceae, Euphorbiaceae, Fabaceae, Juglandaceae, Lamiaceae, Malvaceae, Moracea, Musaceae, Myrtaceae, Oleaceae, Passifloraceae, Poaceae, Rosaceae, Rubiaceae, Rutaceae, Sapindaceae, Sapotaceae, Solanaceae, Theaceae, Vitaceae and Zingiberaceae). As a result of this data grouping, the number of observations for ACP and ALP in this model is the same as in the previous one. Third, the significance of the agricultural management practice was also tested, considering the type of cropping system (crop rotation/continuous cropping), green manure (yes/no), mulching (yes/no), crop residue leaving (yes/no), cover cropping (yes/no), intercropping (yes/no), liming (yes/no), tillage practices (conventional, intensive, reduced and zero tillage), types of fertilization (inorganic, organic, combined inorganic-organic (thereafter referred as both) and non-fertilized (afterward referred as none)) and irrigation system (rainfed, irrigated and wastewater irrigated). As a result of this data grouping, the number of observations for ACP and ALP activity is 1,323 and 804 respectively. The detailed definitions of these management practices are in Supplementary Material Table S1. Finally, to assess the effect of APase activity on crop yield, experiments were categorized according to the availability of data related to it. Similarly to what has been done with APase units, in this case, the selected observations underwent another filtering process concerning the units, which should be reported in kg ha^{-1}). As a result to this data grouping, the number of observations for ACP and ALP activity is 583 and 370 respectively and based on this number of observations, it was also checked whether yield influenced APase, with yield as the independent variable.

5.3.2 Data analysis

We built three different statistical models explaining ACP and ALP activity performed by means of linear mixed-effects models (LME) using RStudio (version 2023.12.1+402). We used the function *lmer* from the package *lme4* (Bates et al., 2015) to perform the linear mixed model analyses: a) In the first model we examined the effect of climatic variables: MAP and MAT; b) In the second model we analysed the effect taxonomical affiliation at the family level, and (c) in the third model, we explored the effect of management-related variables: type of cropping system, green manure, mulching, crop residue leaving, cover cropping, intercropping, liming, tillage practices, types of fertilization and irrigation system. Studies with unreported tillage practices were discarded from the statistical analyses.

Regarding the model for crop yield, ACP and ALP activity were used as independent variables in addition to species family classification and management-related variables. For this dependent variable, again three models were constructed: (i) in the first model, we examined the effect on yield of ACP activity together with family and management-related variables; (ii) in the second model, we analysed the effect on yield of ALP activity and the other explanatory variables of the previous model; (iii) in the third model, we evaluated the effect on yield of APase activity as whole (considering the sum of ACP and ALP activity) together with the other explanator variables already mentioned; (iv) in the fourth model, we evaluated the effect on ACP and ALP activity of yield and the other explanatory variables of the previous model.

The set of independent variables and their interactions in each model were subjected to stepwise backwards model selection of non-significant effects of linear mixed effects model using the *step* function in the same RStudio version cited above. We achieved the best model, based on the lowest Akaike Information Criterion value (AIC, the lower the better) (Akaike, 1998). In order to address individual variations in APase activity and yield, the study identity was included as the random effect in all models in order to capture the variability not explained by the fixed effects. All response variables were log-transformed (using the natural logarithm) to achieve normality of the residuals, that we tested by conducting standard diagnostic plots. The values of APase activity from all studies were analysed, and outliers (those considered unreasonably smaller or larger than most of the observation) were discarded from the analyses. Data points falling outside the interval of -3 to 3 standardized residuals were considered outliers. Outliers were identified using graphical tools to display the distribution of continuous data based on quartiles and shown in the Supplementary Materials (Figures S2 and S3). Excluding these values from the analysis did not change the interpretation of our results. Maximum Likelihood (ML) was used to compare models differing in fixed effects via AIC, whilst Restricted Maximum Likelihood (REML) was used to get the final results. Results were back transformed and are always reported and shown on the original scale. Post-hoc comparisons of estimated marginal means were performed by the Sidak test. When p-values were less than 0.05 they were considered statistically significant, and the respective explanatory variables were interpreted in the results and discussion sections. Back-transformed predicted values, estimated marginals means and 95%-confidence intervals, given in square brackets, are thereafter reported in the text.

All analyses were conducted in R version 4.3.2 (R Core Team, 2023). The packages *effects* (Fox et al., 2016), *jtools* (Long, 2022), and *ggplot2* (Wickham, H. 2016) were used to visualize the results. Post-hoc comparisons and calculation of estimated marginal means were performed by using the *emmeans* package (Lenth et al., 2018).

5.4 Results

Table 1. Factors affecting ACP activity and ALP activity; df = degrees of freedom; *F* = Fisher's F; *p* = probability; p-values < 0.05 are highlighted in bold. # natural logarithm-transformed data. – = not taken up in the model according to the stepwise forward model selection. n.t. = not tested for inclusion.

Source	ACP #			ALP #		
	df	*F*	*p*	df	*F*	*p*
Model 1						
Mean annual temperature (MAT)	1	25.745	**<0.001**	1	12.916	**<0.001**
Mean annual precipitation (MAP)	1	5.416	**0.020**	1	0.881	0.349
MAT x MAP		-	-	1	4.000	**0.046**
Model 2						
Family (Fa)	26	2.775	**<0.001**	23	2.220	**0.001**
Model 3						
Tillage (T)	3	4.520	**0.004**	3	4.051	**0.007**
Type of cropping system (TS)	1	6.038	**0.014**		-	-
Irrigation system (I)	1	0.374	0.541	1	6.858	**0.009**
Fertilization type (F)	3	6.543	**<0.001**	3	11.194	**<0.001**
TS x F	3	2.607	0.050		-	-
I x F	3	4.813	**0.002**		-	-
T x F		-	**-**	9	1.962	**0.041**

Table 2. Factors affecting crop yield. Df = degrees of freedom; F = Fisher's F, p = probability; p-values < 0.05 are highlighted in bold. # natural logarithm-transformed data. – = not taken up in the model according to the stepwise forward model selection. N.t. = not tested for inclusion.

Source		Crop yield # ACP			Crop yield # ALP			Crop yield # APase	
	df	F	p	df	F	p	df	F	p
Crop family (Fa)	6	2.943	**0.010**	6	3.241	**0.010**	8	2.140	**0.041**
Tillage (T)	3	4.104	0.628		-	-		-	-
Type of cropping system (TS)	1	0.237	**0.014**		-	-		-	-
Fertilization type (F)	3	9.500	**<0.001**	3	10.685	**<0.001**	3	19.161	**<0.001**
ACP	1	11.915	**<0.001**		n.t.			n.t.	
ALP		n.t.		1	22.993	**<0.001**	3	n.t.	
ACP x T	3	7.918	**<0.001**		n.t.			-	-
ACP x TS	1	4.639	**0.032**		n.t.			-	-
ACP x Fa	6	2.832	**0.010**		n.t.			-	-
APase		n.t.			n.t.		1	7.410	**0.007**

		ACP # Crop yield			ALP # Crop yield	
	df	F	p	df	F	p
Yield	1	1.016	0.314	1	6.235	**0.013**
Crop family (Fa)	6	1.600	0.158	6	1.169	0.332
Tillage (T)	3	7.096	**<0.001**	4	5.448	**<0.001**
Type of cropping system (TS)	1	0.264	0.608	1	0.000	0.984
Fertilization type (F)	3	19.249	**<0.001**	3	24.778	**<0.001**

5.4.1 Effect of climate factors on ACP and ALP activity

ACP activity showed a pronounced and significant negative relationship with MAT ($F_{1,1}$ = 25.745, p < 0.001) and a positive relationship with MAP ($F_{1,1}$ = 5.416, p = 0.020) (Fig. 1).

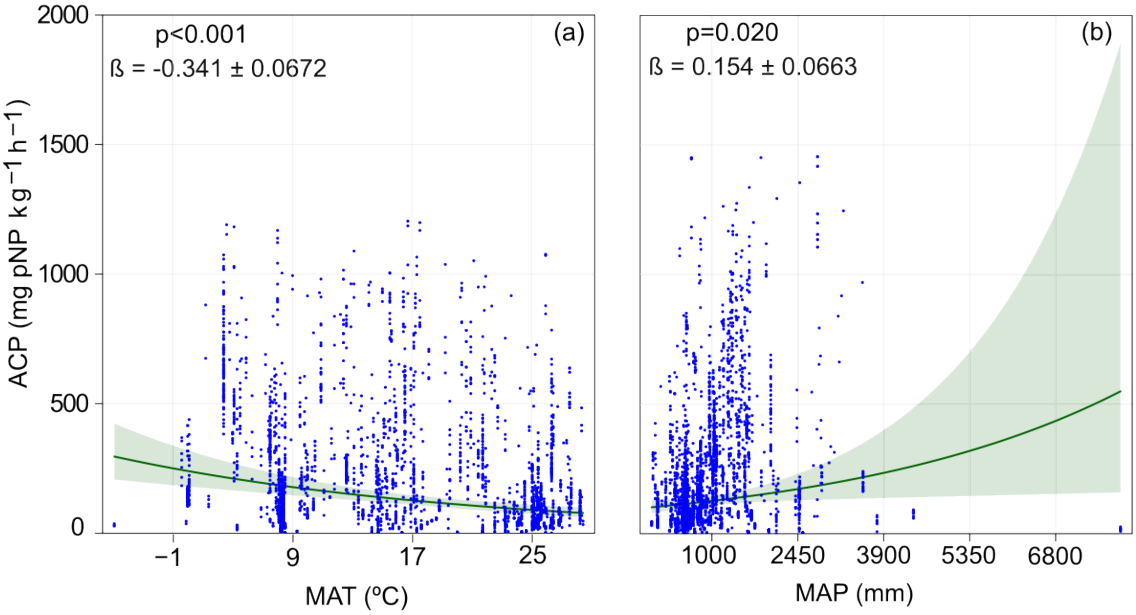

Figure 1. Effect of (a) mean annual temperature (MAT) and (b) mean annual precipitation (MAP) on the ACP activity. Predicted values (green line) and 95%-confidence interval (green shadow) are shown against partial residuals (blue dots). While the analysis was carried out using the natural logarithm-transformed values, the back-transformed values are the ones shown (n=3140). Estimated slope parameters (β) ± SE are reported on the transformed scale.

ALP activity was affected by MAT and by the interaction between MAT and MAP, with the negative effect of temperature on ALP being stronger at higher levels of precipitation ($F_{1,1}$ = 4.000, p = 0.046) (Fig. 2).

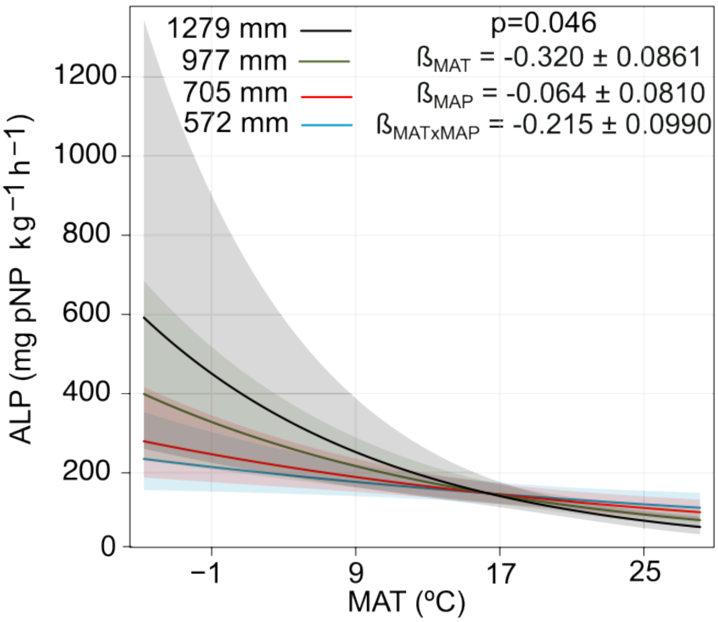

Figure 2. Effect of mean annual temperature (MAT) and mean annual precipitation (MAP) on the ALP activity. Predicted values (lines in different colours) and 95%-confidence interval (in shadow) are shown but partial residuals are not displayed in a multiline plot. While the analysis was carried out using the natural logarithm-transformed values, the back-transformed values are the ones shown (n=2105). Estimated slope parameters (β) ± SE of the reference level ($β_{MAT}$), the difference for levels MAP ($β_{MAP}$) and the interaction ($ß_{MATxMAP}$) are reported on the transformed scale.

5.4.2 Effect of crop species taxonomical affiliation (family) on ACP and ALP activity

ACP and ALP activity were both affected by crop family (F_{26} = 2.775, p < 0.001 and F_{23} = 2.220, p = 0.001, respectively). In particular, ACP activity was observed to have the highest values in fields cropped to Passifloraceae, showing high values (725 [272.3 - 1928] mg pNP $kg^{-1}h^{-1}$, hereafter, values represent the mean and 95% confidence interval) compared to the lower values obtained with Asparagaceae (21.7 [1.35 - 211] mg pNP $kg^{-1}h^{-1}$). For ALP, Anacardiaceae had the highest enzyme activity (718.4 [299.2 - 1725] mg pNP $kg^{-1}h^{-1}$) compared to the lowest values obtained with Malvaceae (80.8 [58.2 - 112] mg pNP $kg^{-1}h^{-1}$) (Fig. 3 and the table of estimated slope parameters (β) ± SE of the reference level ($β_{species}$) in relation to the model of ACP and ALP is included in the Supplementary Material, Table S2).

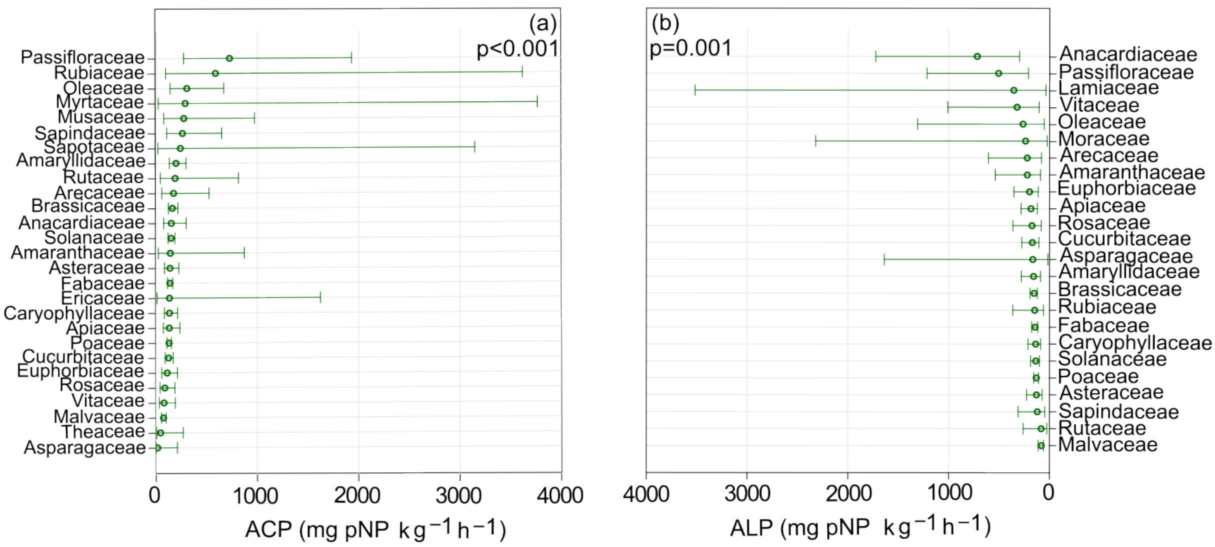

Figure 3. Effect of family on (a) the ACP activity and (b) ALP activity. Predicted values and 95%-confidence interval are shown. While the analysis was carried out using the natural logarithm-transformed values, the back-transformed values are the ones shown (n_{ACP}=3140; n_{ALP}=2105).

Some plant families had contrasting effects on ACP and ALP activity. For instance, Amaryllidaceae, Brassicaceae, Rubiaceae, Rutaceae, Sapindaceae, and Solanaceae exhibited much higher levels of ACP activity compared to ALP activity in the same field plots. In contrast, Vitaceae and Anarcadiaceae showed similar ACP and ALP activity. For families such as Ericaceae, Theaceae, Malvaceae, Musaceae, Myrtaceae, and Sapotaceae only ACP activity was reported while no data available for ALP activity so such comparison was not possible. Conversely, Asparagaceae, Moraceae, and Laminaceae influenced ALP activity, but no data was available for ACP activity (Fig. S5).

5.4.3 Effect of management practices on ACP and ALP activity

The influence of fertilization on APase depended on the type of cropping system ($F_{3,1}$ = 2.607, p = 0.050) and the irrigation system ($F_{3,1}$ = 4.813, p = 0.002). Crop rotation seems to enhance ACP activity compared to continuous cropping, regardless of the fertilizer application or the type of fertilizer used. Crop rotation without fertilization exhibited significantly higher values of ACP activity compared to unfertilized crops in continuous cropping (from 172 [126.9 - 234] mg pNP $kg^{-1}h^{-1}$ to 120 [90.2 - 159] mg pNP $kg^{-1}h^{-1}$). Furthermore, organic fertilization under crop rotation increased ACP activity from 185 [134.5 - 253] mg pNP $kg^{-1}h^{-1}$ to 160 [120.9 - 212] mg pNP $kg^{-1}h^{-1}$ compared to continuous cropping. Moreover, In the case of the irrigation system, organic fertilization increased ACP activity more in irrigated crops (196 [144 - 268] mg pNP $kg^{-1}h^{-1}$) than in rainfed fields (150 [114.9 - 197] mg pNP $kg^{-1}h^{-1}$) (see Fig. 4 and the table of estimated slope parameters (β) ± SE of the reference level ($\beta_{fertilization}$) in relation to the model of ACP is included in the Supplementary Material, Table S3).

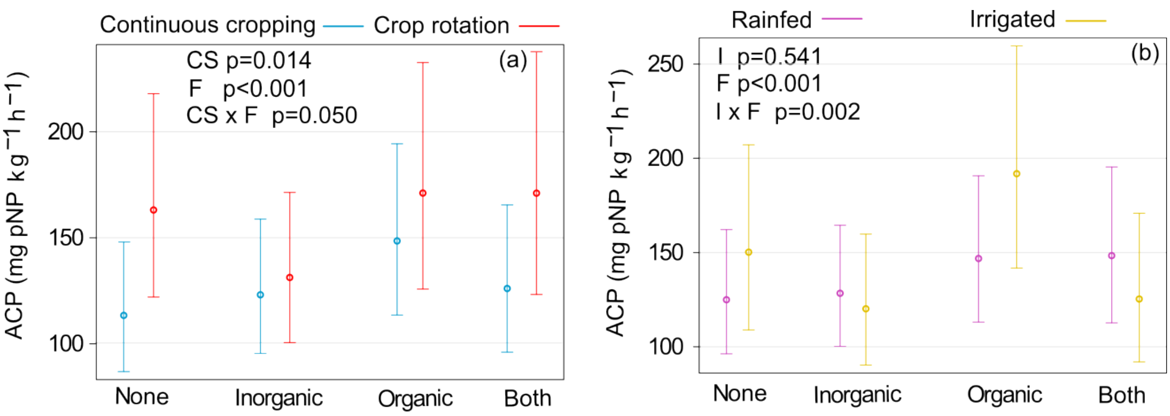

Figure 4 Effect of (a) type of system and fertilization and (b) irrigation practices and fertilization on the ACP activity. Predicted values and 95%-confidence interval are shown. While the analysis was carried out using the natural logarithm-transformed values, the back-transformed values are the ones shown (n=1323).

On the other hand, the influence of fertilization type on ALP activity varied depending on the tillage practices used, with higher values observed when intensive tillage is employed concurrently with mixed organic and inorganic fertilization (310.4 [155.4 - 620] mg pNP $kg^{-1}h^{-1}$). Reduced tillage showed similar values when mixed organic and inorganic fertilization or organic fertilization were used (from 214.6 [124.4 - 370] to 212.0 [150.2 - 299] mg pNP $kg^{-1}h^{-1}$, respectively). Zero tillage followed a similar trend and had higher values of ALP activity than the others (from 206.4 [147.2 - 289] to 205.8 [151.4 - 280] mg pNP $kg^{-1}h^{-1}$, respectively) (see Fig. 5 and the table of estimated slope parameters (β) ± SE of the reference level ($\beta_{fertilization}$) in relation to the model of ALP, included in the Supplementary Material, Table S4).

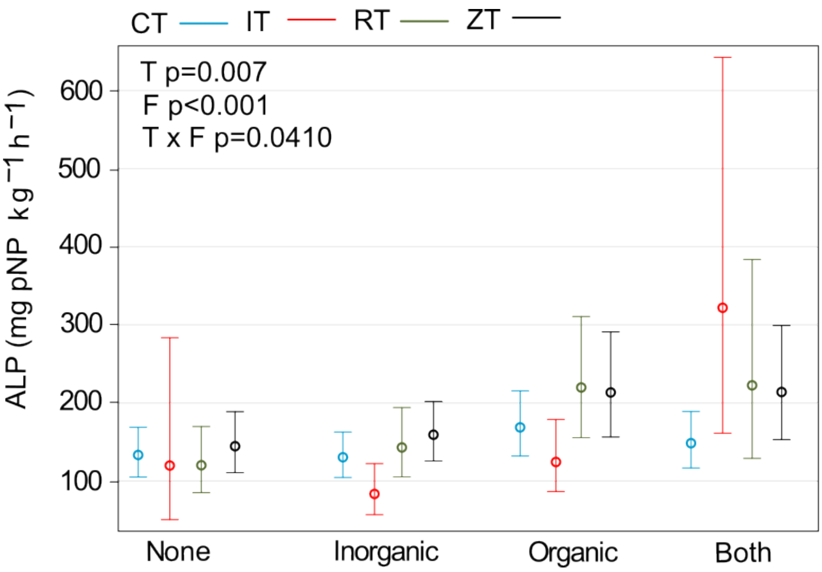

Figure 5. Effect of fertilization and tillage practices on ALP activity. Predicted values and 95%-confidence interval are shown. While the analysis was carried out using the natural logarithm-transformed values, the back-transformed values are the ones shown (n=804). CT= Conventional tillage, IT = Intensive tillage, RT= Reduced tillage, ZT= Zero tillage.

Finally, zero tillage positively affected ACP activity, increasing it to 163 [126.7 - 210] mg pNP $kg^{-1}h^{-1}$ compared to the 138 [107.6 - 177] pNP $kg^{-1}h^{-1}$ in conventional tillage ($F_{3,1}$ = 4.520, p = 0.004). Regarding the type of cropping system, crop rotation was associated to significantly higher in ACP values compared to continuous cropping (162 [123.8 - 211] and 130 [99.7 - 170] mg pNP $kg^{-1}h^{-1}$, respectively) ($F_{1,3}$ = 6.038, p = 0.014). Irrigation system only affected ALP activity, with increased values 172 [136 - 217] pNP $kg^{-1}h^{-1}$ in rainfed fields compared to the 135 [105 - 175] mg pNP $kg^{-1}h^{-1}$ in irrigated fields ($F_{1,3}$ = 6.858, p = 0.009) (Fig. 6).

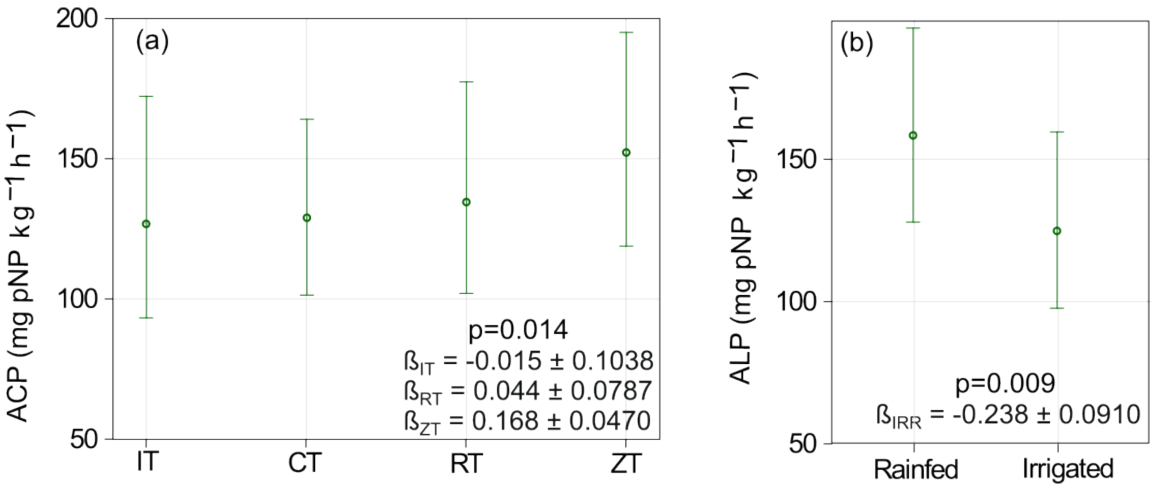

Figure 6. Effect of (a) tillage on ACP activity and (b) irrigation system on ALP activity. Predicted values and 95%-confidence interval are shown. While the analysis was carried out using the natural logarithm-transformed values, the back-transformed values are the ones shown (n_{ACP}=1323, n_{ALP}= 804). Estimated slope parameters (β) ± SE are reported on the transformed scale. IT= intensive tillage, CT= conventional tillage, RT = reduced tillage, ZT = zero tillage.

5.4.4 Factors affecting crop yield

The factors affecting crop yield depended on whether the APase enzymes were assessed separately or combined. In the model concerning only ACP, crop yield exhibited a positive curvilinear relationship when ACP activity interacts with tillage ($F_{3,1}$ = 7.918, p < 0.001), type of cropping system ($F_{1,1}$ = 4.639, p = 0.032) (Fig. 7) and family ($F_{6,1}$ = 2.832, p = 0.010) (Table S5).

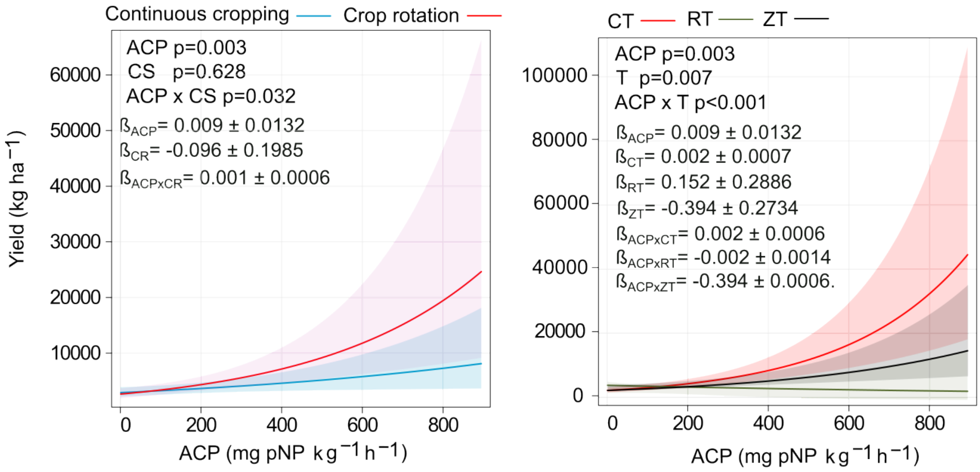

Figure 7. Effect of (a) ACP and type of system and (b) ACP and tillage on the crop yield. Predicted values (in different colours) and 95%-confidence interval (in shadow) are shown. While the analysis was carried out using the natural logarithm-transformed values, the back-transformed values are the ones shown (n=583). In (a) estimated slope parameters (β) ± SE of the reference level (β_{ACP}) and the difference for levels crop rotation (CR) (β_{CR}) are reported on the transformed scale. In (b) estimated slope parameters (β) ± SE of the reference level (β_{ACP}) and the difference for levels conventional tillage (CT) (β_{CT}), reduced tillage (RT) ($ß_{RT}$), zero tillage (ZT) ($ß_{ZT}$) and its interaction (β_{ACPxCR}, β_{ACPxCT}, β_{ACPxRT}, β_{ACPxZT}) are reported on the transformed scale. CR= crop rotation, CT= conventional tillage, RT = reduced tillage, ZT= zero tillage.

Yield increased from 2893 [1707 - 4902] kg ha^{-1} to 7506 [3402 - 16561] kg ha^{-1} as ACP increased from 100 to 200 mg pNP kg^{-1}h^{-1} (F=11.915, p<0.001). The same trend was observed with ALP activity, which increased from 4033 [260 - 6070] kg ha^{-1} to 4732 [3177 - 7047] kg ha^{-1} from 100 to 200 mg pNP kg^{-1} h^{-1} (F=22.993, p<0.001) (Fig.7).

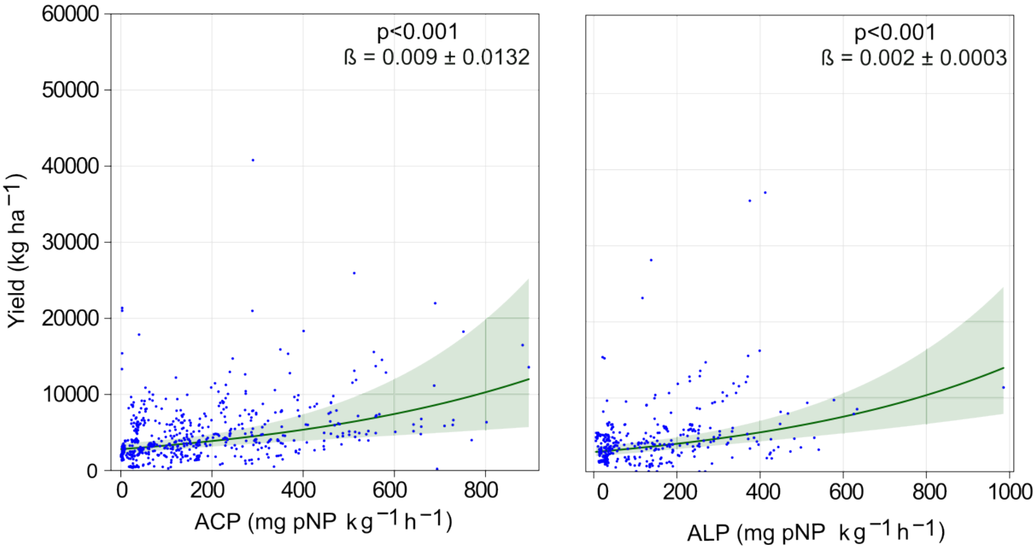

Figure 8. Effect of (a) ACP and (b) ALP on the crop yield. Predicted values (green line) and 95%-confidence interval (green shadow) are shown against partial residuals (blue dots. While the analysis was carried out using the natural logarithm-transformed values, the back-transformed values are the ones shown (n_{ACP}=583, n_{ALP}= 370). Estimated slope parameters (β) ± SE are reported on the transformed scale.

In the model concerning ALP, yield was also shown to be influenced by fertilization type ($F_{3,1}$ = 10.685, p < 0.001) and family ($F_{6,1}$ = 3.241, p = 0.010). In particular, yield was highest under inorganic fertilization, and in soils planted with Asteraceae (Figure S5).

Moreover, the effect of the activity of both APase (ACP and ALP activity together) on crop yield followed the same trend as for ACP and ALP separately, since there was a positive effect between yield and APase activity. In particular, crop yield increased from 4820 [3085 - 7530] kg ha^{-1} to 5089 [3265 - 7930] kg ha^{-1} as APase activity increased from 100 to 200 mg pNP kg^{-1}h^{-1} ($F_{3,1}$ = 7.410, p = 0.007). Moreover, in this final model crop yield was also influenced by fertilization type ($F_{3,8}$ = 19.161, p < 0.001) and family ($F_{8,3}$ = 2.140, p = 0.041) (Figure S6).

Finally, in the case of the model where yield was represented as the independent variable and ACP or ALP activity as the dependent variable, the results showed that ACP activity is not influenced by yield, while ALP activity is indeed influenced by it ($F_{1,1}$=6.235, p=0.013) (Table 2).

5.5 Discussion

5.5.1 Effect of climate factors on ACP and ALP activity

The results of our global analysis confirm the importance of temperature and precipitation on ACP and ALP activity in cropland soils (Fig.1, Fig. 2), although there are differences between the two enzymes. On one hand, ACP activity is negatively influenced by MAT but positively influenced by MAP which partially confirmed our hypothesis. On the other hand, ALP activity reacts to the interaction between MAT and MAP, in general with a negative influence of temperature, but with different responses depending on the precipitation rates.

Concerning the influence of MAT on ACP activity, our results go in contrast to most reports from natural and restored ecosystems, where warming tends to decrease soil available P and microbial biomass P, boosting APase activity (Gong et al., 2020). Thus, a positive effect of temperature on ACP activity is well documented in the literature (Hu et al., 2022; Margalef et al., 2017; Meng et al., 2020; Sun et al., 2020; Wang et al., 2021a; Wang et al., 2022). In these natural systems, the highest enzyme activities occur in the periods of most active growth of plants and coincide with optimum levels of soil water contents and intermediate temperatures (Sardans et al., 2006). However, we found the opposite trend, plausibly due to interactions between high temperature and other factors, for instance the specific management (e.g., nutrient addition) (Zuccarini et al., 2023) which might be our case, as management practices significantly influenced ACP activity (section 4.3). Moreover, higher temperatures are related to lower soil multifunctionality since soil enzymes are immobilized and both substrate and enzyme diffusion rates decrease (Sünnemann et al., 2023). The positive influence of MAP on ACP activity in this study align with the literature for natural ecosystems (Sun et al., 2020). The extreme low precipitation (drought) significantly reduces microbial biomass C, N and P, causing a reduction of P acquiring enzyme activity (Margalef et al., 2021; Qu et al., 2023). However, despite a future drier climate in some regions, ACP activity has been shown to be resilient to drying and rewetting cycles, yet outcomes are shaped by land use, soil characteristics, treatments, and plant presence (Gao et al., 2020).

Concerning ALP activity, we report an interesting complex pattern: at low levels of precipitation, ALP activity is low and there is little effect of temperature, while at higher levels of precipitation ALP activity is relatively high in colder environments, and the negative effect of temperature is more significant. This may be because the decrease in fungal biomass, bacterial diversity (bacterial Shannon index), fungal diversity (fungal Shannon Index), microbial biomass C, microbial biomass P, soil respiration and metabolic quotient caused by high precipitation in afforested areas (Luo et al., 2023) is inhibited at low temperatures. Soil P is increasingly shifted to organic forms in cold climate soils, since P transfer from inorganic to organic forms and further to the residue

P is a mechanism to prevent P losses by leaching of labile inorganic forms (Mou et al., 2020). High precipitation in combination with weaker evapotranspiration in colder climates leads to a larger infiltration and higher leaching (i.e., losses of base cations and carbonates) (Riddle et al., 2018) which causes a higher ALP activity compared to low precipitation at low temperatures. Additionally, in our case, it is also worth noting that most ALP values are within the warm temperature range (data not shown), which implies that the model prediction is more reliable under warm temperatures. The decline in ALP activity observed in long-term temperate grasslands at depths of 10-20 cm aligns with our findings (Zhou et al., 2013). Nevertheless, there is a scarcity of published experiments examining how ALP activity is affected when manipulated both temperature and precipitation in croplands. However, changes in precipitation levels occasionally fail to significantly impact microbial biomass, indicating the ability of soil microbes to adapt to soil drying conditions (Landesman and Dighton, 2010) as shown by the obtained results, since the difference in ALP activity between different precipitation levels is not particularly noteworthy.

Another explanation for our surprising results concerning the interaction between MAT and MAP on ALP activity, is that seasonality has not been considered. Seasonality modifies soil ecology and nutrient availability by causing fluctuations in microbial populations and nutrient requirements (Zuccarini et al., 2020). The highest values of most of enzymes appear during spring, while the lowest are given in autumn or winter however disturbance caused by human activity directly affects enzymatic activity and it has repercussions on the overall behaviour of the soil, due to the complex relations that take place among its components (García-Alvarez and Ibañez, 1994). Since the exponential growth of plants concerning seasons and the specific timing of activities assessed have not been taken into account, we cannot confidently affirm whether this global trend would persist when considering these parameters.

5.5.2 Effect of crop species taxonomical affiliation (family) on ACP and ALP activity

Both ACP and ALP activity were strongly influenced by the crop species family (Fig. 3) emphasizing the importance of plant type in the response to soil P limitation and confirming the first part of our second hypothesis. However, at least part of the patterns observed result from the soil pH requirements and the specific managements associated to each crop species. Differences in ACP and ALP activity are aligned with the soil pH requirements of the members of those families, which also determines which of the two enzymes will be predominant. For instance, the relatively high activity of ACP under

Rubiaceae, Oleaceae and Sapindaceae reflects their ability to grow in acidic soils (Von Uexküll and Mutert, 1995). Similarly, differences in management practices between crops are also behind the differences between APase activity. As an example, generally irrigated crops or requiring humid soils (e.g., Anacardiaceae, Arecaceae, Passifloraceae) have higher values of APase activity compared to crops usually not irrigated (e.g., Poaceae, Rosaceae, Malvaceae, Cucurbitaceae, among others). Furthermore, the measured enzyme activity associated with active microbial cells and plant cells in the rhizosphere soil is directly associated with ACP activity (Nannipieri et al., 2011). Additionally, the differences between families that influence ACP and ALP activity might be also inherently result in variations in microbial and fauna populations, which could be further explored in subsequent studies. Plants have the capacity to increase P-mining strategies via APase exudation, although this ability varies between species (Cong et al., 2020). P acquisition strategies clearly influence APase activity since crops with long growing seasons, short leaf lifespans, and dense stands like Brassicaceae and Linaceae exhibit higher concentrations of P in their grain, particularly due to the significance of P remobilization, especially during later stages of plant development and in conditions of low soil P availability (Schultz and French, 1978; Veneklaas et al., 2012).

We also hypothesised that legumes would be a predominant family to enhance APase activity, as the increased P demand of legumes for N_2 fixation results in increased P exploitation by legume-containing mixtures (Oelmann et al., 2011). However, our results indicate that Fabaceae do not show higher ACP and ALP activity compared to other families, and equivalent to those found for cereals. Nonetheless, management may play a significant role on the effect of legumes on APase activity; for instance, the use of legumes in intercropping (e.g., P-efficient species are mixed with P-inefficient species) and crop rotation (e.g., the residues of the P-efficient crops are used for subsequent P-inefficient crops) systems (Simpson et al., 2011) could make it difficult to discern the relationship of these plants on APase activity, as they only make up part of the vegetation in those soils. However, the relationship between APase activity and families can enhance the design of agroecosystems based on knowledge about the capacities of different plant species, genera or families to obtain P from the soil through APase activity.

5.5.3 Effect of management practices on ACP and ALP activity

The results of our model show that the management practices commonly used in agricultural land such as the type of cropping system (crop rotation/continuous cropping) (Fig. 4), fertilization (Fig. 4, Fig. 5), tillage (Fig 5, Fig. 6), and irrigation (Fig. 4, Fig. 6), have a clear link with ACP and ALP activity. Moreover, management practices that promote soil health, such as zero tillage, crop rotation, and organic fertilization, clearly increase the activity of both enzymes, mostly confirming our third hypothesis, since cover crops practice was not included in the final model.

Crop rotations alter the soil habitat by varying nutrient extraction, root depth, and residue accumulation, all of which affect the soil environment (Balota et al., 2004). In our results, only ACP activity increases when crop rotation is used, particularly in cereal rotations, contributing to P cycling (Yu et al., 2021). On the contrary, no effect was found on ALP activity. Since plant species exhibit variations in P efficiency (Föhse et al., 1988), rotation with P-efficient plants can improve soil P availability and potentially enrich the soil with organic acids and associated microorganisms (He et al., 2010). The lack effect of crop rotation on ALP activity may be because other management practices have more relevance on its activity, particularly by promoting soil microorganisms' growth; for instance, tillage practices affect the distribution of P along the soil profile and change the environment of soil microorganisms (Khan et al., 2023; Lv et al., 2023).

Several meta-analyses have reported a positive effect between APase activity and fertilization in different agro-ecosystems (Chen et al., 2023; Margalef et al., 2021; Miao et al., 2019). Our results confirm this trend in croplands since both enzymes are highly influenced by fertilization type. However, the positive link between chemical fertilizer based on N, P or combined use of NP with APase activity found in the literature (Jian et al., 2016; Marklein and Houlton, 2012; Margalef et al., 2021) are not aligned with our results since inorganic fertilization decreased ACP and ALP activity. The explanation of this result is that APase activity is inhibited by inorganic P addition and stimulated under P deficient conditions (Janes-Bassett et al., 2022; Nannipieri et al., 2011) and so in agriculture the legacy effects of long-term inorganic fertilizer addition could diminish the P soil deficiency. However, the combination of organic and inorganic fertilization, as well as the use of organic fertilizers, clearly promotes both APase activity in our study and in other published studies as well (Campdelacreu Rocabruna et al., 2024; Janes-Bassett et al., 2022; Miao et al., 2019). ACP activity is influenced by the interaction between fertilization and type of cropping system. The positive effect of crop rotation on ACP activity is further enhanced when combined with organic or organic-inorganic fertilization. This confirms previous findings such as the significant interaction effect of crop rotation with nutrient management on ACP activity, specifically in legume-inclusive rotations (Borase et al., 2021).

Both ACP and ALP activity are influenced by tillage practices responding positively when conservation, reduced or zero tillage is used compared to conventional tillage. Although some literature found no influence of tillage practices on APase activity

(Aon and Colaneri, 2001; Cochran et al., 1989), it is generally demonstrated that intensive tillage decreases soil quality and fertility, and that soil enzymes are sensitive to such changes in the soil (García-Ruiz et al., 2008) causing a decrease in their activity. Conversely, reduced tillage creates favourable conditions for the activity of ACP and ALP because it also increases organic C, total N, and total bacterial and fungal abundance (Swedrzynska et al., 2013). Under zero tillage soils contain higher fungi, bacteria and actinomycetes abundance compared to conventional tillage, meaning that ALP activity is higher (Kumar et al., 2017). Additionally, the stable P content is likely due to microbial turnover, where microbes immobilize and release P (via APase activity), maintaining consistency (Oberson et al., 2011).

Although the interaction of tillage with fertilization is not significant for ACP, it is for ALP; the better physical soil condition, provided by the organic matter from organic fertilization, produces less soil disturbance which positively affects establishment and P solubilization by microorganisms (Shahane et al., 2020). The benefits of no tillage are also found under mineral P fertilization where the stratification of soil microbial variables is often interrelated to an increase in soil organic matter in the surface layer (Shi et al., 2012; Kandeler et al., 1999). However, our results showing higher ALP activity under intensive tillage when combined with both inorganic and organic fertilization, and compared to other tillage practices, were totally unexpected. One possible explanation for this result is that fertilization boosts soil P content in plots with minimal soil disturbance (Balota et al., 2014), while intensive tillage, characterized by soil redistribution, significantly impacts the distribution of available N and extractable P (Li et al., 2012). This could stimulate ALP activity to meet the P demand of plants and microorganisms.

Finally, regarding the use of irrigation systems, it has been suggested that water deficiency reduces the supply of inorganic P, inducing microbial communities towards a higher production of exocellular phosphatase (e.g., ALP activity) (Meli et al., 2002). This is supported by our results, since higher ALP activity was observed in rainfed crops compared to those under irrigation, indicating that an irregular water supply may have led to this microbial response (Fig. 6b). Thus, ALP activity seems to be the most sensitive enzyme in revealing differences between irrigated and rainfed areas (Abdalla and Lager, 2009). However, the interaction between irrigation system with fertilization type enhanced only ACP activity, with the combined use of irrigation and organic fertilization being the most beneficial combination. Nutrient management and irrigation system have been previously shown to positively affect soil quality indicators such as ACP activity (Blaise and Rao, 2004; Kumar et al., 2021). Although drip fertigation (inorganic) caused no effect on ACP and ALP activity in peanuts (Jain et al., 2021), fertigation is a common practice in horticulture systems and the results obtained in our study open a door to better knowledge of the potential benefits of aqueous compost/vermicompost extracts used as alternatives to conventional mineral solutions (Carricondo-Martínez et al., 2022).

5.5.4 Factors affecting crop yield

The results obtained from our global analysis demonstrate that both ACP and ALP activity have a positive effect on crop yield (Fig 8), confirming our fourth hypothesis. However, in the model where ACP activity is the independent variable, the two-way interactions between ACP and type of cropping system, tillage, and crop taxonomical affiliation (family) were significant (Fig. 7, Table S5). Regarding the type of cropping system, the positive relationship between ACP and yield was further enhanced under crop rotation compared to continuous cropping as cited in the literature (Jain et al., 2018; Rao et al., 1995). As discussed above, ACP activity was itself positively affected by crop rotation, indicating that there may be a positive feedback effect between this cropping system, ACP activity and crop yield. Regarding tillage, ACP activity exhibited the greatest effect on yield under conventional tillage. This may indicate that there are other positive effects on crop yield under conventional tillage that outweigh any benefit of high ACP activity. Alternatively, it may be related to the fact that the database includes more studies using conventional tillage than reduced or zero, potentially creating a bias in the results (data not shown). These results confirm the fact that ACP activity, which is linked to plants and microorganisms, is more sensitive to agricultural management and therefore can be good indicator of soil P availability. In the case of ALP activity and when both APase have been evaluated together, there are no interactions significantly affecting the crop yield although, as expected, species and fertilization do so separately (Fig. S5, Fig. S6).

As ACP activity doubles from 100 to 200 mg pNP kg-1h-1, the crop yield increases by more than two-fold, which is an outcome that has not been demonstrated in croplands until now as the available previous literature does not show any clear link between yield and APase activity (Campdelacreu Rocabruna et al., 2024) in agriculture. The recently published global datasets show a positive link found between nutrient P availability and optimal crop growth (McDowell et al., 2023; Ringeval et al., 2024) but they not conclusively establish that optimal growth translates into an increase in crop yield. Additionally, a direct bidirectional relationship between ALP activity and yield exists (Fig. S7), not evidenced in the case of ACP activity. Absence of these comprehensive analyses would necessitate long-term studies to understand the links between APase activity and improvements in crop yields (Choudhary et al., 2018; Wang et al., 2021b), as crop yield depends on various factors including species diversity and different soil properties such as total N, soil organic matter, pH, and total P (Qaswar et al., 2019). Additionally, climatic conditions, variations in amendment composition, and irrigation water quality (Chocano et al., 2016) act as confounding factors. Hence, the outcomes outlined in our study offer pertinent insights by illustrating a strong relationship between APase activity and crop yield.

5.5.5 Applicable outcomes of the results

The identified relationships between APase activity and climatic or management factors offer valuable insights for decision-making in agriculture. Farmers can utilize these findings to optimize their farming practices and improve crop productivity by adjusting management practices to enhance APase activity in the soil, thereby improving P availability for crops, leading to better nutrient uptake and yield. The main strategies to enhance APase activity in cropland soils fall within the practices of regenerative agriculture (Giller et al., 2021), providing hopeful prospects for enhanced land management, ensuring food production while strengthening agricultural resilience amid the current climate crisis. Moving away from intensive agriculture, which relies on increased N and P supplies to enhance yield, is likely in the future. Diminishing returns from fertilizer application suggest that additional applications may not be as effective at increasing yields. (Tilman et al., 2002). Addressing these challenges will necessitate substantial improvements in nutrient-use efficiency through practices that meet current and future societal needs for food, ecosystem services, and healthy living and achieve this by maximizing the overall societal benefit when considering all costs and benefits of the practices. Moreover, the study underscores the significance of delving deeper into the intricate interactions between APase and crops. For example, conducting comprehensive investigations into genotype, physiology, and morphology can enhance our comprehension of how to efficiently manage P in croplands and improve yields.

5.6 Conclusions

Phosphomonoesterases play a crucial role in the transformation of P in the soil. In this study focusing on cropland soils, the findings indicate that APase activity is influenced by climatic and agro-ecosystem management factors. Elevated temperatures lead to a decline in the activity of both ACP and ALP. Moreover, ALP activity is influenced by the interaction between mean annual temperature (MAT) and mean annual precipitation (MAP), exhibiting higher activities at lower temperatures, particularly in regions with higher precipitation. Regarding the crop taxonomical affiliation (family), it had a significant effect on APase activity. However, further exploration of their genotype, physiology, and morphology is imperative for a more detailed understanding of the interactions between enzymes and crops, and how to control these variables. Concerning management, ACP activity is enhanced by organic fertilization under crop rotation and irrigation. Conversely, ALP activity is increased by organic and a combination of inorganic-organic fertilization and reduced or zero tillage practices. These results may provide guidance to farmers and researchers, promoting the potential for reducing reliance on chemical fertilizers and promoting ecological farming practices. Lastly, the strong linkage between crop yield and APase activity underscores the potential for demonstrating that, with careful consideration of climatic conditions, crop species, and conservative management practices, cost-benefit analysis can lead to increase yields. These findings have the potential to advance sustainable agricultural practices and address global challenges such as climate change and food security.

5.7 Authorship, data availability, competing interests and acknowledgments

Author contributions

Conceptualization PCR, XD, CP, JP; Data curation PCR; Formal analysis PCR; Funding acquisition XD, JP; Investigation PCR, XD, CP, JP; Methodology PCR; Software PCR, MF-M, JP; Supervision XD, CP, JP; Validation PCR; Visualization PCR; Roles/Writing - original draft PCR; Writing-Review & Editing: PCR, XD, CP, JP; Review- approved final manuscript all authors.

Supporting information

Supplementary materials associated with this article can be found in the online version.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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5.8 References

Abdalla, M.A. and Langer, U. 2009. Soil Enzymes Activities in Irrigated and Rain-Fed Vertisols of the Semi-Arid Tropics of Sudan. International Journal of Soil Science 4: 67-79. https://scialert.net/abstract/?doi=ijss.2009.67.79.

Akaike, H., 1998. Information Theory and an Extension of the Maximum Likelihood Principle. In E. Parzen, K. Tanabe, G. Kitagawa (Eds.), Selected Papers of Hirotugu Akaike (pp. 199–213). Springer New York. https://doi.org/10.1007/978-1-4612-1694-0_15.

Alef, K., Nannipieri, P. (Eds.), 1995. 7 - Enzyme activities, in: Methods in Applied Soil Microbiology and Biochemistry. Academic Press, London, pp. 311–373. https://doi.org/10.1016/B978-012513840-6/50022-7.

Allison, S.D., Weintraub, M.N., Gartner, T.B., Waldrop, M.P., 2010. Evolutionary-Economic Principles as Regulators of Soil Enzyme Production and Ecosystem Function. In G21/06/2024 14:29:00. Shukla and A. Varma (Eds.), Soil Enzymology pp. 229–243. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-14225-3_12.

Aparna, K., Rao, D.L.N., Balachandar, D., 2016. Microbial Populations, Activity and Gene Abundance in Tropical Vertisols Under Intensive Chemical Farming. Pedosphere 26(5), 725–732. https://doi.org/10.1016/S1002-0160(15)60079-0.

Aon, M.A., Colaneri, A.C., 2001. II. Temporal and spatial evolution of enzymatic activities and physico-chemical properties in an agricultural soil. Applied Soil Ecology 18(3), 255–270. https://doi.org/10.1016/S0929-1393(01)00161-5.

Balota, E.L., Kanashiro, M., Filho, A.C., Andrade, D.S., Dick, R.P., 2004. Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agro-ecosystems. Brazilian Journal of Microbiology 35(4), 300–306. https://doi.org/10.1590/S1517-83822004000300006.

Balota, E.L., Machineski, O., Hamid, K.I.A., Yada, I.F.U., Barbosa, G.M.C., Nakatani, A. S., Coyne, M.S., 2014. Soil microbial properties after long-term swine slurry application to conventional and no-tillage systems in Brazil. Science of the Total

Environment 490, 397–404. https://doi.org/10.1016/j.scitotenv.2014.05.019.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67(1), 1–48.8. https://doi.org/10.18637/jss.v067.i0.

Blaise, D., Rao, M.R.K., 2004. Glucosidase and alkaline phosphatase activity as affected by organic and modern method of cotton (Gossypium hirsutum) cultivation of the rainfed Vertisols. Indian Journal of Agricultural Sciences 74(5), 276–278.

Borase, D.N., Murugeasn, S., Nath, C. P., Hazra, K.K., Singh, S.S., Kumar, N., Singh, U., Praharaj, C.S., 2021. Long-term impact of grain legumes and nutrient management practices on soil microbial activity and biochemical properties. Archives of Agronomy and Soil Science 67(14), 2015–2032. https://doi.org/10.1080/03650340.2020.1819532.

Burns, R.G., 1982. Enzyme activity in soil: Location and a possible role in microbial ecology. Soil Biology and Biochemistry 14, 423–427. https://doi.org/10.1016/0038-0717(82)90099-2.

Campdelacreu Rocabruna, P., Domene, X., Preece, C., Peñuelas, J., 2024. Relationship among Soil Biophysicochemical Properties, Agricultural Practices and Climate Factors Influencing Soil Phosphatase Activity in Agricultural Land. Agriculture 14(288). https://doi.org/10.3390/agriculture14020288.

Cao, N., Zhi, M., Zhao, W., Pang, J., Hu, W., Zhou, Z., Meng, Y., 2022. Straw retention combined with phosphorus fertilizer promotes soil phosphorus availability by enhancing soil P-related enzymes and the abundance of phoC and phoD genes. Soil and Tillage Research 220, 105390. https://doi.org/10.1016/j.still.2022.105390.

Carlos, F.S., Schaffer, N., Mariot, R.F., Fernandes, R.S., Boechat, C.L., Roesch, L.F.W., Camargo, F. A. de O., 2022. Soybean crop incorporation in irrigated rice cultivation improves nitrogen availability, soil microbial diversity and activity, and growth of ryegrass. Applied Soil Ecology 170. https://doi.org/10.1016/j.apsoil.2021.104313.

Carricondo-Martínez, I., Falcone, D., Berti, F., Orsini, F., Salas-Sanjuan, M.D.C., 2022. Use of Agro-Waste as a Source of Crop Nutrients in Intensive Horticulture System. Agronomy 12(2), 1–12. https://doi.org/10.3390/agronomy12020447.

Chatterjee, D., Nayak, A.K., Mishra, A., Swain, C.K., Kumar, U., Bhaduri, D., Panneerselvam, P., Lal, B., Gautam, P., Pathak, H., 2021. Effect of Long-Term Organic Fertilization in Flooded Rice Soil on Phosphorus Transformation and Phosphate Solubilizing Microorganisms. Journal of Soil Science and Plant Nutrition 21(2), 1368–1381. https://doi.org/10.1007/s42729-021-00446-8.

Chen, Y., Xia, A., Zhang, Z., Wang, F., Chen, J., Hao, Y., Cui, X., 2023. Extracellular enzyme activities response to nitrogen addition in the rhizosphere and bulk soil: A global meta-analysis. Agriculture Ecosystems & Environment 356. https://doi.org/10.1016/j.agee.2023.108630.

Chocano, C., García, C., González, D., Aguilar, J. M. de, Hernández, T., 2016. Organic plum cultivation in the Mediterranean region: The medium-term effect of five different organic soil management practices on crop production and microbiological soil quality. Agriculture, Ecosystems & Environment 221, 60–70. https://doi.org/10.1016/j.agee.2016.01.03.1

Cochran, V.L., Elliott, L. F., Lewis, C.E., 1989. Soil microbial biomass and enzyme activity in subarctic agricultural and forest soils. Biology and Fertility of Soils 7(4), 283–288. https://doi.org/10.1007/BF00257821.

Choudhary, M., Datta, A., Jat, H.S., Yadav, A.K., Gathala, M.K., Sapkota, T.B., Das, A.K., Sharma, P.C., Jat, M.L., Singh, R., Ladha, J.K., 2018. Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. Geoderma 313, 193–204. https://doi.org/10.1016/j.geoderma.2017.10.041.

Choudhary, M., Meena, V.S., Panday, S.C., Mondal, T., Yadav, R.P., Mishra, P.K., Bisht, J.K., Pattanayak, A., 2021. Long-term effects of organic manure and inorganic fertilization on biological soil quality indicators of soybean-wheat rotation in the Indian mid-Himalaya. Applied Soil Ecology 157, 103754. https://doi.org/10.1016/j.apsoil.2020.103754.

Cong, W.F., Suriyagoda, L.D.B., Lambers, H., 2020. Tightening the Phosphorus Cycle through Phosphorus-Efficient Crop Genotypes. Trends in Plant Science 25, 967–975. https://doi.org/10.1016/j.tplants.2020.04.013.

Cui, Y., Fang, L., Guo, X., Wang, X., Wang, Y., Zhang, Y., Zhang, X., 2019. Responses of soil bacterial communities, enzyme activities, and nutrients to agricultural-to-natural ecosystem conversion in the Loess Plateau, China. Journal of Soils and Sediments 19, 1427–1440. https://doi.org/10.1007/s11368-018-2110-4.

Del Rossi, G., Hoque, M.M., Ji, Y., Kling, C.L., 2023. The Economics of Nutrient Pollution from Agriculture. Annual Review of Resource Economics 15(1), 105–130. https://doi.org/10.1146/annurev-resource-111820-021317.

Dick, R.P., Breakwell, D.P., Turco, R.F., 1997. Soil Enzyme Activities and Biodiversity Measurements as Integrative Microbiological Indicators, in: Methods for Assessing Soil Quality. John Wiley & Sons, Ltd, pp. 247–271. https://doi.org/10.2136/sssaspecpub49.c15.

Eichler-Löbermann, B., Zicker, T., Kavka, M., Busch, S., Brandt, C., Stahn, P., Miegel, K., 2021. Mixed cropping of maize or sorghum with legumes as affected by long-term phosphorus management. Field Crops Research 265.

https://doi.org/10.1016/j.fcr.2021.108120.

Eivazi, F., Tabatabai, M.A., 1977. Phosphatases in soils. Soil Biology and Biochemistry 9(3), 167–172. https://doi.org/10.1016/0038-0717(77)90070-0.

Faostat. Comparar datos (2021, 17 September.). Organización de las Naciones Unidas para la alimentación y la Agricultura http://www.fao.org/faostat/es/#compare.

Feng, H., Sekaran, U., Wang, T., Kumar, S., 2021. On-farm assessment of cover cropping effects on soil C and N pools, enzyme activities, and microbial community structure. Journal of Agricultural Science 159(3–4), 216–226. https://doi.org/10.1017/S002185962100040X.

Föhse, D., Claassen, N., Jungk, A., 1988. Phosphorus efficiency of plants. Plant and Soil 110, 101–109. https://doi.org/10.1007/BF02143545.

Fox, J., Weisberg, S., Friendly, M., Hong, J., Andersen, R., Firth, D., et al., 2016. Package 'effects'. http://www.r-project.org. http://socserv.socsci.mcmaster.ca/jfox.

Furtak, K., Gawryjołek, K., Gajda, A.M., Gałązka, A., 2017. Effects of maize and winter wheat grown under different cultivation techniques on biological activity of soil. Plant, Soil and Environment 63(10), 449–454. https://doi.org/10.17221/486/2017-PSE.

Gao, D., Bai, E., Li, M., Zhao, C., Yu, K., Hagedorn, F., 2020. Responses of soil nitrogen and phosphorus cycling to drying and rewetting cycles: A meta-analysis. Soil Biology and Biochemistry 148, 107896. https://doi.org/10.1016/j.soilbio.2020.107896.

Garcia-Alvarez, A., Ibañez, J.J., 1994. Seasonal fluctuations and crop influence on microbiota and enzyme activity in fully developed soils of central Spain. Arid Soil Research and Rehabilitation 8, 161–178. https://doi.org/10.1080/15324989409381390.

García-Ruiz, R., Ochoa, V., Hinojosa, M.B., Carreira, J.A., 2008. Suitability of enzyme activities for the monitoring of soil quality improvement in organic agricultural systems. Soil Biology and Biochemistry 40(9), 2137–2145. https://doi.org/10.1016/j.soilbio.2008.03.023.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I., Benton, T., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P., Toulmin, C., Vermeulen, S., Godfray, C. 2013. Sustainable Intensification in Agriculture: Premises and Policies. Science (New York, N.Y.) 341 33-4. https://www.science.org/doi/10.1126/science.1234485.

Giller, K. E., Hijbeek, R., Andersson, J. A., Sumberg, J., 2021. Regenerative agriculture: an agronomic perspective. Outlook on Agriculture, 50(1), 13-25. https://doi.org/10.1177/0030727021998063.

Gong, S., Zhang, T., Guo, J., 2020. Warming and nitrogen deposition accelerate soil phosphorus cycling in a temperate meadow ecosystem. Soil Research 58(1), 109.

https://doi.org/10.1071/SR19114.

He, Z., Honeycutt, C.W., Griffin, T.S., Larkin, R.P., Olanya, M., Halloran, J.M., 2010. Increases of soil phosphatase and urease activities in potato fields by cropping rotation practices. Journal of Food, Agriculture and Environment 8(2), 1112–1117.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25, 1965–1978.

Hu, W., Tan, J., Shi, X., Lock, T.R., Kallenbach, R.L., Yuan, Z., 2022. Nutrient addition and warming alter the soil phosphorus cycle in grasslands: A global meta-analysis. Journal of soils and sediments 22(10), 2608–2619. https://doi.org/10.1007/s11368-022-03276-y.

Jain, N.K., Jat, R.S., Meena, H.N., Chakraborty, K., 2018. Productivity, Nutrient, and Soil Enzymes Influenced with Conservation Agriculture Practices in Peanut. Agronomy Journal 110 (3), 1165–1172. https://doi.org/10.2134/agronj2017.08.0467.

Jain, N.K., Yadav, R. S., Jat, R.A., 2021. Productivity, Profitability, Enzyme Activities and Nutrient Balance in Summer Peanut (Arachis hypogaea L.) as Influenced by NPK Drip Fertigation. Communications in Soil Science and Plant Analysis 52(5), 443–455. https://doi.org/10.1080/00103624.2020.1854287.

Janes-Bassett, V., Blackwell, M.S.A., Blair, G., Davies, J., Haygarth, P.M., Mezeli, M. M., Stewart, G., 2022. A meta-analysis of phosphatase activity in agricultural settings in response to phosphorus deficiency. Soil Biology and Biochemistry 165, 108537. https://doi.org/10.1016/j.soilbio.2021.108537.

Jian, S., Li, J., Chen, J., Wang, G., Mayes, M.A., Dzantor, K.E., Hui, D., Luo, Y., 2016. Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. Soil Biology and Biochemistry 101, 32–43. https://doi.org/10.1016/j.soilbio.2016.07.003.

Kandeler, E., Tscherko, D., Spiegel, H., 1999. Long-Term Monitoring of Microbial Biomass, N Mineralisation and Enzyme Activities of a Chernozem under Different Tillage Management'. Biology and Fertility of Soils 28(4), 343–51. https://doi.org.10.1007/s003740050502.

Khan, M. H., Liu, H., Zhu, A., Khan, M. H., Hussain, S., Cao, H., 2023. Conservation tillage practices affect soil microbial diversity and composition in experimental fields. Frontiers in Microbiology 14, 1227297. https://doi.org/10.3389/fmicb.2023.1227297.

Kumar, B., Dhar, S., Paul, S., Paramesh, V., Dass, A., Upadhyay, P.K., Kumar, A., Abdelmohsen, S.A.M., Alkallas, F.H., El-Abedin, T.K.Z., Elansary, H.O., Abdelbacki, A.M.M., 2021. Microbial biomass carbon, activity of soil enzymes, nutrient availability, root growth, and total biomass production in wheat cultivars under variable irrigation and nutrient management. Agronomy 11(4), 1–16. https://doi.org/10.3390/agronomy11040669.

Kumar, R., Shambhavi, S., Beura, K., Kumar, S., Singh, R.G., 2017. Soil microbial budgeting as influenced by contrasting tillage and crop diversification under rice based cropping systems in Inseptisol of Bihar. Journal of Pure and Applied Microbiology 11, 539–547. https://doi.org/10.22207/JPAM.11.1.71.

Landesman, W.J., Dighton, J., 2010. Response of soil microbial communities and the production of plant-available nitrogen to a two-year rainfall manipulation in the New Jersey Pinelands. Soil Biology and Biochemistry 42, 1751–1758. https://doi.org/10.1016/j.soilbio.2010.06.012.

Lenth, R., Singmann, H., Love, J., Buerkner, P., Herve, M., 2018. Package "Emmeans". R Package Version 4.0-3. https://cran.r-project.org/web/packages/emmeans/index.html.

Li, F., Zhang, J., Su, Z., 2012. Changes in SOC and nutrients under intensive tillage in two types of slope landscapes. Journal of Mountain Science 9, 67–76. https://doi.org/10.1007/s11629-012-2192-1.

Long, J.A., 2022. Jtools: Analysis and Presentation of Social Scientific Data. R package version 2.2.0. https://cran.r-project.org/web/packages/jtools/index.html.

Luo, X., Hou, E., Zhang, L., Kuang, Y., Wen, D., 2023. Altered soil microbial properties and functions after afforestation increase soil carbon and nitrogen but not phosphorus accumulation. Biology and fertility of soils 59(6), 645–658. https://doi.org/10.1007/s00374-023-01726-4.

Lv, L., Gao, Z., Liao, K., Zhu, Q., Zhu, J., 2023. Impact of conservation tillage on the distribution of soil nutrients with depth. Soil and Tillage Research 225, 105527. https://doi.org/10.1016/j.still.2022.105527.

Margalef, O., Sardans, J., Fernández-Martínez, M., Molowny-Horas, R., Janssens, I.A., Ciais, P., Goll, D., Richter, A., Obersteiner, M., Asensio, D., Peñuelas, J., 2017. Global patterns of phosphatase activity in natural soils. Scientific Reports 7(1), 1337. https://doi.org/10.1038/s41598-017-01418-8.

Margalef, O., Sardans, J., Maspons, J., Molowny-Horas, R., Fernández-Martínez, M., Janssens, I. A., Richter, A., Ciais, P., Obersteiner, M., Peñuelas, J., 2021. The effect of global change on soil phosphatase activity. Global Change Biology 27(22), 5989–6003. https://doi.org/10.1111/gcb.15832.

Marklein, A.R., Houlton, B.Z., 2012. Nitrogen inputs accelerate phosphorus cycling rates across a wide variety of terrestrial ecosystems. New Phytologist 193, 696–704. https://doi.org/10.1111/j.1469-8137.2011.03967.x.

Martins, L.N.B., Santiago, F.L. de A., Montecchia, M.S., Correa, O.S., Junior, O.J.S., Souza, E.D. de, Paulino, H.B., Carneiro, M.A.C., 2019. Biochemical and biological properties of soil from murundus wetlands converted into agricultural systems. Revista Brasileira de Ciencia Do Solo 43, 1–13. https://doi.org/10.1590/18069657rbcs20180183.

McDowell, R.W., Noble, A., Pletnyakov, P., Haygarth, P.M., 2023. A Global Database of Soil Plant Available Phosphorus. Scientific Data 10(1), 125. https://doi.org/10.1038/s41597-023-02022-4.

Meli, S., Porto, M., Belligno, A., Bufo, S.A., Mazzatura, A., Scopa, A., 2002. Influence of irrigation with lagooned urban wastewater on chemical and microbiological soil parameters in a citrus orchard under Mediterranean condition. Science of the Total Environment 285(1–3), 69–77. https://doi.org/10.1016/S0048-9697(01)00896-8.

Meng, C., Tian, D., Zeng, H., Li, Z., Chen, H.Y.H., Niu, S., 2020. Global meta-analysis on the responses of soil extracellular enzyme activities to warming. Science of the Total Environment 705, 135992. https://doi.org/10.1016/j.scitotenv.2019.135992.

Miao, F., Li, Y., Cui, S., Jagadamma, S., Yang, G., Zhang, Q., 2019. Soil extracellular enzyme activities under long-term fertilization management in the croplands of China: A meta-analysis. Nutrient Cycling in Agroecosystems 114(2), 125–138. https://doi.org/10.1007/s10705-019-09991-2.

Mondal, T., Yadav, R.P., Mishra, P.K., Bisht, J.K., Pattanayak, A., 2021. Long-term effects of organic manure and inorganic fertilization on biological soil quality indicators of soybean-wheat rotation in the Indian mid-Himalaya. Applied Soil Ecology 157, 103754. https://doi.org/10.1016/j.apsoil.2020.103754.

Monkiedje, A., Spiteller, M., Fotio, D., Sukul, P., 2006. The Effect of Land Use on Soil Health Indicators in Peri-Urban Agriculture in the Humid Forest Zone of Southern Cameroon. Journal of Environmental Quality 35(6), 2402–2409. https://doi.org/10.2134/jeq2005.0447.

Mou, X.M., Wu, Y., Niu, Z., Jia, B., Guan, Z.-H., Chen, J., Li, H., Cui, H., Kuzyakov, Y., Li, X.G., 2020. Soil phosphorus accumulation changes with decreasing temperature along a 2300 m altitude gradient. Agriculture, Ecosystems & Environment 301, 107050. https://doi.org/10.1016/j.agee.2020.107050.

Nannipieri, P., Giagnoni, L., Landi, L., Renella, G., 2011. Role of Phosphatase Enzymes in Soil, in: Bünemann, E., Oberson, A., Frossard, E. (Eds.), Phosphorus in Action: Biological Processes in Soil Phosphorus Cycling. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 215–243. https://doi.org/10.1007/978-3-642-15271-9_9.

Oberson, A., Pypers, P., Bünemann, E.K., Frossard, E., 2011. Management Impacts on Biological Phosphorus Cycling in Cropped Soils. In E. Bünemann, A. Oberson, and E. Frossard (Eds.), Phosphorus in Action (Vol. 26, pp. 431–458). Springer Berlin

Heidelberg. https://doi.org/10.1007/978-3-642-15271-9_17.
Oelmann, Y., Richter, A.K., Roscher, C., Rosenkranz, S., Temperton, V.M., Weisser, W. W., Wilcke, W., 2011. Does plant diversity influence phosphorus cycling in experimental grasslands? Geoderma 167–168, 178–187. https://doi.org/10.1016/j.geoderma.2011.09.012.
Panagos, P., Köningner, J., Ballabio, C., Liakos, L., Muntwyler, A., Borrelli, P., Lugato, E., 2022. Improving the phosphorus budget of European agricultural soils. Science of the Total Environment 853, 158706. https://doi.org/10.1016/j.scitotenv.2022.158706.
Peñuelas, J., Poulter, B., Sardans, J., Ciais, P., van der Velde, M., Bopp, L., Boucher, O., Godderis, Y., Hinsinger, P., Llusia, J., Nardin, E., Vicca, S., Obersteiner, M., Janssens, I.A., 2013. Human-induced nitrogen–phosphorus imbalances alter natural and managed ecosystems across the globe. Nature Communications 4(1), 2934. https://doi.org/10.1038/ncomms3934.
Qu, Q., Wang, Z., Gan, Q., Liu, R., Xu, H., 2023. Impact of drought on soil microbial biomass and extracellular enzyme activity. Frontiers in Plant Science 14. https://doi.org/10.3389/fpls.2023.1221288.
Qaswar, M., Jing, H., Ahmed, W., Dongchu, L., Shujun, L., Ali, S., Kailou, L., Yongmei, X., Lu, Z., Lisheng, L., Jusheng, G., Huimin, Z., 2019. Long-term green manure rotations improve soil biochemical properties, yield sustainability and nutrient balances in acidic paddy soil under a rice-based cropping system. Agronomy 9. https://doi.org/10.3390/agronomy9120780.
Rao, A.V., Tarafdar, J.C., Sharma, S.K., Kumar, P., Aggarwal, R.K., 1995. Influence of cropping systems on soil biochemical properties in an arid rain-fed environment. Journal of Arid Environments 31(2), 237–244. https://doi.org/10.1006/jare.1995.0063.
Riddle, M., Bergström, L., Schmieder, F., Kirchmann, H., Condron, L., Aronsson, H., 2018. Phosphorus Leaching from an Organic and a Mineral Arable Soil in a Rainfall Simulation Study. Journal of Environmental Quality 47, 487–495. https://doi.org/10.2134/jeq2018.01.0037.
Riffaldi, R., Saviozzi, A., Levi-Minzi, R., Cardelli, R., 2002. Biochemical properties of a Mediterranean soil as affected by long-term crop management systems. Soil and Tillage Research 67(1), 109–114. https://doi.org/10.1016/S0167-1987(02)00044-2.
Ringeval, B., Demay, J., Goll, D. S., He, X., Wang, Y.P., Hou, E., Matej, S., Erb, K.H., Wang, R., Augusto, L., Lun, F., Nesme, T., Borrelli, P., Helfenstein, J., McDowell, R.W., Pletnyakov, P., Pellerin, S., 2024. A global dataset on phosphorus in agricultural soils. Scientific Data 11(1), 17. https://doi.org/10.1038/s41597-023-02751-6.
Sardans, J., and Peñuelas, J., 2004. Increasing drought decreases phosphorus availability in an evergreen Mediterranean forest. Plant and Soil 267(1), 367–377.

https://doi.org/10.1007/s11104-005-0172-8.

Sardans, J., Peñuelas, J., Estiarte, M., 2006. Warming and drought alter soil phosphatase activity and soil P availability in a Mediterranean shrubland. Plant and Soil 289(1), 227–238. https://doi.org/10.1007/s11104-006-9131-2.

Schultz, J., French, R., 1978. The mineral content of cereals, grain legumes and oilseed crops in South Australia. Australian Journal of Experimental Agriculture 18(93), 579. https://doi.org/10.1071/EA9780579.

Shahane, A.A., Shivay, Y.S., Prasanna, R., 2020. Enhancing phosphorus and iron nutrition of wheat through crop establishment techniques and microbial inoculations in conjunction with fertilization. Soil Science and Plant Nutrition 66(5), 763–771. https://doi.org/10.1080/00380768.2020.1799692.

Shi, Y., Lalande, R., Ziadi, N., Sheng, M., Hu, Z., 2012. An assessment of the soil microbial status after 17 years of tillage and mineral P fertilization management. Applied Soil Ecology 62, 14–23. https://doi.org/10.1016/j.apsoil.2012.07.004.

Simpson, R.J., Oberson, A., Culvenor, R.A., Ryan, M.H., Veneklaas, E.J., Lambers, H., Lynch, J.P., Ryan, P.R., Delhaize, E., Smith, F.A., Smith, S.E., Harvey, P.R., Richardson, A.E., 2011. Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems. Plant and Soil 349(1–2), 89–120. https://doi.org/10.1007/s11104-011-0880-1.

Singh, S.R., Yadav, P., Singh, D., Bahadur, L., Singh, S.P., Yadav, A.S., Mishra, A., Yadav, P.P.S., Kumar, S., 2021. Impact of different cropping systems on the land nutrient index, microbial diversity, and soil quality. Land Degradation and Development 32(14), 3973–3991. https://doi.org/10.1002/ldr.3863.

Sun, Y., Goll, D. S., Ciais, P., Peng, S., Margalef, O., Asensio, D., Sardans, J., Peñuelas, J., 2020. Spatial Pattern and Environmental Drivers of Acid Phosphatase Activity in Europe. Frontiers in Big Data 2, 1–13. https://doi.org/10.3389/fdata.2019.00051.

Sünnemann, M., Beugnon, R., Breitkreuz, C., Buscot, F., Cesarz, S., Jones, A., Lehmann, A., Lochner, A., Orgiazzi, A., Reitz, T., Rillig, M.C., Schädler, M., Smith, L.C., Zeuner, A., Guerra, C.A., Eisenhauer, N., 2023. Climate change and cropland management compromise soil integrity and multifunctionality. Communications Earth & Environment 4, 394. https://doi.org/10.1038/s43247-023-01047-2.

Swedrzynska, D., Małecka, I., Blecharczyk, A., Swędrzyński, A., Starzyk, J., 2013. Effects of Various Long-Term Tillage Systems on Some Chemical and Biological Properties of Soil. Polish Journal of Environmental Studies *22*, 1835–1844.

Tabatabai, M.A., 1994. Soil Enzymes. In Methods of Soil Analysis (pp. 775–833). https://doi.org/10.2136/sssabookser5.2.c37.

Tabatabai, M.A., Bremner, J.M., 1969. Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. Soil Biology and Biochemistry 1(4), 301–307. https://doi.org/10.1016/0038-0717(69)90012-1.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677. https://doi.org/10.1038/nature01014.

Tripathi, S., Chakraborty, A., Chakrabarti, K., Bandyopadhyay, B.K., 2007. Enzyme activities and microbial biomass in coastal soils of India. Soil Biology and Biochemistry 39, 2840–2848. https://doi.org/10.1016/j.soilbio.2007.05.027.

Von Uexküll, H.R., Mutert, E. 1995. Global Extent, Development and Economic Impact of Acid Soils. Plant and Soil 171(1):1–15.

Vågsholm, I., Arzoomand, N.S., Boqvist, S., 2020. Food Security, Safety, and Sustainability—Getting the Trade-Offs Right. Frontiers in Sustainable Food System4, 16. d https://doi.org/10.3389/fsufs.2020.00016.

Veneklaas, E.J., Lambers, H., Bragg, J., Finnegan, P.M., Lovelock, C.E., Plaxton, W.C., Price, C.A., Scheible, W., Shane, M.W., White, P.J., Raven, J.A., 2012. Opportunities for improving phosphorus-use efficiency in crop plants. New Phytologist 195(2), 306–320. https://doi.org/10.1111/j.1469-8137.2012.04190.x.

Wang, F., Tang, J., Li, Z., Xiang, J., Wang, L., Tian, L., Jiang, L., Luo, Y., Hou, E., Shao, X., 2021a. Warming reduces the production of a major annual forage crop on the Tibetan Plateau. Science of the Total Environment 798(2), 149211. https://doi.org/10.1016/j.scitotenv.2021.149211.

Wang, Y., Huang, C., Liu, M., Yuan, L., 2021b. Long-term application of manure reduced nutrient leaching under heavy N deposition. Nutrient Cycling in Agroecosystems 4. https://doi.org/10.1007/s10705-020-10107-4.

Wang, W., Li, Y., Guan, P., Chang, L., Zhu, X., Zhang, P., Wu, D., 2022. How do climate warming affect soil aggregate stability and aggregate-associated phosphorus storage under natural restoration? Geoderma 420(2555), 115891. https://doi.org/10.1016/j.geoderma.2022.115891.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis, Springer-Verlag New York. Available at: https://ggplot2.tidyverse.org.

Weil R.R., Brady N.C., 2016. The Nature and Properties of Soils (15th Edition). Pearson Press. https://doi.org/10.2136/sssaj2016.0005br.

Yang, X., Bao, X., Yang, Y., Zhao, Y., Liang, C., Xie, H., 2019. Comparison of soil phosphorus and phosphatase activity under long-term no-tillage and maize residue management. Plant, Soil and Environment 65(8), 408–415. https://doi.org/10.17221/307/2019-PSE.

Yu, H., Wang, F., Shao, M., Huang, L., Xie, Y., Xu, Y., Kong, L., 2021. Effects of Rotations

With Legume on Soil Functional Microbial Communities Involved in Phosphorus Transformation. Frontiers in Microbiology 12. https://doi.org/10.3389/fmicb.2021.661100.

Yuan, D., Hu, Y., Jia, S., Li, W., Zamanian, K., Han, J., Huang, F., Zhao, X., 2023. Microbial Properties Depending on Fertilization Regime in Agricultural Soils with Different Texture and Climate Conditions: A Meta-Analysis. Agronomy-basel 13(3). https://doi.org/10.3390/agronomy13030764.

Zhong, Y., Tian, J., Li, X., Liao, H., 2023. Cooperative interactions between nitrogenfixation and phosphorus nutrition in legumes. New Phytologist 237(3), 734–745. https://doi.org/10.1111/nph.18593.

Zhou, X., Chen, C., Wang, Y., Xu, Z., Han, H., Li, L., Wan, S., 2013. Warming and increased precipitation have differential effects on soil extracellular enzyme activities in a temperate grassland. Science of The Total Environment 444, 552–558. https://doi.org/10.1016/j.scitotenv.2012.12.023.

Zuccarini, P., Asensio, D., Ogaya, R., Sardans, J., Peñuelas, J., 2020. Effects of seasonal and decadal warming on soil enzymatic activity in a P-deficient Mediterranean shrubland. Global Change Biology 26, 3698–3714. https://doi.org/10.1111/gcb.15077.

Zuccarini, P., Sardans, J., Asensio, L., Penuelas, J., 2023. Altered activities of extracellular soil enzymes by the interacting global environmental changes. Global Change Biology 29(8), 2067–2091. https://doi.org/10.1111/gcb.16604.

5.9 Supplementary material Chapter 2

Figures

Figure S1. PRISMA flow diagram of articles reviewed (PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses).

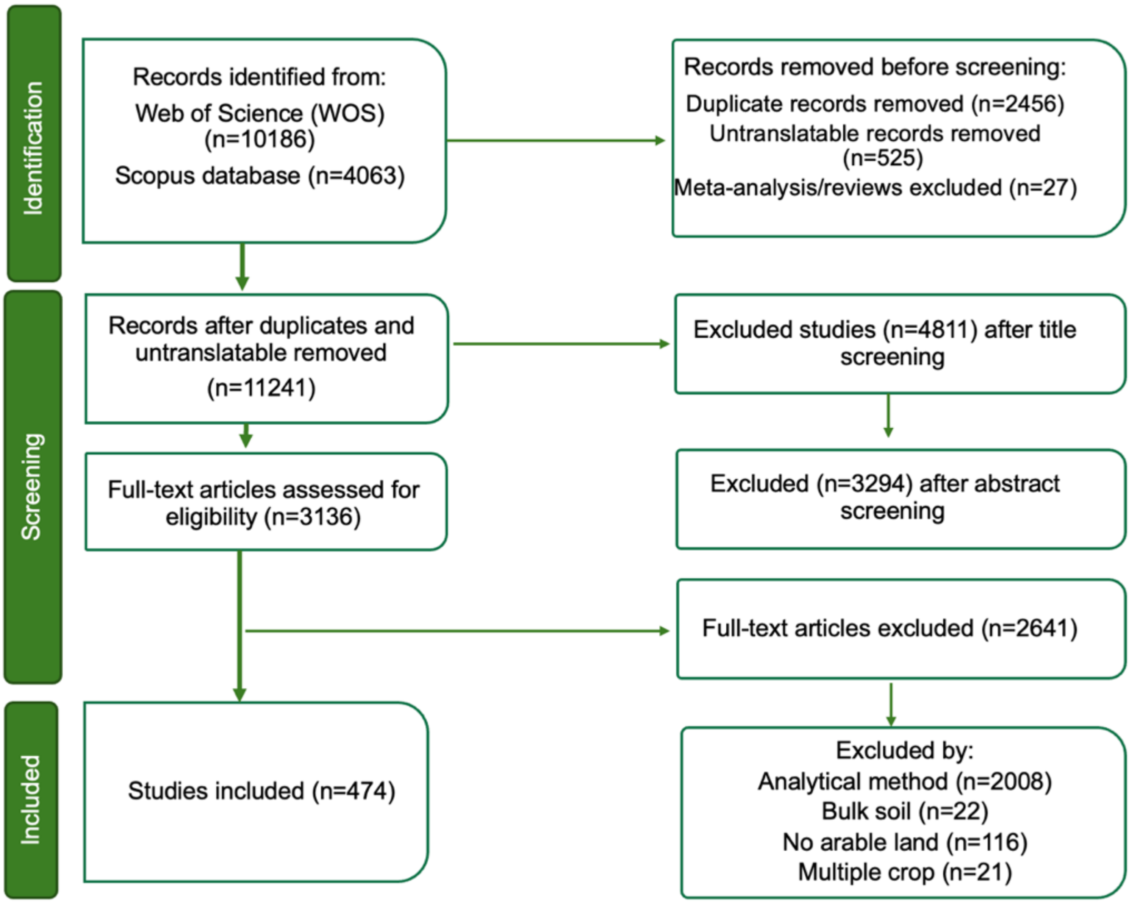


Figure S2. Graphical analysis of observations to verify the outliers on ACP activity. The green lines separate the results considered non-outliers from the outliers (n=3517).

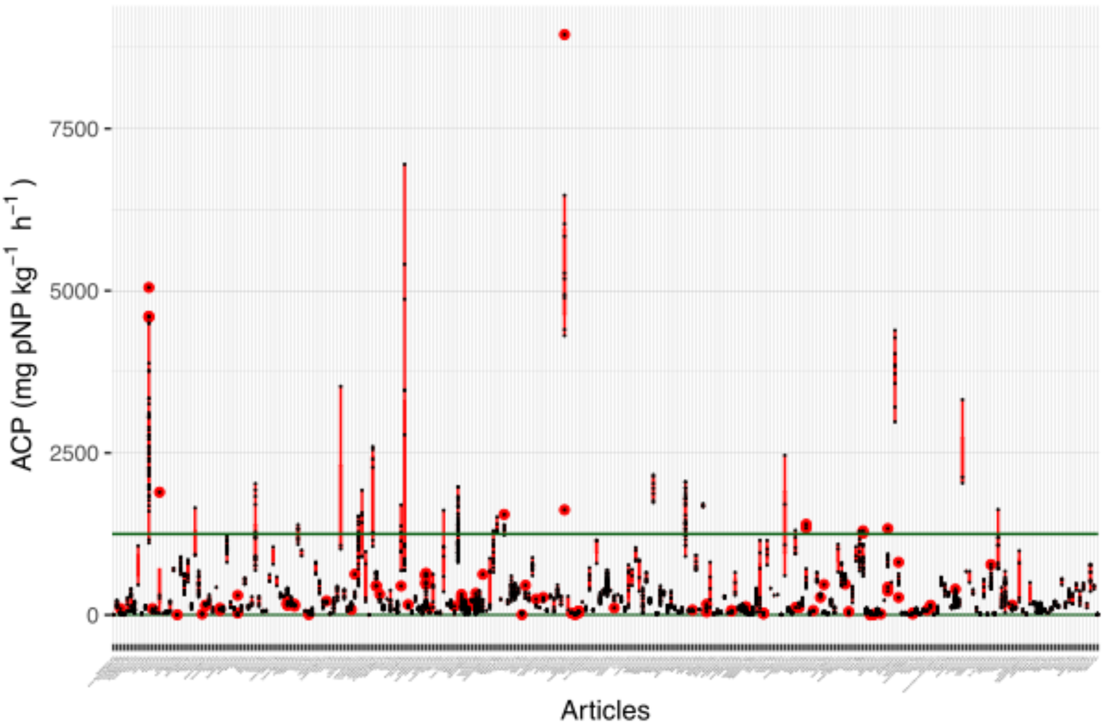


Figure S2. Graphical analysis of observations to verify the outliers on ALP activity. The green lines separate the results considered non-outliers from the outliers (n=2359).

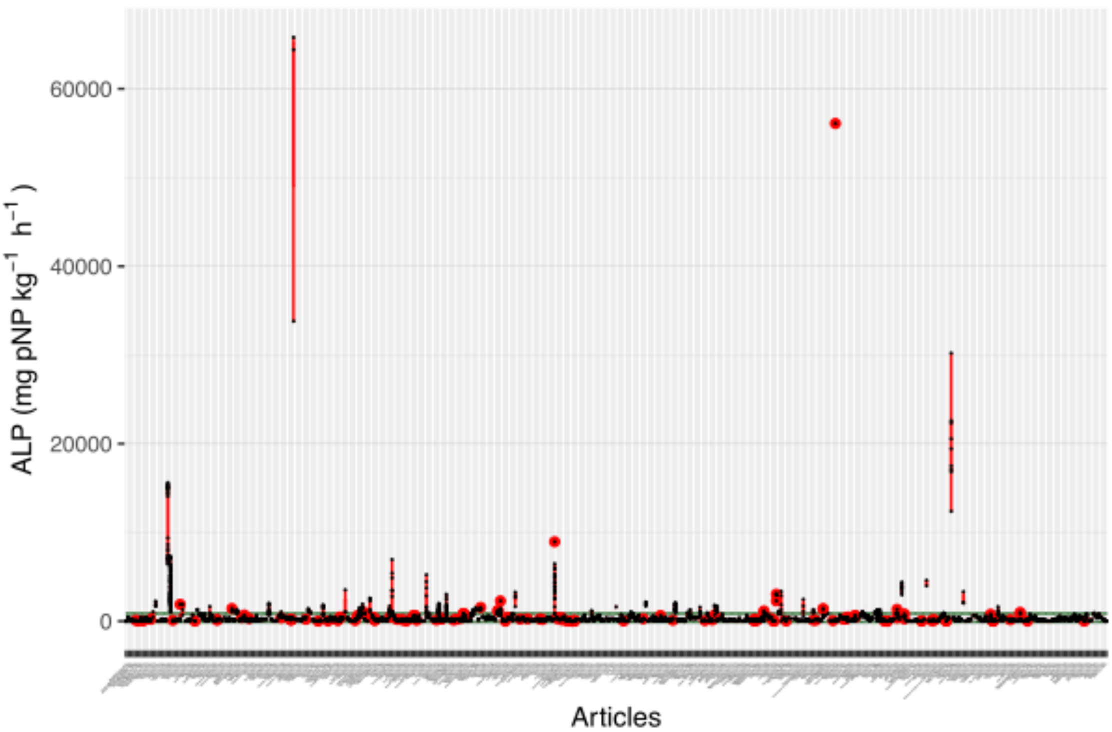


Figure S3. Diagnostic plots for the models described in section 2.2. The histogram of residuals (the individual-level errors) in (a) model 1, (b) model 2, (c) model 3 and (d) yield model for both ACP and ALP activity suggests normality.

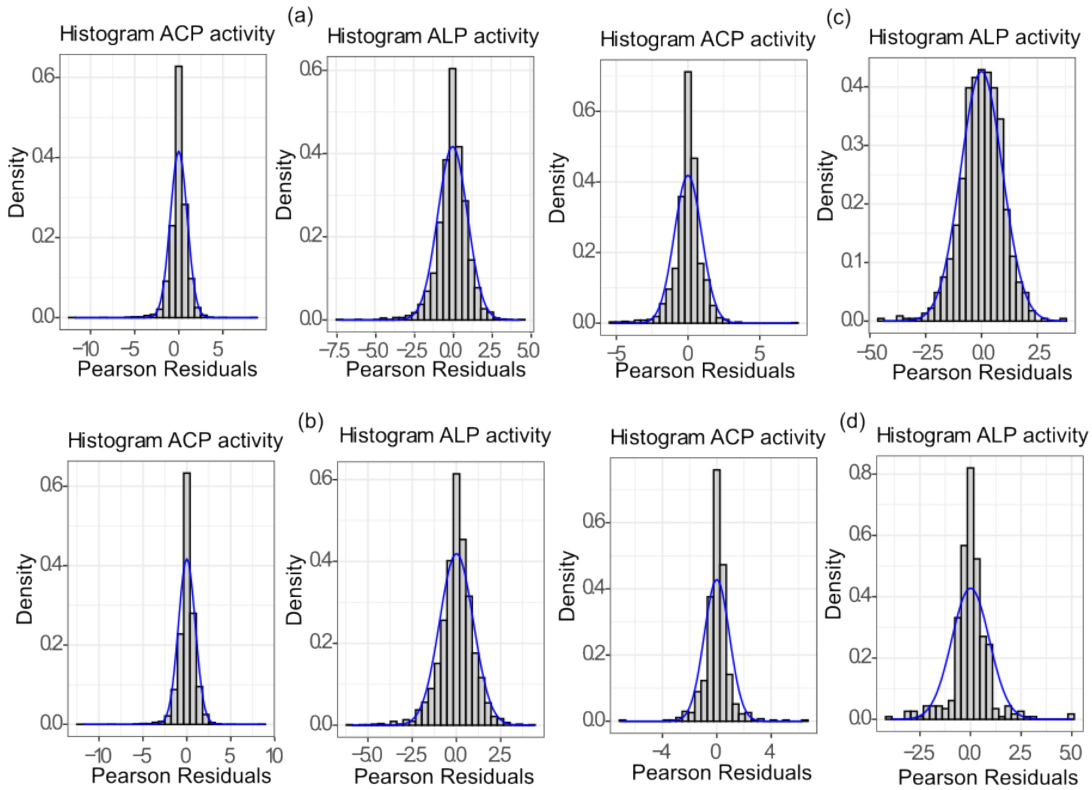


Figure S4. Diagnostic plots for the models described in section 2.2. Boxplot of residuals in (a) model 1, (b) model 2, (c) model 3 and (d) yield model). There are only mild signs of heteroscedasticity (the residuals are not identically distributed between groups). A small number of outliers are also observed (black dots).

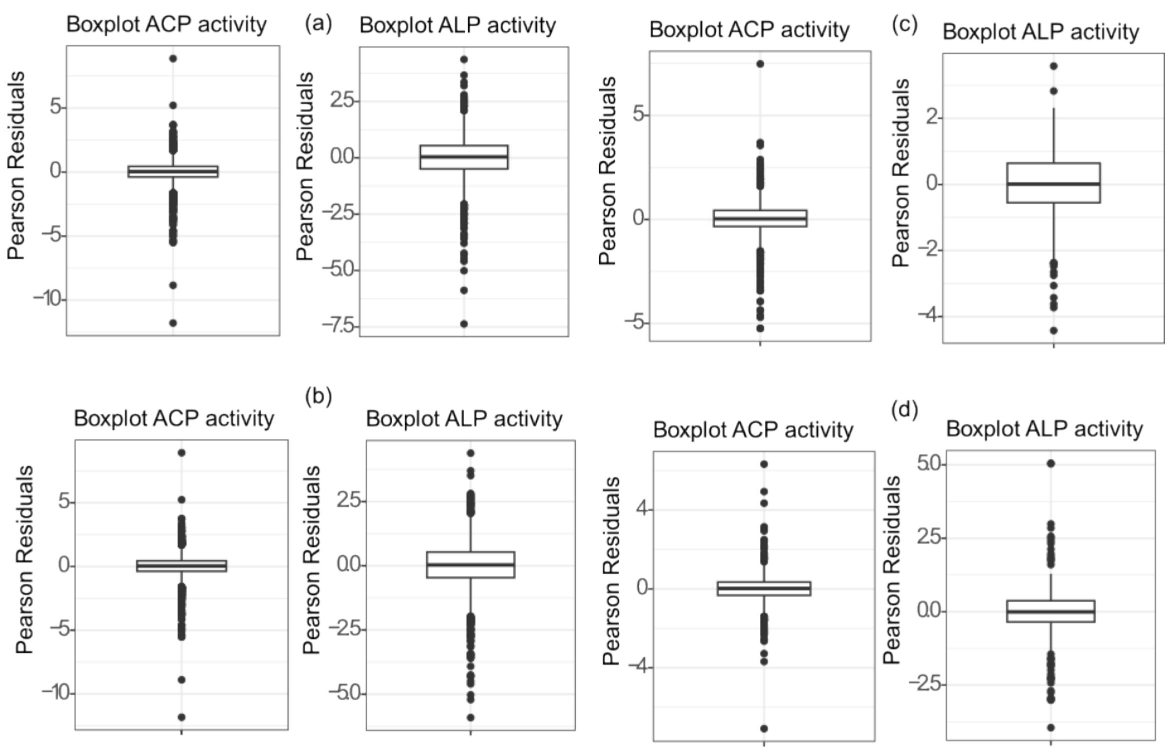


Figure S5. Figure of standardized slopes in ACP activity model (in blue) and ALP activity model (in orange). The circles and squares show the location of the standardized slopes (i.e., standardized regression coefficients) for the predictor and the line around the circles and squares represent the confidence interval (n_{ACP}=3140; n_{ALP}=2105).

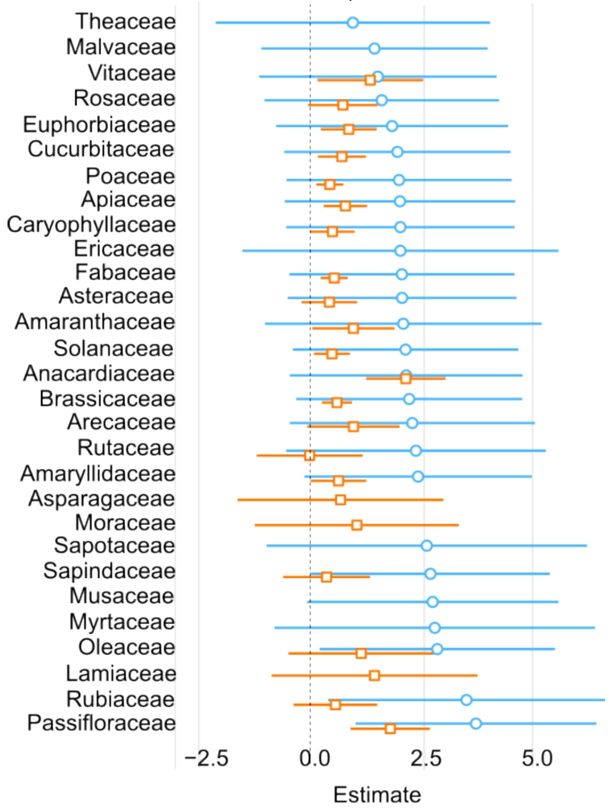
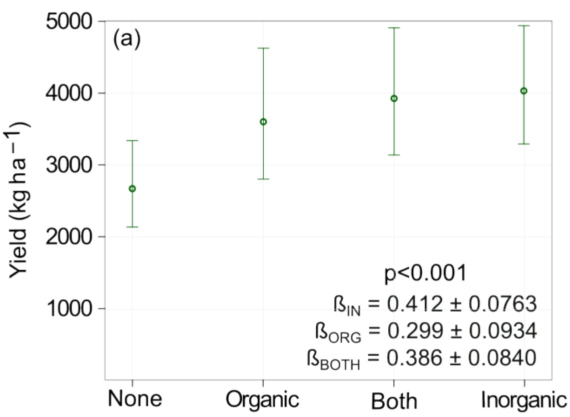


Figure S5. Effect of (a) fertilization and (b) family on the crop yield with ALP in the model. Predicted values and 95%-confidence interval are shown. While the analysis was carried out using the natural logarithm-transformed values, but the back-transformed values are the ones shown (n=370). Api = Apiaceae, Fab = Fabaceae, Sol = Solanaceae, Poa = Poaceae, Lam = Laminaceae, Ast = Asteraceae.



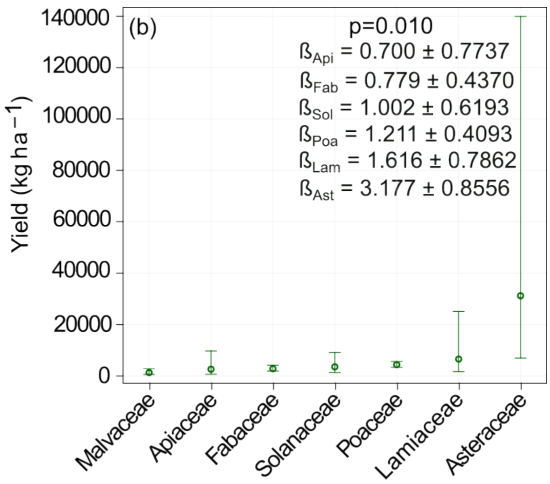
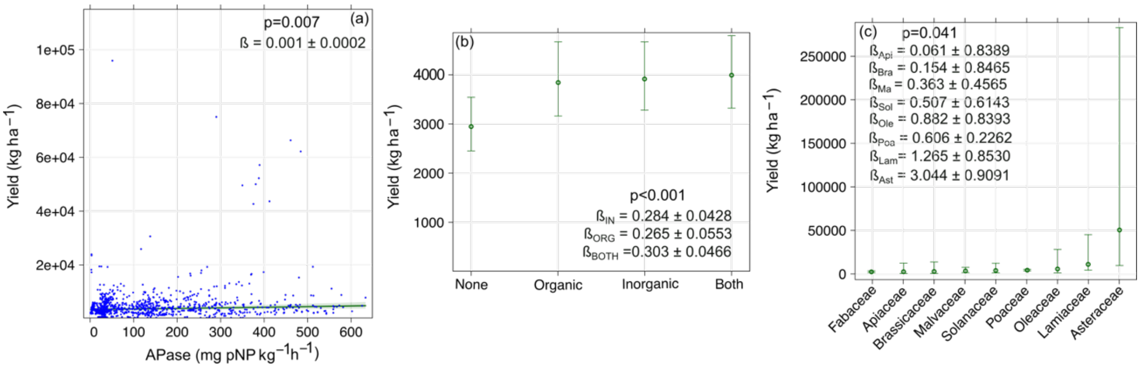


Figure S6. Effect of (a) APase activity, (b) fertilization and (c) family on the crop yield both APase in the model. Predicted values and 95%-confidence interval are shown. While the analysis was carried out using the natural logarithm-transformed values, but the back-transformed values are the ones shown (n=982). Api = Apiaceae, Bras = Brassicaceae, Mal = Malvaceae, Sol = Solanaceae, Poa = Poaceae, Olle = Oleaceae, Lam = Laminaceae, Ast = Asteraceae.



Tables

Table S1. Classification of independent variables and their subgroups used for the statistical analysis.

Climatic variables	Mean annual temperature (MAT) Mean annual precipitation (MAP)	
Crop species taxonomical affiliation (family)	Amaranthaceae *Spinacia oleracea* *Beta vulgaris* Amaryllidaceae *Allium porrum* *Allium cepa* Anacardiaceae *Mangifera indica* *Anacardium occidentale* Apiaceae *Pimpinella anisum* *Coriandrum sativum*	Juglandaceae *Juglans spp* Lamiaceae *Tectona grandis* *Ocimum basilicum* Malvaceae *Abelmoschus esculentus* *Corchorus olitorius* *Gossypium arboreum* *Gossypium herbaceum* *Gossypium hirsutum* *Theobroma cacao*

	Apium graveolens *Daucus carota* Araceae *Amorphophallus paeoniifolius* Arecaceae *Areca catechu* Asparagaceae *Asparagus officinalis* Asteraceae *Lactuca sativa* *Carthamus tinctorius* *Helianthus annuus* Brassicaceae *Brassica napus* *Raphanus sativus* *Brassica chinensis* *Brassica oleracea* *Raphanus raphanistrum* *Brassica juncea* Caryophyllaceae *Spergula arvensis* Cucurbitaceae *Cucumis sativus* *Citrullus lanatus* *Lagenaria siceraria* *Momordica charantia* *Lagenaria vulgaris*	Oleaceae *Olea europaea* Passifloraceae *Passiflora edulis* Poaceae *Zea mays* *Avena sativa* *Oryza sativa* *Triticum aestivum* *Hordeum vulgare* *Saccharum officinarum* *Avena strigosa* *Eleusine coracana* *Sorghum bicolor* *x Triticosecale* *Panicum miliaceum* *Arundo donax* *Pennisetum americanum* *Pennisetum glaucum* *Secale cereale* *Sporobulus indicus* Rosaceae *Malus domestica* *Prunus dulcis* *Fragaria × ananassa* Rubiaceae *Coffea arabica* Rutaceae *Citrus sinensis* *Citrus aurantium*

	Ericaceae *Vaccinium angustifolium* Euphorbiaceae *Hevea brasiliensis* *Manihot esculenta* *Jatropha curcas* *Manihot esculenta* Fabaceae *Arachis hypogaea* *Cajanus cajan* *Cicer arietinum* *Glycine max* *Lens culinaris* *Lupinus albus* *Lupinus angustifolius* *Medicago lupulina* *Medicago sativa* *Phaseolus vulgaris* *Pisum sativum* *Trifolium pratense* *Trifolium repens* *Vicia dasycarpa* *Vicia ervilia* *Vicia faba* *Vicia villosa* *Vigna mungo* *Vigna radiata* *Vigna unguiculata*	Sapindaceae *Melicoccus bijugatus* *Litchi chinensis* Sapotaceae *Manilkara achras* Solanaceae *Capsicum annuum* *Nicotiana tabacum* *Solanum lycopersicum* *Solanum melongena* *Solanum tuberosum* *Withania somnifera* Theaceae *Camellia sinensis* Vitaceae *Vitis vinifera* Zingiberaceae *Zingiber officinale*
Management practices	Type of system *Crop rotation* *Different crops are planted sequentially in the same*	Intercropping *Two or more crops are cultivated together in the same field simultaneously*

	field over a series of growing seasons *Continuous cropping* *The same crop is cultivated in a field year after year without rotating it with other crops* Mulching *A protective layer of material, such as straw, leaves, plastic, or compost, is spread over the soil surface around plants* Crop residue leaving *The practice of intentionally removing the aboveground plant material (such as stalks, leaves, and stems) left in the field after harvesting a crop*	*or in a specific sequence within a single growing season* Cover cropping *Planting specific plant species during periods when the primary cash crop is not growing* Green manure *The practice of incorporating fresh, actively growing plant material into the soil to improve its fertility and structure* Liming *Apply limestone or other materials containing calcium carbonate to soil in order to raise its pH level*
	Tillage practices *Conventional tillage* Involves the mechanical manipulation of the soil using plows, harrows, and other equipment *Intensive tillage* *Frequent and extensive mechanical manipulation of the soil using heavy machinery, such as plows and disks*	Types of fertilization *Inorganic* *Application of synthetic or commercially produced chemical compounds such as N, P and K* *Organic* *Application of natural substances derived from living organisms or their byproducts such as compost, manure, plant*

	Reduced tillage *Involves minimizing the intensity and frequency of mechanical soil disturbance compared to conventional tillage methods* *Zero tillage* *Without prior mechanical soil disturbance to prepare the soil for planting* Irrigation system Rainfed Irrigated *Artificially supplied to crops through methods such as sprinkler systems, drip irrigation, or flood irrigation*	*residues, and other organic materials rich in nutrients* Inorganic/Organic Non fertilized

Table S2 Table of estimated slope parameters (β) ± SE of the reference level ($\beta_{species}$) in relation to the model of ACP and ALP. All values are reported on the transformed scale.

Family	ß ± SE (ACP)	Family	ß ± SE (ALP)
Theaceae	ß = 0.995 ± 1.5741	Rutaceae	ß = 0.024 ± 0.6093
Malvaceae	ß = 1.481 ± 1.2977	Sapindaceae	ß = 0.404 ± 0.4980
Vitaceae	ß = 1.556 ± 1.3623	Asteraceae	ß = 0.469 ± 0.3191
Rosaceae	ß = 1.644 ± 1.3461	Poaceae	ß = 0.478 ± 0.1555
Euphorbiaceae	ß = 1.877 ± 1.3311	Solanaceae	ß = 0.525 ± 0.2069
Cucurbitaceae	ß = 1.997 ± 1.2986	Caryophyllaceae	ß = 0.535 ± 0.2553
Poaceae	ß = 2.032 ± 1.2914	Fabaceae	ß = 0.576 ± 0.1564
Apiaceae	ß = 2.053 ± 1.3224	Rubiaceae	ß = 0.604 ± 0.4799
Caryophyllaceae	ß = 2.063 ± 1.3109	Brassicaceae	ß = 0.638 ± 0.1729
Ericaceae	ß = 2.064 ± 1.8134	Amaryllidaceae	ß = 0.674 ± 0.3198
Fabaceae	ß = 2.097 ± 1.2921	Asparagaceae	ß = 0.718 ± 1.1807
Asteraceae	ß = 2.101 ± 1.3125	Cucurbitaceae	ß = 0.749 ± 0.2764
Amaranthaceae	ß = 2.127 ± 1.5869	Rosaceae	ß = 0.770 ± 0.4001
Solanaceae	ß = 2.178 ± 1.2937	Apiaceae	ß = 0.827 ± 0.2496

Family	ß ± SE (ACP)	Family	ß ± SE (ALP)
Anacardiaceae	ß = 2.193 ± 1.3345	Euphorbiaceae	ß = 0.904 ± 0.3211
Brassicaceae	ß = 2.261 ± 1.2968	Amaranthaceae	ß = 1.010 ± 0.4727
Arecaceae	ß = 2.331 ± 1.4059	Arecaceae	ß = 1.010 ± 0.5302
Rutaceae	ß = 2.413± 1.4890	Moraceae	ß = 1.085 ± 1.1711
Amaryllidaceae	ß = 2.460 ± 1.3051	Oleaceae	ß = 1.182 ± 0.8352
Sapotaceae	ß = 2.657 ± 1.838	Vitaceae	ß = 1.386 ± 0.6048
Sapindaceae	ß = 2.739 ± 1.3695	Lamiaceae	ß = 1.481 ± 1.1810
Musaceae	ß = 2.789 ± 1.4410	Passifloraceae	ß = 1.836 ± 0.4556
Myrtaceae	ß = 2.836 ± 1.8383	Anacardiaceae	ß = 2.185 ± 0.4556
Oleaceae	ß = 2.891 ± 1.3497		
Rubiaceae	ß = 3.548 ± 1.5876		
Passifloraceae	ß = 3.761 ± 1.3818		

Table S3. Table of estimated slope parameters (ß) ± SE of the reference fertilization level "none" ($ß_{fertilization}$) and the difference for levels irrigated ($ß_I$) and crop rotation ($ß_{CR}$) in relation to the model of ACP. The values are reported on the transformed scale.

	Fertilization		
	Inorganic	Organic	Both
I	ß = -0.250 ± 0.1243	ß = 0.083 ± 0.1464	ß = -0.353 ± 0.1227
CR	ß = -0.300 ± 0.1172	ß = -0222 ± 0.1375	ß = -0.058 ± 0.1470

Table S4. Table of estimated slope parameters (ß) ± SE of the reference fertilization level "none" ($ß_{fertilization}$) and the difference for tillage practices; intensive tillage ($ß_{IT}$), reduced tillage ($ß_{RT}$) and zero tillage ($ß_{ZT}$) in relation to the model of ALP. The values are reported on the transformed scale.

	Fertilization		
	Inorganic	Organic	Both
IT	ß = -0339 ± 0.4495	ß = -0.198 ± 0.4490	ß = 0.880 ± 0.5452
RT	ß = 0.195 ± 0.1669	ß = 0.368 ± 0.2063	ß = 0.508 ± 0.2853
ZT	ß = 0.1190 ± 0.1150	ß = 0.154 ± 0.1681	ß = 0.284 ± 0.1757

Table S5. Effect of family and ACP activity on yield (kg ha^{-1}). Multiple comparisons by Sidak. Analysis with natural logarithm-transformed data. Back-transformed estimated marginal means and 95%-confidence intervals (in square brackets) are shown.

Family	ACP
Apiaceae	9823 [258-373,602]
Brassicaceae	4900[864-27,799]
Fabaceae	1705 [1,793-13,099]
Malvaceae	4846 [1,055-2,755]
Oleaceae	30717 [4,954-190,436]
Poaceae	3605 [2,729-4,763]
Solanaceae	6016 [1,089-33,242]

References

1.1 References related to ACP and ALP activity models based on climatic variables and taxonomical affiliation at the family level. These two models share the same number of data for ACP activity and ALP activity.

Abujabhah, I.S., Bound, S.A., Doyle, R., Bowman, J.P., 2016. Effects of biochar and compost amendments on soil physico-chemical properties and the total community within a temperate agricultural soil. Applied Soil Ecology 98, 243–253. https://doi.org/10.1016/j.apsoil.2015.10.021.

Acosta-Martinez, V., Acosta-Mercado, D., Sotomayor-Ramirez, D., Cruz-Rodriguez, L., 2008. Microbial communities and enzymatic activities under different management in semiarid soils. Applied Soil Ecology 38, 249–260. https://doi.org/10.1016/j.apsoil.2007.10.012.

Acosta-Martínez, V., Klose, S., Zobeck, T.M., 2003. Enzyme activities in semiarid soils under conservation reserve program, native rangeland, and cropland. Journal of Plant Nutrition and Soil Science 166, 699–707. https://doi.org/10.1002/jpln.200321215.

Acosta-Martinez, V., Mikha, M.M., Sistani, K.R., Stahlman, P.W., Benjamin, J.G., Vigil, M.F., Erickson, R., 2011. Multi-location study of soil enzyme activities as affected by types and rates of manure application and tillage practices. Agriculture (Switzerland) 1, 4–21. https://doi.org/10.3390/agriculture1010004.

Acosta-Martínez, V., Lascano, R., Calderón, F., Booker, J.D., Zobeck, T.M., Upchurch, D.R., 2011. Dryland cropping systems influence the microbial biomass and enzyme activities in a semiarid sandy soil. Biology and Fertility of Soils 47, 655–667. https://doi.org/10.1007/s00374-011-0565-1.

Acosta-Martínez, V., Pérez-Guzmán, L., Johnson, J.M.F., 2019. Simultaneous determination of β-glucosidase, β-glucosaminidase, acid phosphomonoesterase, and arylsulfatase activities in a soil sample for a biogeochemical cycling index. Applied Soil Ecology 142, 72–80. https://doi.org/10.1016/j.apsoil.2019.05.001.

Acosta-Martínez, V., Tabatabai, M.A., 2000. Enzyme activities in a limed agricultural soil. Biology and Fertility of Soils 31, 85–91. https://doi.org/10.1007/s003740050628.

Acosta-Martínez, V., Upchurch, D.R., Schubert, A.M., Porter, D., Wheeler, T., 2004. Early impacts of cotton and peanut cropping systems on selected soil chemical, physical, microbiological and biochemical properties. Biology and Fertility of Soils 40, 44–54. https://doi.org/10.1007/s00374-004-0745-3.

Adeleke, K.A., Atoloye, I.A., Creech, J.E., Dai, X., Reeve, J.R., 2021. Nutritive and non-nutritive effects of compost on organic dryland wheat in Utah. Agronomy Journal 113, 3518–3531. https://doi.org/10.1002/agj2.20698.

Adrover, M., Farrús, E., Moyà, G., Vadell, J., 2012. Chemical properties and biological activity in soils of Mallorca following twenty years of treated wastewater irrigation. Journal of Environmental Management 95. https://doi.org/10.1016/j.jenvman.2010.08.017.

Aechra, S., Meena, R.H., Meena, S.C., Mundra, S.L., Lakhawat, S.S., Mordia, A., Jat, G., 2021. Soil microbial dynamics and enzyme activities as influenced by biofertilizers and split application of vermicompost in rhizosphere of wheat (Triticum aestivum. L.). Journal of Environmental Biology 42, 1370–1378.

Ahmed, W., Qaswar, M., Jing, H., Wenjun, D., Geng, S., Kailou, L., Ying, M., Ao, T., Mei, S., Chao, L., Yongmei, X., Ali, S., Normatov, Y., Mehmood, S., Khan, M.N., Huimin, Z., 2020. Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils. Journal of Soils and Sediments 20, 850–861. https://doi.org/10.1007/s11368-019-02468-3.

Akmal, M., Altaf, M.S., Hayat, R., Hassan, F.U., Islam, M., 2012. Temporal changes in soil urease, alkaline phosphatase and dehydrogenase activity in rainfed wheat field of Pakistan. Journal of Animal and Plant Sciences 22, 457–462.

Angers, D.A., Bissonnette, N., Legere, A., Samson, N., 1993. Microbial and biochemical changes induced by rotation and tillage in a soil under barley production. Canadian Journal of Soil Science 73, 39–50. https://doi.org/10.4141/cjss93-004.

Ansari, M.A., Saha, S., Das, A., Lal, R., Das, B., Choudhury, B.U., Roy, S.S., Sharma, S.K., Singh, I.M., Meitei, C.B., Changloi, K.L., Singh, L.S., Singh, N.A., Saraswat, P.K., Ramakrishna, Y., Singh, D., Hazarika, S., Punitha, P., Sandhu, S.K., Prakash, N., 2021. Energy and carbon budgeting of traditional land use change with groundnut based cropping system for environmental quality, resilient soil health and farmers income in eastern Indian Himalayas. Journal of Environmental Management 293, 112892. https://doi.org/10.1016/j.jenvman.2021.112892.

Aparna, B., 2010. Quantification of enzyme activities under rice crop in a permanent manurial experiment in the coastal sandy tract of Onattukkara of Kerala. An Asian Journal of Soil Science 5(2), 347-351.

Aparna, K., Rao, D.L.N., Balachandar, D., 2016. Microbial Populations, Activity and Gene Abundance in Tropical Vertisols Under Intensive Chemical Farming. Pedosphere 26, 725–732. https://doi.org/10.1016/S1002-0160(15)60079-0.

Aranda, V., Macci, C., Peruzzi, E., Masciandaro, G., 2015. Biochemical activity and chemical-structural properties of soil organic matter after 17 years of amendments with olive-mill pomace co-compost. Journal of Environmental Management 147, 278–285. https://doi.org/10.1016/j.jenvman.2014.08.024.

Arora, R., Sharma, V., Sharma, S., Maini, A., Dhaliwal, S.S., 2021. Temporal changes in soil biochemical properties with seasons under rainfed land use systems in Shiwalik foothills of northwest India. Agroforestry Systems 95, 1479–1491. https://doi.org/10.1007/s10457-021-00654-2.

Arya, S.R., Syriac, E.K., Aparna, B., 2018. Enzyme dynamics and organic carbon status of soil as influenced by flucetosulfuron in wet seeded rice. Journal of Tropical Agriculture 56, 1–8.

Atoloye, I.A., Jacobson, A., Creech, E., Reeve, J., 2021. Variable impact of compost on phosphorus dynamics in organic dryland soils following a one-time application. Soil Science Society of America Journal 85, 1122–1138. https://doi.org/10.1002/saj2.20275.

Avila-Salem, M.E., Montesdeoca, F., Orellana, M., Pacheco, K., Alvarado, S., Becerra, N., Marín, C., Borie, F., Aguilera, P., Cornejo, P., 2020. Soil Biological Properties and Arbuscular Mycorrhizal Fungal Communities of Representative Crops Established in the Andean Region from Ecuadorian Highlands. Journal of Soil Science and Plant Nutrition 20, 2156–2163. https://doi.org/10.1007/s42729-020-00283-1.

Babu, S., Singh, R., Avasthe, R.K., Yadav, G.S., Das, A., Singh, V.K., Mohapatra, K.P., Rathore, S.S., Chandra, P., Kumar, A., 2020. Impact of land configuration and organic nutrient management on productivity, quality and soil properties under baby corn in Eastern Himalayas. Scientific Reports 10, 1–14. https://doi.org/10.1038/s41598-020-73072-6.

Baligar, V.C., Wright, R.J., Hern, J.L., 2005. Enzyme activities in soil influenced by levels of applied sulfur and phosphorus. Communications in Soil Science and Plant Analysis 36, 1727–1735. https://doi.org/10.1081/CSS-200062431.

Balota, E.L., Chaves, J.C.D., 2010. Enzymatic activity and mineralization of carbon and nitrogen in soil cultivated with coffee and green manures. Rev. Bras. Ciênc. Solo 34, 1573–1583. https://doi.org/10.1590/S0100-06832010000500010.

Balota, E.L., Kanashiro, M., Filho, A.C., Andrade, D.S., Dick, R.P., 2004. Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agro-ecosystems. Brazilian Journal of Microbiology 35, 300–306. https://doi.org/10.1590/S1517-83822004000300006.

Balota, E.L., Machineski, O., Hamid, K.I.A., Yada, I.F.U., Barbosa, G.M.C., Nakatani, A.S., Coyne, M.S., 2014. Soil microbial properties after long-term swine slurry application to conventional and no-tillage systems in Brazil. Science of the Total Environment 490, 397–404. https://doi.org/10.1016/j.scitotenv.2014.05.019.

Balota, E.L., Machineski, O., Truber, P.V., Antonio, P., Auler, M., 2011. Effect of tillage systems and permanent groundcover intercropped with orange trees on soil enzyme activities. Brazilian Archives of Biology and Technology 54, 221–228.

Bana, R.S., Grover, M., Kumar, V., Jat, G.S., Kuri, B.R., Singh, D., Kumar, H., Bamboriya, S.D., 2022. Multi-micronutrient foliar fertilization in eggplant under diverse fertility scenarios: Effects on productivity, nutrient biofortification and soil microbial activity. Scientia Horticulturae 294, 110781. https://doi.org/10.1016/j.scienta.2021.110781.

Banik, P., Ghosal, P.K., Sasmal, T.K., Bhattacharya, S., Sarkar, B.K., Bagchi, D.K., 2006. Effect of organic and inorganic nutrients for soil quality conservation and yield of rainfed low land rice in sub-tropical plateau region. Journal of Agronomy and Crop Science 192, 331–343. https://doi.org/10.1111/j.1439-037X.2006.00219.x.

Barros, L.S., Melo, V.F., Senwo, Z.N., Evald, A., Siqueira, R.H.S., Bardales, R.M., Nunes, T.K. de O., 2018. Effects of Management Practices and Land Use on Biological and Enzymatic Attributes of an Agricultural Area. Journal of Agricultural Science 10, 110. https://doi.org/10.5539/jas.v10n6p110.

Basak, N., Mandal, B., Datta, A., Mitran, T., Biswas, S., Dhar, D., Badole, S., Saha, B., Hazra, G.C., 2017. Impact of Long-Term Application of Organics, Biological, and Inorganic Fertilizers on Microbial Activities in Rice-Based Cropping System. Communications in Soil Science and Plant Analysis 48, 2390–2401. https://doi.org/10.1080/00103624.2017.1411502.

Batool, K., Khan, Q.U.Q.U., Naz, R., Khan, M.J., Sayal, O.U.O.U., Bashir, A., Latif, A., 2015. Source and rate of inorganic P fertilizer affecting soil phosphatase enzymes, yield and P-uptake of chillies. Soil and Environment 34, 27–33.

Baziramakenga, R., Simard, R.R., Lalande, R., 2001. Effect of de-inking paper sludge compost application on soil chemical and biological properties. Canadian Journal of Soil Science 81, 561–575. https://doi.org/10.4141/S00-063.

Becagli, M., Arduini, I., Cardelli, R., 2022. Using Biochar and Vermiwash to Improve Biological Activities of Soil. Agriculture (Switzerland) 12. https://doi.org/10.3390/agriculture12020178.

Bera, T., Collins, H.P., Alva, A.K., Purakayastha, T.J., Patra, A.K., 2016. Biochar and manure effluent effects on soil biochemical properties under corn production. Applied Soil Ecology 107, 360–367. https://doi.org/10.1016/j.apsoil.2016.07.011.

Bergstrom, D.W., Monreal, C.M., King, D.J., 1998. Sensitivity of Soil Enzyme Activities to Conservation Practices. Soil Science Society of America Journal 62, 1286–1295. https://doi.org/10.2136/sssaj1998.03615995006200050020x.

Bhambure, A.B., Mahajan, G.R., Kerkar, S., 2018. Salt Tolerant Bacterial Inoculants as Promoters of Rice Growth and Microbial Activity in Coastal Saline Soil. Proceedings of the National Academy of Sciences India Section B - Biological Sciences 88, 1531–1538. https://doi.org/10.1007/s40011-017-0901-9.

Bhatt, B., Chandra, R., Ram, S., Pareek, N., 2016. Long-term effects of fertilization and manuring on productivity and soil biological properties under rice (Oryza sativa)–wheat (Triticum aestivum) sequence in Mollisols. Archives of Agronomy and Soil Science 62, 1109–1122. https://doi.org/10.1080/03650340.2015.1125471.

Bhattacharyya, P., Tripathy, S., Chakrabarti, K., Chakraborty, A., Banik, P., 2008. Fractionation and bioavailability of metals and their impacts on microbial properties in sewage irrigated soil. Chemosphere 72, 543–550. https://doi.org/10.1016/j.chemosphere.2008.03.035.

Bi, Q.F., Li, K.J., Zheng, B.X., Liu, X.P., Li, H.Z., Jin, B.J., Ding, K., Yang, X.R., Lin, X.Y., Zhu, Y.G., 2020. Partial replacement of inorganic phosphorus (P) by organic manure reshapes phosphate mobilizing bacterial community and promotes P bioavailability in a paddy soil. Science of the Total Environment 703, 134977. https://doi.org/10.1016/j.scitotenv.2019.134977.

Bi, Q.F., Zheng, B.X., Lin, X.Y., Li, K.J., Liu, X.P., Hao, X.L., Zhang, H., Zhang, J.B., Jaisi, D.P., Zhu, Y.G., 2018. The microbial cycling of phosphorus on long-term fertilized soil: Insights from phosphate oxygen isotope ratios. Chemical Geology 483, 56–64. https://doi.org/10.1016/j.chemgeo.2018.02.013.

Biau, A., Santiveri, F., Mijangos, I., Lloveras, J., 2012. The impact of organic and mineral fertilizers on soil quality parameters and the productivity of irrigated maize crops in semiarid regions. European Journal of Soil Biology 53, 56–61. https://doi.org/10.1016/j.ejsobi.2012.08.008.

Bissonnette, N., Angers, D.A., Simard, R.R., Lafond, J., 2001. Interactive effects of management practices on water-stable aggregation and organic matter of a Humic Gleysol. Canadian Journal of Soil Science 81, 545–551. https://doi.org/10.4141/S00-

078.

Biswas, S., Kundu, D.K., Mazumdar, S.P., Saha, A.R., Majumdar, B., Ghorai, A.K., Ghosh, D., Yadav, A.N., Saxena, A.K., 2018. Study on the activity and diversity of bacteria in a New Gangetic alluvial soil (Eutrocrept) under rice-wheat-jute cropping system. Journal of Environmental Biology 39, 379–386.

Blaise, D., Rao, M.R.K., 2004. ß-glucosidase and alkaline phosphatase activity as affected by organic and modern method of cotton (Gossypium hirsutum) cultivation of the rainfed Vertisols. Indian Journal of Agricultural Sciences 74, 276–278.

Boccolini, M.F., Cazorla, C.R., Galantini, J.A., Belluccini, P.A., Baigorria, T., 2019. Cultivos de cobertura disminuyen el impacto ambiental mejorando propiedades biológicas del suelo y el rendimiento de los cultivos. Revista de Investigaciones Agropecuarias 45, 412–425.

Borase, D.N., Murugeasn, S., Nath, C.P., Hazra, K.K., Singh, S.S., Kumar, N., Singh, U., Praharaj, C.S., 2021. Long-term impact of grain legumes and nutrient management practices on soil microbial activity and biochemical properties. Archives of Agronomy and Soil Science 67, 2015–2032. https://doi.org/10.1080/03650340.2020.1819532.

Borase, D.N., Nath, C.P., Hazra, K.K., Senthilkumar, M., Singh, S.S., Praharaj, C.S., Singh, U., Kumar, N., 2020. Long-term impact of diversified crop rotations and nutrient management practices on soil microbial functions and soil enzymes activity. Ecological Indicators 114, 106322. https://doi.org/10.1016/j.ecolind.2020.106322.

Borges, C.D., Corá, J.E., Barbosa, J.C., Nahas, E., 2013. Soil microbiological attributes under summer/winter crops rotation in a no-tillage system. Archives of Agronomy and Soil Science 59, 1471–1485. https://doi.org/10.1080/03650340.2012.725938.

Brandan, Carolina Pérez, Chavarría, D., Huidobro, J., Meriles, J.M., Brandan, Cecilia Pérez, Gil, S.V., 2017. Influence of a tropical grass (Brachiaria brizantha cv. Mulato) as cover crop on soil biochemical properties in a degraded agricultural soil. European Journal of Soil Biology 83, 84–90. https://doi.org/10.1016/j.ejsobi.2017.10.009.

Campbell, C.A., Biederbeck, V.O., Schnitzer, M., Selles, F., Zentner, R.P., 1989. Effect of 6 Years of Zero Tillage and N Fertilizer Management on Changes in Soil Quality of an Orthic Brown Chernozem in Southwestern Saskatchewan. Soil & Tillage Research, 14, 39-52. http://dx.doi.org/10.1016/0167-1987(89)90019-6.

Cao, N., Zhi, M., Zhao, W., Pang, J., Hu, W., Zhou, Z., Meng, Y., 2022. Straw retention combined with phosphorus fertilizer promotes soil phosphorus availability by enhancing soil P-related enzymes and the abundance of phoC and phoD genes. Soil and Tillage Research 220, 105390. https://doi.org/10.1016/j.still.2022.105390.

Carpenter-Boggs, L., Stahl, P.D., Lindstrom, M.J., Schumacher, T.E., 2003. Soil microbial properties under permanent grass, conventional tillage, and no-fill management in South Dakota. Soil and Tillage Research 71, 15–23. https://doi.org/10.1016/S0167-1987(02)00158-7.

Carter, M.R., Sanderson, J.B., Holmstrom, D.A., Ivany, J.A., DeHaan, K.R., 2007. Influence of conservation tillage and glyphosate on soil structure and organic carbon fractions through the cycle of a 3-year potato rotation in Atlantic Canada. Soil and Tillage Research 93, 206–221. https://doi.org/10.1016/j.still.2006.04.004.

Chakrabarti, K., Sarkar, B., Chakraborty, A., Banik, P., Bagchi, D.K., 2000. Organic recycling for soil quality conservation in a sub-tropical plateau region. Journal of Agronomy and Crop Science 184, 137–142. https://doi.org/10.1046/j.1439-037X.2000.00352.x.

Chander, K., Goyal, S., Mundra, M.C., Kapoor, K.K., 1997. Organic matter, microbial biomass and enzyme activity of soils under different crop rotations in the tropics. Biology and Fertility of Soils 24, 306–310. https://doi.org/10.1007/s003740050248.

Chatterjee, D., Nayak, A.K., Mishra, A., Swain, C.K., Kumar, U., Bhaduri, D., Panneerselvam, P., Lal, B., Gautam, P., Pathak, H., 2021. Effect of Long-Term Organic Fertilization in Flooded Rice Soil on Phosphorus Transformation and Phosphate Solubilizing Microorganisms. Journal of Soil Science and Plant Nutrition 21, 1368–1381. https://doi.org/10.1007/s42729-021-00446-8.

Chaudhary, D.R., Gautam, R.K., Ghosh, A., Chikara, J., Jha, B., 2015. Effect of Nitrogen Management on Soil Microbial Community and Enzymatic Activities in Jatropha curcas L. Plantation. Clean - Soil, Air, Water 43, 1058–1065. https://doi.org/10.1002/clen.201400357.

Chaudhary, P., Sharma, A., Chaudhary, A., Khati, P., Gangola, S., Maithani, D., 2021. Illumina based high throughput analysis of microbial diversity of maize rhizosphere treated with nanocompounds and Bacillus sp. Applied Soil Ecology 159. https://doi.org/10.1016/j.apsoil.2020.103836.

Chen, H., Liang, Q., Gong, Y., Kuzyakov, Y., Fan, M., Plante, A.F., 2019. Reduced tillage and increased residue retention increase enzyme activity and carbon and nitrogen concentrations in soil particle size fractions in a long-term field experiment on Loess Plateau in China. Soil and Tillage Research 194, 104296. https://doi.org/10.1016/j.still.2019.104296.

Chen, S., Cade-Menun, B.J., Bainard, L.D., Luce, M.S., Hu, Y., Chen, Q., 2021. The influence of long-term N and P fertilization on soil P forms and cycling in a wheat/fallow cropping system. Geoderma 404, 115274. https://doi.org/10.1016/j.geoderma.2021.115274.

Chen, Y.P., Tsai, C.F., Hameed, A., Chang, Y.J., Young, C.C., 2021a. Agricultural management and cultivation period alter soil enzymatic activity and bacterial diversity in litchi (Litchi chinensis Sonn.) orchards. Botanical Studies 62. https://doi.org/10.1186/s40529-021-00322-9.

Chen, Y.P., Tsai, C.F., Rekha, P.D., Ghate, S.D., Huang, H.Y., Hsu, Y.H., Liaw, L.L., Young, C.C., 2021b. Agricultural management practices influence the soil enzyme activity and bacterial community structure in tea plantations. Botanical Studies 62. https://doi.org/10.1186/s40529-021-00314-9.

Chinnadurai, C., Gopalaswamy, G., Balachandar, D., 2014. Impact of long-term organic and inorganic nutrient managements on the biological properties and eubacterial community diversity of the Indian semi-arid Alfisol. Archives of Agronomy and Soil Science 60, 531–548. https://doi.org/10.1080/03650340.2013.803072.

Choudhary, M., Meena, V.S., Panday, S.C., Mondal, T., Yadav, R.P., Mishra, P.K., Bisht, J.K., Pattanayak, A., 2021. Long-term effects of organic manure and inorganic fertilization on biological soil quality indicators of soybean-wheat rotation in the Indian mid-Himalaya. Applied Soil Ecology 157, 103754. https://doi.org/10.1016/j.apsoil.2020.103754.

Choudhary, M., Datta, A., Jat, H.S., Yadav, A.K., Gathala, M.K., Sapkota, T.B., Das, A.K., Sharma, P.C., Jat, M.L., Singh, R., Ladha, J.K., 2018a. Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. Geoderma 313, 193–204. https://doi.org/10.1016/j.geoderma.2017.10.041.

Choudhary, M., Sharma, P.C., Jat, H.S., McDonald, A., Jat, M.L., Choudhary, S., Garg, N., 2018b. Soil biological properties and fungal diversity under conservation agriculture in indo-gangetic plains of india. Journal of Soil Science and Plant Nutrition 18, 1142–1156. https://doi.org/10.4067/S0718-95162018005003201.

Chowdhury, N., Rasid, M.M., 2021. Heavy metal concentrations and its impact on soil microbial and enzyme activities in agricultural lands around ship yards in Chattogram, Bangladesh. Soil Science Annual 72, 1–21. https://doi.org/10.37501/soilsa/135994.

Cicatelli, A., Baldantoni, D., Iovieno, P., Carotenuto, M., Alfani, A., Feis, I.D., Castiglione, S., 2014. Genetically biodiverse potato cultivars grown on a suitable agricultural soil under compost amendment or mineral fertilization: Yield, quality, genetic and epigenetic variations, soil properties. Science of the Total Environment 493, 1025–1035. https://doi.org/10.1016/j.scitotenv.2014.05.122.

Cochran, V.L., Elliott, L.F., Lewis, C.E., 1989. Soil microbial biomass and enzyme activity in subarctic agricultural and forest soils. Biology and Fertility of Soils 7, 283–288. https://doi.org/10.1007/BF00257821.

Comino, F., Aranda, V., García-Ruiz, R., Ayora-Cañada, M.J., Domínguez-Vidal, A., 2018. Infrared spectroscopy as a tool for the assessment of soil biological quality in

agricultural soils under contrasting management practices. Ecological Indicators 87, 117–126. https://doi.org/10.1016/j.ecolind.2017.12.046.
Cox, D., Bezdicek, D., Fauci, M., 2001. Effects of compost, coal ash, and straw amendments on restoring the quality of eroded Palouse soil. Biology and Fertility of Soils 33, 365–372. https://doi.org/10.1007/s003740000335.
Cruz-Ruíz, A., Cruz-Ruíz, E., Vaca, R., Aguila, P.D., Lugo, J., 2016. Effects of pumice mining on soil quality. Solid Earth 7, 1–9. https://doi.org/10.5194/se-7-1-2016.
Das, S.K., Ghosh, G.K., Avasthe, R., Choudhury, B.U., Mishra, V.K., Kundu, M.C., Roy, A., Mondal, T., Lama, A., Dhakre, D.S., 2021. Organic nutrient sources and biochar technology on microbial biomass carbon and soil enzyme activity in maize-black gram cropping system. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-021-01625-4.
Deng, S.P., Tabatabai, M.A., 1996. Effect of tillage and residue management on enzyme activities in soils. II. Glycosidases. Biology and Fertility of Soils 22, 208–213. https://doi.org/10.1007/BF00382514.
Diallo-Diagne, N.H., Assigbetse, K., Sall, S., Masse, D., Bonzi, M., Ndoye, I., Chotte, J.L., 2016. Response of Soil Microbial Properties to Long-Term Application of Organic and Inorganic Amendments in a Tropical Soil (Saria, Burkina Faso). Open Journal of Soil Science 06, 21–33. https://doi.org/10.4236/ojss.2016.62003.
Dick, R.P., Sandor, J.A., Eash, N.S., 1994. Soil enzyme activities after 1500 years of terrace agriculture in the Colca Valley, Peru. Agriculture, Ecosystems and Environment 50, 123–131. https://doi.org/10.1016/0167-8809(94)90131-7
Dick, W.A., 1984. Influence of Long-Term Tillage and Crop Rotation Combinations on Soil Enzyme Activities. Soil Science Society of America Journal 48, 569–574. https://doi.org/10.2136/sssaj1984.03615995004800030020x.
Dong, W.H., Zhang, S., Rao, X., Liu, C.A., 2016. Newly-reclaimed alfalfa forage land improved soil properties comparison to farmland in wheat-maize cropping systems at the margins of oases. Ecological Engineering 94, 57–64. https://doi.org/10.1016/j.ecoleng.2016.05.056.
Doran, J.W., 1980. Soil Microbial and Biochemical Changes Associated with Reduced Tillage. Soil Science Society of America Journal 44, 765-771. https://doi.org/10.2136/sssaj1980.03615995004400040022x.
Dormaar, J.F., Willms, W.D., 2000. Rangeland management impacts on soil biological indicators in southern Alberta. Journal of Range Management 53, 233–238. https://doi.org/10.2307/4003289
Dou, F., Wright, A.L., Mylavarapu, R.S., Jiang, X., Matocha, J.E., 2016. Soil Enzyme Activities and Organic Matter Composition Affected by 26 Years of Continuous

Cropping. Pedosphere 26, 618–625. https://doi.org/10.1016/S1002-0160(15)60070-4.

Dubey, R.K., Dubey, P.K., Chaurasia, R., Singh, H.B., Abhilash, P.C., 2020. Sustainable agronomic practices for enhancing the soil quality and yield of Cicer arietinum L. under diverse agroecosystems. Journal of Environmental Management 262, 110284. https://doi.org/10.1016/j.jenvman.2020.110284.

Dutta, D., Meena, A.L., Kumar, G.C., Mishra, R.P., Ghasal, P.C., Kumar, Amit, Chaudhary, J., Bhanu, C., Kumar, V., Kumar, Ankur, Tewari, R.B., Panwar, A.S., 2020. Long Term Effect of Organic, Inorganic and Integrated Nutrient Management on Phosphorous Dynamics under Different Cropping Systems of Typic Ustochrept Soil of India. Communications in Soil Science and Plant Analysis 51, 2746–2763. https://doi.org/10.1080/00103624.2020.1849258.

Efthimiadou, E., Papatheodorou, E.M., Monokrousos, N., Stamou, G.P., 2010. Changes of soil chemical, microbiological, and enzymatic variables in relation to management regime and the duration of organic farming in Phaseolus vulgaris. Journal of Biological Research 14, 151–159.

Eichler-Löbermann, B., Zicker, T., Kavka, M., Busch, S., Brandt, C., Stahn, P., Miegel, K., 2021. Mixed cropping of maize or sorghum with legumes as affected by long-term phosphorus management. Field Crops Research 265. https://doi.org/10.1016/j.fcr.2021.108120.

Fang, H., Dong, B., Yan, H., Tang, F., Wang, B., Yu, Y., 2012. Effect of vegetation of transgenic Bt rice lines and their straw amendment on soil enzymes, respiration, functional diversity and community structure of soil microorganisms under field conditions. Journal of Environmental Sciences (China) 24, 1259–1270. https://doi.org/10.1016/S1001-0742(11)60939-X.

Fernández, L.A., Sagardoy, M.A., Gómez, M.A., 2008. Estudio de la fosfatasa ácida y alcalina en suelos de la Región Pampeana norte del área sojera argentina. Ciencia del suelo 26, 35–40.

Fernández-Calviño, D., Soler-Rovira, P., Polo, A., Díaz-Raviña, M., Arias-Estévez, M., Plaza, C., 2010. Enzyme activities in vineyard soils long-term treated with copper-based fungicides. Soil Biology and Biochemistry 42, 2119–2127. https://doi.org/10.1016/j.soilbio.2010.08.007.

Ferreira, E.P.D.B., Wendland, A., Didonet, A.D., 2011. Microbial biomass and enzyme activity of a Cerrado Oxisol under agroecological production system. Bragantia 70, 899–907. https://doi.org/10.1590/S0006-87052011000400024.

Ferreras, L., Toresani, S., Bonel, B., Fernández, E., Bacigaluppo, S., Faggioli, V., BeltráN, C., 2009. Parámetros químicos y biológicos como indicadores de calidad del suelo en diferentes manejos. Ciencia del Suelo 27, 103–114.

Fialho, J.S., Gomes, V.F.F., de Oliveira, T.S., Júnior, J.M. da S., 2008. Indicadores da qualidade do solo, em sistema de rotaçao, na Chapada do Apodi- CE. Revista Ciencia Agronomica 39, 353–361.

Fontalvo, R.M.S., Andrade, J.L.C., 2018. Effect of organic amendments and sulfur on chemical and biological properties of a sodic soil efeito de corretivos orgânicos e enxofre nas propriedades químicas e biológicas de um solo sódico. Spanish Journal of Soil Science 8, 347–362. https://doi.org/10.3232/SJSS.2018.V8.N3.04.

Fraser, T., Lynch, D.H., Entz, M.H., Dunfield, K.E., 2015. Linking alkaline phosphatase activity with bacterial phoD gene abundance in soil from a long-term management trial. Geoderma 257–258, 115–122. https://doi.org/10.1016/j.geoderma.2014.10.016.

Frąc, M., 2011. Agricultural utilisation of dairy sewage sludge: Its effect on enzymatic activity and microorganisms of the soil environment. African Journal of Microbiology Research 5, 1755–1762. https://doi.org/10.5897/ajmr10.707.

Furtak, K., Gawryjołek, K., Gajda, A.M., Gałązka, A., 2017. Effects of maize and winter wheat grown under different cultivation techniques on biological activity of soil. Plant, Soil and Environment 63, 449–454. https://doi.org/10.17221/486/2017-PSE.

Gagnon, B., Lalande, R., Simard, R.R., Roy, M., 2000. Soil enzyme activities following paper sludge addition in a winter cabbage-sweet corn rotation. Canadian Journal of Soil Science 80, 91–97. https://doi.org/10.4141/S99-033.

Gagnon, B., Simard, R.R., Lalande, R., Lafond, J., 2003. Improvement of soil properties and fruit yield of native lowbush blueberry by papermill sludge addition. Canadian Journal of Soil Science 83, 1–9. https://doi.org/10.4141/S02-011.

Gaind, S., Nain, L., 2010. Exploration of composted cereal waste and poultry manure for soil restoration. Bioresource Technology 101, 2996–3003. https://doi.org/10.1016/j.biortech.2009.12.016.

Gaind, S., Nain, L., 2007. Chemical and biological properties of wheat soil in response to paddy straw incorporation and its biodegradation by fungal inoculants. Biodegradation 18, 495–503. https://doi.org/10.1007/s10532-006-9082-6.

Gaind, S., Singh, Y.V., 2016. Soil organic phosphorus fractions in response to long-term fertilization with composted manures under rice–wheat cropping system. Journal of Plant Nutrition 39, 1336–1347. https://doi.org/10.1080/01904167.2015.1086795.

Gaind, S., Singh, Y.V., 2016. Short-Term Impact of Organic Fertilization and Seasonal Variations on Enzymes and Microbial Indices Under Rice–Wheat Rotation. Clean - Soil, Air, Water 44, 1396–1404. https://doi.org/10.1002/clen.201500946.

Gajda, A., Martyniuk, S., 2005. Microbial biomass C and N and activity of enzymes in soil under winter wheat grown in different crop management systems. Polish Journal

of Environmental Studies 14, 159–163.
Gao, X., Shi, D., Lv, A., Wang, S., Yuan, S., Zhou, P., An, Y., 2016. Increase phosphorus availability from the use of alfalfa (Medicago sativa L) green manure in rice (Oryza sativa L.) agroecosystem. Scientific Reports 6, 1–13. https://doi.org/10.1038/srep36981.
García-Orenes, F., Caravaca, F., Morugán-Coronado, A., Roldán, A., 2015. Prolonged irrigation with municipal wastewater promotes a persistent and active soil microbial community in a semiarid agroecosystem. Agricultural Water Management 149, 115–122. https://doi.org/10.1016/j.agwat.2014.10.030.
García-Ruiz, R., Ochoa, V., Hinojosa, M.B., Carreira, J.A., 2008. Suitability of enzyme activities for the monitoring of soil quality improvement in organic agricultural systems. Soil Biology and Biochemistry 40, 2137–2145. https://doi.org/10.1016/j.soilbio.2008.03.023.
Gelsomino, A., Azzellino, A., 2011. Multivariate analysis of soils: microbial biomass, metabolic activity, and bacterial-community structure and their relationships with soil depth and type. Journal of Plant Nutrition and Soil Science 174, 381–394. https://doi.org/10.1002/jpln.200900267.
George, S., Wright, D.L., Marois, J.J., 2013. Impact of grazing on soil properties and cotton yield in an integrated crop-livestock system. Soil and Tillage Research 132, 47–55. https://doi.org/10.1016/j.still.2013.05.004.
Gispert, M., Emran, M., Pardini, G., Doni, S., Ceccanti, B., 2013. The impact of land management and abandonment on soil enzymatic activity, glomalin content and aggregate stability. Geoderma 202–203, 51–61. https://doi.org/10.1016/j.geoderma.2013.03.012.
Gopinath, K.A., Saha, S., Mina, B.L., Pande, H., Kumar, N., Srivastva, A.K., Gupta, H.S., 2009. Yield potential of garden pea (Pisum sativum L.) varieties, and soil properties under organic and integrated nutrient management systems. Archives of Agronomy and Soil Science 55, 157–167. https://doi.org/10.1080/03650340802382207.
Gopinath, K.A., Saha, S., Mina, B.L., Pande, H., Kundu, S., Gupta, H.S., 2008. Influence of organic amendments on growth, yield and quality of wheat and on soil properties during transition to organic production. Nutrient Cycling in Agroecosystems 82, 51–60. https://doi.org/10.1007/s10705-008-9168-0.
Goyal, S., Chander, K., Mundra, M.C., Kapoor, K.K., 1999. Influence of inorganic fertilizers and organic amendments on soil organic matter and soil microbial properties under tropical conditions. Biology and Fertility of Soils 29, 196–200. https://doi.org/10.1007/s003740050544.
Green, V.S., Stott, D.E., Cruz, J.C., Curi, N., 2007. Tillage impacts on soil biological

activity and aggregation in a Brazilian Cerrado Oxisol. Soil and Tillage Research 92, 114–121. https://doi.org/10.1016/j.still.2006.01.004.

Guan, G., Tu, S., Li, H., Yang, J., Zhang, J., Wen, S., Yang, L., 2013. Phosphorus Fertilization Modes Affect Crop Yield, Nutrient Uptake, and Soil Biological Properties in the Rice-Wheat Cropping System. Soil Science Society of America Journal 77, 166–172. https://doi.org/10.2136/sssaj2011.0324.

Guan, G., Tu, S.-X., Yang, J.-C., Zhang, J.-F., Yang, L., 2011. A Field Study on Effects of Nitrogen Fertilization Modes on Nutrient Uptake, Crop Yield and Soil Biological Properties in Rice-Wheat Rotation System. Agricultural Sciences in China 10, 1254–1261. https://doi.org/10.1016/S1671-2927(11)60117-X.

Gupta, V.V.S.R., Lawrence, J.R., Germida, J.J., 1988. Impact of elemental sulfur fertilization on agricultural soils. I. Effects on microbial biomass and enzyme activities. Canadian Journal of Soil Science 68, 463–473. https://doi.org/10.4141/cjss88-045.

Gupta, M., Srivastava, P.K., Shikha, Niranjan, A., Tewari, S.K., 2016. Use of a Bioaugmented Organic Soil Amendment in Combination with Gypsum for Withania somnifera Growth on Sodic Soil. Pedosphere 26, 299–309. https://doi.org/10.1016/S1002-0160(15)60044-3.

Habig, J., Labuschagne, J., Marais, M., Swart, A., Claassens, S., 2018. The effect of a medic-wheat rotational system and contrasting degrees of soil disturbance on nematode functional groups and soil microbial communities. Agriculture, Ecosystems and Environment 268, 103–114. https://doi.org/10.1016/j.agee.2018.09.013.

Hatti, V., Ramachandrappa, B.K., Sathishand, A., Thimmegowda, M.N., 2018. Soil properties and productivity of rainfed finger millet under conservation tillage and nutrient management in Eastern dry zone of Karnataka. Journal of Environmental Biology 39, 612–624.

Hazarika, S., Ganeshamurthy, A.N., Sakthivel, T., 2011. Long-term management effects on spatial variability of quality characteristics of soils under guava (Psidium guajava) and sapota (Manilkara achras) orchards in south-western climate of India. Indian Journal of Agricultural Sciences 81, 119–124.

Hazarika, S., Parkinson, R., Bol, R., Dixon, L., Russell, P., Donovan, S., Allen, D., 2009. Effect of tillage system and straw management on organic matter dynamics. Agronomy for Sustainable Development 29, 525–533. https://doi.org/10.1051/agro/2009024.

He, Z., Honeycutt, C.W., Griffin, T.S., Larkin, R.P., Olanya, M., Halloran, J.M., 2010. Increases of soil phosphatase and urease activities in potato fields by cropping rotation practices. Journal of Food, Agriculture and Environment 8, 1112–1117.

Hojati, S., Nourbakhsh, F., 2006. Enzyme activities and microbial biomass carbon in a soil amended with organic and inorganic fertilizers. Journal of Agronomy 5(4), 563-569.

Hoyle, F.C., Murphy, D.V., 2006. Seasonal changes in microbial function and diversity associated with stubble retention versus burning. Australian Journal of Soil Research 44, 407–423. https://doi.org/10.1071/SR05183.

Igalavithana, A.D., Lee, S.S., Niazi, N.K., Lee, Y.H., Kim, K.H., Park, J.H., Moon, D.H., Ok, Y.S., 2017. Assessment of soil health in urban agriculture: Soil enzymes and microbial properties. Sustainability (Switzerland) 9. https://doi.org/10.3390/su9020310.

Iovieno, P., Morra, L., Leone, A., Pagano, L., Alfani, A., 2009. Effect of organic and mineral fertilizers on soil respiration and enzyme activities of two Mediterranean horticultural soils. Biology and Fertility of Soils 45, 555–561. https://doi.org/10.1007/s00374-009-0365-z.

Islam, F., Yasmeen, T., Arif, M.S., Ali, S., Ali, B., Hameed, S., Zhou, W., 2016. Plant growth promoting bacteria confer salt tolerance in Vigna radiata by up-regulating antioxidant defense and biological soil fertility. Plant Growth Regulation 80, 23–36. https://doi.org/10.1007/s10725-015-0142-y.

Jain, N.K., Jat, R.S., Meena, H.N., Chakraborty, K., 2018. Productivity, Nutrient, and Soil Enzymes Influenced with Conservation Agriculture Practices in Peanut. Agronomy journal 110, 1165–1172. https://doi.org/10.2134/agronj2017.08.0467.

Jaskulska, I., Romaneckas, K., Jaskulski, D., Gałęzewski, L., Breza-Boruta, B., Dębska, B., Lemanowicz, J., 2020. Soil properties after eight years of the use of strip-till one-pass technology. Agronomy 10, 1–16. https://doi.org/10.3390/agronomy10101596.

Jaskulska, R. 2020. The Level of Luvisols Biochemical Activity in Midfield Shelterbelt and Winter Triticale (xTriticosecale Wittm. ex A.Camus) Cultivation. Agronomy 10, 1644. https://doi.org/10.3390/agronomy10111644.

Jat, H.S., Choudhary, M., Datta, A., Yadav, A.K., Meena, M.D., Devi, R., Gathala, M.K., Jat, M.L., McDonald, A., Sharma, P.C., 2020. Temporal changes in soil microbial properties and nutrient dynamics under climate smart agriculture practices. Soil and Tillage Research 199, 104595. https://doi.org/10.1016/j.still.2020.104595.

Jat, H.S., Datta, A., Choudhary, M., Sharma, P.C., Yadav, A.K., Choudhary, V., Gathala, M.K., Jat, M.L., McDonald, A., 2019. Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. Catena 181, 104059. https://doi.org/10.1016/j.catena.2019.05.005.

Jia, Q., Kamran, M., Ali, S., Sun, L., Zhang, P., Ren, X., Jia, Z., 2018. Deficit irrigation and fertilization strategies to improve soil quality and alfalfa yield in arid and semi-arid areas of northern China. PeerJ 2018, 1–21. https://doi.org/10.7717/peerj.4410.

Johnson, J.M.F., Acosta-Martinez, V., Cambardella, C.A., Barbour, N.W., 2013. Crop and soil responses to using corn stover as a bioenergy feedstock: Observations from the northern us corn belt. Agriculture (Switzerland) 3, 72–89. https://doi.org/10.3390/agriculture3010072.

Jordan, D., Kremer, R.J., Bergfield, W.A., Kim, K.Y., Cacnio, V.N., 1995. Evaluation of microbial methods as potential indicators of soil quality in historical agricultural fields. Biology and Fertility of Soils 19, 297–302. https://doi.org/10.1007/BF00336098.

Jr, H.B., Elliott, L.F., Papendick, R.I., Bezdicek, D.F., 1985. Soil microbial biomass and selected soil enzyme activities: Effect of fertilization and cropping practices. Soil Biology and Biochemistry 17, 297–302. https://doi.org/10.1016/0038-0717(85)90064-1.

Kanchikerimath, M., Singh, D., 2001. Soil organic matter and biological properties after 26 years of maize-wheat-cowpea cropping as affected by manure and fertilization in a Cambisol in semiarid region of India. Agriculture, Ecosystems and Environment 86, 155–162. https://doi.org/10.1016/S0167-8809(00)00280-2.

Katsalirou, E., Deng, S., Gerakis, A., Nofziger, D.L., 2016. Long-term management effects on soil P, microbial biomass P, and phosphatase activities in prairie soils. European Journal of Soil Biology 76, 61–69. https://doi.org/10.1016/j.ejsobi.2016.07.001.

Kayikcioglu, H.H., 2018. Can treated wastewater be used as an alternative water resource for agricultural irrigation? Changes in soil and plant health after three years of maize cultivation in western anatolia, Turkey. Applied Ecology and Environmental Research 16, 8131–8161. https://doi.org/10.15666/aeer/1606_81318161.

Kayikcioglu, H.H., Sahin, B., 2013. Long-term effects of olive mill wastewater sludge on soil biological properties and yield efficiency: A case study of a fig grove in southern Turkey. Journal of Food, Agriculture and Environment 11, 950–958.

Khajanchi -Lal, M., P.S., Yadav, R.K., 2015. Long-term impact of wastewater irrigation and nutrient rates II. Nutrient balance, nitrate leaching and soil properties under peri-urban cropping systems. Agricultural Water Management 156, 110–117. https://doi.org/10.1016/j.agwat.2015.04.001.

Khandare, R.N., Chandra, R., Pareek, N., Raverkar, K.P., 2020. Carrier-based and liquid bioinoculants of Azotobacter and PSB saved chemical fertilizers in wheat (Triticum aestivum L.) and enhanced soil biological properties in Mollisols. Journal of Plant Nutrition 43, 36–50. https://doi.org/10.1080/01904167.2019.1659333.

Klose, S., Ajwa, H.A., 2004. Enzyme activities in agricultural soils fumigated with methyl bromide alternatives. Soil Biology and Biochemistry 36, 1625–1635.

https://doi.org/10.1016/j.soilbio.2004.07.009.

Kohler, J., Tortosa, G., Cegarra, J., Caravaca, F., Roldán, A., 2008. Impact of DOM from composted "alperujo" on soil structure, AM fungi, microbial activity and growth of Medicago sativa. Waste Management 28, 1423–1431. https://doi.org/10.1016/j.wasman.2007.05.008.

Kooch, Y., Ehsani, S., Akbarinia, M., 2019. Stoichiometry of microbial indicators shows clearly more soil responses to land cover changes than absolute microbial activities. Ecological Engineering 131, 99–106. https://doi.org/10.1016/j.ecoleng.2019.03.009.

Koper, J., Lemanowicz, J., 2008. Effect of varied mineral nitrogen fertilization on changes in the content of phosphorus in soil and in plant and the activity of soil phosphatases. Ecological Chemistry and Engineering S 15, 465–471.

Kremer, R.J., Li, J., 2003. Developing weed-suppressive soils through improved soil quality management. Soil and Tillage Research 72, 193–202. https://doi.org/10.1016/S0167-1987(03)00088-6.

Kumar, M., Bauddh, K., Kumar, S., Sainger, M., Sainger, P.A., Singh, R.P., 2013. Increase in growth, productivity and nutritional status of wheat (Triticum aestivum L. cv. WH-711) and enrichment in soil fertility applied with organic matrix entrapped urea. Journal of Environmental Biology 34, 1–9.

Kumar, R., Shambhavi, S., Beura, K., Kumar, S., Singh, R.G., 2017. Soil microbial budgeting as influenced by contrasting tillage and crop diversification under rice based cropping systems in Inseptisol of Bihar. Journal of Pure and Applied Microbiology 11, 539–547. https://doi.org/10.22207/JPAM.11.1.71.

Kunito, T., Saeki, K., Goto, S., Hayashi, H., Oyaizu, H., Matsumoto, S., 2001. Copper and zinc fractions affecting microorganisms in long-term sludge-amended soils. Bioresource Technology 79, 135–146. https://doi.org/10.1016/S0960-8524(01)00047-5.

Kunze, A., Costa, M.D., Epping, J., Loffaguen, J.C., Schuh, R., Lovato, P.E., 2011. Phosphatase activity in sandy soil influenced by mycorrhizal and non-mycorrhizal cover crops. Revista Brasileira de Ciencia do Solo 35, 705–711. https://doi.org/10.1590/s0100-06832011000300005.

Kuwano, B.H., Nogueira, M.A., Santos, C.A., Fagotti, D.S.L., Santos, M.B., Lescano, L.E.A.M., Andrade, D.S., Barbosa, G.M.C., Tavares-Filho, J., 2017. Application of Landfill Leachate Improves Wheat Nutrition and Yield but Has Minor Effects on Soil Properties. Journal of Environmental Quality 46, 153–159. https://doi.org/10.2134/jeq2016.02.0041.

Lalande, R., Gagnon, B., Simard, R.R., 2003. Papermill biosolid and hog manure compost affect short-term biological activity and crop yield of a sandy soil. Canadian

Journal of Soil Science 83, 353–362. https://doi.org/10.4141/S03-004.

Lalande, R., Gagnon, B., Royer, I., 2009. Impact of natural or industrial liming materials on soil properties and microbial activity. Canadian Journal of Soil Science 89, 209–222. https://doi.org/10.4141/CJSS08015.

Leirós, M.C., Trasar-Cepeda, C., García-Fernández, F., Gil-Sotres, F., 1999. Defining the validity of a biochemical index of soil quality. Biology and Fertility of Soils 30, 140–146. https://doi.org/10.1007/s003740050600.

Lemanowicz, J., Bartkowiak, A., Breza-Boruta, B., 2016. Changes in phosphorus content, phosphatase activity and some physicochemical and microbiological parameters of soil within the range of impact of illegal dumping sites in Bydgoszcz (Poland). Environmental Earth Sciences 75, 1–14. https://doi.org/10.1007/s12665-015-5162-4.

Lemanowicz, J., Siwik-Ziomek, A., Koper, J., 2013. Content of total phosphorus in soil uner maize treated with mineral fertilization against the phosphatase activity. Journal of Elementology 18, 415–424. https://doi.org/10.5601/jelem.2013.18.3.06.

Li, X.H., Han, X.Z., Li, H.B., Song, C., Yan, J., Liang, Y., 2012. Soil chemical and biological properties affected by 21-year application of composted manure with chemical fertilizers in a Chinese mollisol. Canadian Journal of Soil Science 92, 419–428. https://doi.org/10.4141/CJSS2010-046.

Liu, E., Yan, C., Mei, X., He, W., Bing, S.H., Ding, L., Liu, Q., Liu, S., Fan, T., 2010. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. Geoderma 158, 173–180. https://doi.org/10.1016/j.geoderma.2010.04.029.

Liu, X. Chen, Q-w, Zeng, Z-x., 2011. The Effects of Different Tillages on Crop Residue Sequestration, Soil Available Nutrients and Some Biochemical Properties in the Chinese Black Soil Region. Agricultural Sciences in China 10, 576–584. https://doi.org/10.1016/S1671-2927(11)60039-4.

Liu, X.M., Li, Q., Liang, W.J., Jiang, Y., 2008. Distribution of Soil Enzyme Activities and Microbial Biomass Along a Latitudinal Gradient in Farmlands of Songliao Plain, Northeast China1 1 Project supported by the National Key Basic Research Support Foundation of China (No. 2005CB121105) and the Nation. Pedosphere 18, 431–440. https://doi.org/10.1016/S1002-0160(08)60034-X.

Liu, Z., Bai, J., Qin, H., Sun, D., Li, M., Hu, J., Lin, X., 2021. Application of rice straw and horse manure coameliorated soil arbuscular mycorrhizal fungal community: Impacts on structure and diversity in a degraded field in Eastern China. Land Degradation and Development 32, 2595–2605. https://doi.org/10.1002/ldr.3927.

Lopes, A.A. de C., Sousa, D.M.G. de, Chaer, G.M., Junior, F.B. dos R., Goedert, W.J., Mendes, I. de C., 2013. Interpretation of Microbial Soil Indicators as a Function of Crop Yield and Organic Carbon. Soil Science Society of America Journal 77, 461–472. https://doi.org/10.2136/sssaj2012.0191.

Lungmuana, Singh, S.B., Choudhury, B.U., Vanthawmliana, Saha, S., Hnamte, V., 2019. Transforming jhum to plantations: Effect on soil microbiological and biochemical properties in the foot hills of North Eastern Himalayas, India. Catena 177, 84–91. https://doi.org/10.1016/j.catena.2019.02.008.

Ma, H., Egamberdieva, D., Wirth, S., Li, Q., Omari, R.A., Hou, M., Bellingrath-Kimura, S.D., 2019. Effect of biochar and irrigation on the interrelationships among soybean growth, root nodulation, plant p uptake, and soil nutrients in a sandy field. Sustainability 11, 1–16. https://doi.org/10.3390/su11236542.

Madejón, E., Burgos, P., López, R., Cabrera, F., 2003. Agricultural use of three organic residues: Effect on orange production and on properties of a soil of the “Comarca Costa de Huelva” (SW Spain). Nutrient Cycling in Agroecosystems 65, 281–288. https://doi.org/10.1023/A:1022608828694.

Mahajan, G.R., Manjunath, B.L., Latare, A.M., D’Souza, R., Vishwakarma, S., Singh, N.P., 2016. Microbial and Enzyme Activities and Carbon Stock in Unique Coastal Acid Saline Soils of Goa. Proceedings of the National Academy of Sciences India Section B - Biological Sciences 86, 961–971. https://doi.org/10.1007/s40011-015-0552-7.

Mahajan, G.R., Manjunath, B.L., Morajkar, S., Desai, A., Das, B., Paramesh, V., 2021. Long-Term Effect of Various Organic and Inorganic Nutrient Sources on Rice Yield and Soil Quality in West Coast India Using Suitable Indexing Techniques. Communications in Soil Science and Plant Analysis 52, 1819–1833. https://doi.org/10.1080/00103624.2021.1900221.

Majumdar, B., Saha, A.R., Sarkar, S., Maji, B., Mahapatra, B.S., 2010. Effect of herbicides and fungicides application on fibre yield and nutrient uptake by jute (Corchorus olitorius), residual nutrient status and soil quality. Indian Journal of Agricultural Sciences 80, 878–883.

Mandal, A., Patra, A.K., Singh, D., Swarup, A., Masto, R.E., 2007. Effect of long-term application of manure and fertilizer on biological and biochemical activities in soil during crop development stages. Bioresource Technology 98, 3585–3592. https://doi.org/10.1016/j.biortech.2006.11.027.

Mandal, A., Thakur, J.K., Sahu, A., Manna, M.C., Rao, A.S., Sarkar, B., Patra, A.K., 2019. Effects of Bt-cotton on biological properties of Vertisols in central India. Archives of Agronomy and Soil Science 65, 670–685. https://doi.org/10.1080/03650340.2018.1520978.

Mankolo, R., Reddy, C., Senwo, Z., Nyakatawa, E., Sajjala, S., 2012. Soil biochemical changes induced by poultry litter application and conservation tillage under cotton production systems. Agronomy 2, 187–198. https://doi.org/10.3390/agronomy2030187.

Mankolo, R.N., Senwo, Z.N., Ranatunga, T.D., Tazisong, I.A., 2006. Phosphorus partitioning and phosphatase activity along topographic gradients of an ggricultural watershed cropped with corn and soybean. Journal of Sustainable Agriculture 28, 131–143. https://doi.org/10.1300/J064v28n02_10.

Manna, M.C., Rao, A.S., Ganguly, T.K., 2007. Effect of fertilizer P and farmyard manure on bioavailable P as influenced by rhizosphere microbial activities in soybean-wheat rotation. Journal of Sustainable Agriculture 29, 149–166. https://doi.org/10.1300/J064v29n03_12.

Mariela, F.P., Pável, M.E.I., Manuel, S.R.L., Jesús, F.G.M., Reyes, L.O., 2016. Dehydrogenase and mycorrhizal colonization: Tools for monitoring agrosystem soil quality. Applied Soil Ecology 100, 144–153. https://doi.org/10.1016/j.apsoil.2015.12.011.

Martins, L.N.B., Santiago, F.L. de A., Montecchia, M.S., Correa, O.S., Junior, O.J.S., Souza, E.D. de, Paulino, H.B., Carneiro, M.A.C., 2019. Biochemical and biological properties of soil from murundus wetlands converted into agricultural systems. Revista Brasileira de Ciencia do Solo 43, 1–13. https://doi.org/10.1590/18069657rbcs20180183.

Masto, R.E., Chhonkar, P.K., Singh, D., Patra, A.K., 2009. Changes in soil quality indicators under long-term sewage irrigation in a sub-tropical environment. Environmental Geology 56, 1237–1243. https://doi.org/10.1007/s00254-008-1223-2.

Masto, R.E., Chhonkar, P.K., Singh, D., Patra, A.K., 2006. Changes in soil biological and biochemical characteristics in a long-term field trial on a sub-tropical inceptisol. Soil Biology and Biochemistry 38, 1577–1582. https://doi.org/10.1016/j.soilbio.2005.11.012.

Meena, M.D., Joshi, P.K., Jat, H.S., Chinchmalatpure, A.R., Narjary, B., Sheoran, P., Sharma, D.K., 2016. Changes in biological and chemical properties of saline soil amended with municipal solid waste compost and chemical fertilizers in a mustard-pearl millet cropping system. Catena 140, 1–8.

Melero, S., López-Bellido, R.J., López-Bellido, L., Muñoz-Romero, V., Moreno, F., Murillo, J.M., 2011. Long-term effect of tillage, rotation and nitrogen fertiliser on soil quality in a Mediterranean Vertisol. Soil and Tillage Research 114, 97–107. https://doi.org/10.1016/j.still.2011.04.007.

Melero, S., Madejón, E., Herencia, J.F., Ruiz, J.C., 2008a. Effect of implementing organic farming on chemical and biochemical properties of an irrigated loam soil. Agronomy

Journal 100, 136–144. https://doi.org/10.2134/agronj2007.0087.
Melero, S., Porras, J.C.R., Herencia, J.F., Madejon, E., 2006. Chemical and biochemical properties in a silty loam soil under conventional and organic management. Soil and Tillage Research 90, 162–170. https://doi.org/10.1016/j.still.2005.08.016.
Melero, S., Vanderlinden, K., Ruiz, J.C., Madejn, E., 2009. Soil biochemical response after 23 years of direct drilling under a dryland agriculture system in southwest Spain. Journal of Agricultural Science 147, 9–15. https://doi.org/10.1017/S0021859608008204.
Melero, S., Vanderlinden, K., Ruiz, J.C., Madejon, E., 2008b. Long-term effect on soil biochemical status of a Vertisol under conservation tillage system in semi-arid Mediterranean conditions. European Journal of Soil Biology 44, 437–442. https://doi.org/10.1016/j.ejsobi.2008.06.003.
Meli, S., Porto, M., Belligno, A., Bufo, S.A., Mazzatura, A., Scopa, A., 2002. Influence of irrigation with lagooned urban wastewater on chemical and microbiological soil parameters in a citrus orchard under Mediterranean condition. Science of the Total Environment 285, 69–77. https://doi.org/10.1016/S0048-9697(01)00896-8.
Meshram, N.A., Ismail, S., Patil, V.D., 2016. Long-term effect of organic manuring and inorganic fertilization on humus fractionation, microbial community and enzymes assay in vertisol. Journal of Pure and Applied Microbiology 10, 139–150.
Mijangos, I., Pérez, R., Albizu, I., Garbisu, C., 2006. Effects of fertilization and tillage on soil biological parameters. Enzyme and Microbial Technology 40, 100–106. https://doi.org/10.1016/j.enzmictec.2005.10.043.
Mina, B.L., Saha, S., Kumar, N., Srivastva, A.K., Gupta, H.S., 2008. Changes in soil nutrient content and enzymatic activity under conventional and zero-tillage practices in an Indian sandy clay loam soil. Nutrient Cycling in Agroecosystems 82, 273–281. https://doi.org/10.1007/s10705-008-9189-8.
Mina, U., Chaudhary, A., 2012. Impact of transgenic cotton varieties on activity of enzymes in their rhizosphere. Indian Journal of Biochemistry and Biophysics 49, 195–201.
Mohammadi, K., Eskandari, M., Heidari, G., Nezhad, M.T.K., 2011. Canola traits and some soil biological parameters in response to fertilization and tillage management. African Journal of Biotechnology 10, 14067–14072. https://doi.org/10.5897/ajb11.2161.
Monaci, E., Polverigiani, S., Neri, D., Bianchelli, M., Santilocchi, R., Toderi, M., D'Ottavio, P., Vischetti, C., 2017. Effect of contrasting crop rotation systems on soil chemical and biochemical properties and plant root growth in organic farming: First results. Italian Journal of Agronomy 12, 364–374. https://doi.org/10.4081/ija.2017.831.

Monkiedje, A., Spiteller, M., Fotio, D., Sukul, P., 2006. The Effect of Land Use on Soil Health Indicators in Peri-Urban Agriculture in the Humid Forest Zone of Southern Cameroon. Journal of Environmental Quality 35, 2402–2409. https://doi.org/10.2134/jeq2005.0447.

Monokrousos, N., Papatheodorou, E.M., Diamantopoulos, J.D., Stamou, G.P., 2006. Soil quality variables in organically and conventionally cultivated field sites. Soil Biology and Biochemistry 38, 1282–1289. https://doi.org/10.1016/j.soilbio.2005.09.023.

Moreira, R.S., Chiba, M.K., Nunes, S.B., Maria, I.C.D., 2017. Air-drying pretreatment effect on soil enzymatic activity. Plant, Soil and Environment 63, 29–33. https://doi.org/10.17221/656/2016-PSE.

Morugán-Coronado, A., García-Orenes, F., Cerdà, A., 2015. Changes in soil microbial activity and physicochemical properties in agricultural soils in Eastern Spain. Spanish Journal of Soil Science 5, 201–213. https://doi.org/10.3232/SJSS.2015.V5.N3.02.

Mukumbareza, C., Muchaonyerwa, P., Chiduza, C., 2015. Effects of oats and grazing vetch cover crops and fertilisation on microbial biomass and activity after five years of rotation with maize. South African Journal of Plant and Soil 32, 189–197. https://doi.org/10.1080/02571862.2015.1025446.

Nayyar, A., Hamel, C., Lafond, G., Gossen, B.D., Hanson, K., Germida, J., 2009. Soil microbial quality associated with yield reduction in continuous-pea. Applied Soil Ecology 43, 115–121. https://doi.org/10.1016/j.apsoil.2009.06.008.

N'Dayegamiye, A., 2006. Mixed paper mill sludge effects on corn yield, nitrogen efficiency, and soil properties. Agronomy Journal 98, 1471–1478. https://doi.org/10.2134/agronj2005.0339.

Nedunchezhiyan, M., Laxminarayana, K., Chauhan, V.B.S., 2018. Soil Microbial Activities and Yield of Elephant Foot Yam as Influenced by Weed Management Practices in Alfisols. International Journal of Vegetable Science 24, 583–596. https://doi.org/10.1080/19315260.2018.1454567.

Nedyalkova, K., Donkova, R., Malinov, I., 2020. Acid phosphatase activity under the impact of erosion level in agricultural soils of different type and land use. Bulgarian Journal of Agricultural Science 26, 1217–1222.

Neha, Chandra, R., Pareek, N., Raverkar, K.P., 2019. Effect of rhizobium and pgpr inoculation in mungbean on productivity and soil properties in mungbean-wheat sequence. Journal of the Indian Society of Soil Science 67, 458–464. https://doi.org/10.5958/0974-0228.2019.00050.1.

Niewiadomska, A., Gaj, R., Przybył, J., Budka, A., Mioduszewska, N., Wolna-Maruwka, A., 2016. Analysis of microbial parameters of soil in different tillage systems under sugar beets (Beta vulgaris L.). Polish Journal of Environmental Studies 25, 1803–

1811. https://doi.org/10.15244/pjoes/62644.
Niewiadomska, A., Majchrzak, L., Borowiak, K., Wolna-Maruwka, A., Waraczewska, Z., Budka, A., Gaj, R., 2020a. The influence of tillage and cover cropping on soil microbial parameters and spring wheat physiology. Agronomy 10. https://doi.org/10.3390/agronomy10020200.
Niewiadomska, A., Sawińska, Z., Wolma-Maruwka, A., 2011. Impact of selected seed dressings on soil microbiological activity in spring barley cultivation. Fresenius Environmental Bulletin 20, 1252–1261.
Niewiadomska, A., Sulewska, H., Wolna-Maruwka, A., Ratajczak, K., Waraczewska, Z., Budka, A., 2020b. The influence of bio-stimulants and foliar fertilizers on yield, plant features, and the level of soil biochemical activity in white lupine (Lupinus albus L.) cultivation. Agronomy 10. https://doi.org/10.3390/agronomy10010150.
Ning, C-c., Gao, P-d., Wang, B-q., Lin, W-p., Jiang, N-h., Cai, K-z., 2017. Impacts of chemical fertilizer reduction and organic amendments supplementation on soil nutrient, enzyme activity and heavy metal content. Journal of Integrative Agriculture 16, 1819–1831. https://doi.org/10.1016/S2095-3119(16)61476-4.
Notaro, K.A., Medeiros, E.V. de, Duda, G.P., Moreira, K.A., Barros, J.A. de, Santos, U.J. dos, Lima, J.R. de S., Moraes, W. da S., 2018. Enzymatic activity, microbial biomass, and organic carbon of entisols from brazilian tropical dry forest and annual and perennial crops. Chilean Journal of Agricultural Research 78, 68–77. https://doi.org/10.4067/S0718-58392018000100068.
Oehl, F., Frossard, E., Fliessbach, A., Dubois, D., Oberson, A., 2004. Basal organic phosphorus mineralization in soils under different farming systems. Soil Biology and Biochemistry 36, 667–675. https://doi.org/10.1016/j.soilbio.2003.12.010.
Okur, N., Altindisli, A., Cengel, M., Gocmez, S., Kayikcioglu, H.H., 2009. Microbial biomass and enzyme activity in vineyard soils under organic and conventional farming systems. Turkish Journal of Agriculture and Forestry 33, 413–423. https://doi.org/10.3906/tar-0806-23.
Okur, N., Kayikcioglu, H.H., Ates, F., Yagmur, B., 2016. A comparison of soil quality and yield parameters under organic and conventional vineyard systems in Mediterranean conditions (West Turkey). Biological Agriculture and Horticulture 32, 73–84. https://doi.org/10.1080/01448765.2015.1033645.
Okur, N., Kayikçioğlu, H.H.H., Okur, B., Delibacak, S., 2008. Organic amendment based on tobacco waste compost and farmyard manure: Influence on soil biological properties and butter-head lettuce yield. Turkish Journal of Agriculture and Forestry 32, 91–99. https://doi.org/10.3906/tar-0707-24.
Omenda, J.A., Ngetich, K.F., Kiboi, M.N., Mucheru-Muna, M.W., Mugendi, D.N., 2019.

Soil Organic Carbon and Acid Phosphatase Enzyme Activity Response to Phosphate Rock and Organic Inputs in Acidic Soils of Central Highlands of Kenya in Maize. International Journal of Plant & Soil Science 30, 1–13. https://doi.org/10.9734/ijpss/2019/v30i230169.

Ortiz, J., Faggioli, V.S., Ghio, H., Boccolini, M.F., Ioele, J.P., Tamburrini, P., Garcia, F.O., Gudelj, V., 2020. Long-term impact of fertilization on the structure and functionality of microbial soil community | Impacto a largo plazo de la fertilización sobre la estructura y funcionalidad de la comunidad microbiana del suelo. Ciencia del Suelo 38, 45–55.

Pandey, J., Pandey, U., Shubhashish, K., Pandey, R., 2008. Inter-species variations in soil fertility stability in organic farm. Plant Archives 8, 61–63.

Pandey, J., Pandey, U., 2009. Atmospheric deposition and heavy metal contamination in an organic farming system in a seasonally dry tropical region of India. Journal of Sustainable Agriculture 33, 361–378. https://doi.org/10.1080/10440040902834954.

Pandey, S., Singh, D.K., 2006. Soil dehydrogenase, phosphomonoesterase and arginine deaminase activities in an insecticide treated groundnut (Arachis hypogaea L.) field. Chemosphere 63, 869–880.

Patel, G., Dwivedi, B.S., Dwivedi, A.K., Thakur, R., Singh, M., 2018. Long-term effect of nutrient management on soil biochemical properties in a vertisol under soybean-wheat cropping sequence. Journal of the Indian Society of Soil Science 66, 215–221. https://doi.org/10.5958/0974-0228.2018.00027.0.

Pramanik, P., Safique, S., Jahan, A., Bhagat, R.M., 2017. Humic substrates application in diluted form enhanced availability of phosphorus (P) and its uptake by tea bushes in the tea-growing soil of Northeast India. Journal of Plant Nutrition 40, 2841–2849. https://doi.org/10.1080/01904167.2017.1383420.

Prasanthi, G., Kumar, N.G., Raghu, S., Srinivasa, N., Gurumurthy, H., 2019. Study on the effect of different levels of organic and inorganic fertilizers on microbial enzymes and soil mesofauna in soybean ecosystem. Legume Research 42, 233–237. https://doi.org/10.18805/LR-3850.

Pupin, B., Freddi, O. da S., Nahas, E., 2009. Microbial alterations of the soil influenced by induced compaction. Revista Brasileira de Ciencia do Solo 33, 1207–1213. https://doi.org/10.1590/s0100-06832009000500014.

Qaswar, M., Chai, R., Ahmed, W., Jing, H., Han, T., Liu, K., Ye, X., Xu, Y., Anthonio, C.K., Zhang, H., 2020. Partial substitution of chemical fertilizers with organic amendments increased rice yield by changing phosphorus fractions and improving phosphatase activities in fluvo-aquic soil. Journal of Soils and Sediments 20, 1285–1296. https://doi.org/10.1007/s11368-019-02476-3.

Qaswar, M., Jing, H., Ahmed, W., Dongchu, L., Shujun, L., Ali, S., Kailou, L., Yongmei, X., Lu, Z., Lisheng, L., Jusheng, G., Huimin, Z., 2019. Long-term green manure rotations improve soil biochemical properties, yield sustainability and nutrient balances in acidic paddy soil under a rice-based cropping system. Agronomy 9. https://doi.org/10.3390/agronomy9120780.

Qin, X., Guo, S., Zhai, L., Pan, J., Khoshnevisan, B., Wu, S., Wang, H., Yang, B., Ji, J., Liu, H., 2020. How long-term excessive manure application affects soil phosphorous species and risk of phosphorous loss in fluvo-aquic soil. Environmental Pollution 266, 115304.

Radersma, S., Grierson, P.F., 2004. Phosphorus mobilization in agroforestry: Organic anions, phosphatase activity and phosphorus fractions in the rhizosphere. Plant and Soil 259, 209–219. https://doi.org/10.1023/B:PLSO.0000020970.40167.40.

Rajeela, T.H.K., Gopal, M., Gupta, A., Bhat, R., Thomas, G.V., 2017. Cross-compatibility evaluation of plant growth promoting rhizobacteria of coconut and cocoa on yield and rhizosphere properties of vegetable crops. Biocatalysis and Agricultural Biotechnology 9, 67–73. https://doi.org/10.1016/j.bcab.2016.11.006.

Rakshit, R., Patra, A.K., Purakayastha, T.J., Singh, R.D., Dhar, S., Pathak, H., Das, A., 2016. Effect of super-optimal levels of fertilizers on soil enzymatic activities during growth stages of wheat crop on an Inceptisol. Journal of Applied and Natural Science 8, 1398–1403. https://doi.org/10.31018/jans.v8i3.972.

Ram, R.A., Singha, A., Singh, V.K., 2019. Improvement in yield and fruit quality of mango (Mangifera indica) with organic amendments. Indian Journal of Agricultural Sciences 89, 1429–1433.

Ramanandan, L.G., Swaroop, N., David, A.A., Thomas, T., 2020. Effectiveness of Organics with Nitrogen Levels and Bio-fertilizers on Soil Chemico-biological Properties of Wheat (Triticum aestivum L.) Crop [Cv.PBW-343] in Inseptisol. Asian Journal of Soil Science and Plant Nutrition 6, 30–50. https://doi.org/10.9734/ajsspn/2020/v6i230084.

Ramdas, M.G., Manjunath, B.L., Pratap, S.N., Ramesh, R., Verma, R.R., Marutrao, L.A., Ruenna, D., Natasha, B., Rahul, K., 2017. Effect of organic and inorganic sources of nutrients on soil microbial activity and soil organic carbon build-up under rice in west coast of India. Archives of Agronomy and Soil Science 63, 414–426. https://doi.org/10.1080/03650340.2016.1213813.

Ramos, M.E., Benítez, E., García, P.A., Robles, A.B., 2010. Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: Effects on soil quality. Applied Soil Ecology 44, 6–14. https://doi.org/10.1016/j.apsoil.2009.08.005.

Ramos, M.E., Robles, A.B., Sánchez-Navarro, A., González-Rebollar, J.L., 2011. Soil responses to different management practices in rainfed orchards in semiarid environments. Soil and Tillage Research 112, 85–91. https://doi.org/10.1016/j.still.2010.11.007.

Rana, M., Chandra, R., Pareek, N., 2015. Co-inoculation effect of endophytic bacteria with Mesorhizobium sp. In Chickpea (cicer arietinum L.) on nodulation, yields, nutrient uptake and soil biological properties. Journal of the Indian Society of Soil Science 63, 429–435. https://doi.org/10.5958/0974-0228.2015.00057.2.

Rana, Monika, Raverkar, K.P.P., Pareek, N., Chandra, R., Singh, D.K.K., 2015. Impact of biodynamic preparations and panchgavya in organically managed cropping systems comprising legumes on soil biological health. Legume Research 38, 219–228. https://doi.org/10.5958/0976-0571.2015.00081.8.

Reardon, C.L., Wuest, S.B., 2016. Soil amendments yield persisting effects on the microbial communities-a 7-year study. Applied Soil Ecology 101, 107–116. https://doi.org/10.1016/j.apsoil.2015.12.013.

Reeve, J.R., Endelman, J.B., Miller, B.E., Hole, D.J., 2011. Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. Soil Science Society of America Journal 76, 278–286. https://doi.org/10.2136/sssai20n.0t23.

Riffaldi, R., Saviozzi, A., Levi-Minzi, R., Cardelli, R., 2002. Biochemical properties of a Mediterranean soil as affected by long-term crop management systems. Soil and Tillage Research 67, 109–114. https://doi.org/10.1016/S0167-1987(02)00044-2.

Riffaldi, R., Saviozzi, A., Levi-Minzi, R., Menchetti, F., 1994. Chemical characteristics of soil after 40 years of continuous maize cultivation. Agriculture, Ecosystems and Environment 49, 239–245. https://doi.org/10.1016/0167-8809(94)90053-1.

Roberto, G.R., Ochoa, M.V., Hinojosa, M.B., Beatriz, G.M., 2012. Improved soil quality after 16 years of olive mill pomace application in olive oil groves. Agronomy for Sustainable Development 32, 803–810. https://doi.org/10.1007/s13593-011-0080-7.

Rodrigues, M.Â.Â., Dimande, P., Pereira, E.L.E.L.E.L., Ferreira, I.Q.I.Q.I.Q., Freitas, S., Correia, C.M.C.M., Moutinho-Pereira, J., Arrobas, M., 2015. Early-maturing annual legumes: an option for cover cropping in rainfed olive orchards. Nutrient Cycling in Agroecosystems 103, 153–166. https://doi.org/10.1007/s10705-015-9730-5.

Rodríguez-Salgado, I., Pérez-Rodríguez, P., Gómez-Armesto, A., Díaz-Raviña, M., Nóvoa-Muñoz, J.C., Arias-Estévez, M., Fernández-Calviño, D., 2017. Modification of chemical properties, Cu fractionation and enzymatic activities in an acid vineyard soil amended with winery wastes: A field study. Journal of Environmental Management 202, 167–177. https://doi.org/10.1016/j.jenvman.2017.07.021.

Romanyà, J., Blanco-Moreno, J.M., Sans F.X., 2017. Phosphorus mobilization in low-P arable soils may involve soil organic C depletion. Soil Biology and Biochemistry 113, 250–259. https://doi.org/10.1016/j.soilbio.2017.06.015.

Roohi, M., Arif, M.S., Yasmeen, T., Riaz, M., Rizwan, M., Shahzad, S.M., Ali, S., Bragazza, L., 2020. Effects of cropping system and fertilization regime on soil phosphorous are mediated by rhizosphere-microbial processes in a semi-arid agroecosystem. Journal of Environmental Management 271, 111033. https://doi.org/10.1016/j.jenvman.2020.111033.

Ros, M., García, C., Hernandez, M.T., 2007. Evaluation of different pig slurry composts as fertilizer of horticultural crops: Effects on selected chemical and microbial properties. Renewable Agriculture and Food Systems 22, 307–315. https://doi.org/10.1017/S1742170507001913.

Saha, A., Bhaduri, D., Pipariya, A., Jain, N.K., 2016. Influence of imazethapyr and quizalofop-p-ethyl application on microbial biomass and enzymatic activity in peanut grown soil. Environmental Science and Pollution Research 23, 23758–23771. https://doi.org/10.1007/s11356-016-7553-9.

Saha, A., Bhaduri, D., Pipariya, A., Jain, N.K., Basak, B.B., 2015. Behaviour of pendimethalin and oxyfluorfen in peanut field soil: effects on soil biological and biochemical activities. Chemistry and Ecology 31, 550–566. https://doi.org/10.1080/02757540.2015.1039526.

Saha, S., Mina, B.L., Gopinath, K.A., Kundu, S., Gupta, H.S., 2008. Organic amendments affect biochemical properties of a subtemperate soil of the Indian Himalayas. Nutrient Cycling in Agroecosystems 80, 233–242. https://doi.org/10.1007/s10705-007-9139-x.

Saha, Supradip, Mina, B.L., Gopinath, K.A., Kundu, S., Gupta, H.S., 2008. Relative changes in phosphatase activities as influenced by source and application rate of organic composts in field crops. Bioresource Technology 99, 1750–1757. https://doi.org/10.1016/j.biortech.2007.03.049.

Samuel, A.D., Domuţa, C., Şandor, M., 1970. Soil Enzyme Activities Under Crop Rotations Systems in a Brown Luvic Soil. Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agriculture 62, 2–7. https://doi.org/10.15835/buasvmcn-agr:1578.

Sánchez, S.M., Madejón, E., Herencia, J.F., Ruiz-Porras, J.C., 2008. Long-term study of properties of a xerofluvent of the Guadalquivir River Valley under organic fertilization. Agronomy Journal 100, 611–618. https://doi.org/10.2134/agronj2006.0316.

Sangma, C.B.K., Thakuria, D., Biam, D.E.D., 2016. Rice ecosystems in hill agriculture: Effect on soil biological pools of carbon, nitrogen and phosphorus. Journal of the Indian Society of Soil Science 64, 391–401. https://doi.org/10.5958/0974-

0228.2016.00051.7.

Sarkar, I.U.I.U.I.U., Jahan, A., Naher, U.A.U.A., Iqbal, M., Mamun, A.A., Biswas, J.C.J.C.J.C., Islam, R., 2020. Organic and inorganic amendment of wetland paddy soil for five years: effects on phosphorus fraction dynamics. Journal of Crop Improvement 34, 875–896. https://doi.org/10.1080/15427528.2020.1784343.

Sarma, B., Gogoi, N., 2017. Nitrogen Management for Sustainable Soil Organic Carbon Increase in Inceptisols Under Wheat Cultivation. Communications in Soil Science and Plant Analysis 48, 1428–1437. https://doi.org/10.1080/00103624.2017.1373785.

Selvamurugan, M., Doraisamy, P., Maheswari, M., 2011. Effect of biomethanated distillery spentwash and pressmud biocompost on microbial and enzyme dynamics in sugarcane grown soil. Journal of Biological Sciences 11(6), 417-422. http://scialert.net/fulltext/?doi=jbs.2011.417.422&org=11.

Sepat, S., Behera, U.K., Sharma, A.R., Das, T.K., Bhattacharyya, R., 2014. Productivity, organic carbon and residual soil fertility of Pigeonpea-wheat cropping system under varying tillage and residue management. Proceedings of the National Academy of Sciences India Section B - Biological Sciences 84, 561–571. https://doi.org/10.1007/s40011-014-0359-y.

Serafim, M.E., Zeviani, W.M., Ono, F.B., Neves, L.G., Silva, B.M., Lal, R., 2019. Reference values and soil quality in areas of high soybean yield in Cerrado region, Brazil. Soil and Tillage Research 195. https://doi.org/10.1016/j.still.2019.104362.

Serri, D.L., Boccolini, M., Oberto, R., Chavarría, D., Bustos, N., Vettorello, C., Apezteguía, H., Miranda, J., Alvarez, C., Galarza, C., Chiófalo, S., Manrique, M., Sueldo, R., Belmonte, M.C.F., Mattalia, L., Cholaky, C., Gil, S.V., 2018. Efecto de la agriculturización sobre la calidad biológica del suelo. Ciencia del suelo 36 (2), 92-104.

Shange, R.S., Ankumah, R.O., Ibekwe, A.M., Zabawa, R., Dowd, S.E., 2012. Distinct soil bacterial communities revealed under a diversely managed agroecosystem. PLoS ONE 7. https://doi.org/10.1371/journal.pone.0040338.

Sharifi, M., Lynch, D.H., Hammermeister, A., Burton, D.L., Messiga, A.J., 2014. Effect of green manure and supplemental fertility amendments on selected soil quality parameters in an organic potato rotation in Eastern Canada. Nutrient Cycling in Agroecosystems 100, 135–146. https://doi.org/10.1007/s10705-014-9633-x.

Sharma, M.P., Gupta, S., Sharma, S.K., Vyas, A.K., 2012. Effect of tillage and crop sequences on arbuscular mycorrhizal symbiosis and soil enzyme activities in soybean (Glycine max) rhizosphere. Indian Journal of Agricultural Sciences 82, 25–30.

Sharma, P., Singh, G., Singh, R.P., 2013. Conservation tillage and optimal water supply enhance microbial enzyme (glucosidase, urease and phosphatase) activities in fields under wheat cultivation during various nitrogen management practices. Archives of Agronomy and Soil Science 59, 911–928. https://doi.org/10.1080/03650340.2012.690143.

Sharma, R.C., Banik, P., 2016. Sustaining Productivity of Baby Corn–Rice Cropping System and Soil Health through Integrated Nutrient Management. Communications in Soil Science and Plant Analysis 47, 1–10. https://doi.org/10.1080/00103624.2015.1089260.

Sharma, R.C., Banik, P., 2014. Vermicompost and fertilizer application: Effect on productivity and profitability of baby corn (Zea mays L.) and soil health. Compost Science and Utilization 22, 83–92. https://doi.org/10.1080/1065657X.2014.895456.

Sharma, R.C., Sarkar, S., Das, D., Banik, P., 2013. Impact Assessment of Arbuscular Mycorrhiza Azospirillum and Chemical Fertilizer Application on Soil Health and Ecology. Communications in Soil Science and Plant Analysis 44, 1116–1126. https://doi.org/10.1080/00103624.2012.750335.

Sharma, S., Thind, H.S., Singh, Y., Singh, V., Singh, B., 2015. Soil enzyme activities with biomass ashes and phosphorus fertilization to rice–wheat cropping system in the Indo-Gangetic plains of India. Nutrient Cycling in Agroecosystems 101, 391–400. https://doi.org/10.1007/s10705-015-9684-7.

Sharma, S., Dhaliwal, S.S., 2019. Effect of Sewage Sludge and Rice Straw Compost on Yield, Micronutrient Availability and Soil Quality under Rice–Wheat System. Communications in Soil Science and Plant Analysis 50, 1943–1954. https://doi.org/10.1080/00103624.2019.1648489.

Siebielec, G., Siebielec, S., Lipski, D., 2018. Long-term impact of sewage sludge, digestate and mineral fertilizers on plant yield and soil biological activity. Journal of Cleaner Production 187, 372–379. https://doi.org/10.1016/j.jclepro.2018.03.245.

Sigua, G.C., Stone, K.C., Bauer, P.J., Szogi, A.A., 2017. Phosphorus dynamics and phosphatase activity of soils under corn production with supplemental irrigation in humid coastal plain region, USA. Nutrient Cycling in Agroecosystems 109, 249–267. https://doi.org/10.1007/s10705-017-9882-6.

Silva, A.S.D., Colozzi Filho, A., Nakatani, A.S., Alves, S.J., Andrade, D.D.S., Guimarães, M.D.F., 2015. Microbial characteristics of soils under an integrated crop-livestock system. Revista Brasilera de Ciência du Solo 39, 40–48. https://doi.org/10.1590/01000683rbcs20150185.

Silva, É. de O., Medeiros, E.V. de, Duda, G.P., Junior, M.A.L., Brossard, M., Oliveira, J.B. de, Santos, U.J. dos, Hammecker, C., 2019. Seasonal effect of land use type on soil absolute and specific enzyme activities in a Brazilian semi-arid region. Catena 172, 397–407. https://doi.org/10.1016/j.catena.2018.09.007.

Silvestro, L.B., Biganzoli, F., Forjan, H., Albanesi, A., Arambarri, A.M., Manso, L., Moreno, M.V., 2017. Mollisol: Biological characterization under zero tillage with different crops sequences. Journal of Agricultural Science and Technology 19, 245–257.

Simon, C.A., Lima, S.F. de, Cordeiro, M.S., Secco, V.A., Nacata, G., Silva, A.M.M., Simon, C. da C., Brasil, M. da S., 2019. Cover crops as modifying agents of microbiological soil attribute. Australian Journal of Crop Science 13, 1578–1585. https://doi.org/10.21475/ajcs.19.13.10.p1723.

Singh, A., Ghoshal, N., 2013. Impact of herbicide and various soil amendments on soil enzymes activities in a tropical rainfed agroecosystem. European Journal of Soil Biology 54, 56–62. https://doi.org/10.1016/j.ejsobi.2012.10.003.

Singh, C., Rakshit, R., Das, A., Bharti, P., 2020. Interpretations of Elemental and Microbial Phosphorus Indicators to Understand P Availability in Soils Under Rice–Wheat Cropping System. Agricultural Research 9, 329–339. https://doi.org/10.1007/s40003-019-00439-1.

Singh, S., Sharma, S., 2020. Temporal changes in rhizosphere biological soil quality indicators of wheat in response to nitrogen and straw incorporation. Tropical Ecology 61, 328–344. https://doi.org/10.1007/s42965-020-00092-8.

Singh, S.R., Kundu, D.K., Dey, P., Singh, P., Mahapatra, B.S., 2018. Effect of balanced fertilizers on soil quality and lentil yield in Gangetic alluvial soils of India. Journal of Agricultural Science 156, 225–240. https://doi.org/10.1017/S0021859618000254.

Singh, S.R., Kundu, D.K., Tripathi, M.K., Dey, P., Saha, A.R., Kumar, M., Singh, I., Mahapatra, B.S., 2015. Impact of balanced fertilization on nutrient acquisition, fibre yield of jute and soil quality in New Gangetic alluvial soils of India. Applied Soil Ecology 92, 24–34. https://doi.org/10.1016/j.apsoil.2015.03.007.

Siwik-Ziomek, A., Lemanowicz, J., Koper, J., 2016. Sulphur and phosphorus content as well as the activity of hydrolases in soil fertilised with macroelements. Journal of Elementology 21, 847–858. https://doi.org/10.5601/jelem.2015.20.3.982.

Soon, Y.K., Rice, W.A., Arshad, M.A., Mills, P., 2000. Effect of pipeline installation on crop yield and some biological properties of boreal soils. Canadian Journal of Soil Science 80, 483–488. https://doi.org/10.4141/S99-096.

Sousa, H.M., Correa, A.R., Silva, B. de M., Oliveira, S. da S., Campos, D.T. da S., Wruck, F.J., 2020. Dynamics of soil microbiological attributes in integrated crop-livestock systems in the Cerrado-Amazonia ecotone. Revista Caatinga 33, 9–20. https://doi.org/10.1590/1983-21252020v33n102rc.

Srivastava, P.K., Gupta, M., Shikha, Singh, N., Tewari, S.K., 2016. Amelioration of Sodic Soil for Wheat Cultivation Using Bioaugmented Organic Soil Amendment. Land

Degradation and Development 27, 1245–1254. https://doi.org/10.1002/ldr.2292.

Srivastava, P.K., Gupta, M., Upadhyay, R.K., Sharma, S., Shikha, Singh, N., Tewari, S.K., Singh, B., 2012. Effects of combined application of vermicompost and mineral fertilizer on the growth of Allium cepa L. and soil fertility. Journal of Plant Nutrition and Soil Science 175, 101–107.

Stehouwer, R.C., Dick, W.A., Traina, S.J., 1993. Characteristics of earthworm burrow lining affecting atrazine sorption. Journal of Environmental Quality 22, 181–185. https://doi.org/10.2134/jeq1993.00472425002200010024x.

Stieven, A.C., Oliveira, D.A., Santos, J.O., Wruck, F.J., Campos, D.T.D.S., 2014. Impacts of integrated crop-livestock-forest on microbiological indicators of soil. Revista Brasileirade Ciencias Agrarias 9, 53–58. https://doi.org/10.5039/agraria.v9i1a3525.

Stutter, M.I., Langan, S.J., Lumsdon, D.G., 2009. Vegetated buffer strips can lead to increased release of phosphorus to waters: A biogeochemical assessment of the mechanisms. Environmental Science and Technology 43, 1858–1863. https://doi.org/10.1021/es8030193.

Sudhakaran, M., Ramamoorthy, D., Savitha, V., Kirubakaran, N., 2019. Soil Enzyme Activities and Their Relationship with Soil Physico-Chemical Properties and Oxide Minerals in Coastal Agroecosystem of Puducherry. Geomicrobiology Journal 36, 452–459. https://doi.org/10.1080/01490451.2019.1570396.

Sudhakaran, M., Avudainayagam, S., Radha, M., Rajasekar, M., 2020. Stable Isotope (δ13C and δ15N) Signatures and Their Relationship among Soil Enzyme Activities in Indian Semi-arid Agricultural Soils. Communications in Soil Science and Plant Analysis 51, 1747–1756. https://doi.org/10.1080/00103624.2020.1798982.

Sun, B., Gao, Y., Wu, X., Ma, H., Zheng, C., Wang, X., Zhang, H., Li, Z., Yang, H., 2020. The relative contributions of pH, organic anions, and phosphatase to rhizosphere soil phosphorus mobilization and crop phosphorus uptake in maize/alfalfa polyculture. Plant and Soil 447, 117–133. https://doi.org/10.1007/s11104-019-04110-0.

Sun, J., Li, W., Li, C., Chang, W., Zhang, S., Zeng, Y., Zeng, C., Peng, M., 2020. Effect of Different Rates of Nitrogen Fertilization on Crop Yield, Soil Properties and Leaf Physiological Attributes in Banana Under Subtropical Regions of China. Frontiers in Plant Science 11. https://doi.org/10.3389/fpls.2020.613760.

Swedrzyńska, D., Małecka, I., Blecharczyk, A., Swedrzyński, A., Starzyk, J., 2013. Effects of various long-term tillage systems on some chemical and biological properties of soil. Polish Journal of Environmental Studies 22, 1835–1844.

Takeda, M., Nakamoto, T., Miyazawa, K., Murayama, T., Okada, H., 2009. Phosphorus availability and soil biological activity in an Andosol under compost application and winter cover cropping. Applied Soil Ecology 42, 86–95. https://doi.org/10.1016/j.apsoil.2009.02.003.

Tamilselvi, S.M., Chinnadurai, C., Ilamurugu, K., Arulmozhiselvan, K., Balachandar, D., 2015. Effect of long-term nutrient managements on biological and biochemical properties of semi-arid tropical alfisol during maize crop development stages. Ecological Indicators 48, 76–87. https://doi.org/10.1016/j.ecolind.2014.08.001.

Tang, H.M., Xiao, X.P., Tang, W.G., Lin, Y.C., Wang, K., Yang, G.L., 2014. Effects of winter cover crops residue returning on soil enzyme activities and soil microbial community in double-cropping rice fields. PLoS ONE 9, 1–8. https://doi.org/10.1371/journal.pone.0100443.

Tiecher, T., Santos, D.R. dos, Calegari, A., 2012. Soil organic phosphorus forms under different soil management systems and winter crops, in a long term experiment. Soil and Tillage Research 124, 57–67. https://doi.org/10.1016/j.still.2012.05.001.

Tiecher, T., Tiecher, T.L., Mallmann, F.J.K., Zafar, M., Ceretta, C.A., Lourenzi, C.R., Brunetto, G., Gatiboni, L.C., Santos, D.R. dos, 2017. Chemical, biological, and biochemical parameters of the soil P cycle after Long-Term pig slurry application in No-Tillage system. Revista Brasileira de Ciencia do Solo 41, 1–16. https://doi.org/10.1590/18069657rbcs20170037.

Tripathi, S., Chakraborty, A., Chakrabarti, K., Bandyopadhyay, B.K., 2007. Enzyme activities and microbial biomass in coastal soils of India. Soil Biology and Biochemistry 39, 2840–2848. https://doi.org/10.1016/j.soilbio.2007.05.027.

Truu, M., Truu, J., Ivask, M., 2008. Soil microbiological and biochemical properties for assessing the effect of agricultural management practices in Estonian cultivated soils. European Journal of Soil Biology 44, 231–237. https://doi.org/10.1016/j.ejsobi.2007.12.003.

Turan, M., Gulluce, M., Wirén, N. von, Sahin, F., 2012. Yield promotion and phosphorus solubilization by plant growth-promoting rhizobacteria in extensive wheat production in Turkey. Journal of Plant Nutrition and Soil Science 175, 818–826. https://doi.org/10.1002/jpln.201200054.

Tuti, M.D., Pal, R.S., Mahanta, D., Pandey, B.M., Bisht, J.K., 2020. Soil Chemical and Biological Activities under Vegetable Intensive Colocasia-based Cropping System in Indian Sub-Himalayas. Communications in Soil Science and Plant Analysis 51, 948–962. https://doi.org/10.1080/00103624.2020.1744623.

Uz, I., Sonmez, S., Tavali, I.E., Citak, Sedat, Uras, D.S., Citak, Sevil, 2016. Effect of vermicompost on chemical and biological properties of an alkaline soil with high lime content during celery (Apium graveolens L. var. dulce Mill.) production. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 44, 280–290.

https://doi.org/10.15835/nbha44110157.

Vanegas, J.J.C., Zambrano, K.B.M., Avellaneda-Torres, L.M., 2018. Effect of ecological and conventional managements on soil enzymatic activities in coffee agroecosystems. Pesquisa Agropecuaria Tropical 48, 420–428. https://doi.org/10.1590/1983-40632018V4852373.

Vanlalveni, C., Lalfakzuala, R., 2018. Effect of seasonal variation on soil enzymes activity and fertility of soil in paddy fields of North Vanlaiphai, Mizoram, India. Science Vision 18, 70–73. https://doi.org/10.33493/scivis.18.02.04.

Varennes, A.D., Torres, M.O., 2011. Post-fallow tillage and crop effects on soil enzymes and other indicators. Soil Use and Management 27, 18–27. https://doi.org/10.1111/j.1475-2743.2010.00307.x.

Verdenelli, R.A., Conforto, C.B., Pérez-Brandán, C., Chavarría, D., Rovea, A., Vargas-Gil, S., Meriles, J.M., 2013. Integrated multivariate analysis of selected soil microbial properties and their relationships with mineral fertilization management in a conservation agriculture system. Acta Agriculturae Scandinavica Section B: Soil and Plant Science 63, 623–632. https://doi.org/10.1080/09064710.2013.837193.

Verma, S., Adak, A., Prasanna, R., Dhar, S., Choudhary, H., Nain, L., Shivay, Y.S., 2016. Microbial priming elicits improved plant growth promotion and nutrient uptake in pea. Israel Journal of Plant Sciences 63, 191–207. https://doi.org/10.1080/07929978.2016.1200352.

Verma, S.K., Pankaj, U., Khan, K., Singh, R., Verma, R.K., 2016. Bioinoculants and Vermicompost Improve Ocimum basilicum Yield and Soil Health in a Sustainable Production System. Clean - Soil, Air, Water 44, 686–693. https://doi.org/10.1002/clen.201400639.

Vinhal-Freitas, I.C., Correa, G.F., Wendling, B., Bobul'ska, L., Ferreira, A.S., 2017. Soil textural class plays a major role in evaluating the effects of land use on soil quality indicators. Ecological indicators 74, 182–190. https://doi.org/10.1016/j.ecolind.2016.11.020.

Wang, F., Tang, J., Li, Z., Xiang, J., Wang, L., Tian, L., Jiang, L., Luo, Y., Hou, E., Shao, X., 2021. Warming reduces the production of a major annual forage crop on the Tibetan Plateau. Science of the Total Environment 798, 149211. https://doi.org/10.1016/j.scitotenv.2021.149211.

Wang, J.B., Chen, Z.H., Chen, L.J., Zhu, A.N., Wu, Z.J., 2011. Surface soil phosphorus and phosphatase activities affected by tillage and crop residue input amounts. Plant, Soil and Environment 57, 251–257. https://doi.org/10.17221/437/2010-pse.

Wang, X., Deng, X., Pu, T., Song, C., Yong, T., Yang, F., Sun, X., Liu, W., Yan, Y., Du, J., Liu, J., Su, K., Yang, W., 2017. Contribution of interspecific interactions and phosphorus application to increasing soil phosphorus availability in relay intercropping systems. Field Crops Research 204, 12–22. https://doi.org/10.1016/j.fcr.2016.12.020.

Wang, Y., Huang, Q., Gao, H., Zhang, R., Yang, L., Guo, Y., Li, H., Awasthi, M.K., Li, G., 2021. Long-term cover crops improved soil phosphorus availability in a rain-fed apple orchard. Chemosphere 275, 130093. https://doi.org/10.1016/j.chemosphere.2021.130093.

Wang, Z.-G., Jin, X., Bao, X.-G., Li, X.-F., Zhao, J.-H., Sun, J.-H., Christie, P., Li, L., 2014. Intercropping enhances productivity and maintains the most soil fertility properties relative to sole cropping. PLoS ONE 9. https://doi.org/10.1371/journal.pone.0113984.

Wei, K., Bao, H., Huang, S., Chen, L., 2017. Effects of long-term fertilization on available P, P composition and phosphatase activities in soil from the Huang-Huai-Hai Plain of China. Agriculture, Ecosystems and Environment 237, 134–142. https://doi.org/10.1016/j.agee.2016.12.030.

Wei, K., Chen, Z., Zhu, A., Zhang, J., Chen, L., 2014a. Application of 31P NMR spectroscopy in determining phosphatase activities and P composition in soil aggregates influenced by tillage and residue management practices. Soil and Tillage Research 138, 35–43. https://doi.org/10.1016/j.still.2014.01.001.

Wei, K., Chen, Z.H., Zhang, X.P., Liang, W.J., Chen, L.J., 2014b. Tillage effects on phosphorus composition and phosphatase activities in soil aggregates. Geoderma 217–218, 37–44. https://doi.org/10.1016/j.geoderma.2013.11.002.

Wei, M., Tan, F., Zhu, H., Cheng, K., Wu, X., Wang, J., Zhao, K., Tang, X., 2012. Impact of Bt-transgenic rice (SHK601) on soil ecosystems in the rhizosphere during crop development. Plant, Soil and Environment 58, 217–223.

Wick, B., Kühne, R.F., Paul, L.G.V., 1998. Soil microbiological parameters as indicators of soil quality under improved fallow management systems in south-western. Plant and Soil 202, 97-107. https://doi.org/10.1023/A:1004305615397.

Wightwick, A.M., Salzman, S.A., Reichman, S.M., Allinson, G., Menzies, N.W., 2013. Effects of copper fungicide residues on the microbial function of vineyard soils. Environmental Science and Pollution Research 20, 1574–1585. https://doi.org/10.1007/s11356-012-1114-7.

Wyszkowska, J., Borowik, A., Olszewski, J., Kucharski, J., 2019. Soil Bacterial Community and Soil Enzyme Activity. Diversity 11(12), 246. https://doi.org/10.3390/d11120246.

Xavier, F.A. da S., Pereira, B.L. da S., Souza, E. de A., Borges, A.L., Coelho, E.F., 2020. Irrigation Systems, Fertigation and Mulch: Effects on the Physical, Chemical and Biological Attributes of the Soil with Banana Crop in Northeastern Brazil.

Communications in Soil Science and Plant Analysis 51, 2592–2605. https://doi.org/10.1080/00103624.2020.1845359.

Xomphoutheb, T., Jiao, S., Guo, X., Mabagala, F.S., Sui, B., Wang, H., Zhao, L., Zhao, X., 2020. The effect of tillage systems on phosphorus distribution and forms in rhizosphere and non-rhizosphere soil under maize (Zea mays L.) in Northeast China. Scientific Reports 10, 1–9. https://doi.org/10.1038/s41598-020-63567-7.

Yadav, D., Shivay, Y.S., Singh, Y.V., Sharma, V.K., Bhatia, A., 2019. Water Use and Soil Fertility under Rice–Wheat Cropping System in Response to Green Manuring and Zinc Nutrition. Communications in Soil Science and Plant Analysis 50, 2836–2847. https://doi.org/10.1080/00103624.2019.1686516.

Yang, X., Bao, X., Yang, Y., Zhao, Y., Liang, C., Xie, H., 2019. Comparison of soil phosphorus and phosphatase activity under long-term no-tillage and maize residue management. Plant, Soil and Environment 65, 408–415. https://doi.org/10.17221/307/2019-PSE.

Yoshioka T., I. C., Sánchez de Prager, M. y Bolaños B, M. M., 2006. Actividad de fosfatasas ácida y alcalina en suelo cultivado con plátano en tres sistemas de manejo. Acta Agronómica, 55(2), 1–8. https://revistas.unal.edu.co/index.php/acta_agronomica/article/view/211.

Zhang, J., Bo, G., Zhang, Z., Kong, F., Wang, Y., Shen, G., 2016. Effects of straw incorporation on soil nutrients, enzymes, and aggregate stability in tobacco fields of China. Sustainability 8, 1–12. https://doi.org/10.3390/su8080710.

Zhang, Y., Finn, D., Bhattacharyya, R., Dennis, P.G., Doolette, A.L., Smernik, R.J., Dalal, R.C., Meyer, G., Lombi, E., Klysubun, W., Jones, A.R., Wang, P., Menzies, N.W., Kopittke, P.M., 2021. Long-term changes in land use influence phosphorus concentrations, speciation, and cycling within subtropical soils. Geoderma 393. https://doi.org/10.1016/j.geoderma.2021.115010.

Zhao, Y., Yan, Z., Qin, J., Ma, Z., Zhang, Y., Zhang, L., 2016. The potential of residues of furfural and biogas as calcareous soil amendments for corn seed production. Environmental Science and Pollution Research 23, 6217–6226. https://doi.org/10.1007/s11356-015-5828-1.

Zhaolei, L., Naishun, B., Jun, C., Xueping, C., Manqiu, X., Feng, W., Zhiping, S., Changming, F., 2017. Effects of long-term cultivation of transgenic Bt rice (Kefeng-6) on soil microbial functioning and C cycling. Scientific Reports 7, 1–13. https://doi.org/10.1038/s41598-017-04997-8.

Zhong, S., Zeng, H., Jin, Z., 2015. Soil Microbiological and Biochemical Properties as Affected by Different Long-Term Banana-Based Rotations in the Tropics. Pedosphere 25, 868–877. https://doi.org/10.1016/S1002-0160(15)30067-9.

Zibilske, L.M., Makus, D.J., 2009. Black oat cover crop management effects on soil temperature and biological properties on a Mollisol in Texas, USA. Geoderma 149, 379–385. https://doi.org/10.1016/j.geoderma.2009.01.001.

Zuazo, V.H.D., Rodríguez, B.C., García-Tejero, I.F., Ruiz, B.G., Tavira, S.C., 2020. Benefits of organic olive rainfed systems to control soil erosion and runoff and improve soil health restoration. Agronomy for Sustainable Development 40, 1–15. https://doi.org/10.1007/s13593-020-00644-1.

Zydlik, Z., Pacholak, E., StyŁa, K., 2011. Effect exerted on soil properties by apple- tree cultivation for many years and by replantation. part I. biochemical soil properties. Acta Scientiarum Polonorum, Hortorum Cultus 10, 113–122.

1.2 References related to ACP and ALP activity models based on management-related variables.

Abujabhah, I.S., Bound, S.A., Doyle, R., Bowman, J.P., 2016. Effects of biochar and compost amendments on soil physico-chemical properties and the total community within a temperate agricultural soil. Applied Soil Ecology 98, 243–253. https://doi.org/10.1016/j.apsoil.2015.10.021.

Acosta-Martinez, V., Acosta-Mercado, D., Sotomayor-Ramirez, D., Cruz-Rodriguez, L., 2008. Microbial communities and enzymatic activities under different management in semiarid soils. Applied Soil Ecology 38, 249–260. https://doi.org/10.1016/j.apsoil.2007.10.012.

Acosta-Martínez, V., Harmel, R.D., 2006. Soil Microbial Communities and Enzyme Activities under Various Poultry Litter Application Rates. Journal of Environmental Quality 35, 1309–1318. https://doi.org/10.2134/jeq2005.0470.

Acosta-Martínez, V., Klose, S., Zobeck, T.M., 2003a. Enzyme activities in semiarid soils under conservation reserve program, native rangeland, and cropland. Journal of Plant Nutrition and Soil Science 166, 699–707. https://doi.org/10.1002/jpln.200321215.

Acosta-Martínez, V., Lascano, R., Calderón, F., Booker, J.D., Zobeck, T.M., Upchurch, D.R., 2011. Dryland cropping systems influence the microbial biomass and enzyme activities in a semiarid sandy soil. Biology and Fertility of Soils 47, 655–667. https://doi.org/10.1007/s00374-011-0565-1.

Acosta-Martinez, V., Mikha, M.M., Sistani, K.R., Stahlman, P.W., Benjamin, J.G., Vigil, M.F., Erickson, R., 2011. Multi-location study of soil enzyme activities as affected by types and rates of manure application and tillage practices. Agriculture (Switzerland) 1, 4–21. https://doi.org/10.3390/agriculture1010004.

Acosta-Martínez, V., Zobeck, T.M., Gill, T.E., Kennedy, A.C., 2003b. Enzyme activities and microbial community structure in semiarid agricultural soils. Biology and Fertility of Soils 38, 216–227. https://doi.org/10.1007/s00374-003-0626-1.

Aechra, S., Meena, R.H., Meena, S.C., Mundra, S.L., Lakhawat, S.S., Mordia, A., Jat, G., 2021. Soil microbial dynamics and enzyme activities as influenced by biofertilizers and split application of vermicompost in rhizosphere of wheat (Triticum aestivum. L.). Journal of Environmental Biology 42, 1370–1378.

Ahmed, W., Qaswar, M., Jing, H., Wenjun, D., Geng, S., Kailou, L., Ying, M., Ao, T., Mei, S., Chao, L., Yongmei, X., Ali, S., Normatov, Y., Mehmood, S., Khan, M.N., Huimin, Z., 2020. Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils. Journal of Soils and Sediments 20, 850–861. https://doi.org/10.1007/s11368-019-02468-3.

Angers, D.A., Bissonnette, N., Legere, A., Samson, N., 1993. Microbial and biochemical changes induced by rotation and tillage in a soil under barley production. Canadian Journal of Soil Science 73, 39–50. https://doi.org/10.4141/cjss93-004.

Arya, S.R., Syriac, E.K., Aparna, B., 2018. Enzyme dynamics and organic carbon status of soil as influenced by flucetosulfuron in wet seeded rice. Journal of Tropical Agriculture 56, 1–8.

Atoloye, I.A., Jacobson, A., Creech, E., Reeve, J., 2021. Variable impact of compost on phosphorus dynamics in organic dryland soils following a one-time application. Soil Science Society of America Journal 85, 1122–1138. https://doi.org/10.1002/saj2.20275.

Avila-Salem, M.E., Montesdeoca, F., Orellana, M., Pacheco, K., Alvarado, S., Becerra, N., Marín, C., Borie, F., Aguilera, P., Cornejo, P., 2020. Soil Biological Properties and Arbuscular Mycorrhizal Fungal Communities of Representative Crops Established in the Andean Region from Ecuadorian Highlands. Journal of Soil Science and Plant Nutrition 20, 2156–2163. https://doi.org/10.1007/s42729-020-00283-1.

Baligar, V.C., Wright, R.J., Hern, J.L., 2005. Enzyme activities in soil influenced by levels of applied sulfur and phosphorus. Communications in Soil Science and Plant Analysis 36, 1727–1735. https://doi.org/10.1081/CSS-200062431.

Balota, E.L., Kanashiro, M., Filho, A.C., Andrade, D.S., Dick, R.P., 2004. Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agro-ecosystems. Brazilian Journal of Microbiology 35, 300–306. https://doi.org/10.1590/S1517-83822004000300006.

Balota, E.L., Machineski, O., Truber, P.V., Antonio, P., Auler, M., 2011. Effect of tillage systems and permanent groundcover intercropped with orange trees on soil enzyme activities. Brazilian Archives of Biology and Technology 54, 221–228.

Balota, E.L., Yada, I.F., Amaral, H., Nakatani, A.S., Dick, R.P., Coyne, M.S., 2013. Long-term land use influences soil microbial biomass P and S, phosphatase and arylsulfatase activities, and s mineralization in a Brazilian oxisol. Land Degradation and Development 25, 397–406. https://doi.org/10.1002/ldr.2242.

Banik, P., Ghosal, P.K., Sasmal, T.K., Bhattacharya, S., Sarkar, B.K., Bagchi, D.K., 2006. Effect of organic and inorganic nutrients for soil quality conservation and yield of rainfed low land rice in sub-tropical plateau region. Journal of Agronomy and Crop Science 192, 331–343. https://doi.org/10.1111/j.1439-037X.2006.00219.x.

Barros, L.S., Melo, V.F., Senwo, Z.N., Evald, A., Siqueira, R.H.S., Bardales, R.M., Nunes, T.K. de O., 2018. Effects of Management Practices and Land Use on Biological and Enzymatic Attributes of an Agricultural Area. Journal of Agricultural Science 10, 110. https://doi.org/10.5539/jas.v10n6p110.

Bergstrom, D.W., Monreal, C.M., King, D.J., 1998. Sensitivity of Soil Enzyme Activities to Conservation Practices. Soil Science Society of America Journal 62, 1286–1295. https://doi.org/10.2136/sssaj1998.03615995006200050020x.

Bhatt, B., Chandra, R., Ram, S., Pareek, N., 2016. Long-term effects of fertilization and manuring on productivity and soil biological properties under rice (Oryza sativa)–wheat (Triticum aestivum) sequence in Mollisols. Archives of Agronomy and Soil Science 62, 1109–1122. https://doi.org/10.1080/03650340.2015.1125471.

Biau, A., Santiveri, F., Mijangos, I., Lloveras, J., 2012. The impact of organic and mineral fertilizers on soil quality parameters and the productivity of irrigated maize crops in semiarid regions. European Journal of Soil Biology 53, 56–61. https://doi.org/10.1016/j.ejsobi.2012.08.008.

Bissonnette, N., Angers, D.A., Simard, R.R., Lafond, J., 2001. Interactive effects of management practices on water-stable aggregation and organic matter of a Humic Gleysol. Canadian Journal of Soil Science 81, 545–551. https://doi.org/10.4141/S00-078.

Boccolini, M.F., Cazorla, C.R., Galantini, J.A., Belluccini, P.A., Baigorria, T., 2019. Cultivos de cobertura disminuyen el impacto ambiental mejorando propiedades biológicas del suelo y el rendimiento de los cultivos. Revista de Investigaciones Agropecuarias 45, 412–425.

Borase, D.N., Nath, C.P., Hazra, K.K., Senthilkumar, M., Singh, S.S., Praharaj, C.S., Singh, U., Kumar, N., 2020. Long-term impact of diversified crop rotations and nutrient management practices on soil microbial functions and soil enzymes activity. Ecological Indicators 114, 106322. https://doi.org/10.1016/j.ecolind.2020.106322.

Borges, C.D., Corá, J.E., Barbosa, J.C., Nahas, E., 2013. Soil microbiological attributes under summer/winter crops rotation in a no-tillage system. Archives of Agronomy and Soil Science 59, 1471–1485. https://doi.org/10.1080/03650340.2012.725938.

Brandan, Carolina Pérez, Chavarría, D., Huidobro, J., Meriles, J.M., Brandan, Cecilia Pérez, Gil, S.V., 2017. Influence of a tropical grass (Brachiaria brizantha cv. Mulato) as cover crop on soil biochemical properties in a degraded agricultural soil. European Journal of Soil Biology 83, 84–90. https://doi.org/10.1016/j.ejsobi.2017.10.009.

Carpenter-Boggs, L., Stahl, P.D., Lindstrom, M.J., Schumacher, T.E., 2003. Soil microbial properties under permanent grass, conventional tillage, and no-fill management in South Dakota. Soil and Tillage Research 71, 15–23. https://doi.org/10.1016/S0167-1987(02)00158-7.

Carter, M.R., Sanderson, J.B., Holmstrom, D.A., Ivany, J.A., DeHaan, K.R., 2007. Influence of conservation tillage and glyphosate on soil structure and organic carbon fractions through the cycle of a 3-year potato rotation in Atlantic Canada. Soil and Tillage Research 93, 206–221. https://doi.org/10.1016/j.still.2006.04.004.

Chakrabarti, K., Sarkar, B., Chakraborty, A., Banik, P., Bagchi, D.K., 2000. Organic recycling for soil quality conservation in a sub-tropical plateau region. Journal of Agronomy and Crop Science 184, 137–142. https://doi.org/10.1046/j.1439-037X.2000.00352.x.

Chatterjee, D., Nayak, A.K., Mishra, A., Swain, C.K., Kumar, U., Bhaduri, D., Panneerselvam, P., Lal, B., Gautam, P., Pathak, H., 2021. Effect of Long-Term Organic Fertilization in Flooded Rice Soil on Phosphorus Transformation and Phosphate Solubilizing Microorganisms. Journal of Soil Science and Plant Nutrition 21, 1368–1381. https://doi.org/10.1007/s42729-021-00446-8.

Chen, H., Liang, Q., Gong, Y., Kuzyakov, Y., Fan, M., Plante, A.F., 2019. Reduced tillage and increased residue retention increase enzyme activity and carbon and nitrogen concentrations in soil particle size fractions in a long-term field experiment on Loess Plateau in China. Soil and Tillage Research 194, 104296. https://doi.org/10.1016/j.still.2019.104296.

Choudhary, M., Datta, A., Jat, H.S., Yadav, A.K., Gathala, M.K., Sapkota, T.B., Das, A.K., Sharma, P.C., Jat, M.L., Singh, R., Ladha, J.K., 2018a. Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. Geoderma 313, 193–204. https://doi.org/10.1016/j.geoderma.2017.10.041.

Choudhary, M., Meena, V.S., Panday, S.C., Mondal, T., Yadav, R.P., Mishra, P.K., Bisht, J.K., Pattanayak, A., 2021. Long-term effects of organic manure and inorganic fertilization on biological soil quality indicators of soybean-wheat rotation in the Indian mid-Himalaya. Applied Soil Ecology 157, 103754. https://doi.org/10.1016/j.apsoil.2020.103754.

Choudhary, M., Sharma, P.C., Jat, H.S., McDonald, A., Jat, M.L., Choudhary, S., Garg, N., 2018b. Soil biological properties and fungal diversity under conservation agriculture in indo-gangetic plains of india. Journal of Soil Science and Plant Nutrition 18, 1142–1156. https://doi.org/10.4067/S0718-95162018005003201.

Cochran, V.L., Elliott, L.F., Lewis, C.E., 1989. Soil microbial biomass and enzyme activity in subarctic agricultural and forest soils. Biology and Fertility of Soils 7, 283–288. https://doi.org/10.1007/BF00257821.

Comino, F., Aranda, V., García-Ruiz, R., Ayora-Cañada, M.J., Domínguez-Vidal, A., 2018. Infrared spectroscopy as a tool for the assessment of soil biological quality in agricultural soils under contrasting management practices. Ecological Indicators 87, 117–126. https://doi.org/10.1016/j.ecolind.2017.12.046.

Cox, D., Bezdicek, D., Fauci, M., 2001. Effects of compost, coal ash, and straw amendments on restoring the quality of eroded Palouse soil. Biology and Fertility of Soils 33, 365–372. https://doi.org/10.1007/s003740000335.

Das, S.K., Ghosh, G.K., Avasthe, R., Choudhury, B.U., Mishra, V.K., Kundu, M.C., Roy, A., Mondal, T., Lama, A., Dhakre, D.S., 2021. Organic nutrient sources and biochar technology on microbial biomass carbon and soil enzyme activity in maize-black gram cropping system. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-021-01625-4.

Deng, S.P., Tabatabai, M.A., 1996. Effect of tillage and residue management on enzyme activities in soils. II. Glycosidases. Biology and Fertility of Soils 22, 208–213. https://doi.org/10.1007/BF00382514.

Diallo-Diagne, N.H., Assigbetse, K., Sall, S., Masse, D., Bonzi, M., Ndoye, I., Chotte, J.L., 2016. Response of Soil Microbial Properties to Long-Term Application of Organic and Inorganic Amendments in a Tropical Soil (Saria, Burkina Faso). Open Journal of Soil Science 06, 21–33. https://doi.org/10.4236/ojss.2016.62003.

Dick, W.A., 1984. Influence of Long-Term Tillage and Crop Rotation Combinations on Soil Enzyme Activities. Soil Science Society of America Journal 48, 569–574. https://doi.org/10.2136/sssaj1984.03615995004800030020x.

Doran, J.W., 1980. Soil Microbial and Biochemical Changes Associated with Reduced Tillage. Soil Science Society of America Journal 44, 765–771. https://doi.org/10.2136/sssaj1980.03615995004400040022x.

Dou, F., Wright, A.L., Mylavarapu, R.S., Jiang, X., Matocha, J.E., 2016. Soil Enzyme Activities and Organic Matter Composition Affected by 26 Years of Continuous Cropping. Pedosphere 26, 618–625. https://doi.org/10.1016/S1002-0160(15)60070-4.

Efthimiadou, E., Papatheodorou, E.M., Monokrousos, N., Stamou, G.P., 2010. Changes of soil chemical, microbiological, and enzymatic variables in relation to management regime and the duration of organic farming in Phaseolus vulgaris. Journal of Biological Research 14, 151–159.

Evangelista, C.R., Partelli, F.L., Ferreira, E.P.D.B., Correchel, V., 2012. Atividade enzimática do solo sob sistema de produção orgânica e convencional na cultura da cana-de-açúcar em Goiás. Semina:Ciencias Agrarias 33, 1251–1261. https://doi.org/10.5433/1679-0359.2012v33n4p1251.

Ferreira, E.P.D.B., Wendland, A., Didonet, A.D., 2011. Microbial biomass and enzyme activity of a Cerrado Oxisol under agroecological production system. Bragantia 70, 899–907. https://doi.org/10.1590/S0006-87052011000400024.

Fontalvo, R.M.S., Andrade, J.L.C., 2018. Effect of organic amendments and sulfur on chemical and biological properties of a sodic soil efeito de corretivos orgânicos e enxofre nas propriedades químicas e biológicas de um solo sódico. Spanish Journal of Soil Science 8, 347–362. https://doi.org/10.3232/SJSS.2018.V8.N3.04.

Fraser, T., Lynch, D.H., Entz, M.H., Dunfield, K.E., 2015. Linking alkaline phosphatase activity with bacterial phoD gene abundance in soil from a long-term management trial. Geoderma 257–258, 115–122. https://doi.org/10.1016/j.geoderma.2014.10.016.

Furtak, K., Gawryjołek, K., Gajda, A.M., Gałązka, A., 2017. Effects of maize and winter wheat grown under different cultivation techniques on biological activity of soil. Plant, Soil and Environment 63, 449–454. https://doi.org/10.17221/486/2017-PSE.

Gaind, S., Singh, Y.V., 2016. Soil organic phosphorus fractions in response to long-term fertilization with composted manures under rice–wheat cropping system. Journal of Plant Nutrition 39, 1336–1347. https://doi.org/10.1080/01904167.2015.1086795.

García-Ruiz, R., Ochoa, V., Viñegla, B., Hinojosa, M.B., Peña-Santiago, R., Liébanas, G., Linares, J.C., Carreira, J.A., 2009. Soil enzymes, nematode community and selected physico-chemical properties as soil quality indicators in organic and conventional olive oil farming: Influence of seasonality and site features. Applied Soil Ecology 41, 305–314. https://doi.org/10.1016/j.apsoil.2008.12.004.

George, S., Wright, D.L., Marois, J.J., 2013. Impact of grazing on soil properties and cotton yield in an integrated crop-livestock system. Soil and Tillage Research 132, 47–55. https://doi.org/10.1016/j.still.2013.05.004.

Green, V.S., Stott, D.E., Cruz, J.C., Curi, N., 2007. Tillage impacts on soil biological activity and aggregation in a Brazilian Cerrado Oxisol. Soil and Tillage Research 92, 114–121. https://doi.org/10.1016/j.still.2006.01.004.

Guan, G., Tu, S.-X., Yang, J.-C., Zhang, J.-F., Yang, L., 2011. A Field Study on Effects of Nitrogen Fertilization Modes on Nutrient Uptake, Crop Yield and Soil Biological Properties in Rice-Wheat Rotation System. Agricultural Sciences in China 10, 1254–1261. https://doi.org/10.1016/S1671-2927(11)60117-X.

Habig, J., Labuschagne, J., Marais, M., Swart, A., Claassens, S., 2018. The effect of a medic-wheat rotational system and contrasting degrees of soil disturbance on nematode functional groups and soil microbial communities. Agriculture, Ecosystems and Environment 268, 103–114. https://doi.org/10.1016/j.agee.2018.09.013.

Hatti, V., Ramachandrappa, B.K., Sathishand, A., Thimmegowda, M.N., 2018. Soil properties and productivity of rainfed finger millet under conservation tillage and nutrient management in Eastern dry zone of Karnataka. Journal of Environmental Biology 39, 612–624.

Hazarika, S., Parkinson, R., Bol, R., Dixon, L., Russell, P., Donovan, S., Allen, D., 2009. Effect of tillage system and straw management on organic matter dynamics. Agronomy for Sustainable Development 29, 525–533. https://doi.org/10.1051/agro/2009024.

He, Z., Honeycutt, C.W., Griffin, T.S., Larkin, R.P., Olanya, M., Halloran, J.M., 2010. Increases of soil phosphatase and urease activities in potato fields by cropping rotation practices. Journal of Food, Agriculture and Environment 8, 1112–1117.

Iovieno, P., Morra, L., Leone, A., Pagano, L., Alfani, A., 2009. Effect of organic and mineral fertilizers on soil respiration and enzyme activities of two Mediterranean horticultural soils. Biology and Fertility of Soils 45, 555–561. https://doi.org/10.1007/s00374-009-0365-z.

Jain, N.K., Jat, R.S., Meena, H.N., Chakraborty, K., 2018. Productivity, Nutrient, and Soil Enzymes Influenced with Conservation Agriculture Practices in Peanut. Agronomy Journal 110, 1165–1172. https://doi.org/10.2134/agronj2017.08.0467.

Jaskulska, I., Romaneckas, K., Jaskulski, D., Gałęzewski, L., Breza-Boruta, B., Dębska, B., Lemanowicz, J., 2020. Soil properties after eight years of the use of strip-till one-pass technology. Agronomy 10, 1–16. https://doi.org/10.3390/agronomy10101596.

Jat, H.S., Choudhary, M., Datta, A., Yadav, A.K., Meena, M.D., Devi, R., Gathala, M.K., Jat, M.L., McDonald, A., Sharma, P.C., 2020. Temporal changes in soil microbial properties and nutrient dynamics under climate smart agriculture practices. Soil and Tillage Research 199, 104595. https://doi.org/10.1016/j.still.2020.104595.

Jat, H.S., Datta, A., Choudhary, M., Sharma, P.C., Yadav, A.K., Choudhary, V., Gathala, M.K., Jat, M.L., McDonald, A., 2019. Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. Catena 181, 104059. https://doi.org/10.1016/j.catena.2019.05.005.

Johnson, J.M.F., Acosta-Martinez, V., Cambardella, C.A., Barbour, N.W., 2013. Crop and soil responses to using corn stover as a bioenergy feedstock: Observations from the northern us corn belt. Agriculture 3, 72–89.

https://doi.org/10.3390/agriculture3010072.
Jordan, D., Miles, R.J., Hubbard, V.C., Lorenz, T., 2004. Effect of management practices and cropping systems on earthworm abundance and microbial activity in Sanborn Field: A 115-year-old agricultural field. Pedobiologia 48, 99–110. https://doi.org/10.1016/j.pedobi.2003.06.001.
Jr, H.B., Elliott, L.F., Papendick, R.I., Bezdicek, D.F., 1985. Soil microbial biomass and selected soil enzyme activities: Effect of fertilization and cropping practices. Soil Biology and Biochemistry 17, 297–302. https://doi.org/10.1016/0038-0717(85)90064-1.
Kayikcioglu, H.H., 2018. Can treated wastewater be used as an alternative water resource for agricultural irrigation? Changes in soil and plant health after three years of maize cultivation in western anatolia, Turkey. Applied Ecology and Environmental Research 16, 8131–8161. https://doi.org/10.15666/aeer/1606_81318161.
Klose, S., Ajwa, H.A., 2004. Enzyme activities in agricultural soils fumigated with methyl bromide alternatives. Soil Biology and Biochemistry 36, 1625–1635. https://doi.org/10.1016/j.soilbio.2004.07.009.
Kremer, R.J., Li, J., 2003. Developing weed-suppressive soils through improved soil quality management. Soil and Tillage Research 72, 193–202. https://doi.org/10.1016/S0167-1987(03)00088-6.
Kumar, R., Shambhavi, S., Beura, K., Kumar, S., Singh, R.G., 2017. Soil microbial budgeting as influenced by contrasting tillage and crop diversification under rice based cropping systems in Inseptisol of Bihar. Journal of Pure and Applied Microbiology 11, 539–547. https://doi.org/10.22207/JPAM.11.1.71.
Kunze, A., Costa, M.D., Epping, J., Loffaguen, J.C., Schuh, R., Lovato, P.E., 2011. Phosphatase activity in sandy soil influenced by mycorrhizal and non-mycorrhizal cover crops. Revista Brasileira de Ciencia do Solo 35, 705–711. https://doi.org/10.1590/s0100-06832011000300005.
Liu, E., Yan, C., Mei, X., He, W., Bing, S.H., Ding, L., Liu, Q., Liu, S., Fan, T., 2010. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. Geoderma 158, 173–180. https://doi.org/10.1016/j.geoderma.2010.04.029.
Liu, X. li, Chen, Q. wen, Zeng, Z. xia, 2011. The Effects of Different Tillages on Crop Residue Sequestration, Soil Available Nutrients and Some Biochemical Properties in the Chinese Black Soil Region. Agricultural Sciences in China 10, 576–584. https://doi.org/10.1016/S1671-2927(11)60039-4.
Liu, X.M., Li, Q., Liang, W.J., Jiang, Y., 2008. Distribution of Soil Enzyme Activities and Microbial Biomass Along a Latitudinal Gradient in Farmlands of Songliao Plain,

Northeast China. Pedosphere 18, 431–440. https://doi.org/10.1016/S1002-0160(08)60034-X.

Lopes, A.A. de C., Sousa, D.M.G. de, Chaer, G.M., Junior, F.B. dos R., Goedert, W.J., Mendes, I. de C., 2013. Interpretation of Microbial Soil Indicators as a Function of Crop Yield and Organic Carbon. Soil Science Society of America Journal 77, 461–472. https://doi.org/10.2136/sssaj2012.0191.

Ma, H., Egamberdieva, D., Wirth, S., Li, Q., Omari, R.A., Hou, M., Bellingrath-Kimura, S.D., 2019. Effect of biochar and irrigation on the interrelationships among soybean growth, root nodulation, plant p uptake, and soil nutrients in a sandy field. Sustainability 11, 1–16. https://doi.org/10.3390/su11236542.

Mahajan, G.R., Manjunath, B.L., Morajkar, S., Desai, A., Das, B., Paramesh, V., 2021. Long-Term Effect of Various Organic and Inorganic Nutrient Sources on Rice Yield and Soil Quality in West Coast India Using Suitable Indexing Techniques. Communications in Soil Science and Plant Analysis 52, 1819–1833. https://doi.org/10.1080/00103624.2021.1900221.

Mankolo, R., Reddy, C., Senwo, Z., Nyakatawa, E., Sajjala, S., 2012. Soil biochemical changes induced by poultry litter application and conservation tillage under cotton production systems. Agronomy 2, 187–198. https://doi.org/10.3390/agronomy2030187.

Mariela, F.P., Pável, M.E.I., Manuel, S.R.L., Jesús, F.G.M., Reyes, L.O., 2016. Dehydrogenase and mycorrhizal colonization: Tools for monitoring agrosystem soil quality. Applied Soil Ecology 100, 144–153. https://doi.org/10.1016/j.apsoil.2015.12.011.

Martins, L.N.B., Santiago, F.L. de A., Montecchia, M.S., Correa, O.S., Junior, O.J.S., Souza, E.D. de, Paulino, H.B., Carneiro, M.A.C., 2019. Biochemical and biological properties of soil from murundus wetlands converted into agricultural systems. Revista Brasileira de Ciencia do Solo 43, 1–13. https://doi.org/10.1590/18069657rbcs20180183.

Meena, M.D., Joshi, P.K., Jat, H.S., Chinchmalatpure, A.R., Narjary, B., Sheoran, P., Sharma, D.K., 2016. Changes in biological and chemical properties of saline soil amended with municipal solid waste compost and chemical fertilizers in a mustard-pearl millet cropping system. Catena 140, 1–8. https://doi.org/10.1016/j.catena.2016.01.009.

Melero, S., López-Bellido, R.J., López-Bellido, L., Muñoz-Romero, V., Moreno, F., Murillo, J.M., 2011. Long-term effect of tillage, rotation and nitrogen fertiliser on soil quality in a Mediterranean Vertisol. Soil and Tillage Research 114, 97–107. https://doi.org/10.1016/j.still.2011.04.007.

Melero, S., Madejón, E., Herencia, J.F., Ruiz, J.C., 2008a. Effect of implementing organic farming on chemical and biochemical properties of an irrigated loam soil. Agronomy Journal 100, 136–144. https://doi.org/10.2134/agronj2007.0087.

Melero, S., Porras, J.C.R., Herencia, J.F., Madejon, E., 2006. Chemical and biochemical properties in a silty loam soil under conventional and organic management. Soil and Tillage Research 90, 162–170. https://doi.org/10.1016/j.still.2005.08.016.

Melero, S., Vanderlinden, K., Ruiz, J.C., Madejn, E., 2009. Soil biochemical response after 23 years of direct drilling under a dryland agriculture system in southwest Spain. Journal of Agricultural Science 147, 9–15. https://doi.org/10.1017/S0021859608008204.

Melero, S., Vanderlinden, K., Ruiz, J.C., Madejon, E., 2008b. Long-term effect on soil biochemical status of a Vertisol under conservation tillage system in semi-arid Mediterranean conditions. European Journal of Soil Biology 44, 437–442. https://doi.org/10.1016/j.ejsobi.2008.06.003.

Mijangos, I., Pérez, R., Albizu, I., Garbisu, C., 2006. Effects of fertilization and tillage on soil biological parameters. Enzyme and Microbial Technology 40, 100–106. https://doi.org/10.1016/j.enzmictec.2005.10.043.

Mina, B.L., Saha, S., Kumar, N., Srivastva, A.K., Gupta, H.S., 2008. Changes in soil nutrient content and enzymatic activity under conventional and zero-tillage practices in an Indian sandy clay loam soil. Nutrient Cycling in Agroecosystems 82, 273–281. https://doi.org/10.1007/s10705-008-9189-8.

Mohammadi, K., Eskandari, M., Heidari, G., Nezhad, M.T.K., 2011. Canola traits and some soil biological parameters in response to fertilization and tillage management. African Journal of Biotechnology 10, 14067–14072. https://doi.org/10.5897/ajb11.2161.

Monaci, E., Polverigiani, S., Neri, D., Bianchelli, M., Santilocchi, R., Toderi, M., D'Ottavio, P., Vischetti, C., 2017. Effect of contrasting crop rotation systems on soil chemical and biochemical properties and plant root growth in organic farming: First results. Italian Journal of Agronomy 12, 364–374. https://doi.org/10.4081/ija.2017.831.

Morugán-Coronado, A., García-Orenes, F., Cerdà, A., 2015. Changes in soil microbial activity and physicochemical properties in agricultural soils in Eastern Spain. Spanish Journal of Soil Science 5, 201–213. https://doi.org/10.3232/SJSS.2015.V5.N3.02.

Morugán-Coronado, A., García-Orenes, F., McMillan, M., Pereg, L., 2019. The effect of moisture on soil microbial properties and nitrogen cyclers in Mediterranean sweet orange orchards under organic and inorganic fertilization. Science of the Total Environment 655, 158–167. https://doi.org/10.1016/j.scitotenv.2018.11.174.

Mukumbareza, C., Muchaonyerwa, P., Chiduza, C., 2015. Effects of oats and grazing vetch cover crops and fertilisation on microbial biomass and activity after five years of rotation with maize. South African Journal of Plant and Soil 32, 189–197. https://doi.org/10.1080/02571862.2015.1025446.

Nedunchezhiyan, M., Laxminarayana, K., Chauhan, V.B.S., 2018. Soil Microbial Activities and Yield of Elephant Foot Yam as Influenced by Weed Management Practices in Alfisols. International Journal of Vegetable Science 24, 583–596. https://doi.org/10.1080/19315260.2018.1454567.

Niewiadomska, A., Gaj, R., Przybył, J., Budka, A., Mioduszewska, N., Wolna-Maruwka, A., 2016. Analysis of microbial parameters of soil in different tillage systems under sugar beets (Beta vulgaris L.). Polish Journal of Environmental Studies 25, 1803–1811. https://doi.org/10.15244/pjoes/62644.

Niewiadomska, A., Majchrzak, L., Borowiak, K., Wolna-Maruwka, A., Waraczewska, Z., Budka, A., Gaj, R., 2020a. The influence of tillage and cover cropping on soil microbial parameters and spring wheat physiology. Agronomy 10. https://doi.org/10.3390/agronomy10020200.

Niewiadomska, A., Sawińska, Z., Wolma-Maruwka, A., 2011. Impact of selected seed dressings on soil microbiological activity in spring barley cultivation. Fresenius Environmental Bulletin 20, 1252–1261.

Niewiadomska, A., Sulewska, H., Wolna-Maruwka, A., Ratajczak, K., Waraczewska, Z., Budka, A., 2020b. The influence of bio-stimulants and foliar fertilizers on yield, plant features, and the level of soil biochemical activity in white lupine (Lupinus albus L.) cultivation. Agronomy 10. https://doi.org/10.3390/agronomy10010150.

Okur, N., Altindisli, A., Cengel, M., Gocmez, S., Kayikcioglu, H.H., 2009. Microbial biomass and enzyme activity in vineyard soils under organic and conventional farming systems. Turkish Journal of Agriculture and Forestry 33, 413–423. https://doi.org/10.3906/tar-0806-23.

Okur, N., Kayikcioglu, H.H., Ates, F., Yagmur, B., 2016. A comparison of soil quality and yield parameters under organic and conventional vineyard systems in Mediterranean conditions (West Turkey). Biological Agriculture and Horticulture 32, 73–84. https://doi.org/10.1080/01448765.2015.1033645.

Ramos, M.E., Benítez, E., García, P.A., Robles, A.B., 2010. Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: Effects on soil quality. Applied Soil Ecology 44, 6–14. https://doi.org/10.1016/j.apsoil.2009.08.005.

Ramos, M.E., Robles, A.B., Sánchez-Navarro, A., González-Rebollar, J.L., 2011. Soil responses to different management practices in rainfed orchards in semiarid environments. Soil and Tillage Research 112, 85–91.

https://doi.org/10.1016/j.still.2010.11.007.
Reeve, J.R., Endelman, J.B., Miller, B.E., Hole, D.J., 2011. Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. Soil Science Society of America Journal 76, 278–286. https://doi.org/10.2136/sssai20n.0t23.
Riffaldi, R., Saviozzi, A., Levi-Minzi, R., Cardelli, R., 2002. Biochemical properties of a Mediterranean soil as affected by long-term crop management systems. Soil and Tillage Research 67, 109–114. https://doi.org/10.1016/S0167-1987(02)00044-2.
Riffaldi, R., Saviozzi, A., Levi-Minzi, R., Menchetti, F., 1994. Chemical characteristics of soil after 40 years of continuous maize cultivation. Agriculture, Ecosystems and Environment 49, 239–245. https://doi.org/10.1016/0167-8809(94)90053-1.
Rodrigues, M.Â.Â., Dimande, P., Pereira, E.L.E.L.E.L., Ferreira, I.Q.I.Q.I.Q., Freitas, S., Correia, C.M.C.M., Moutinho-Pereira, J., Arrobas, M., 2015. Early-maturing annual legumes: an option for cover cropping in rainfed olive orchards. Nutrient Cycling in Agroecosystems 103, 153–166. https://doi.org/10.1007/s10705-015-9730-5.
Samuel, A.D., Domuţa, C., Şandor, M., 1970. Soil Enzyme Activities Under Crop Rotations Systems in a Brown Luvic Soil. Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agriculture 62, 2–7. https://doi.org/10.15835/buasvmcn-agr:1578.
Sánchez, S.M., Madejón, E., Herencia, J.F., Ruiz-Porras, J.C., 2008. Long-term study of properties of a xerofluvent of the Guadalquivir River Valley under organic fertilization. Agronomy Journal 100, 611–618. https://doi.org/10.2134/agronj2006.0316.
Sangma, C.B.K., Thakuria, D., Biam, D.E.D., 2016. Rice ecosystems in hill agriculture: Effect on soil biological pools of carbon, nitrogen and phosphorus. Journal of the Indian Society of Soil Science 64, 391–401. https://doi.org/10.5958/0974-0228.2016.00051.7.
Selvamurugan, M., Doraisamy, P., Maheswari, M., 2011. Effect of biomethanated distillery spentwash and pressmud biocompost on microbial and enzyme dynamics in sugarcane grown soil. Journal of Biological Sciences 11 (6), 417-422. https://doi.org/10.3923/jbs.2011.417.422.
Sepat, S., Behera, U.K., Sharma, A.R., Das, T.K., Bhattacharyya, R., 2014. Productivity, organic carbon and residual soil fertility of Pigeonpea-wheat cropping system under varying tillage and residue management. Proceedings of the National Academy of Sciences India Section B - Biological Sciences 84, 561–571. https://doi.org/10.1007/s40011-014-0359-y.
Serafim, M.E., Zeviani, W.M., Ono, F.B., Neves, L.G., Silva, B.M., Lal, R., 2019. Reference values and soil quality in areas of high soybean yield in Cerrado region,

Brazil. Soil and Tillage Research 195. https://doi.org/10.1016/j.still.2019.104362.
Sharifi, M., Lynch, D.H., Hammermeister, A., Burton, D.L., Messiga, A.J., 2014. Effect of green manure and supplemental fertility amendments on selected soil quality parameters in an organic potato rotation in Eastern Canada. Nutrient Cycling in Agroecosystems 100, 135–146. https://doi.org/10.1007/s10705-014-9633-x.
Sharma, M.P., Gupta, S., Sharma, S.K., Vyas, A.K., 2012. Effect of tillage and crop sequences on arbuscular mycorrhizal symbiosis and soil enzyme activities in soybean (Glycine max) rhizosphere. Indian Journal of Agricultural Sciences 82, 25–30.
Sharma, P., Singh, G., Singh, R.P., 2013. Conservation tillage and optimal water supply enhance microbial enzyme (glucosidase, urease and phosphatase) activities in fields under wheat cultivation during various nitrogen management practices. Archives of Agronomy and Soil Science 59, 911–928. https://doi.org/10.1080/03650340.2012.690143.
Sharma, R.C., Banik, P., 2016. Sustaining Productivity of Baby Corn–Rice Cropping System and Soil Health through Integrated Nutrient Management. Communications in Soil Science and Plant Analysis 47, 1–10. https://doi.org/10.1080/00103624.2015.1089260.
Sharma, S., Dhaliwal, S.S., 2019. Effect of Sewage Sludge and Rice Straw Compost on Yield, Micronutrient Availability and Soil Quality under Rice–Wheat System. Communications in Soil Science and Plant Analysis 50, 1943–1954. https://doi.org/10.1080/00103624.2019.1648489.
Sharma, S., Thind, H.S., Singh, Y., Singh, V., Singh, B., 2015. Soil enzyme activities with biomass ashes and phosphorus fertilization to rice–wheat cropping system in the Indo-Gangetic plains of India. Nutrient Cycling in Agroecosystems 101, 391–400. https://doi.org/10.1007/s10705-015-9684-7.
Sigua, G.C., Stone, K.C., Bauer, P.J., Szogi, A.A., 2017. Phosphorus dynamics and phosphatase activity of soils under corn production with supplemental irrigation in humid coastal plain region, USA. Nutrient Cycling in Agroecosystems 109, 249–267. https://doi.org/10.1007/s10705-017-9882-6.
Silvestro, L.B., Biganzoli, F., Forjan, H., Albanesi, A., Arambarri, A.M., Manso, L., Moreno, M.V., 2017. Mollisol: Biological characterization under zero tillage with different crops sequences. Journal of Agricultural Science and Technology 19, 245–257.
Simon, C.A., Lima, S.F. de, Cordeiro, M.S., Secco, V.A., Nacata, G., Silva, A.M.M., Simon, C. da C., Brasil, M. da S., 2019. Cover crops as modifying agents of microbiological soil attribute. Australian Journal of Crop Science 13, 1578–1585. https://doi.org/10.21475/ajcs.19.13.10.p1723.

Singh, S.R., Kundu, D.K., Dey, P., Singh, P., Mahapatra, B.S., 2018. Effect of balanced fertilizers on soil quality and lentil yield in Gangetic alluvial soils of India. Journal of Agricultural Science 156, 225–240. https://doi.org/10.1017/S0021859618000254.

Singh, S.R., Kundu, D.K., Tripathi, M.K., Dey, P., Saha, A.R., Kumar, M., Singh, I., Mahapatra, B.S., 2015. Impact of balanced fertilization on nutrient acquisition, fibre yield of jute and soil quality in New Gangetic alluvial soils of India. Applied Soil Ecology 92, 24–34. https://doi.org/10.1016/j.apsoil.2015.03.007.

Stehouwer, R.C., Dick, W.A., Traina, S.J., 1993. Characteristics of earthworm burrow lining affecting atrazine sorption. Journal of Environmental Quality 22, 181–185. https://doi.org/10.2134/jeq1993.00472425002200010024x.

Sun, J., Li, W., Li, C., Chang, W., Zhang, S., Zeng, Y., Zeng, C., Peng, M., 2020. Effect of Different Rates of Nitrogen Fertilization on Crop Yield, Soil Properties and Leaf Physiological Attributes in Banana Under Subtropical Regions of China. Frontiers in Plant Science 11. https://doi.org/10.3389/fpls.2020.613760.

Swedrzyńska, D., Małecka, I., Blecharczyk, A., Swedrzyński, A., Starzyk, J., 2013. Effects of various long-term tillage systems on some chemical and biological properties of soil. Polish Journal of Environmental Studies 22, 1835–1844.

Tang, H.M., Xiao, X.P., Tang, W.G., Lin, Y.C., Wang, K., Yang, G.L., 2014. Effects of winter cover crops residue returning on soil enzyme activities and soil microbial community in double-cropping rice fields. PLoS One 9, 1–8. https://doi.org/10.1371/journal.pone.0100443.

Tiecher, T., Santos, D.R. dos, Calegari, A., 2012. Soil organic phosphorus forms under different soil management systems and winter crops, in a long term experiment. Soil and Tillage Research 124, 57–67. https://doi.org/10.1016/j.still.2012.05.001.

Tiecher, T., Tiecher, T.L., Mallmann, F.J.K., Zafar, M., Ceretta, C.A., Lourenzi, C.R., Brunetto, G., Gatiboni, L.C., Santos, D.R. dos, 2017. Chemical, biological, and biochemical parameters of the soil P cycle after Long-Term pig slurry application in No-Tillage system. Revista Brasileira de Ciencia do Solo 41, 1–16. https://doi.org/10.1590/18069657rbcs20170037.

Tuti, M.D., Pal, R.S., Mahanta, D., Pandey, B.M., Bisht, J.K., 2020. Soil Chemical and Biological Activities under Vegetable Intensive Colocasia-based Cropping System in Indian Sub-Himalayas. Communications in Soil Science and Plant Analysis 51, 948–962. https://doi.org/10.1080/00103624.2020.1744623.

Vanegas, J.J.C., Zambrano, K.B.M., Avellaneda-Torres, L.M., 2018. Effect of ecological and conventional managements on soil enzymatic activities in coffee agroecosystems. Pesquisa Agropecuaria Tropical 48, 420–428. https://doi.org/10.1590/1983-40632018V4852373.

Varennes, A.D., Torres, M.O., 2011. Post-fallow tillage and crop effects on soil enzymes and other indicators. Soil Use and Management 27, 18–27. https://doi.org/10.1111/j.1475-2743.2010.00307.x.

Verdenelli, R.A., Conforto, C.B., Pérez-Brandán, C., Chavarría, D., Rovea, A., Vargas-Gil, S., Meriles, J.M., 2013. Integrated multivariate analysis of selected soil microbial properties and their relationships with mineral fertilization management in a conservation agriculture system. Acta Agriculturae Scandinavica Section B: Soil and Plant Science 63, 623–632. https://doi.org/10.1080/09064710.2013.837193.

Wang, F., Tang, J., Li, Z., Xiang, J., Wang, L., Tian, L., Jiang, L., Luo, Y., Hou, E., Shao, X., 2021. Warming reduces the production of a major annual forage crop on the Tibetan Plateau. Science of The Total Environment 798, 149211. https://doi.org/10.1016/j.scitotenv.2021.149211.

Wang, J.B., Chen, Z.H., Chen, L.J., Zhu, A.N., Wu, Z.J., 2011. Surface soil phosphorus and phosphatase activities affected by tillage and crop residue input amounts. Plant, Soil and Environment 57, 251–257. https://doi.org/10.17221/437/2010-pse.

Wang, Y., Huang, Q., Gao, H., Zhang, R., Yang, L., Guo, Y., Li, H., Awasthi, M.K., Li, G., 2021. Long-term cover crops improved soil phosphorus availability in a rain-fed apple orchard. Chemosphere 275, 130093. https://doi.org/10.1016/j.chemosphere.2021.130093.

Wang, Y.P., Li, X.G., Hai, L., Siddique, K.H.M., Gan, Y., Li, F.M., 2014. Film fully-mulched ridge-furrow cropping affects soil biochemical properties and maize nutrient uptake in a rainfed semi-arid environment. Soil Science and Plant Nutrition 60, 486–498. https://doi.org/10.1080/00380768.2014.909709.

Wei, K., Chen, Z.H., Zhang, X.P., Liang, W.J., Chen, L.J., 2014. Tillage effects on phosphorus composition and phosphatase activities in soil aggregates. Geoderma 217–218, 37–44. https://doi.org/10.1016/j.geoderma.2013.11.002.

Wick, B., Kühne, R.F., Paul, L.G.V., 1998. Soil microbiological parameters as indicators of soil quality under improved fallow management systems in south-western. Plant and Soil 202, 97-107. https://doi.org/10.1023/A:1004305615397.

Xomphoutheb, T., Jiao, S., Guo, X., Mabagala, F.S., Sui, B., Wang, H., Zhao, L., Zhao, X., 2020. The effect of tillage systems on phosphorus distribution and forms in rhizosphere and non-rhizosphere soil under maize (Zea mays L.) in Northeast China. Scientific Reports 10, 1–9. https://doi.org/10.1038/s41598-020-63567-7.

Yang, X., Bao, X., Yang, Y., Zhao, Y., Liang, C., Xie, H., 2019. Comparison of soil phosphorus and phosphatase activity under long-term no-tillage and maize residue management. Plant, Soil and Environment 65, 408–415. https://doi.org/10.17221/307/2019-PSE.

Zhang, J., Bo, G., Zhang, Z., Kong, F., Wang, Y., Shen, G., 2016. Effects of straw incorporation on soil nutrients, enzymes, and aggregate stability in tobacco fields of China. Sustainability 8, 1–12. https://doi.org/10.3390/su8080710.

Zhong, S., Zeng, H., Jin, Z., 2015. Soil Microbiological and Biochemical Properties as Affected by Different Long-Term Banana-Based Rotations in the Tropics. Pedosphere 25, 868–877. https://doi.org/10.1016/S1002-0160(15)30067-9.

Zibilske, L.M., Makus, D.J., 2009. Black oat cover crop management effects on soil temperature and biological properties on a Mollisol in Texas, USA. Geoderma 149, 379–385. https://doi.org/10.1016/j.geoderma.2009.01.001.

Zuazo, V.H.D., Rodríguez, B.C., García-Tejero, I.F., Ruiz, B.G., Tavira, S.C., 2020. Benefits of organic olive rainfed systems to control soil erosion and runoff and improve soil health restoration. Agronomy for Sustainable Development 40, 1–15. https://doi.org/10.1007/s13593-020-00644-1.

1.3 References related to yield models based on ACP and ALP activity taxonomical affiliation at the family level and management practices.

Ahmed, W., Qaswar, M., Jing, H., Wenjun, D., Geng, S., Kailou, L., Ying, M., Ao, T., Mei, S., Chao, L., Yongmei, X., Ali, S., Normatov, Y., Mehmood, S., Khan, M.N., Huimin, Z., 2020. Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils. Journal of Soils and Sediments 20, 850–861. https://doi.org/10.1007/s11368-019-02468-3.

Aparna, B., 2010. Quantification of enzyme activities under rice crop in a permanent manurial experiment in the coastal sandy tract of Onattukkara of Kerala. An Asian Journal of Soil Science Soil Science 5(2), 347-351.

Aparna, K., Rao, D.L.N., Balachandar, D., 2016. Microbial Populations, Activity and Gene Abundance in Tropical Vertisols Under Intensive Chemical Farming. Pedosphere 26, 725–732. https://doi.org/10.1016/S1002-0160(15)60079-0.

Arya, S.R., Syriac, E.K., Aparna, B., 2018. Enzyme dynamics and organic carbon status of soil as influenced by flucetosulfuron in wet seeded rice. Journal of Tropical Agriculture 56, 1–8.

Babu, S., Singh, R., Avasthe, R.K., Yadav, G.S., Das, A., Singh, V.K., Mohapatra, K.P., Rathore, S.S., Chandra, P., Kumar, A., 2020. Impact of land configuration and organic nutrient management on productivity, quality and soil properties under baby corn in Eastern Himalayas. Scientific Reports 10, 1–14. https://doi.org/10.1038/s41598-020-73072-6.

Banik, P., Ghosal, P.K., Sasmal, T.K., Bhattacharya, S., Sarkar, B.K., Bagchi, D.K., 2006. Effect of organic and inorganic nutrients for soil quality conservation and yield of rainfed low land rice in sub-tropical plateau region. Journal of Agronomy and Crop Science 192, 331–343. https://doi.org/10.1111/j.1439-037X.2006.00219.x.

Batool, K., Khan, Q.U.Q.U., Naz, R., Khan, M.J., Sayal, O.U.O.U., Bashir, A., Latif, A., 2015. Source and rate of inorganic P fertilizer affecting soil phosphatase enzymes, yield and P-uptake of chillies. Soil and Environment 34, 27–33.

Bhatt, B., Chandra, R., Ram, S., Pareek, N., 2016. Long-term effects of fertilization and manuring on productivity and soil biological properties under rice (Oryza sativa)–wheat (Triticum aestivum) sequence in Mollisols. Archives of Agronomy and Soil Science 62, 1109–1122. https://doi.org/10.1080/03650340.2015.1125471.

Bi, Q.F., Li, K.J., Zheng, B.X., Liu, X.P., Li, H.Z., Jin, B.J., Ding, K., Yang, X.R., Lin, X.Y., Zhu, Y.G., 2020. Partial replacement of inorganic phosphorus (P) by organic manure reshapes phosphate mobilizing bacterial community and promotes P bioavailability in a paddy soil. Science of the Total Environment 703, 134977. https://doi.org/10.1016/j.scitotenv.2019.134977.

Bi, Q.F., Zheng, B.X., Lin, X.Y., Li, K.J., Liu, X.P., Hao, X.L., Zhang, H., Zhang, J.B., Jaisi, D.P., Zhu, Y.G., 2018. The microbial cycling of phosphorus on long-term fertilized soil: Insights from phosphate oxygen isotope ratios. Chemical Geology 483, 56–64. https://doi.org/10.1016/j.chemgeo.2018.02.013.

Biau, A., Santiveri, F., Mijangos, I., Lloveras, J., 2012. The impact of organic and mineral fertilizers on soil quality parameters and the productivity of irrigated maize crops in semiarid regions. European Journal of Soil Biology 53, 56–61. https://doi.org/10.1016/j.ejsobi.2012.08.008.

Boccolini, M.F., Cazorla, C.R., Galantini, J.A., Belluccini, P.A., Baigorria, T., 2019. Cultivos de cobertura disminuyen el impacto ambiental mejorando propiedades biológicas del suelo y el rendimiento de los cultivos. Revista de Investigaciones Agropecuarias 45, 412–425.

Bolton, H., Smith, J.L., Link, S.O., 1993. Soil microbial biomass and activity of a disturbed and undisturbed shrub-steppe ecosystem. Soil Biology and Biochemistry 25, 545–552. https://doi.org/10.1016/0038-0717(93)90192-E.

Borase, D.N., Murugeasn, S., Nath, C.P., Hazra, K.K., Singh, S.S., Kumar, N., Singh, U., Praharaj, C.S., 2021. Long-term impact of grain legumes and nutrient management practices on soil microbial activity and biochemical properties. Archives of Agronomy and Soil Science 67, 2015–2032. https://doi.org/10.1080/03650340.2020.1819532.

Chander, K., Goyal, S., Mundra, M.C., Kapoor, K.K., 1997. Organic matter, microbial biomass and enzyme activity of soils under different crop rotations in the tropics. Biology and Fertility of Soils 24, 306–310. https://doi.org/10.1007/s003740050248.

Chatterjee, D., Nayak, A.K., Mishra, A., Swain, C.K., Kumar, U., Bhaduri, D., Panneerselvam, P., Lal, B., Gautam, P., Pathak, H., 2021. Effect of Long-Term Organic Fertilization in Flooded Rice Soil on Phosphorus Transformation and Phosphate Solubilizing Microorganisms. Journal of Soil Science and Plant Nutrition 21, 1368–1381. https://doi.org/10.1007/s42729-021-00446-8.

Choudhary, M., Sharma, P.C., Jat, H.S., McDonald, A., Jat, M.L., Choudhary, S., Garg, N., 2018. Soil biological properties and fungal diversity under conservation agriculture in indo-gangetic plains of india. Journal of Soil Science and Plant Nutrition 18, 1142–1156. https://doi.org/10.4067/S0718-95162018005003201.

Cox, D., Bezdicek, D., Fauci, M., 2001. Effects of compost, coal ash, and straw amendments on restoring the quality of eroded Palouse soil. Biology and Fertility of Soils 33, 365–372. https://doi.org/10.1007/s003740000335.

Diallo-Diagne, N.H., Assigbetse, K., Sall, S., Masse, D., Bonzi, M., Ndoye, I., Chotte, J.L., 2016. Response of Soil Microbial Properties to Long-Term Application of Organic and Inorganic Amendments in a Tropical Soil (Saria, Burkina Faso). Open Journal of Soil Science 06, 21–33. https://doi.org/10.4236/ojss.2016.62003.

Dou, F., Wright, A.L., Mylavarapu, R.S., Jiang, X., Matocha, J.E., 2016. Soil Enzyme Activities and Organic Matter Composition Affected by 26 Years of Continuous Cropping. Pedosphere 26, 618–625. https://doi.org/10.1016/S1002-0160(15)60070-4.

Gaind, S., Singh, Y.V., 2016a. Short-Term Impact of Organic Fertilization and Seasonal Variations on Enzymes and Microbial Indices Under Rice–Wheat Rotation. Clean - Soil, Air, Water 44, 1396–1404. https://doi.org/10.1002/clen.201500946.

Gaind, S., Singh, Y.V., 2016b. Soil organic phosphorus fractions in response to long-term fertilization with composted manures under rice–wheat cropping system. Journal of Plant Nutrition 39, 1336–1347. https://doi.org/10.1080/01904167.2015.1086795.

Gao, X., Shi, D., Lv, A., Wang, S., Yuan, S., Zhou, P., An, Y., 2016. Increase phosphorus availability from the use of alfalfa (Medicago sativa L) green manure in rice (Oryza sativa L.) agroecosystem. Scientific Reports 6, 1–13. https://doi.org/10.1038/srep36981.

George, S., Wright, D.L., Marois, J.J., 2013. Impact of grazing on soil properties and cotton yield in an integrated crop-livestock system. Soil and Tillage Research 132, 47–55. https://doi.org/10.1016/j.still.2013.05.004.

Gopinath, K.A., Saha, S., Mina, B.L., Pande, H., Kumar, N., Srivastva, A.K., Gupta, H.S., 2009. Yield potential of garden pea (Pisum sativum L.) varieties, and soil properties under organic and integrated nutrient management systems. Archives of Agronomy and Soil Science 55, 157–167. https://doi.org/10.1080/03650340802382207.

Gopinath, K.A., Saha, S., Mina, B.L., Pande, H., Kundu, S., Gupta, H.S., 2008. Influence of organic amendments on growth, yield and quality of wheat and on soil properties during transition to organic production. Nutrient Cycling in Agroecosystems 82, 51–60. https://doi.org/10.1007/s10705-008-9168-0.

Goyal, S., Chander, K., Mundra, M.C., Kapoor, K.K., 1999. Influence of inorganic fertilizers and organic amendments on soil organic matter and soil microbial properties under tropical conditions. Biology and Fertility of Soils 29, 196–200. https://doi.org/10.1007/s003740050544.

Guan, G., Tu, S., Li, H., Yang, J., Zhang, J., Wen, S., Yang, L., 2013. Phosphorus Fertilization Modes Affect Crop Yield, Nutrient Uptake, and Soil Biological Properties in the Rice-Wheat Cropping System. Soil Science Society of America Journal 77, 166–172. https://doi.org/10.2136/sssaj2011.0324.

Guan, G., Tu, S.-X., Yang, J.-C., Zhang, J.-F., Yang, L., 2011. A Field Study on Effects of Nitrogen Fertilization Modes on Nutrient Uptake, Crop Yield and Soil Biological Properties in Rice-Wheat Rotation System. Agricultural Sciences in China 10, 1254–1261. https://doi.org/10.1016/S1671-2927(11)60117-X.

Hatti, V., Ramachandrappa, B.K., Sathishand, A., Thimmegowda, M.N., 2018. Soil properties and productivity of rainfed finger millet under conservation tillage and nutrient management in Eastern dry zone of Karnataka. Journal of Environmental Biology 39, 612–624.

Hoyle, F.C., Murphy, D.V., 2006. Seasonal changes in microbial function and diversity associated with stubble retention versus burning. Australian Journal of Soil Research 44, 407–423. https://doi.org/10.1071/SR05183.

Jain, N.K., Jat, R.S., Meena, H.N., Chakraborty, K., 2018. Productivity, Nutrient, and Soil Enzymes Influenced with Conservation Agriculture Practices in Peanut. Agronomy Journal 110, 1165–1172. https://doi.org/10.2134/agronj2017.08.0467.

Jaskulska, I., Romaneckas, K., Jaskulski, D., Gałęzewski, L., Breza-Boruta, B., Dębska, B., Lemanowicz, J., 2020. Soil properties after eight years of the use of strip-till one-pass technology. Agronomy 10, 1–16. https://doi.org/10.3390/agronomy10101596.

Jat, H.S., Choudhary, M., Datta, A., Yadav, A.K., Meena, M.D., Devi, R., Gathala, M.K., Jat, M.L., McDonald, A., Sharma, P.C., 2020. Temporal changes in soil microbial properties and nutrient dynamics under climate smart agriculture practices. Soil and Tillage Research 199, 104595. https://doi.org/10.1016/j.still.2020.104595.

Jat, H.S., Datta, A., Choudhary, M., Sharma, P.C., Yadav, A.K., Choudhary, V., Gathala, M.K., Jat, M.L., McDonald, A., 2019. Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. Catena 181, 104059. https://doi.org/10.1016/j.catena.2019.05.005.

Jia, Q., Kamran, M., Ali, S., Sun, L., Zhang, P., Ren, X., Jia, Z., 2018. Deficit irrigation and fertilization strategies to improve soil quality and alfalfa yield in arid and semi-arid areas of northern China. PeerJ 2018, 1–21. https://doi.org/10.7717/peerj.4410.

Johnson, J.M.F., Acosta-Martinez, V., Cambardella, C.A., Barbour, N.W., 2013. Crop and soil responses to using corn stover as a bioenergy feedstock: Observations from the northern us corn belt. Agriculture (Switzerland) 3, 72–89. https://doi.org/10.3390/agriculture3010072.

Kayikcioglu, H.H., 2018. Can treated wastewater be used as an alternative water resource for agricultural irrigation? Changes in soil and plant health after three years of maize cultivation in western anatolia, Turkey. Applied Ecology and Environmental Research 16, 8131–8161. https://doi.org/10.15666/aeer/1606_81318161.

Khandare, R.N., Chandra, R., Pareek, N., Raverkar, K.P., 2020. Carrier-based and liquid bioinoculants of Azotobacter and PSB saved chemical fertilizers in wheat (Triticum aestivum L.) and enhanced soil biological properties in Mollisols. Journal of Plant Nutrition 43, 36–50. https://doi.org/10.1080/01904167.2019.1659333.

Kuwano, B.H., Nogueira, M.A., Santos, C.A., Fagotti, D.S.L., Santos, M.B., Lescano, L.E.A.M., Andrade, D.S., Barbosa, G.M.C., Tavares-Filho, J., 2017. Application of Landfill Leachate Improves Wheat Nutrition and Yield but Has Minor Effects on Soil Properties. Journal of Environmental Quality 46, 153–159. https://doi.org/10.2134/jeq2016.02.0041.

Liu, E., Yan, C., Mei, X., He, W., Bing, S.H., Ding, L., Liu, Q., Liu, S., Fan, T., 2010. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. Geoderma 158, 173–180. https://doi.org/10.1016/j.geoderma.2010.04.029.

Lopes, A.A. de C., Sousa, D.M.G. de, Chaer, G.M., Junior, F.B. dos R., Goedert, W.J., Mendes, I. de C., 2013. Interpretation of Microbial Soil Indicators as a Function of Crop Yield and Organic Carbon. Soil Science Society of America Journal 77, 461–472. https://doi.org/10.2136/sssaj2012.0191.

Ma, H., Egamberdieva, D., Wirth, S., Li, Q., Omari, R.A., Hou, M., Bellingrath-Kimura, S.D., 2019. Effect of biochar and irrigation on the interrelationships among soybean growth, root nodulation, plant p uptake, and soil nutrients in a sandy field. Sustainability (Switzerland) 11, 1–16. https://doi.org/10.3390/su11236542.

Mahajan, G.R., Manjunath, B.L., Morajkar, S., Desai, A., Das, B., Paramesh, V., 2021. Long-Term Effect of Various Organic and Inorganic Nutrient Sources on Rice Yield and Soil Quality in West Coast India Using Suitable Indexing Techniques. Communications in Soil Science and Plant Analysis 52, 1819–1833. https://doi.org/10.1080/00103624.2021.1900221.

Majumdar, B., Saha, A.R., Sarkar, S., Maji, B., Mahapatra, B.S., 2010. Effect of herbicides and fungicides application on fibre yield and nutrient uptake by jute (Corchorus olitorius), residual nutrient status and soil quality. Indian Journal of Agricultural Sciences 80, 878–883.

Mijangos, I., Pérez, R., Albizu, I., Garbisu, C., 2006. Effects of fertilization and tillage on soil biological parameters. Enzyme and Microbial Technology 40, 100–106. https://doi.org/10.1016/j.enzmictec.2005.10.043.

Mina, B.L., Saha, S., Kumar, N., Srivastva, A.K., Gupta, H.S., 2008. Changes in soil nutrient content and enzymatic activity under conventional and zero-tillage practices in an Indian sandy clay loam soil. Nutrient Cycling in Agroecosystems 82, 273–281. https://doi.org/10.1007/s10705-008-9189-8.

Mohammadi, K., Eskandari, M., Heidari, G., Nezhad, M.T.K., 2011. Canola traits and some soil biological parameters in response to fertilization and tillage management. African Journal of Biotechnology 10, 14067–14072. https://doi.org/10.5897/ajb11.2161.

N'Dayegamiye, A., 2006. Mixed paper mill sludge effects on corn yield, nitrogen efficiency, and soil properties. Agronomy Journal 98, 1471–1478. https://doi.org/10.2134/agronj2005.0339.

Nedunchezhiyan, M., Laxminarayana, K., Chauhan, V.B.S., 2018. Soil Microbial Activities and Yield of Elephant Foot Yam as Influenced by Weed Management Practices in Alfisols. International Journal of Vegetable Science 24, 583–596. https://doi.org/10.1080/19315260.2018.1454567.

Niewiadomska, A., Sulewska, H., Wolna-Maruwka, A., Ratajczak, K., Waraczewska, Z., Budka, A., 2020. The influence of bio-stimulants and foliar fertilizers on yield, plant features, and the level of soil biochemical activity in white lupine (Lupinus albus L.) cultivation. Agronomy 10. https://doi.org/10.3390/agronomy10010150.

Okur, N., Kayikçioğlu, H.H.H., Okur, B., Delibacak, S., 2008. Organic amendment based on tobacco waste compost and farmyard manure: Influence on soil biological properties and butter-head lettuce yield. Turkish Journal of Agriculture and Forestry 32, 91–99. https://doi.org/10.3906/tar-0707-24.

Patel, G., Dwivedi, B.S., Dwivedi, A.K., Thakur, R., Singh, M., 2018. Long-term effect of nutrient management on soil biochemical properties in a vertisol under soybean-wheat cropping sequence. Journal of the Indian Society of Soil Science 66, 215–221. https://doi.org/10.5958/0974-0228.2018.00027.0.

Prasanthi, G., Kumar, N.G., Raghu, S., Srinivasa, N., Gurumurthy, H., 2019. Study on the effect of different levels of organic and inorganic fertilizers on microbial enzymes and soil mesofauna in soybean ecosystem. Legume Research 42, 233–237. https://doi.org/10.18805/LR-3850.

Qaswar, M., Chai, R., Ahmed, W., Jing, H., Han, T., Liu, K., Ye, X., Xu, Y., Anthonio, C.K., Zhang, H., 2020. Partial substitution of chemical fertilizers with organic amendments increased rice yield by changing phosphorus fractions and improving phosphatase activities in fluvo-aquic soil. Journal of Soils and Sediments 20, 1285–1296. https://doi.org/10.1007/s11368-019-02476-3.

Qaswar, M., Jing, H., Ahmed, W., Dongchu, L., Shujun, L., Ali, S., Kailou, L., Yongmei, X., Lu, Z., Lisheng, L., Jusheng, G., Huimin, Z., 2019. Long-term green manure rotations improve soil biochemical properties, yield sustainability and nutrient balances in acidic paddy soil under a rice-based cropping system. Agronomy 9. https://doi.org/10.3390/agronomy9120780.

Ramdas, M.G., Manjunath, B.L., Pratap, S.N., Ramesh, R., Verma, R.R., Marutrao, L.A., Ruenna, D., Natasha, B., Rahul, K., 2017. Effect of organic and inorganic sources of nutrients on soil microbial activity and soil organic carbon build-up under rice in west coast of India. Archives of Agronomy and Soil Science 63, 414–426. https://doi.org/10.1080/03650340.2016.1213813.

Rana, M., Chandra, R., Pareek, N., 2015. Co-inoculation effect of endophytic bacteria with Mesorhizobium sp. In Chickpea (cicer arietinum L.) on nodulation, yields, nutrient uptake and soil biological properties. Journal of the Indian Society of Soil Science 63, 429–435. https://doi.org/10.5958/0974-0228.2015.00057.2.

Rana, M., Raverkar, K.P.P., Pareek, N., Chandra, R., Singh, D.K.K., 2015. Impact of biodynamic preparations and panchgavya in organically managed cropping systems comprising legumes on soil biological health. Legume Research 38, 219–228. https://doi.org/10.5958/0976-0571.2015.00081.8.

Sarma, B., Gogoi, N., 2017. Nitrogen Management for Sustainable Soil Organic Carbon Increase in Inceptisols Under Wheat Cultivation. Communications in Soil Science and Plant Analysis 48, 1428–1437. https://doi.org/10.1080/00103624.2017.1373785.

Sharma, M.P., Gupta, S., Sharma, S.K., Vyas, A.K., 2012. Effect of tillage and crop sequences on arbuscular mycorrhizal symbiosis and soil enzyme activities in soybean (Glycine max) rhizosphere. Indian Journal of Agricultural Sciences 82, 25–30.

Sharma, R.C., Banik, P., 2016. Sustaining Productivity of Baby Corn–Rice Cropping System and Soil Health through Integrated Nutrient Management. Communications in Soil Science and Plant Analysis 47, 1–10. https://doi.org/10.1080/00103624.2015.1089260.

Sharma, R.C., Banik, P., 2014. Vermicompost and fertilizer application: Effect on productivity and profitability of baby corn (Zea mays L.) and soil health. Compost Science and Utilization 22, 83–92. https://doi.org/10.1080/1065657X.2014.895456.

Sharma, S., Dhaliwal, S.S., 2019. Effect of Sewage Sludge and Rice Straw Compost on Yield, Micronutrient Availability and Soil Quality under Rice–Wheat System. Communications in Soil Science and Plant Analysis 50, 1943–1954. https://doi.org/10.1080/00103624.2019.1648489.

Simon, C.A., Lima, S.F. de, Cordeiro, M.S., Secco, V.A., Nacata, G., Silva, A.M.M., Simon, C. da C., Brasil, M. da S., 2019. Cover crops as modifying agents of microbiological soil attribute. Australian Journal of Crop Science 13, 1578–1585. https://doi.org/10.21475/ajcs.19.13.10.p1723.

Singh, C., Rakshit, R., Das, A., Bharti, P., 2020. Interpretations of Elemental and Microbial Phosphorus Indicators to Understand P Availability in Soils Under Rice–Wheat Cropping System. Agricultural Research 9, 329–339. https://doi.org/10.1007/s40003-019-00439-1.

Singh, S., Sharma, S., 2020. Temporal changes in rhizosphere biological soil quality indicators of wheat in response to nitrogen and straw incorporation. Tropical Ecology 61, 328–344. https://doi.org/10.1007/s42965-020-00092-8.

Singh, S.R., Kundu, D.K., Dey, P., Singh, P., Mahapatra, B.S., 2018. Effect of balanced fertilizers on soil quality and lentil yield in Gangetic alluvial soils of India. Journal of Agricultural Science 156, 225–240. https://doi.org/10.1017/S0021859618000254.

Singh, S.R., Kundu, D.K., Tripathi, M.K., Dey, P., Saha, A.R., Kumar, M., Singh, I., Mahapatra, B.S., 2015. Impact of balanced fertilization on nutrient acquisition, fibre yield of jute and soil quality in New Gangetic alluvial soils of India. Applied Soil Ecology 92, 24–34. https://doi.org/10.1016/j.apsoil.2015.03.007.

Soon, Y.K., Rice, W.A., Arshad, M.A., Mills, P., 2000. Effect of pipeline installation on crop yield and some biological properties of boreal soils. Canadian Journal of Soil Science 80, 483–488. https://doi.org/10.4141/S99-096.

Srivastava, P.K., Gupta, M., Shikha, Singh, N., Tewari, S.K., 2016. Amelioration of Sodic Soil for Wheat Cultivation Using Bioaugmented Organic Soil Amendment. Land Degradation and Development 27, 1245–1254. https://doi.org/10.1002/ldr.2292.

Turan, M., Gulluce, M., Wirén, N. von, Sahin, F., 2012. Yield promotion and phosphorus solubilization by plant growth-promoting rhizobacteria in extensive wheat production in Turkey. Journal of Plant Nutrition and Soil Science 175, 818–826. https://doi.org/10.1002/jpln.201200054.

Ullah, R., Aslam, Z., Maitah, M., Zaman, Q.U., Bashir, S., Hassan, W., Chen, Z., 2020. Sustainable weed control and enhancing nutrient use efficiency in crops through brassica (Brassica compestris l.) allelopathy. Sustainability (Switzerland) 12, 1–17. https://doi.org/10.3390/su12145763.

Verma, S.K., Pankaj, U., Khan, K., Singh, R., Verma, R.K., 2016. Bioinoculants and Vermicompost Improve Ocimum basilicum Yield and Soil Health in a Sustainable Production System. Clean - Soil, Air, Water 44, 686–693. https://doi.org/10.1002/clen.201400639.

Wang, Z.-G., Jin, X., Bao, X.-G., Li, X.-F., Zhao, J.-H., Sun, J.-H., Christie, P., Li, L., 2014. Intercropping enhances productivity and maintains the most soil fertility properties relative to sole cropping. PLoS ONE 9. https://doi.org/10.1371/journal.pone.0113984.

Wei, K., Bao, H., Huang, S., Chen, L., 2017. Effects of long-term fertilization on available P, P composition and phosphatase activities in soil from the Huang-Huai-Hai Plain of China. Agriculture, Ecosystems and Environment 237, 134–142. https://doi.org/10.1016/j.agee.2016.12.030.

Yang, X., Bao, X., Yang, Y., Zhao, Y., Liang, C., Xie, H., 2019. Comparison of soil phosphorus and phosphatase activity under long-term no-tillage and maize residue management. Plant, Soil and Environment 65, 408–415. https://doi.org/10.17221/307/2019-PSE.

Zuazo, V.H.D., Rodríguez, B.C., García-Tejero, I.F., Ruiz, B.G., Tavira, S.C., 2020. Benefits of organic olive rainfed systems to control soil erosion and runoff and improve soil health restoration. Agronomy for Sustainable Development 40, 1–15. https://doi.org/10.1007/s13593-020-00644-1

6. Chapter 3

Research article

Effect of organic fertilisation on soil phosphatase activity, phosphorus availability and forage yield in mountain permanent meadows

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6.1 Abstract

Grassland management aims to ensure sufficient yield, forage quality and biodiversity. Robust knowledge supports sustainable management practices. In South Tyrol (NE Italy), we studied the effect of organic fertilisation on soil acid and alkaline phosphatase activity (ACP, ALP, or both APase), phosphorus (P) availability and forage yield in mountain permanent meadows. Three factors were included in the experimental design, which was arranged as a split-plot design: the initial vegetation class (moderately species-poor = C1 or moderately species-rich = C2), being the main plot, randomised within three study areas, as well as the manure type (slurry, farmyard manure, and a combination of farmyard manure and manure effluent) and the nitrogen (N) fertilisation input (0, 55.5 and 111 kg N $ha^{-1}yr^{-1}$), both randomised within the vegetation class. Soil samples were collected from the top 10 cm before the last cut in summer 2022. Results showed that the combined use of farmyard manure and manure effluent decreased ACP activity with increasing N input, whilst ALP activity remained unaffected. These novel findings show that organic N input does not imply an increase in APase activity. Moreover, the C2 meadow class showed higher ACP activity than C1, possibly due to higher species diversity, a lower mowing frequency and the legacy effect of more extensive management prior to the start of the trial. Both ACP and ALP activity responded to pH (negatively for ACP activity and positively for ALP activity) and both were negatively affected by soil moisture, highlighting their sensitivity to changes in the soil conditions. ALP activity was positively influenced by total organic carbon (TOC) and by the Shannon diversity index of the plant communities, possibly due to its link with the soil microbial community. Soil available P increased with pH, TOC, soil moisture, K_2O content, and N organic input from farmyard manure, which provided the highest P input. The forage yield of the last growth cycle was positively affected by organic N input but negatively affected by TOC, whilst the activity of both APase had no effect on it. The annual yield increased with the N input and was higher in the C1 meadow class than in the C2. On the whole, the results suggest that organic fertilisation, rather than APase activity, was the main driver of forage yield.

Keywords: soil phosphorus; nutrient input; slurry; farmyard manure; manure effluent; phosphomonoesterases; plant diversity

6.2 Introduction

Phosphorus (P) is a crucial element for all living organisms and a major limiting nutrient for plant growth in many agroecosystems (Zhu et al., 2018). In these systems, the activity of soil P enzymes is essential for mobilising P by catalysing the hydrolysis of P esters into phosphate ions (i.e., H_2PO^{4-}, HPO_4^{2-}, PO_4^{3-}), thereby making them soluble and accessible for plant uptake (Schmidt and Laskowski, 1961). Acid phosphatase (ACP, EC 3.1.3.2) and alkaline phosphatase (ALP, EC 3.1.3.1) are the predominant forms among the monoester phosphatases (APase) (Alef and Nannipieri, 1995). ACP is secreted by plants and fungi, while ALP is secreted by microorganisms and mesofauna (Carricondo-Martínez et al., 2022; Juma and Tabatabai, 1988). The available scientific literature has extensively shown that enzymes play a significant role in the decomposition of organic matter, facilitating nutrient recycling (Burns, 1978).

Grassland covers a significant portion of Europe's agricultural area, contributing to over one-third of the land (Eurostat, 2022). It provides a vital role in livestock farming systems, providing forage for herbivores (Jäger et al., 2020). Grassland also delivers essential ecosystem services including erosion control, water management and water purification (Hernández-Becerra et al., 2016). The vegetation of grassland can include grasses, graminoids, legumes and forbs, and woody species may also be present (Velthof et al., 2014). The vegetation cover and absorption capacity of grasslands significantly reduce nitrogen (N) leaching, thanks to their effective absorption rates throughout the growing season (Scherer-Lorenzen et al., 2003). Additionally, grasslands contribute significantly to enriching soils in organic matter, leading to a global decrease in carbon (C) dioxide emissions (Dignac et al., 2017). Permanent meadows are a form of utilising grassland, harvested mostly by mowing over the last five years and not having been completely renewed for ten years or longer. They are one of the most common forms of agriculturally managed grassland in Europe (Euromontana, 2021). N and P addition increases soil P availability, promoting plant nutrient uptake of nutrients, potentially increasing leaf N and P contents (Shi et al., 2020) and resulting in lower C inputs into soils through roots (Zi et al., 2022). Low APase activity values indicate that biological communities have adapted to acquiring most of their P from inorganic sources, where inorganic P content is much higher than organic P, or the remaining organic P is relatively resistant to mineralisation (Zhang et al., 2021). In general, ACP and ALP activity are thought to increase following N and P fertilisation, often associated with increased plant production (Touhami et al., 2021). However, a comprehensive investigation of patterns of APase activity in permanent meadows and their relationship with soil, biodiversity, yield and the agricultural management (especially concerning organic fertilisation) is still lacking.

Over the whole range of fertilisation intensity there is a clear trade-off in managed grasslands between yield and plant diversity (Fraser et al., 2015; Humbert et al., 2016; Müller et al., 2016). Agricultural practices involving the use of N mineral fertilisers can stimulate the activity of hydrolase enzymes such as ACP and enhance microbial biomass content in grasslands (Jian et al., 2016). In P-deficient soils, some plants hydrolyse soil organic P compounds into inorganic phosphate to transfer phosphate from senesced tissue to young tissue, reducing their reliance on soil P and P fertilisation (Yang and Yang, 2021). Organic manure fertilisation aids this plant nutrient resorption process and contributes substantial amounts of organic matter to the soil, which positively affects APase activity (Zhang et al., 2015) and other nutrient cycles. P supplementation enhances nutrient cycling in P-limited and N:P imbalanced grasslands, potentially improving nutrient use efficiency in these systems (Gong et al., 2022). In conditions of poor N and P availability, microorganisms may increase enzyme production to mobilise resources from complex substrates (Garcia et al., 1997; Lucas-Borja et al., 2011). However, the relationship between changes in productivity and the response of APase is still not fully understood. Additionally, climate indices like mean annual temperature or mean annual precipitation have been found in two meta-analyses to have a linear, positive relationship with APase activity (Meng et al., 2020; Sun et al., 2020). To comprehensively understand the factors affecting ACP and ALP activity in organically fertilised permanent meadows, we investigated the effect of different kinds of manures along a gradient of total N up to 111 kg^{-1} ha^{-1} yr^{-1} consistently applied over five growing seasons in mountain meadows located in the Alps (South Tyrol, NE Italy), corresponding to two different classes of vegetation, a moderately species-poor and a moderately species-rich botanical composition, along with other site factors related to soil and vegetation. Furthermore, we investigated the effect of the above-mentioned factors plus ACP and ALP activity on P availability, and finally the combined effect of all of them on forage yield.

We hypothesised that (I) the short-term application of organic N would positively affect the activity of both ACP and ALP, (II) P availability would increase with APase activity, (III) soil physiochemical parameters, along with vegetation-related parameters and meteorological indices, would affect the activity of both APase and P availability and (IV) forage yield would be positively affected by increased APase activity and P availability.

6.3 Materials and methods

6.3.1 Study areas and experimental design

In 2017, a field experiment, laid out as a split-plot design, was established at three study areas within South Tyrol (NE Italy): Rüdeferia/Rudiferia, Radsberg/Monterota, and Montal/Mantena, encompassing altitudes between 1112 and 1714 m above sea level (m a.s.l.), from the montane to the subalpine zone (Table 1). Within each study area, two experimental sites were established, each corresponding to different starting botanical compositions, herein referred to as meadow classes, being the main plot; C1: moderately species-poor and C2: moderately species-rich, according to Tomasi et al. (2016), also taking into consideration minor adaptations decided by the working group "Managementleitlinien zur Ausbringung von Wirtschaftsdünger in Natura 2000 Gebieten" of the Autonomous Province of Bozen-Bolzano (South Tyrol, Italy). C2 fulfils the requirements to be classified as habitat type 6510 lowland hay meadow or 6520 mountain hay meadow (European Commission, 2007), whilst C1 does not. At the start of the trial, the botanical composition of C1 meadows resembled nutrient-rich forms of the alliance Centaureo transalpinae-Trisetetum flavescentis (Scotton et al., 2012) or Poo-Trisetetum (Tasser et al., 2010), whilst that of C2 meadows resembled nutrient-poor forms of the alliance Centaureo transalpinae-Trisetetum flavescentis (Scotton et al., 2012) or Trisetetum flavescentis (Tasser et al., 2010; Zwack, 2019).

Altitude, aspect and inclination were not entangled with the meadow class (Table 1). Regarding the texture, it is worth noting that the soils in Rüdeferia/Rudiferia had a higher proportion of clay (clay to clay loam), while the other sites had a similar loamy texture.

Table 1. Location, mean topographic features, soil pH and soil texture (mean of sand, silt and clay percentage) ± SD of the six experimental sites. The coordinates refer to the centroid of the respective experimental field; altitude, aspect and inclination are mean values of the respective experimental site.

Study site	Meadow class	Montal/ Mantena	Radsberg/ Monterota	Rüdeferia/ Rudiferia
Coordinates (N, E)	C1	46° 42' 33.8" N 11° 55' 05.0"E	46° 44' 46.7" N 12° 13' 19.9" E	46° 35' 06.1" N 11° 55' 36.8" E
	C2	46° 42' 33.4" N 11° 55' 03.1" E	46° 45' 07.0" N 12° 12' 27.7" E	46° 35' 08.6" N 11° 55' 35.3" E
Altitude (m a.s.l.)	C1	1120 (montane)	1542 (higher-montane)	1678 (subalpine)

	C2	1112 (montane)	1714 (subalpine)	1698 (subalpine)
Aspect	C1	WNW	SSO	S
	C2	W	S	SSW
Inclination (°)	C1	5	18	12
	C2	18	19	23
pH	C1	7.36 ± 0.063	7.03 ± 0.259	7.63 ± 0.028
	C2	7.41 ± 0.098	6.09 ± 0.171	7.79 ± 0.046
Soil texture	C1	Loam	Clay	Loam
	C2	Loam	Clay loam	Loam
Sand (%)	C1	47.3 ± 3.87	44.8 ± 2.17	33.0 ± 3.43
	C2	50.6 ± 3.94	49.7± 3.04	37.2 ± 2.11
Silt (%)	C1	30.9 ± 2.47	44.1 ± 2.03	24.1 ± 1.54
	C2	30.4 ± 1.51	36.6 ± 1.81	23.1 ± 1.05
Clay (%)	C1	21.8 ± 1.86	11.1 ± 1.05	42.9 ± 2.26
	C2	19 ± 3.24	13.8 ± 1.86	39.7± 2.45

Within each experimental site, nine plots with a size of 5 x 5 m (Fig. S1) were established, with two fertilisation-related factors and all the possible combinations of their levels randomly allocated to the plots. These plots were separated by a 0.5 m wide buffer zone.

The first factor was the manure type including three levels: (1) S = slurry: a mixture of faeces and urine, which may also contain water (rainwater, cleansing water), fragments of bedding material, waste feed and silage effluents; (2) F = farmyard manure: a mixture of straw or other forms of bedding, which are used to absorb faeces and urine of animals housed in tie stalls, with only a part of the urine being absorbed and bound by the bedding material; (3) L = combined use of farmyard manure (as previously described) and manure effluent, with manure effluent providing 30% of the total N. Manure effluent (German: Jauche) primarily consists of urine of animals housed in tie stalls that has not been bound by the bedding material. It may also contain, to a minor extent, effluents from stored farmyard manure or small amounts of faeces and bedding material and it is usually collected in specifically designed pits.

All manures used in the field experiment were obtained by cattle farms located in the surroundings of the experimental sites.

The second factor was N input, corresponding to 0, 55.5 and 111 kg ha^{-1} yr^{-1} of total N provided by the manures.

6.3.2 Determination of nutrient content in manures and manure application

Before each fertilisation event, the total N content in the manure charge to be used was measured in the laboratory by means of an Elemental Analyzer (Truspec N, LECO, Miami, USA) according to DIN-EN-ISO16634-1:2009 and the exact amount of manure to be applied in each plot was determined. The potassium (K) and P content was determined by means of ICP-OES 720 (Agilent, Santa Clara, USA) and according to Naumann et al. (1997). Total organic C was determined by the method 10.2 of VDLUFA (1995), after incineration at 550°C for four hours.

The ratio between total N, other nutrients, and C depends on the manure type (Peratoner et al., 2022) and, to a lesser extent, on the single manure batch (Table S1). Therefore, a variable input of the other nutrients and of total organic C is unavoidable. For example, P input increased from S to F (from 8.7 to 13.3 kg ha^{-1} yr^{-1} at intermediate nutrient input), K input more than doubled from F to L (from 45.5 to 98.1 kg ha^{-1} yr^{-1} at intermediate nutrient input) and total organic C increased by about 50% from S to F (from 1013.7 to 1546.7 kg ha^{-1} yr^{-1} at intermediate nutrient input) (Table 2).

Table 2. Annual mean fertilisation input ± SD of total nitrogen (N), phosphorus (P), potassium (K) and total organic carbon (C) over the whole investigation period (2017-2022) depending on manure type and nutrient input level.

Manure type	Total N (kg ha^{-1} yr^{-1})	P (kg ha^{-1} yr^{-1})	K (kg ha^{-1} yr^{-1})	Total organic C (kg ha^{-1} yr^{-1})
S	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00
	55.5 ± 0.00	8.7 ± 2.20	78.2 ± 12.50	1013.7 ± 345.12
	111.0 ± 0.00	17.5 ± 4.63	151.5 ± 19.78	2007.4 ± 647.93
F	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00
	55.5 ± 0.00	13.3 ± 3.31	45.5 ± 20.62	1546.7 ± 335.26
	111.0 ± 0.00	26.6 ± 6.62	91.1 ± 41.24	3094.3 ± 670.79
L	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00
	55.5 ± 0.00	10.4 ± 2.53	98.1 ± 28.95	1237.7 ± 226.57
	111.0 ± 0.00	20.9 ± 4.93	194.1 ± 59.60	2464.8 ± 468.78

S: slurry, F: farmyard manure, L: combined use of farmyard manure and manure effluent.

The application of manure followed a specific pattern in accordance with good agricultural practice: farmyard manure was applied in autumn at the end of the growing season, while liquid manures (slurry and manure effluent) were applied at the beginning of the growing season (see Table S2 for details). At the higher nutrient input level, the total N input of the liquid manures was applied in two equal doses at the beginning of the growing season and just after the first cut. All manures were manually applied at plot level. Farmyard manure was evenly spread using pitchforks, while liquid manures were distributed using watering cans.

The mowing schedule of the experimental plots closely followed the mowing dates chosen by the owner of the meadows in which the experimental sites were located. Whenever the last grass regrowth of the grassland surrounding the experimental site was grazed, we performed an additional cut in the experimental plots at the time the grazing event in the surrounding grassland was concluded. In 2022, C1 meadows were mown three times per year, while C2 meadows were mown twice. Over the preceding years (2018-2021), the average cut frequency was 2.8 cuts yr^{-1} for C1 and 2.0 cuts yr^{-1} for C2.

6.3.3 Soil sampling and preparation

In spring 2022, prior to the start of the growing season, composite soil samples for determining soil texture and total organic C (TOC) content were gathered from each plot using a grassland soil core sampler (2 cm diameter). Twenty subsamples were collected per plot from the topsoil layer (0-10 cm).

ACP and ALP activity, and thus available P, are known to be affected by the nutrient input as well as by the time elapsed since the application of manures (Gong et al., 2022). As the fertilisation timetable differed depending on manure type and nutrient input level (Table S2), the timing of the sampling event to quantify APase activity and available P was chosen to maximise the time since the last fertilisation event and to avoid the disturbance caused by cutting. Hence, soil samples were collected in each plot in late summer 2022, just before the last cut at each experimental site. This corresponded to the third cut at C1 sites and to the second cut at the C2 sites: August 23rd (C2) and September 17th (C1) at Montal/Mantena; August 24th (C1) and September 18th (C2) at Radsberg/Monterota; September 12th for both meadow classes at Rüdeferia/Rudiferia. This ensured that a minimum of 54 days had passed since the last fertilisation event (Table S3). Within each plot, four samples were taken within a 0.5 x 0.5 m metal frame placed randomly along a plot diagonal. Each sample comprised four to six subsamples, depending on the stoniness and root density in the soil, ensuring the minimum amount of soil required for analyses. Subsamples were blended, transferred to sealed plastic bags, and kept in a cooling box at approximately 4°C for up to four hours. Subsequently, they were stored in a refrigerator at a temperature of 4°C ± 2 ºC in dark, anaerobic conditions for a maximum of three months until analyses completion.

6.3.4 Physicochemical soil analyses

Half of the fresh soil sample from each sampling event in summer was air-dried (7 days) and sieved to 2 mm to remove stones and plant parts debris and used to analyse the physicochemical parameters. Soil pH was determined in H_2O (1:2.5 soil:water ratio) using a digital pH meter (Robotics analyzer SP2000, Skalar, Breda, NL). TOC was assessed by an Elemental Analyzer (Primacs SNC 100, Skalar, Breda, NL), according to ISO10694:1995, the P and K soil content, expressed as phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O) content, by means of ICP-OES 720 (Agilent, Santa Clara, USA) according to ÖNORM L1087:2019 A.5. Soil moisture was measured as weight loss of 30 g of fresh soil after drying at 105°C for 24 hours and expressed as a percentage of dry soil on a weight basis. Soil texture was gravimetrically determined according to ÖNORM L1061-2:2019.

Soil solution P (hence available P) was extracted in sodium bicarbonate (Olsen et al., 1954) and quantified by using the ammonium molybdate tetrahydrate-malachite green reaction as modified by Ohno and Zibilske (1991). This method was selected because of its greater sensitivity in soil-water extracts with low P concentrations in a small sample volume. Four grams of dry soil were mixed with sodium bicarbonate solution 0.5 M, and the suspension was shaken for 30 minutes, and then centrifuged for 5 minutes at 8000 rpm. The liquid extract was then filtered with qualitative filter paper (MN 619 eh, Macherey-Nagel GmbH & Co.KG, Düren, Germany). Then two reagents were added to the filtrate: ammonium molybdate 4-hydrate BioChemica 14.2 nM (AppliChem GmbH, Darmstadt, Germany) prepared in sulphuric acid 3.15 M, and a mixture composed of polyvinyl alcohol (Mowiol® 6-98, Sigma-Aldrich, Darmstadt, Germany) and malachite green oxalate (TCI Europe N.V, Zwijndrecht, Belgium). The green colour obtained was measured after 30 minutes using a SHIMADZU UV-1800 spectrophotometer (Shimadzu Corporation, Kyoto-Shi, Japan) at 630 nm wavelength. The actual P availability concentration in soil extract was extrapolated from a simultaneously assessed calibration curve that enabled the absorbance to be related to that of an increasing concentration of standard phosphate solution submitted to the same analytical steps of the method (Ohno and Zibilske, 1991). The concentration of P extract or available P in soils was expressed in mg P kg^{-1} soil.

6.3.5 Soil phosphatase enzyme assay

ACP and ALP activity were measured following the method proposed by Tabatabai and Bremner (1969) and the following improvements (Eivazi and Tabatabai, 1977; Tabatabai, 1994). The other half of the fresh soil samples collected in late summer (see section 2.3) was sieved to 5 mm. One gram of soil was then mixed with 0.2 ml of toluene, 4 ml of modified universal buffer (MUB) (pH 6.5 for assay of ACP and pH 11 for assay of ALP), and 1 ml of 4-nitrophenyl phosphate (sodium salt hydrate) (Cayman chemical, MI, USA). The mixture was placed in a sealed centrifugation tube and incubated at 37°C for one hour. After the incubation, 1 ml of 0.5 M calcium chloride ($CaCl_2$) and 4 ml of 0.5 M sodium hydroxide (NaOH) were added and thoroughly mixed. The soil suspension was then filtered with qualitative filter paper (MN 619 eh, Macherey-Nagel GmbH & Co.KG, Düren, Germany) and the yellow colour of para-nitrophenol (pNP) released by the enzyme was measured by a SHIMADZU UV-1800 spectrophotometer (Shimadzu Corporation, Kyoto-Shi, Japan) using the colorimetric absorbance at 405 nm wavelength. The actual pNP concentrations in soil extracts were extrapolated from a simultaneously assessed calibration curve relating the absorbance to increasing pNP concentration solutions (Supelco®, Merck Life Science, Milano, Italy) (Tabatabai and Bremner 1969). The actual pNP concentrations in samples were then translated to the enzymatic activity rates by expressing them in mg of pNP kg^{-1} dry soil h^{-1}. Analytical methods only generate estimates of the potential APase activity due to the possibility that the results might not accurately portray the true activity of APase on site (Duly and Nannipieri, 1998; Wang et al., 2013). In this case, the pH of the buffer used for ALP activity strongly differed from that of the meadow soil samples (ranging between 5.7 and 7.9) and also the pH buffer used for ACP activity was not exactly the same as those in all soil samples.

6.3.6 Vegetation-related parameters

In 2022, a detailed assessment of the plant diversity was performed shortly before the end of the first growth cycle. In one third of the plots, the plant cover of each species across all vegetation layers was measured by means of point quadrat analysis (Levy and Madden, 1933) with 80 observation points per plot (20 points spaced 10 cm apart along each plot side), starting 1.5 m from the plot side and keeping a distance of 25 cm from the plot margin in order to avoid margin effects (Fig. S1). At each observation point, all contacts of plant parts with the tip of iron rods vertically led towards the soil with the aid of a wooden frame (Peratoner, 2003) were recorded. Species occurring in the plot, but not having been hit by the iron rods, were assigned a conventional value of 0.5% (Peratoner and Pötsch, 2019). The cover of single species in the remaining plots was visually estimated using the results of the measurements as a reference. The Shannon-

Index, combining species richness and their evenness (Shannon, 1948), was calculated based on this data related to the first growth cycle alone. For the last growth cycle, evenness was calculated based on the yield proportions of the functional groups (grasses, including also graminoids, legumes and forbs), which were visually estimated in each plot just before the last cut. Community-weighted mean of Ellenberg indicator values (Ellenberg and Leuscher, 2010) for nutrient availability (Ellenberg N) were computed based on the cover of each species.

In each plot, just before each cut, forage yield on dry matter basis (DM) was quantified by subsequently placing a 0.5 x 0.5 m metal frame along one of the plot diagonals, and by harvesting the biomass within the frame at a stubble height of 5 cm by means of electric scissors (Gardena ClassicCut, Husqvarna Italia, Erba, Italy). The samples were oven-dried at 60°C until weight constancy, and average values at plot level were computed.

6.3.7 Meteorological indices

Meteorological data were obtained by automated weather stations in Bruneck/Brunico at 828 m a.s.l., St. Martin in Thurn/S. Martino in Badia at 1150 m a.s.l., and Toblach/Dobbiaco at 1219 m a.s.l., located near Montal/Mantena, Rüdeferia/Rudiferia and Radsberg/Monterota, respectively (Meteo Browser Eurac Research, 2022). Daily maximum temperature and minimum temperature correspond to the average at each experimental site over the time between the date of farmyard manure application in autumn 2021 and the sampling date of the last growth cycle. An adjustment of each temperature was applied (-0.59 ºC for every 100 m a.s.l. increase in altitude). Precipitation was summed at each experimental site over the time comprising between the date of farmyard manure application in autumn 2021 and the sampling date of the last growth cycle.

6.3.8 Statistical analysis

Four different dependent variables (ACP activity, ALP activity, available P and forage yield) were studied in separate analyses. Concerning ACP and ALP activity, along with the factors of the experimental design (meadow class, manure type, N input), further soil, vegetation, and meteorological variables were tested for inclusion as explanatory variables into the statistical model: i) soil-related variables: TOC before the start of the growing season, pH, phosphorus pentoxide (P_2O5) and K_2O content, sand proportion, clay proportion, soil moisture content and available P, ii) fertilisation-related variables: C, P and K input during the growing season 2021-2022, iii) vegetation-related parameters:

Shannon-Index at the end of the first growth cycle, evenness based on the yield proportion of the functional groups (grasses, legumes and forbs) in the last growth cycle and yield proportion of grasses, forbs and legumes (both from the last growth cycle and the whole growing season), and iv) meteorological indices: mean maximum and minimum temperature, and precipitation sum. In the analysis concerning available P, ACP and ALP activity were included together with all the already mentioned set of independent variables possibly affecting available P in the soil. Finally, ACP and ALP activity and available P in soil were included in the cited set of independent variables potentially affecting forage yield. Additional data analyses according to the experimental design only and following the methods described above were performed at plot level for additional dependent variables needed for the discussion of the results: the species number and the weighted community mean of Ellenberg N at the time of the first cut as well as the total N content in soil at the end of the last growth cycle.

All the statistical analyses were performed by means of linear mixed models. As a first step, a baseline model was investigated, accounting for the split plot design (study site as fixed term and the interaction between study site and meadow class as random term), for the main terms of meadow class, manure type and N input (all treated as categorial factors) as well as their interactions. Repeated measurements within the plots were accounted for by considering the plot as a random term. This term was omitted for the analyses of the variables describing the yield, for which it was impossible to establish a univocal relationship between pseudoreplicates of soil parameters and yield measurements. Therefore, measurements of all variables were averaged at plot level. In a second step, the non-significant interactions between N input and the other factors were dropped, and then all further analyses were performed by treating N input as a covariate and by performing a stepwise forward model development to explore the improvement of model fit by adding further available explanatory variables (all metric). The Satterthwaite approximation for degrees of freedom in combination with type III sum of squares and treatment contrasts were used. The choice of including new explanatory variables was made based on the Akaike Information Criterion (AIC, the lower the better) (Akaike, 1998) and the p-value of the terms (a p-value of 0.1 was regarded as a threshold for keeping nonsignificant terms in case of AIC improvement). Interactions of designed factors that became non-significant during model development and exceeded a p-value of 0.1 were dropped at the end of model development. During model development Maximum Likelihood (ML) was used in order to compare models differing in fixed effects via AIC, whilst Restricted Maximum Likelihood (REML) was used to get the final results. Terms turning non-significant in this last step were retained in the model. Diagnostic plots were used to visually check the assumptions concerning the normal distribution of residuals and homoscedasticity (Kozak and Piepho, 2018). In case they were not fulfilled, the analysis was performed with natural log-transformed data after checking that the transformation allowed fulfilling the assumptions. Results were back transformed and are always mentioned or shown on the original scale. Collinearity due to the inclusion in the model of not designed factors was checked by means of Variance Inflation Factor (VIF) using 10 as a threshold. In the event of collinearity among the designated explanatory variables, priority was assigned to the latter ones, followed by the covariate that resulted in a better model fit. This prevented C input, P input and K input from being included in the models. Metric variables were centred around their mean for the models having yield as a dependent variable, in order to achieve convergence. Post-hoc comparisons of estimated marginal means were performed by the Sidak test. When p-values were less than 0.05 they were considered statistically significant, and the respective explanatory variables were interpreted in the results and discussion sections. Back-transformed predicted values, estimated marginals means and 95%-confidence intervals, given in square brackets, are reported in the text.

All analyses were conducted in R version 4.3.2 (R Core Team, 2023) and RStudio (version 2022.07.2+576). The function lmer from the package lmerTest was used to conduct the linear mixed model analyses. The package effects was used to visualize the results. Post-hoc comparisons and calculation of estimated marginal means were performed by using the emmeans package.

6.4 Results

6.4.1 Overview of factors affecting the dependent variables

The statistical analyses revealed that different groups of independent variables exerted a significant influence on the investigated dependent variables (Table 3).

Of the soil-related variables, soil moisture and pH consistently played a relevant role in determining ACP activity, ALP activity (section 3.2) and available P (section 3.3). Whilst both ACP activity and available P were affected by the interaction between N input and manure type, no effect of the fertilisation was detected on ALP activity. Interestingly, available P was the only dependent variable affected by K soil content and ALP activity. The meadow class affected ACP activity alone, whilst ALP activity was the only soil-related dependent variable being affected by TOC and a diversity-related parameter, namely the Shannon Index (section 3.2). None of the investigated meteorological variables were retained for inclusion into the models during their development. Concerning the yield-related parameters (section 3.4), N input emerged as the primary influential factor, followed by meadow class, which also interacted with manure type in the case of the yield of the last growth cycle. Additionally, TOC also affected the yield of the last growth cycle. Neither the ACP or ALP activity nor the available P had any detectable influence on the yield-related dependent variables.

Regarding the yield-related parameters (section 3.4), N input emerged as the foremost influential factor, with meadow class following closely behind. Meadow class also displayed an interaction with manure type in the model constructed for the yield of the last growth cycle. The latter was also affected by TOC. Neither the ACP or ALP activity nor the available P were found to affect the yield.

Table 2. Factors affecting ACP activity, ALP activity, available P, and forage yield (last growth cycle = forage yield of the last growth cycle; whole year = annual cumulative forage yield overall growth cycles).

Source		ACP #		ALP #		Available P #		Forage yield (last growth cycle) #		Forage yield (whole year) #	
	df	F	p	F	p	F	p	F	p	F	p
Site	2	2.5	0.249	2.1	0.324	10.6	**0.047**	8.4	**0.001**	4.0	**0.025**
Meadow class (MC)	1	53.4	**<0.001**	2.5	0.248	0.4	0.581	10.7	**0.002**	61.0	**<0.001**
Manure type (MT)	2	2.5	0.094	0.5	0.602	3.2	**0.048**	3.0	0.060	3.2	**0.048**
N input (N)	1	3.2	0.082	0.2	0.684	5.9	**0.018**	12.2	**0.001**	64.2	**<0.001**
MC x MT	2	3.0	0.060	-	-	-	-	3.4	**0.043**	2.5	0.094
MT x N	2	6.0	**0.006**	-	-	9.2	**<0.001**	-	-	-	-
MC x MT x N	3	2.2	0.099	-	-	-	-	-	-	-	-
pH	1	10.2	**0.002**	7.4	**0.008**	6.3	**0.014**	-	-	-	-
Soil moisture	1	40.6	**<0.001**	71.0	**<0.001**	11.7	**0.001**	-	-	-	-
TOC	1	-	-	4.1	**0.048**	3.7	0.060	12.1	**0.001**	-	-
Shannon-Index	1	-	-	7.8	**0.008**	-	-	-	-	-	-
K_2O soil content	1	-	-	-	-	23.3	**<0.001**	-	-	-	-
ALP	1	n.t.		n.t.		4.1	**0.045**	-	-	-	-
ACP	1	n.t.		n.t.		-	-	3.2	0.081	-	-

df = degrees of freedom; F = Fisher's F, p = probability; p-values < 0.05 are highlighted in bold. # Analysis with natural logarithm-transformed data. – = not taken up in the model according to the stepwise forward model selection. n.t. = not tested for inclusion.

6.4.2 Effects of management and physiochemical parameters on ACP and ALP activity

Several soil physiochemical parameters were found to affect ACP and ALP activity (Table 3). Concerning the designed factors, ACP activity was affected by all of them, whereas none of them had an effect on ALP activity. The meadow class strongly affected the activity of ACP (F=53.4, p<0.001), which increased by 151 [115-198] mg pNP kg^{-1} h^{-1} from C1 (91 [70-119] mg pNP kg^{-1} h^{-1}) to C2 (242 [185-317] mg pNP kg^{-1} h^{-1}).

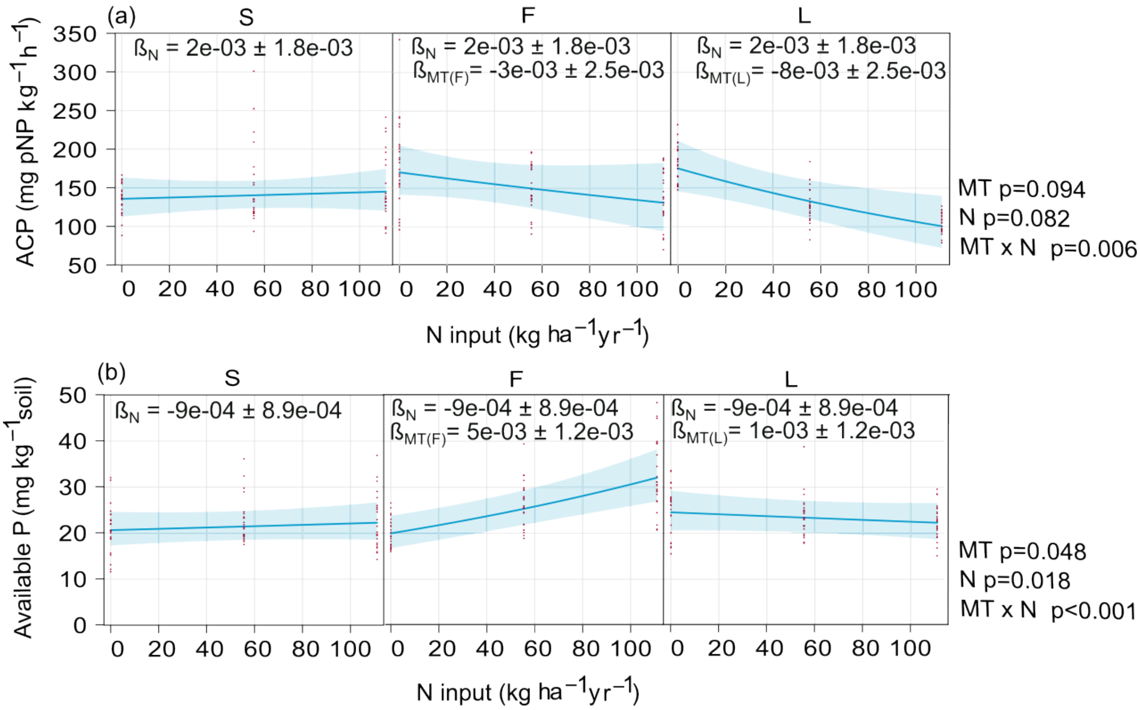

Fig. 1. Effect of N input and manure type on (a) ACP activity and (b) available P at the end of the last growth cycle. S: slurry, F: farmyard manure, L: combined use of farmyard manure and manure effluent. Predicted values and 95%-confidence interval are shown against partial residuals. Analysis with natural logarithm-transformed values; back-transformed values are shown (n=72). MT= Manure type, N = N input; estimated slope parameters (β) ± SE of the reference level (βN) and the difference for levels F (βMT(F)) and L (βMT(L)) are reported on the transformed scale.

The influence of N input on ACP activity varied depending on the type of manure used (F=6.0, p=0.006). Whilst no effect of increasing N input was found for slurry, a slightly negative effect was found for farmyard manure and the combination of farmyard manure and manure effluent along the N input gradient from 136 [111-165] to 145 [119-176] mg pNP kg^{-1} h^{-1} when using slurry, from 171 [140-208] to 154 [127-188] mg pNP kg⁻

^{1} h^{-1} when using farmyard manure and from 176 [144-214] to 118 [97-144] mg pNP kg^{-1} h^{-1} when using a combination of farmyard manure and manure effluent (Fig. 1a).

When investigating additional physiochemical parameters, ACP activity was observed to decrease with rising pH levels (from 229 [171-307] at pH 5.5 to 123 [103-146] mg pNP kg^{-1} h^{-1} at pH 8.0, F=10.2, p=0.002) (Fig. S2a), with a more pronounced decline linked to increasing soil moisture content (from 282.2 [226-353] at approximately 10% soil moisture content to 96 [80-114] mg pNP kg^{-1} h^{-1} at 70% soil moisture content, F=40.6, p<0.001) (Fig. S2b). Both relationships exhibited a convex pattern, displaying a steeper decrease at lower values of pH and soil moisture values.

ALP activity was also affected by the observed pH gradient (F=7.4, p=0.008). In contrast to ACP activity, ALP activity exhibited an opposite trend, increasing from 166 [121-227] to 277 [213-360] mg pNP kg^{-1} h^{-1} with a slight convex course (Fig. S3a). Like ACP, ALP activity was strongly negatively affected by soil moisture (F=71, p<0.001), displaying a considerable decrease of 448 [338-593] mg pNP kg^{-1} h^{-1} between 10% and 70% soil moisture with a marked convex course (Fig. S3b). Unlike ACP activity, two additional physiochemical parameters positively influenced ALP activity, which increased from 193 [147-254] to 293 [221-389] mg pNP kg^{-1} h^{-1} as TOC increased from 6 to 20% (F=4.1, p=0.048) and from 196 [152-253] to 267 [202-353] mg pNP kg^{-1} h^{-1} as the botanical diversity at the end of the first growth cycle, expressed as the Shannon index, increased from 2.5 to 3.3 (F=7.8, p=0.008) (Fig. 2a and Fig. 2b respectively).

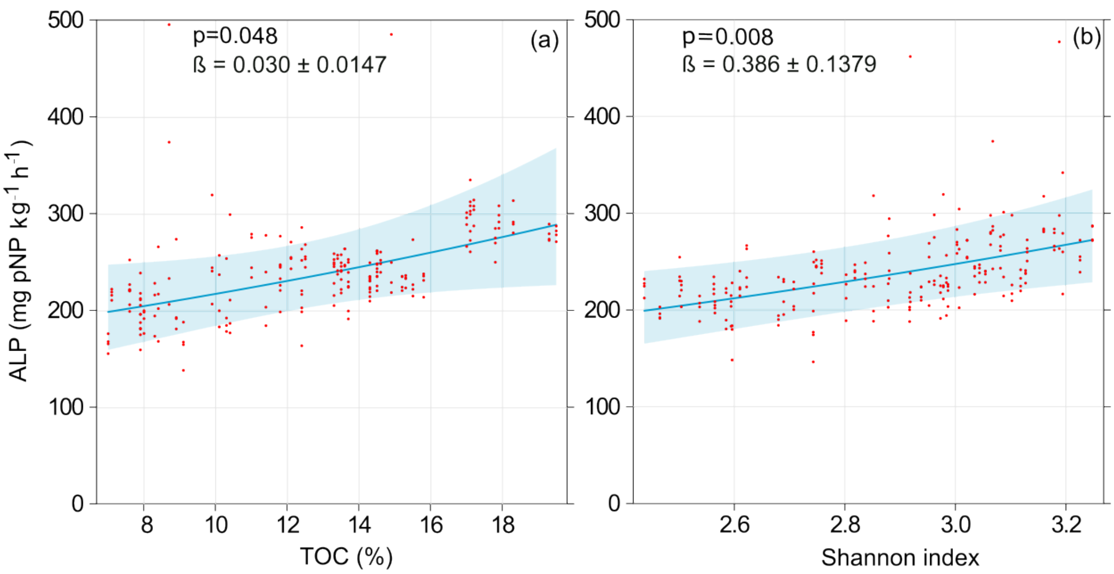

Fig. 2. Effect of (a) total organic carbon (TOC), and (b) Shannon index on the ALP activity at the end of the last growth cycle. Predicted values and 95%-confidence interval are shown against partial residuals. Analysis carried out with natural logarithm-transformed values; back-transformed values are shown (n=216). Estimated slope parameters (β) ± SE are reported on the transformed scale.

6.4.3 Effects of management and physiochemical parameters on available P

When considering the designed factors, meadow class had no effect on available P ($F=0.4$, $p=0.581$), which was instead affected by the interaction between N input and manure type ($F=9.2$, $p<0.001$) (Fig. 1b). N input from slurry or the combination of farmyard and manure effluent did not significantly impact available P, whereas an increase was observed with increasing N input from farmyard manure (from 20.0 [16.0-25.0] to 32.1 [25.6-40.2] mg P kg^{-1} soil along the N input gradient).

Available P exhibited a positive curvilinear relationship with soil physicochemical parameters such as K_2O ($F=23.3$, $p<0.001$), soil moisture content ($F=11.7$, $p=0.001$) and pH ($F=6.3$, $p=0.014$). Increasing K_2O content in soil (ranging between 9 and 118 mg 100 g^{-1} soil) led instead to a substantial increase in available P from 19.4 [15.2-24.8] to 45.7 [33.4-62.5] mg P kg^{-1} soil (Fig. 3a). Moreover, with a pH increase from 5.5 to 8.0, available P increased from 14.6 [9.8-21.9] to 28.7 [22.4-36.8] mg P kg^{-1} soil (Fig. S4a). Concerning the APase, only ALP activity positively affected available P ($F=4.1$, $p=0.045$) (Fig. 3b). However, despite ALP activity increasing from 100 to 700 mg pNP kg^{-1} h^{-1}, the increase in available P was only 7.6 [5.3-10.8] mg P kg^{-1} soil (from 21.7 [17.0-27.6] to 29.3 [22.3-38.4] mg P kg^{-1} soil). Similarly, a moderately steep increase was observed depending on soil moisture from 13.5 [9.6-19.2] to 33.9 [25.9-44.3] mg P kg^{-1} soil along a moisture gradient ranging from 10% to 70% (Fig. S4b).

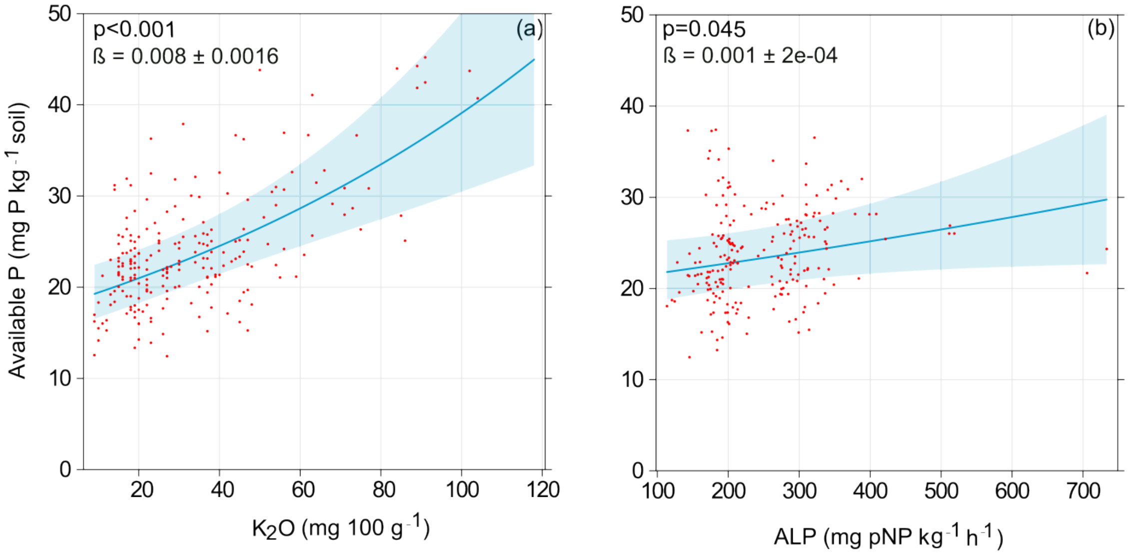

Fig. 3. Effect of (a) K_2O content in soil and (b) ALP activity on the available P at the end of the last growth cycle. Predicted values and 95%-confidence interval are shown against partial residuals. Analysis with natural logarithm-transformed values; back-transformed values are shown ($n=216$). Estimated slope parameters (β) ± SE are reported on the transformed scale.

6.4.4 Effects of management and physiochemical parameters on forage yield

The forage yield of the last growth cycle exhibited a positive relationship with N input (F=12.1, p=0.001) and a negative relationship with TOC (F=12.1, p=0.001). As N input increased, forage yield increased from 1.24 [1.11-1.38] to 1.66 [1.49-1.85] Mg ha^{-1} (Fig. 4a). Conversely, yield strongly decreased from 2.49 [1.80-3.44] to 0.83 [0.60-1.14] Mg ha^{-1} as the TOC increased from 6.75% to 19% (Fig. S5). We did not find any effect of other physiochemical parameters on forage yield.

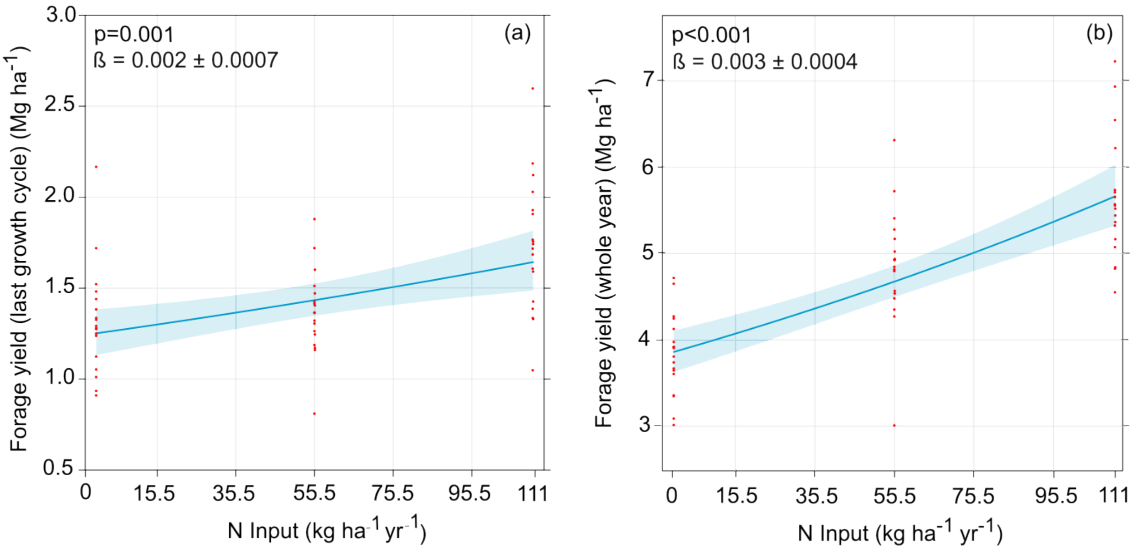

Fig. 4. Effect of N input (a) on the forage yield of the last regrowth at the end of the last growth cycle and (b) on the annual cumulative forage yield over all growth cycles. Predicted values and 95%-confidence interval are shown against partial residuals. Analysis with natural logarithm-transformed values; back-transformed values are shown (n=54). Estimated slope parameters (β) ± SE are reported on the transformed scale.

Furthermore, the forage yield of the last growth cycle was affected by the interaction of manure type and meadow class (F=3.4, p=0.043) (Table 4). Whilst no effect of the manure type was found within C1, fertilisation with farmyard manure resulted in higher yields than those resulting from fertilisation with slurry. Only when the combination of farmyard manure and manure effluent was used for fertilisation, higher yield was observed in C1 than in C2.

Table 4. Effect of manure type (S: slurry, F: farmyard manure, L: combined use of farmyard manure and manure effluent) and meadow class (C1: moderately species-poor meadows, C2: moderately species-rich meadows) on the DM forage yield of the last growth cycle (Mg ha^{-1}). Multiple comparisons by Sidak. Analysis with natural logarithm-transformed data. Back-transformed estimated marginal means and 95%-confidence intervals (in square brackets) are shown. Means between manure type within the same meadow class sharing no upper-case letters and means between meadow classes within

the same manure type sharing no lower caser letters significantly differ from each other (n=9).

Meadow class	Manure type		
	S	F	L
C1	1.61 [1.33-1.95] ^{Aa}	1.66 [1.38-2.00] ^{Aa}	2.04 [1.68-2.46] ^{Aa}
C2	1.03 [0.84-1.25] ^{Ba}	1.37 [1.13-1.65] ^{Aa}	1.14 [0.95-1.36] ^{ABb}

The cumulative annual forage yield was influenced by the meadow class (F=61.0, p<0.001) and was 1.44 [1.35-1.52] Mg ha^{-1} higher for C1 (5.45 [5.15-5.76] Mg ha^{-1}) than for C2 (4.01 [3.80-4.24] Mg ha^{-1}). Additionally, it was positively affected by N input (p<0.001) and it increased from 3.80 [3.56-4.06] to 5.75 [5.39-6.14] Mg ha^{-1} along the investigated N input gradient (Fig. 4b). The influence of manure type was less pronounced: the combined use of farmyard manure and manure effluent led to the highest mean annual forage yield (4.96 [4.63-5.31] Mg ha^{-1}), the lowest one was observed with slurry (4.39 [4.10-4.70] Mg ha^{-1}), whilst that of farmyard manure achieved an intermediate value (4.69 [4.38-5.02] Mg ha^{-1}) (F=3.2, p=0.048).

6.5 Discussion

6.5.1 Effects of management and physiochemical parameters on ACP and ALP activity

Several findings of this study align with evidence from existing literature concerning ACP and ALP activity. Firstly, ACP activity exhibited a negative correlation with soil pH, while ALP activity showed a positive correlation. This observation is consistent with various meta-analyses conducted in different agroecosystems (Janes-Bassett et al., 2022; Sun et al., 2020; Pokharel et al., 2020). Soil pH influences P availability, impacting plant access to essential forms of P. The study emphasizes the critical role of soil pH within the common range of meadows, where enzyme activity is vital for making P accessible to plants and microorganisms.

Secondly, plant diversity positively influenced both ACP and ALP activity. Increased soil microbial diversity, which is known to be linked to higher plant diversity (Liu et al., 2020), resulted in elevated enzyme activity. Specifically, ACP activity was higher in meadow class C2 than C1, attributed to the higher species diversity in C2. Indeed, despite five years of differentiated N input, the initial status in terms of meadow class hasn't changed in most of the plots (in 51 out of 54 plots, corresponding to 94.4%) and there is still a significant effect of the meadow class (F=26.2, p=0.036), leading to a higher species number in C2 (45.4 [37.9-52.9]) compared to C1 (32.7 [25.2-40.2]), (Table

S4). This suggests that species diversity results in a variety of coexisting N and P acquisition strategies (Lambers et al., 2008), enhancing ACP activity. Similarly, ALP activity is positively correlated with the Shannon index based on the botanical composition of the vegetation at the time of the first cut, indicating the importance of vegetation diversity in influencing the activity of both APase. The importance of species diversity for ACP and ALP activity can also be attributed to a higher likelihood of having community-level combinations of conservative and acquisitive traits that regulate tissue P demand and the need for acquiring P through APase activity function (White and Hammond, 2008). Indeed, a positive correlation between the diversity of the soil microbial community and ACP activity has been found in arable crops elsewhere (Diallo-Diagne et al., 2016; Sun et al., 2018). Additionally, Liu et al. (2021) found out in a newly established ryegrass (Lolium perenne L.) sward that the treatment showing the highest ALP activity was that also showing the highest value of diversity-related parameters such as Shannon index and Pielou's evenness for the fungal soil community.

As a third finding, we confirm the positive association between ALP activity and soil organic C that has been well demonstrated in previous studies (Shi et al., 2020; Pokharel et al., 2020).

Finally, the statistical analysis detected an inverse relationship between soil moisture and the activity of both APase. A negative correlation between the activity of APase and soil moisture has been reported in pastures with P input only (Speir and Cowling, 1991) or input of P and N (Touhami et al., 2022a; Touhami et al. 2022b) in addition to the nutrient input provided by grazing animals.

Nevertheless, our study also yielded an unexpected outcome, as no effect of the N input was found on ALP activity, whilst a clear interaction between manure type and N input was detected for ACP activity. ACP activity decreased with increasing N input only in the treatment combining farmyard manure and manure effluent, whilst it remained unaffected by the N input when using the other manures. Our results seem to contradict the outcome of several meta-analyses based on natural soils, including grasslands, demonstrating that N mineral fertilisation (Jian et al., 2016; Margalef et al., 2021; Marklein and Houlton, 2012) and organic fertilisation (Miao et al., 2019) increase ACP and ALP activity. In any case, the activity of ACP increases if P plant demand increases (Nannipieri et al., 1978), provided that the P availability in the soil is insufficient for both plant and microorganism growth. Considering that the available P is directly related to the type of manure and N input gradient (see section 4.2), the obtained results concerning ACP activity are surprising and at the same time novel suggesting that an increase in N input does not consistently result in increased ACP activity when utilizing organic manures. Moreover, ACP activity can even decrease when using increasing addition of manure effluent in combination with farmyard manure. Although our design does not allow us to provide an explanation for it, the examination of the composition of the utilized manures (Table S1) and of the respective nutrient inputs (Table S2) highlights that the combined use of farmyard manure and manure effluent differs by the other treatments mainly by the very low N:K and very high K:P ratio. Moreover, as a difference to the fertilisation with farmyard manure only, its application was closer in time to the sampling date at the highest fertilisation rate. This suggests a complex mechanism governing ACP's activity response, which is not readily explicable for our study. Further data would be required to interpret the acquired results, including additional sampling data during growth and available soil macronutrient ratios.

Consequently, our first hypothesis was proved false, as short-term organic N fertilisation did not positively affect the activity of either enzyme. However, our third hypothesis holds true, since there was an effect of pH and soil moisture on ACP and ALP activity. The response of both ACP and ALP activity to pH was as expected, whereas their response to soil moisture was found to be negative. Furthermore, organic matter had a positive and significant influence on ALP activity and plant diversity positively affected the activity of both APase.

6.5.2 Effects of management and physiochemical parameters on P availability

The results indicate an interaction between manure type and N input, as well as a positive relationship between soil moisture, K_2O, pH and ALP activity, influencing P availability, and these align with the existing literature.

Depending on their P content and on the applied amount, manures contribute organic P to P cycling, increasing P content (Edmeades, 2003) and P availability (Kidd et al., 2017) in soils. Indeed, in our study, available P was shown to increase by increasing nutrient input only when fertilisation was implemented with farmyard manure, the manure type having the highest P and C content (Table S1) and providing the highest input of both elements (Table 2). A long-term study investigating the effect of organic and inorganic fertilisation in meadows has shown a positive correlation between ALP activity and organic extractable P (i.e., check the method explained by Bowman and Cole, 1978) in plots receiving mineral P and farmyard manure (Colvan et al., 2001). We found a positive correlation between ALP activity and available P, which is likely to be related to increased microbial biomass, as ALP activity is released by microorganisms. Indeed, long-term application of farmyard manure has been found to result in both higher microbial biomass and ALP activity in comparison to mineral fertilisation (Langer and Klimanek, 2006). On the other hand, having observed a neutral or negative response of ACP activity to the addition of slurry, farmyard manure or the combination of farmyard manure and manure effluent respectively, it is logical that no significant correlation in our statistical analysis has been found between ACP activity and available P. It is well known that physicochemical parameters that strongly influence APase activity also impact P availability. In some cases, the presence of potential P-mobilizing microbes in grasslands with high P availability may be influenced by environmental factors like soil pH and moisture (Graça et al., 2021). Therefore, low soil moisture content leads to lower P availability (Meisser et al., 2019). In our study, both pH and soil moisture positively affect available P, and these correlations also explain the link between P and uptake of other nutrients, such as N, since N-cycling microbial communities are influenced by soil P content under P application (O'Neill et al., 2022). Moreover, under conditions of high N content in the soil, the enhanced ability of organic C degradation leads to further degradation of complex organic matter, releasing more organic phosphoric acid and ultimately improving the utilization rate of organic P by soil microorganisms (Chen et al., 2021).

In our study, we observed a positive relationship between soil K content and P availability. When abiotic conditions improve and plants and microbes increase their productivity, various mechanisms for mobilizing nutrients become activated. These mechanisms include enzyme activity, exudation, release of acidic compounds, and increased soil volume occupancy (Sardans et al., 2011; Sardans et al., 2023). As a result, both K and P are mobilized into soluble and available forms (Sardans et al., 2023). The enhancement of physiological activities and interactions among plants and microbes leads to their greater mobilization and availability in the soil. For instance, root proton release facilitates the mobilization of P and K in soil (Jungk and Claasen, 1986). Over evolutionary time, numerous synergistic processes likely developed between these two essential nutrients for plants and microbes. Although the molecular mechanisms underlying K and P interaction require further investigation, existing literature suggests for example the existence of cross-talk between signalling pathways involved in plant responses to K and P (Wang et al., 2002).

These results are partially consistent with our second hypothesis, as it appears that microbial communities, which release ALP, play a positive role concerning P availability, similar to other parameters such as manure type, N input, K_2O, pH and soil moisture.

6.5.3 Effects of management and physiochemical parameters on forage yield

The primary aim in forage production is to attain a satisfactory yield and quality of forage, with P being a key macroelement that could potentially limit the grass growth. However, to our best knowledge, the only study simultaneously examining the relationship between forage yield, APase activity and available P is based on pastures (Speir and Cowling, 1991), with no study addressing this topic in permanent meadows. We investigated the effect of organic fertilisation as well as of soil physiochemical parameters on the forage yield of the last growth cycle and in a second step, we focused on the effect of these factors on the forage yield of the whole year (henceforth, annual yield). Concerning the forage yield of the last regrowth, we found a positive effect of N input, a negative effect of TOC, as well as an interaction of manure type with meadow class. Regarding the annual yield, the results showed a positive relationship with N input, an effect of the meadow class and one of the manure type.

The consistent increase of forage yield with increasing N input along the whole gradient is a typical agronomic response, suggesting that even at the highest fertilisation rate the yield potential was not fully exploited yet. Moreover, the results did not indicate any effect of P availability on the forage yield of both the last growth cycle and the annual yield, suggesting that P was not limiting. As for the annual yield, the higher annual forage yield observed for C1 compared with C2 is likely to be due to a combination of factors entangled within the factor meadow class. The results suggest that after five years of differentiated fertilisation treatment there is still a residual effect of the meadow class on nutrient availability beside that of the fertilisation itself. This can be interpreted as a legacy effect of the management of the experimental fields prior to the start of the trial. So, C1 exhibited a constant soil N content at the end of the last growth cycle, whilst that of C2 was observed to rise with increasing N input (Table S5 and Fig. S6). However, no significant differences were found between C2 and C1 at the two extremes of the N input gradient (6.8 [4.7-9.0] vs. 8.4 [6.3-10.6] in case of 0 kg N ha^{-1} yr^{1-} and 7.3 [5.0-9.5] vs. 8.4 [6.1-10.6] at an input of 111 kg N ha^{-1} yr^{-1}), suggesting that the this is not the main cause for the observed yield differences. The second factor involved is the higher proportion of competitive species in C1 than in C2 as shown by the higher values of the community-weighted Ellenberg N, which increased with increasing N input in both C1 and C2, but exhibited greater differences at the lower end of the N-input gradient (5.1 [4.9-5.4] for C1 and 3.5 [3.2-3.8] for C2) than at the upper end of it (5.7 [5.4-6.0] for C1 and 4.5 [4.2-4.8] for C2) (Table S6, Fig. S7). A further role of the mowing frequency cannot be excluded, although there is evidence that, if not supported by increased nutrient availability, it does not necessarily positively affect forage yield (Pavlů et al. 2011).

Furthermore, the forage yield of the last growth cycle was negatively influenced by TOC. Organic matter affects soil structure, water-holding capacity, and its accumulation can fix minerals whereas its decomposition will increase mineral availability (Hoogerkamp, 1973). The observed inverse correlation may be explained by the diversity and composition of the microbial community altering organic matter components and stocks, and ultimately impacting forage production (Li et al., 2021). Under specific weather conditions, this excess organic matter could temporarily sequester nutrients during microbial decomposition, diminishing their availability to plants. The higher yield in C1 compared to C2, specifically where the combination of farmyard manure and manure effluent was used, is probably due to the greater presence of competitive species in C1. These species tend to respond more strongly to N availability and in manure effluent N is almost entirely in ammonium form which is readily available (Table S1). The relationship between crop yield and APase activity has primarily been studied in arable crops, showing a positive correlation between ACP activity and yield (Antolín et al., 2005; Gao et al., 2016; Moharana and Biswas, 2022; Wei et al., 2021). However, we found no effect of ACP activity on the forage yield of the last growth cycle and on the annual yield, which requires further investigation. The results obtained are inconsistent with our third hypothesis, as neither ACP nor ALP activity have an impact on the forage yield of the investigated permanent meadows. This suggests that organic fertilisation under the given conditions is the main driver of forage yield.

6.5.4 Limitations of the study

Whilst most of the investigated independent and dependent variables are a summary of the whole growing season or at least of single growth cycles or are expected not to greatly change during the growing season, APase values refer to the end of the growing season only. On one hand, this was necessary to minimise the effect of the time elapsed from the last fertilisation event, which was treatment-dependent. On the other hand, this is not sufficient to fully characterise the APase activity in terms of activity peak or changes over time. For this reason, it cannot be excluded that APase played a more significant role in specific parts of the growing season. Future studies may benefit from repeated sampling throughout the entire growing season to elucidate the role of APase at other specific stages of the growing season, thereby providing a more comprehensive understanding of their dynamics and contributions to plant development.

6.6 Conclusions

This study demonstrates that the activity of both APase, which are directly related to the P cycle, are influenced by soil physicochemical factors, such as pH and soil moisture, but also by factors related to biodiversity; ACP, primarily released by plants, exhibits higher activity in moderately species-rich meadows, whilst ALP activity is positively influenced by biological factors like TOC and the Shannon diversity index of the aboveground vegetation.

The combined use of farmyard manure and manure effluent, along with an increasing rate of nutrient input, causes a negative response in ACP activity, whilst there is no response when using farmyard manure alone or slurry.

Regarding available P in soil, multiple factors play a significant role, including soil physicochemical factors and concentrations of other macronutrients like N and K. The type of organic manure also affects the P availability emphasising the importance of being aware of the ratios between the macronutrients in different manures. Concerning the APase, their impact is of limited relevance at the sampling time.

In the investigation of the annual yield, the study did not detect significant effects of APase activity and available P, indicating that nutrient input from organic fertilisation plays a predominant role here, overshadowing the positive impact of APase activity and P availability. However, as in the long term a negative relationship between management intensity and biodiversity is expected, our findings suggest that APase activity contributes more strongly to the P cycle under extensive management.

6.7 Authorship, data availability, competing interests and acknowledgments

Author contributions

Conceptualization PCR, GP, XD; Data curation PCR, GP; Formal analysis PCR, GP, MF-M; Funding acquisition GP; Investigation PCR, UF, AM, GP, AF; Methodology PCR, GP, XD; Lab analyses: PCR. Resources GP, EV, PR, AM; Supervision GP, XD; Visualization PCR, GP; Roles/Writing - original draft PCR, GP; Review- approved final manuscript all authors.

Supporting information

Supplementary materials associated with this article can be found in the online version.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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6.8 References

Akaike, H., 1998. Information theory and an extension of the maximum likelihood principle. In: Parzen, E., Tanabe, K., Kitagawa, G. (eds). Selected Papers of Hirotugu Akaike. Springer. New York, pp. 199–213.

Alef, K., Nannipieri, P. (eds.), 1995. 7 - Enzyme activities, in: Methods in applied soil microbiology and biochemistry. Academic Press, London, pp. 311–373. https://doi.org/10.1016/B978-012513840-6/50022-7.

Antolín, M.C., Pascual, I., García, C., Polo, A., Sánchez-Díaz, M., 2005. Growth, yield and solute content of barley in soils treated with sewage sludge under semiarid Mediterranean conditions. Field Crops Res. 94(2–3), 224–37. https://doi.org/10.1016/j.fcr.2005.01.009.

Bowman, R.A., Cole, C.V., 1978. An exploratory method for fractionation of organic phosphorus from grassland soils. Soil Sci. 125, 95–101.

Burns, R.G., 1978. Soil enzymes. Academic Press, London.

Carricondo-Martínez, I., Falcone, D., Berti, F., Orsini, F., Salas-Sanjuan, M.d.C., 2022. Use of agro-waste as a source of crop nutrients in intensive horticulture system. Agron. 12(2), 1–12. https://doi.org/10.3390/agronomy12020447.

Chen, Q., Yuan, Y., Hu, Y., Wang, J., Si, G., Xu, R., Zhou, J., Xi, C., Hu, A., Zhang, G., 2021. Excessive nitrogen addition accelerates N assimilation and P utilization by enhancing organic carbon decomposition in a Tibetan alpine steppe. Sci. Total Environ. 764, 142848. https://doi.org/10.1016/j.scitotenv.2020.142848.

Colvan, S.R., Syersm, J.K., O'Donnell, A.G., 2001. Effect of long-term fertiliser use on acid and alkaline phosphomonoesterase and phosphodiesterase activities in managed grassland. Biol. Fert. Soils 34(4), 258–63. https://doi.org/10.1007/s003740100411.

Diallo-Diagne, N.H., Assigbetse, K., Sall, S., Masse, D., Bonzi, M., Ndoye, I., Chotte, J.L., 2016. Response of soil microbial properties to long-term application of organic and inorganic amendments in a tropical soil (Saria, Burkina Faso). Open J. Soil Sci. 6, 21–33. https://doi.org/10.4236/ojss.2016.62003.

Dignac, M.F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G.T., Garnier, P., Guenet, B., Hedde, M., Klumpp, K., Lashermes, G., Maron, P.-A., Nunan, N., Roumet, C., Basile-Doelsch, I., 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agron. Sustain. Dev. 37, 14. https://doi.org/10.1007/s13593-017-0421-2.

Duly, O., Nannipieri, P., 1998. Intracellular and extracellular enzyme activity in soil with reference to elemental cycling. Zeitschrift für Pflanzenernährung und Bodenkunde, 161(3), 243–8. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/jpln.1998.3581610310.

Edmeades, D.C., 2003. The long-term effects of manures and fertilisers on soil productivity and quality: a review. Nutr. Cycl. Agroecosyst., 66, 165–180 https://doi.org/10.1023/A:1023999816690.

Eivazi, F., Tabatabai, M.A., 1977. Phosphatases in soils. Soil Biol. Biochem. 9(3), 167–72. https://doi.org/10.1016/0038-0717(77)90070-0.

Ellenberg, H., Leuscher, C., 2010. Vegetation Mitteleuropas mit den Alpen, 6. Auflage, Ulmer UTB, Stuttgart.

Euromontana, 2021. Overview of sustainable practices for the management of mountain grasslands in Europe. https://www.euromontana.org/wp-content/uploads/2021/10/2021-09-27-OREKA-MENDIAN_Report_FinalEN-1.pdf.

European Commission, 2007. Interpretation manual of European Union habitats. EUR28. https://doi.org/10.1016/S0021-9290(99)00083-4.

Farms and farmland in the European Union - statistics. Eurostat Statistics explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farms_and_farmland_in_the_European_Union_-_statistics#Farms_in_2020 (accessed 21 November 2022).

Fraser, L.H., Pither, J., Jentsch, A., Sternberg, M., Zobel, M., Askarizadeh, D., Bartha, S., Beierkuhnlein, C., Bennett, J.A., Bittel, A., Boldgiv, B., Boldrini, I.I., Bork, E., Brown,

L. , Cabido, M. , Cahill, J. , Carlyle, C.N., Campetella, G., Chelli, S., Cohen, O., Csergo, A.-M., Díaz, S., Enrico, L., Ensing, D., Fidelis, A., Fridley, J.D., Foster, B., Garris, H., Goheen, J.R., Henry, H.A. L., Hohn, M., Jouri, M.H., Klironomos, J., Koorem, K., Lawrence-Lodge, R., Long, R., Manning, P., Mitchell, R., Moora, M., Müller, S.C., Nabinger, C. , Naseri, K., Overbeck, G.E., Palmer, T.M., Parsons, S., Pesek, M., Pillar, V.D., Pringle, R.M., Roccaforte, K., Schmidt, A., Shang, Z., Stahlmann, R., Stotz, G., Sugiyama, S., Szentes, S., Thompson, D., Tungalag, R., Undrakhbold, S., van Rooyen, M., Wellstein, C., Wilson, J.B., Zupo, T., 2015. Worldwide evidence of a unimodal relationship between productivity and plant species richness. Science 349, 302-305. https://doi.org/10.1126/science.aab3916.

Gao, X., Shi, D., Wang, A.L.S., Yuan, S., Zhou, P., An, Y., 2016. Increase phosphorus availability from the use of alfalfa (Medicago sativa L) green manure in rice (Oryza sativa L.) Agroecosystem. Sci. Rep. 6, 1–13. https://doi.org/10.1038/srep36981.

Garcia, C., Roldan, A., Hernandez, T., 1997. Changes in microbial activity after abandonment of cultivation in a semiarid Mediterranean environment. J. Environ. Qual. 26(1), 285–92. https://doi.org/10.2134/jeq1997.00472425002600010040x.

Gong, J., Zhang, Z., Zhu, C., Shi, J., Zhang, W., Song, L., Li, Y., Zhang, S., Dong, J., Li, X., 2022. The response of litter decomposition to phosphorus addition in typical temperate grassland in inner Mongolia. J. Arid Environ. 197, 104677. https://doi.org/10.1016/j.jaridenv.2021.104677.

Graça, J., Daly, K., Bondi, G., Ikoyi, I., Crispie, F., Cabrera-Rubio, R., Cotter, P.D., Schmalenberger, A., 2021. Drainage class and soil phosphorus availability shape microbial communities in Irish grasslands. Eur. J. Soil Biol. 104, 103297. https://doi.org/10.1016/j.ejsobi.2021.103297.

Hernández-Becerra, N., Tapia-Torres, Y., Beltrán-Paz, O., Blaz, J., Souza, V., García-Oliva, F., 2016. Agricultural land-use change in a Mexican oligotrophic desert depletes ecosystem stability. PeerJ 4, e2365. https://doi.org/10.7717/peerj.2365.

Hoogerkamp, M., 1973. Accumulation of organic matter under grassland and its effects on grassland an on arable crops. Agricultural Research Reports 806, Centre for Agricultural Publishing and Documentation, Wageningen. https://edepot.wur.nl/361903.

Humbert, J-Y., Dwyer, J.M., Andrey, A., Arlettaz, R., 2016. Impacts of nitrogen addition on plant biodiversity in mountain grasslands depend on dose, application duration and climate: A Systematic Review. Global Change Biol. 22(1), 110–20. https://doi.org/10.1111/gcb.12986.

Jäger, H., Peratoner, G., Tappeiner, U., Tasser, E., 2020. Grassland biomass balance in the European alps: Current and future ecosystem service perspectives. Ecosyst. Serv. 45, 101163. https://doi.org/10.1016/j.ecoser.2020.101163.

Janes-Bassett, V., Blackwell, M.S.A., Blair, G., Davies, J., Haygarth, P.M., Mezeli, M.M., Stewart, G., 2022. A meta-Analysis of phosphatase activity in agricultural settings in response to phosphorus deficiency. Soil Biol. Biochem. 165, 108537. https://doi.org/10.1016/j.soilbio.2021.108537.

Jian, S., Li, J., Chen, J., Wang, G., Mayes, M.A., Dzantor, K.E., Hui, D., Luo, Y., 2016. Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilisation: A meta-analysis. Soil Biol. Biochem. 101, 32–43. https://doi.org/10.1016/j.soilbio.2016.07.003.

Juma, N.G., Tabatabai, M.A., 1988. Comparison of kinetic and thermodynamic parameters of phosphomonoesterases of soils and of corn and soybean roots. Soil Biol. Biochem. 20(4), 533–39. https://doi.org/10.1016/0038-0717(88)90069-7.

Jungk, A., Claassen, N., 1986. Availability of phosphate and potassium as the result of interactions between root and soil in the rhizosphere. Z. Pflanzenernaehr. Bodenk., 149, 411-427. https://doi.org/10.1002/jpln.19861490406.

Kidd, J., Manning, P., Simkin, J., Peacock, S., Stockdale, E., 2017. Impacts of 120 years of fertilizer addition on a temperate grassland ecosystem. PLoS ONE 12(3), e0174632. https://doi.org/10.1371/journal.pone.0174632.

Kozak, M., Piepho, H.P., 2018. What's normal anyway? Residual plots are more telling than significance tests when checking ANOVA assumptions. J. Agro. Crop Sci. 204(1), 86–98. https://doi.org/10.1111/jac.12220.

Lambers, H., Raven, J.A., Shaver, G.R., Smith, S.E., 2008. Plant nutrient-acquisition strategies change with soil age. Trends Ecol. Evol. 23(2), 95–103. https://doi.org/10.1016/j.tree.2007.10.008.

Langer, U., Klimanek, E.M., 2006. Soil microbial diversity of four German long-term field experiments. Archives of Agro. Soil Sci. 52, 507–523. https://doi.org/10.1080/03650340600915554.

Levy, F.B., Madden, E.A., 1933. The point method of pasture analysis. New Zealand, Exp. Agr. J. 46, 267–279.

Li, Y., Duan, Y., Wang, G., Wang, A., Shao, G., Meng, X., Hu, H., Zhang, D., 2021. Straw alters the soil organic carbon composition and microbial community under different tillage practices in a meadow soil in Northeast China. Soil Till. Res. 208, 104879. https://doi.org/10.1016/j.still.2020.104879.

Liu, L., Zhu, K., Wurzburger, N., Zhang., J., 2020. Relationships between plant diversity and soil microbial diversity vary across taxonomic groups and spatial scales. Ecosphere 11(1), e02999. https://doi.org/10.1002/ecs2.2999.

Liu, Z., Bai, J., Qin, H., Sun, D., Li, M., Hu, J., Lin, X., 2021. Application of rice straw and horse manure coameliorated soil arbuscular mycorrhizal fungal community: Impacts on structure and diversity in a degraded field in Eastern China. Land Degrad. Dev. 32, 2595–2605. https://doi.org/10.1002/ldr.3927.

Lucas-Borja, M.E.M.E., Wic-Baena, C., Moreno, J.L.J.L., Dadi, T., García, C., Andrés-Abellán, M., 2011. Microbial activity in soils under fast-growing Paulownia (Paulownia elongata x fortunei) plantations in Mediterranean areas. Appl. Soil Ecol. 51, 42–51. https://doi.org/10.1016/j.apsoil.2011.08.

Margalef, O., Sardans, J., Maspons, J., Molowny-Horas, R., Fernández-Martínez, M., Janssens, I.A., Richter, A., Ciais, P., Obersteiner, M., Peñuelas, J., 2021. The effect of global change on soil phosphatase activity. Global Change Biol. 27, 5989–6003. https://doi.org/10.1111/gcb.15832.

Marklein, A.R., Houlton, B.Z., 2012. Nitrogen inputs accelerate phosphorus cycling rates across a wide variety of terrestrial ecosystems. New Phyto. 193, 696–704. https://doi.org/10.1111/j.1469-8137.2011.03967.x.

Meisser, M., Vitra, A., Deléglise, C., Dubois, S., Probo, M., Mosimann, E., Buttler, A., Mariotte, P., 2019. Nutrient limitations induced by drought affect forage N and P differently in two permanent grasslands. Agri., Ecosyst. Environ. 280, 85–94. https://doi.org/10.1016/j.agee.2019.04.027.

Meng, C., Tian, D., Zeng, H., Li, Z., Chen, H.Y.H., Niu, S., 2020. Global meta-analysis on the responses of soil extracellular enzyme activities to warming. Sci. Total Environ. 705, 135992. https://doi.org/10.1016/j.scitotenv.2019.135992.

Meteo Browser, Eurac Research. Historical daily station observations (Temperature, Precipitation). https://meteo.provincia.bz.it/download-dati.asp (accessed 22 September 2022).

Miao, F., Li, Y., Cui, S., Jagadamma, S., Yang, G., Zhang, Q., 2019. Soil extracellular enzyme activities under long-term fertilisation management in the croplands of China: a meta-analysis. Nutr. Cycl. Agroecosyst. 114, 125–138. https://doi.org/10.1007/s10705-019-09991-2.

Moharana, P.C., Biswas, D.R., 2022. Phosphorus delivery potential in soil amended with rock phosphate enriched composts of variable crop residues under wheat–green gram cropping sequence. Commun. Soil Sci. Plant Anal. 53, 1000–1017. https://doi.org/10.1080/00103624.2022.2039175.

Müller, I.B., Buhk, C., Lange, D., Entling, M. H., Schirmel, J., 2016. Contrasting effects of irrigation and fertilization on plant diversity in hay meadows. Basic and Applied Ecology 17:576–585. https://doi.org/10.1016/j.baae.2016.04.008.

Nannipieri, P., Johnson, R.L., Paul, E.A., 1978. Criteria for measurement of microbial growth and activity in soil. Soil Biol. Biochem. 10, 223–229. https://doi.org/10.1016/0038-0717(78)90100-1.

Ohno, T., Zibilske, L.M., 1991. Determination of Low Concentrations of Phosphorus in Soil Extracts Using Malachite Green. Soil Sci. Soc. Am. J. 55, 892–895. https://doi.org/10.2136/sssaj1991.03615995005500030046x.

Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean L.A., 1954. Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. U.S.D.A, Washington.

O'Neill, R.M., Duff, A.M., Brennan, F.P., Gebremichael, A.W., Girkin, N.T., Lanigan, G.J., Krol, D.J., Wall, D.P., Renou-Wilson, F., Müller, C., Richards, K.G., Deveautour, C., 2022. Linking long-term soil phosphorus management to microbial communities involved in nitrogen reactions. Biol. Fert. Soils 58, 89–402. https://doi.org/10.1007/s00374-022-01627-y.

Pavlů, V., Schellberg, J., Hejcman, M., 2011. Cutting frequency vs. N application: effect of a 20-year management in Lolio-Cynosuretum grassland. Grass Forage Sci. 66, 501–515. https://doi.org/10.1111/j.1365-2494.2011.00807.x.

Peratoner, G., 2003. Organic seed propagation of alpine species and their use in ecological restoration of ski runs in mountain regions. PhD thesis, University of Kassel. Kassel University Press, Kassel, 240 pp.

Peratoner, G, Pötsch, E.M., 2019. Methods to describe the botanical composition of vegetation in grassland research. Die Bodenkultur: J. Land Manag., Food Environ. 70(1), 1–18. https://doi.org/10.2478/boku-2019-0001.

Peratoner, G., Sicher, G., Matteazzi, A., 2022. Richtwerte des Nährstoffgehalts von Wirtschaftsdüngern in Südtirol. Tabellenwerk 2022. [Standard values of the nutrient content of farm manures in South Tyrol. Table 2022.] Pfatten/Vadena: Versuchszentrum Laimburg. Online available under https://t1p.de/kmm9.

Pokharel, P., Ma, Z., Chang, S.X., 2020. Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: a global meta-analysis. Biochar 2, 65–79. https://doi.org/10.1007/s42773-020-00039-1.

R Core Team (2023). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Scherer-Lorenzen, M., Palmborg, C., Prinz, A., Detlef, S.E., 2003. The role of plant diversity and composition for nitrate leaching in grasslands. Ecol. 84, 1539-1552 (2003) 84. https://doi.org/10.1890/0012-9658(2003)084[1539:TROPDA]2.0.CO;2.

Sardans, J., Peñuelas, J., Rivas-Ubach, A., 2011. Ecological metabolomics: Overview of current developments and future challenges. Chemoecology, 21(4), 191–225. https://doi.org/10.1007/s00049-011-0083-5.

Sardans, J., Lambers, H., Preece, C., Alrefaei, A.F., Peñuelas, J., 2023. Role of mycorrhizas and root exudates in plant uptake of soil nutrients (calcium, iron, magnesium, and potassium): Has the puzzle been completely solved? Plant J. 114(6), 1227–1242. https://doi.org/10.1111/tpj.16184.

Schmidt, G., Laskowski, M., 1961. Phosphate ester cleavage (survey). P.D. Boyer, H. Lardy, K. Myrback (Eds.), The Enzymes (2nd ed.), Academic Press, New York (1961), pp. 3-35.

Scotton, M., Pecile, A., Franchi, R., 2012. I tipi di prato permanente in Trentino [Permanent meadow types in the Province of Trento]. Fondazione Edmund Mach, San Michele all'Adige.

Shannon, C.E., 1948. A mathematical theory of communication. Bell Syst. Tech. J., 27, 379-42. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.

Shi, Y., Ziadi, N., Hamel, C., Bélanger, G., Abdi, D., Lajeunesse, J., Lafond, J., Lalande, R., Shang, J., 2020. Soil microbial biomass, activity and community structure as affected by mineral phosphorus fertilisation in grasslands. Appl. Soil Ecol. 146, 103391. https://doi.org/10.1016/j.apsoil.2019.103391.

Speir, T.W., Cowling, J.C., 1991. Phosphatase activities of pasture plants and soils: Relationship with plant productivity and soil P fertility indices. Biol. Fert. Soils 12, 189–194. https://doi.org/10.1007/BF00337200.

Sun, J., Zou, L., Li, W., Yang, J., Wang, Y., Xia, Q., Peng, M., 2018. Rhizosphere soil properties and banana Fusarium wilt suppression influenced by combined chemical and organic fertilisations. Agri. Ecosyst. Environ. 254, 60–68. https://doi.org/10.1016/j.agee.2017.10.010.

Sun, Y., Goll, D.S., Ciais, P., Peng, S., Margalef, O., Asensio, D., Sardans, J., Peñuelas, J., 2020. Spatial Pattern and Environmental Drivers of Acid Phosphatase Activity in Europe. Frontiers in Big Data 2, 1–13. https://doi.org/10.3389/fdata.2019.00051.

Tabatabai, M.A., 1994. Soil enzymes. Pp. 775–833 in Methods of soil analysis, SSSA Book Series.

Tabatabai, M.A., Bremner, J.M., 1969. Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. Soil Biol. Biochem. 1, 301–307. https://doi.org/10.1016/0038-0717(69)90012-1.

Tasser, E., Lüth, C., Niedrist, G., Tappeiner, U., 2010. Bestimmungsschlüssel für landwirtschaftlich genutzte Grünlandgesellschaften in Tirol und Südtirol [Determination key for agricultural grassland plant communities in Tyrol and South Tyrol]. Gredleriana 10, 11–62.

Tomasi, M., Odasso, M., Lasen, C., Mulser, J., Gamper, U., Kußtatscher, K., (2016): Metodologia per l'identificazione delle cenosi prative riconducibili agli habitat Natura 2000 "Praterie magre da fieno a bassa altitudine" (6510) e "Praterie montane da fieno" (6520) in Alto Adige - Südtirol [Methodology for identifying meadow coenoses attributable to the Natura 2000 habitats “Lowland hay meadows” (6510) and “Mountain hay meadows” (6520) in South Tyrol (Italy)]. Gredleriana 16, 35–62.

Touhami, D., Condron, L.M., McDowell, R.W., 2021. Plant Species Rather than Elevated Atmospheric CO2 Impact Rhizosphere Properties and Phosphorus Fractions in a Phosphorus-Deficient Soil. J. Soil Sci. Plant Nutr. 21, 622–636. https://doi.org/10.1007/s42729-020-00388-7.

Touhami, D., McDowell, R.W., Condron, L.M., Bouray, M., 2022a. Nitrogen Fertilization Effects on Soil Phosphorus Dynamics under a Grass-Pasture System. Nutr. Cycling Agroecosyst. 124(2), 227–46. https://doi.org/10.1007/s10705-021-10191-0.

Touhami, D.; Condron, L. M.; McDowell, R. W.; Moss, R., 2022b. Effects of Long-Term Phosphorus Fertilizer Inputs and Seasonal Conditions on Organic Soil Phosphorus Cycling under Grazed Pasture. Soil Use Manag., 39 (1), 385–401. https://doi.org/10.1111/sum.12830.

Velthof G.L., Lesschen J.P., Schils R.M.L., Smit A., Elbersen B.S., Hazeu G.W., Mucher C.A., Oenema O., 2014. Grassland areas, production and use. Methodological studies in the field of agro-environmental indicators. Lot 2. Alterra Wageningen UR.

Wang, Y.H., Garvin, D.F., Kochian, L.V., 2002. Rapid induction of regulatory and transporter genes in response to phosphorus, potassium, and iron deficiencies in tomato roots. Evidence for cross talk and root/rhizosphere-mediated signals. Plant Physiol. 130, 1361-1370. https://doi.org/10.1104/pp.008854.

Wang, F., Jiang, R., Kertesz, M.A., Zhang, F., Feng, G., 2013. Arbuscular mycorrhizal fungal hyphae mediating acidification can promote phytate mineralization in the hyphosphere of maize (Zea mays L.). Soil Biol. Biochem., 65, 69-74. https://doi.org/10.1016/j.soilbio.2013.05.010.

Wei, K., Chen, Z., Jiang, N., Zhang, Y., Feng, J., Tian, J., Chen, X., Lou, C., Chen, L., 2021. Effects of mineral phosphorus fertilizer reduction and maize straw incorporation on soil phosphorus availability, acid phosphatase activity, and maize grain yield in northeast China. Archives Agro. Soil Sci. 67, 66–78. https://doi.org/10.1080/03650340.2020.1714031.

White, P.J., Hammond, J.P., 2008. Phosphorus nutrition of terrestrial plants. Pp. 51–81 in The Ecophysiology of Plant-Phosphorus Interactions, edited by P. J. White and J. P. Hammond. Dordrecht: Springer Netherlands.

Yang, M., Yang, H., 2021. Utilization of soil residual phosphorus and internal reuse of phosphorus by crops. Edited by Y. Orlov and Peer J. 9, e11704. https://doi.org/10.7717/peerj.11704.

Zhang, W., Zhao, J., Pan, F., Li, D., Chen, H., Wang, K., 2015. Changes in nitrogen and phosphorus limitation during secondary succession in a karst region in southwest China. Plant Soil 391(1–2), 77–91. https://doi.org/10.1007/s11104-015-2406-8.

Zhang, Y., Finn, D., Bhattacharyya, R., Dennis, P.G., Doolette, A.L., Smernik, R.J., Dalal, R.C., Meyer, G., Lombi, E., Klysubun, W., Jones, A.R., Wang, P., Menzies, N.W., Kopittke, P.M., 2021. Long-term changes in land use influence phosphorus concentrations, speciation, and cycling within subtropical soils. Geoderma 393, 115010. https://doi.org/10.1016/j.geoderma.2021.115010.

Zhu, J., Li, M., Whelan, M., 2018. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. Sci. Total Environ. 612, 522–37. https://doi.org/10.1016/j.scitotenv.2017.08.095.

Zi, H., Hu, L., Wang, C., 2022. Differentiate Responses of Soil Microbial Community and Enzyme Activities to Nitrogen and Phosphorus Addition Rates in an Alpine Meadow. Front. Plant Sci. 13, 829381. https://doi.org/10.3389/fpls.2022.829381.

Zwack, B., 2019. Seed bank and short-term effect of organic fertilisation on the botanical composition of permanent meadows in South Tyrol. MSc thesis. Free University of Bozen-Bolzano, Faculty of Science and Technology, Bozen.

6.9 Supplementary materials Chapter 3

Tables

Table S1. Characteristics of the manures used in the study from Autumn 2021 until the last growth cycle of 2022. Means of all used batches (some of them used for more than one fertilisation event, each event counted as a replicate, with n being the total number of fertilisation events for the highest nutrient input treatment corresponding to 111.0 kg N ha^{-1} year^{-1}) ± standard deviation are given.

Parameter	Farmyard manure (n=6)	Manure effluent (n=12)	Slurry (n=12)
pH	8.7 + 0.27	7.9 + 0.15	7.3 + 0.34
Dry matter content (%)	22.1 + 2.51	1.9 + 0.34	7.2 + 2.36
Ashes (% FM)	6.5 + 2.12	0.9 + 0.25	1.8 + 0.10
Organic matter (% FM)	15.5 + 0.50	0.9 + 0.10	5.4 + 2.26
Total N (% FM)	0.56 + 0.128	0.10 + 0.015	0.34 + 0.039
NH_4-N (% FM)	0.04 + 0.016	0.10 + 0.005	0.10 + 0.005
NH_4-N proportion (%)	6.5 + 2.23	98.1 + 10.63	30.7 + 5.37
P (% FM)	0.14 + 0.037	0.01 + 0.002	0.05 + 0.011
K (% FM)	0.54 + 0.327	0.46 + 0.135	0.52 + 0.069
Mg (% FM)	0.24 + 0.158	0.03 + 0.009	0.07 + 0.006
Ca (% FM)	0.87 + 0.507	0.02 + 0.004	0.19 + 0.028
N:P	4.2 + 0.60	19.9 + 7.90	7.9 + 2.30
N:K	1.2 + 0.39	0.2 + 0.04	0.7 + 0.010
K:P	3.7 + 1.23	94.2 + 46.40	11.9 + 3.67
Ca:P	6.1 + 2.16	4.4 + 0.81	4.2 + 0.31

FM = fresh mass. Chemical elements are named using their standard abbreviations.

Table S2. Input of macronutrients depending on manure type and application event from Autumn 2021 until the last growth cycle of 2022. Means ± standard deviation are given. Values in red are nutrients provided with farmyard manure, those in yellow are nutrients provided with manure effluent and those in blue are nutrients provided with slurry (n=6).

Manure type	Nutrient input ($LU\ ha^{-1}\ year^{-1}$)	Element	Application time		
			Autumn	Spring	After the first cut
Farmyard manure (F)	0.65	N	55.5 ± 0.00	-	-
		P	13.5 ± 1.92	-	-
		K	50.5 ± 18.59	-	-
	1.30	N	111.0 ± 0.00	-	-
		P	27.1 ± 3.85	-	-
		K	101.0 ± 37.18	-	-
Farmyard manure +	0.65	N	38.9 ± 0.00	16.7 ± 0.00	-
		P	9.5 ± 1.35	1.0 ± 0.57	-
		K	35.4 ± 13.03	74.5 ± 12.80	-

manure effluent (L)	1.30	N	77.7 ± 0.00	16.7 ± 0.00	16.7 ± 0.00
		P	19.0 ± 2.69	1.0 ± 0.57	1.0 ± 0.60
		K	70.7 ± 26.03	74.5 ± 12.80	74.5 ± 13.42
Slurry (S)	0.65	N	-	55.5 ± 0.00	-
		P	-	7.8 ± 2.85	-
		K	-	83.4 ± 1.80	-
	1.30	N	-	55.5 ± 0.00	55.5 ± 0.00
		P	-	7.8 ± 2.85	7.8 ± 2.99
		K	-	83.4 ± 1.80	83.4 ± 1.88

S: slurry, F: farmyard manure, L: combined use of farmyard manure and manure effluent. LU = livestock units.

Table S3. Time elapsed in days (mean ± standard deviation) between the last fertilization event and soil sampling depending on manure type, meadow class and nutrient input level (n=3).

Manure type	N-Input (kg ha^{-1} $year^{-1}$)	Meadow class C1	Meadow class C2
S	55.5	135.3 ± 10.69	120.0 ± 9.54
S	111.0	89.7 ± 5.86	54.7 ± 6.51
L	55.5	135.3 ± 10.69	120.0 ± 9.54
L	111.0	89.7 ± 5.86	54.7 ± 6.51
F	55.5	336.3 ± 5.86	323.0 ± 13.45
F	111.0	336.3 ± 5.86	323.0 ± 13.45

S: slurry, F: farmyard manure, L: combined use of farmyard manure and manure effluent.

Table S4. ANOVA table of designed effects (meadow class, manure type, N input and their designed interactions (excluded those with N input having been found not to be significant) on the species number of vascular plants found at the time of the first cut in the investigation year (2022).

Source	Species number df	F	p
Site	2	0.5	0.675
Meadow class (MC)	1	26.3	**0.036**
Manure type (MT)	2	3.3	**0.048**

N input (N)	1	0.1	0.955
MC x MT	2	2.9	0.067

df = degrees of freedom; F = Fisher's F, p = probability;
p-values < 0.05 are highlighted in bold.

Table S5. ANOVA table of designed effects (meadow class, manure type, N input and their designed interactions (excluded those with N input having been found not to be significant) on the total N content in soil (in g kg^{-1}) measured at the end of the last growth cycle in the investigation year (2022).

Source	Species number		
	df	F	p
Site	2	12.7	0.072
Meadow class (MC)	1	4.4	0.159
Manure type (MT)	2	1.1	0.342
N input (N)	1	5.4	**0.025**
MC x MT	2	0.5	0.593
MC x N	1	9.2	**0.004**
MT x N	2	3.4	**0.044**

df = degrees of freedom; F = Fisher's F, p = probability;
p-values < 0.05 are highlighted in bold.

Table S6. ANOVA table of designed effects (meadow class, manure type, N input and their designed interactions (excluded those with N input having been found not to be significant) on the weighted community mean of Ellenberg nutrient indicator.

Source	Weighted community mean of Ellenberg nutrient indicator		
	df	F	p
Site	2	20.6	0.124
Meadow class (MC)	1	111.8	**0.008**
Manure type (MT)	2	2.5	0.504
N input (N)	1	64.2	**<0.001**
MC x N	1	5.4	0.647
MC x MT	2	0.4	0.690

df = degrees of freedom; F = Fisher's F, p = probability; p-values < 0.05 are highlighted in bold.

Figures

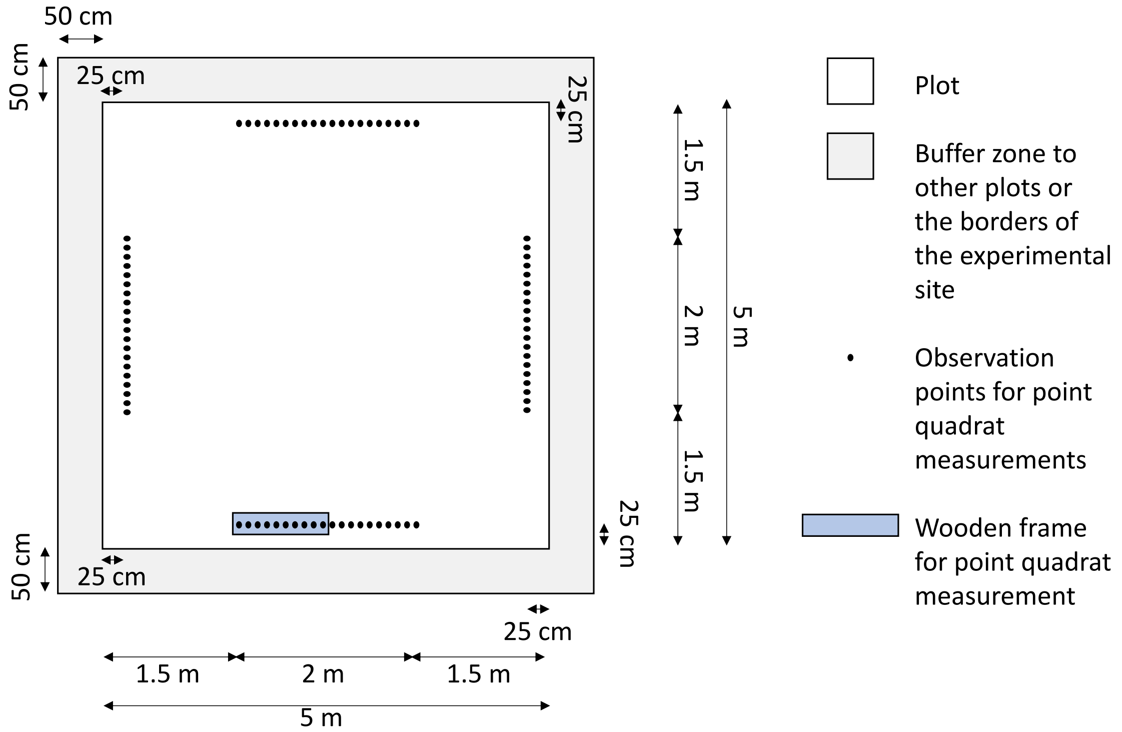


Fig. S1. Plot size and sampling scheme within plots by means of point quadrat measurements.

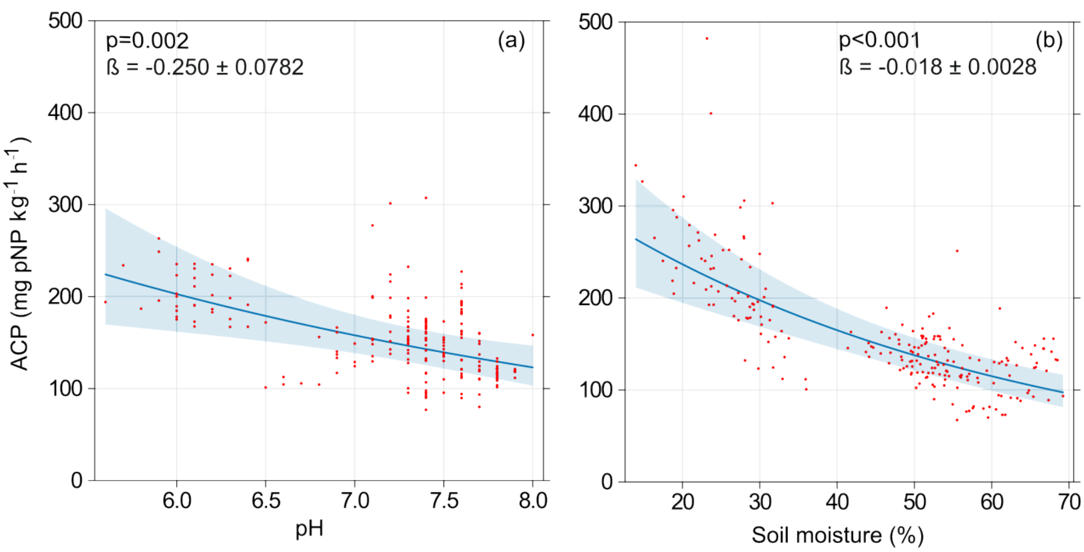


Fig. S2. Effect of (a) pH and (b) soil moisture on ACP activity at the end of the last growth cycle. Predicted values and 95%-confidence interval are shown against partial residuals. Analysis with natural logarithm-transformed values; back-transformed values are shown (n=216). Estimated slope parameters (β) ± SE are reported on the transformed scale.

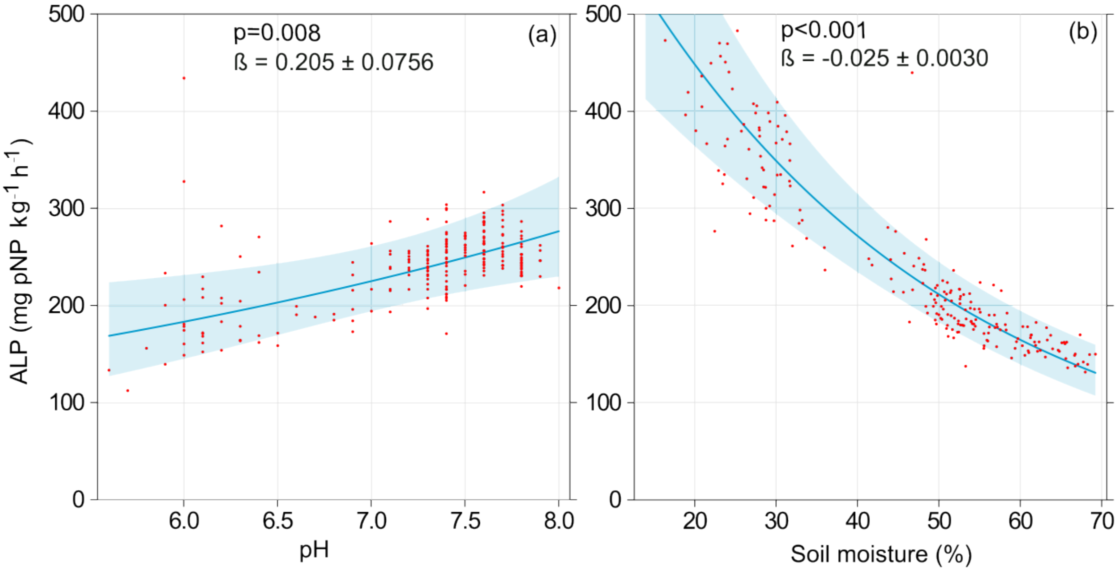


Fig. S3. Effect of (a) pH, and (b) soil moisture on the ALP activity at the end of the last growth cycle. Predicted values and 95%-confidence interval are shown against partial residuals. Analysis carried out with natural logarithm-transformed values; back-transformed values are shown (n=216). Estimated slope parameters (β) ± SE are reported on the transformed scale.

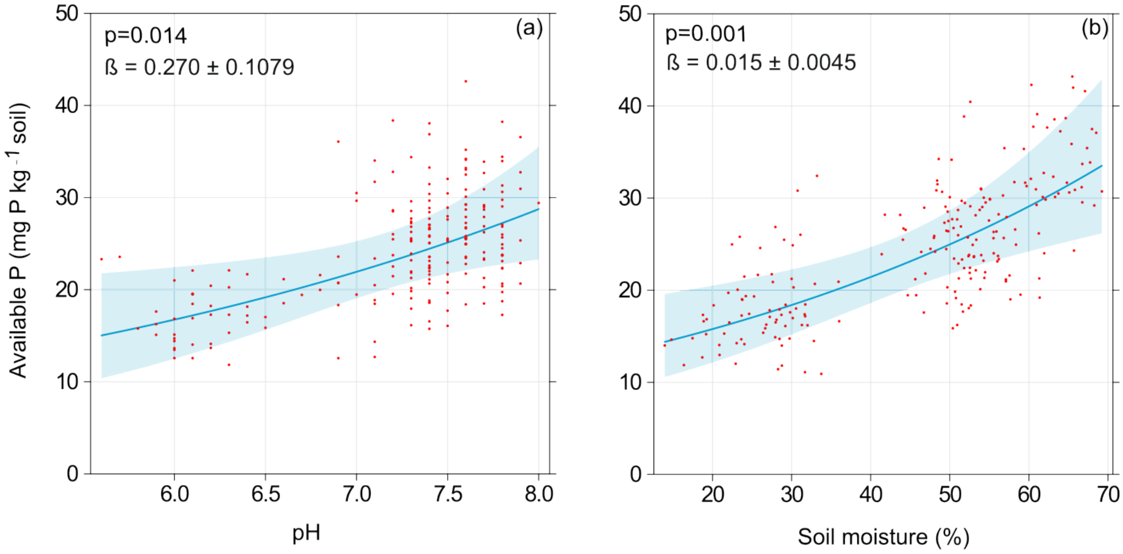


Fig. S4. Effect of (a) pH and (b) soil moisture on the available P at the end of the last growth cycle. Predicted values and 95%-confidence interval are shown against partial residuals. Analysis with natural logarithm-transformed values; back-transformed values are shown (n=216). Estimated slope parameters (β) ± SE are reported on the transformed scale.

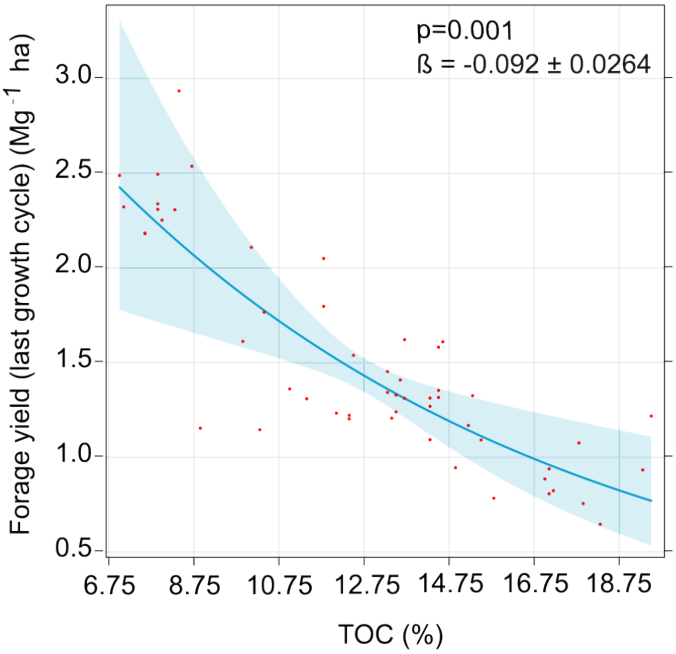


Fig. S5. Effect of TOC on the forage yield of the last regrowth at the end of the last growth cycle. Predicted values and 95%-confidence interval are shown against partial residuals. Analysis with natural logarithm-transformed values; back-transformed values are shown (n=54). The estimated slope parameter (β) ± SE is reported on the transformed scale.

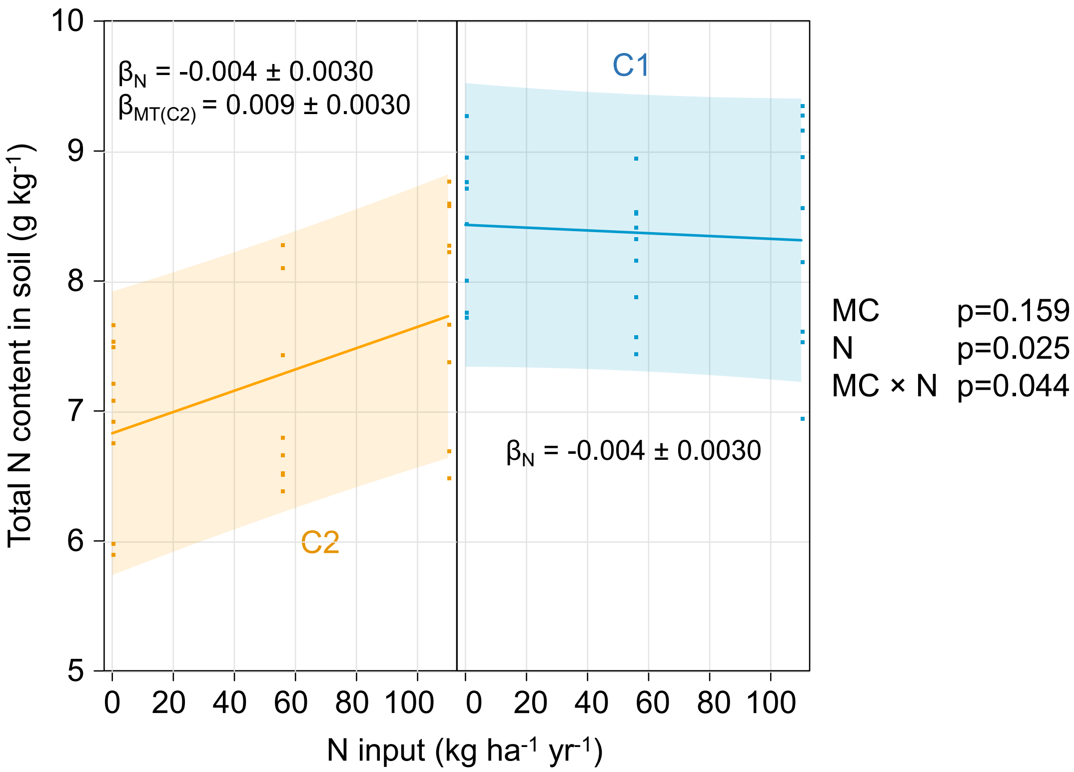


Fig. S6. Predicted values, 95%-confidence intervals and partial residuals of total N content in soil measured at the at the end of the last growth cycle in the investigation year (2022) depending on meadow class and N input (n=27). Estimated slope parameters (β) ± SE of the reference level (βN) and the difference for level C2 (βMT(C2)) are reported on the transformed scale. MC = meadow class, N = nutrient input, C2 = moderately species-poor, C1 = moderately species-rich.

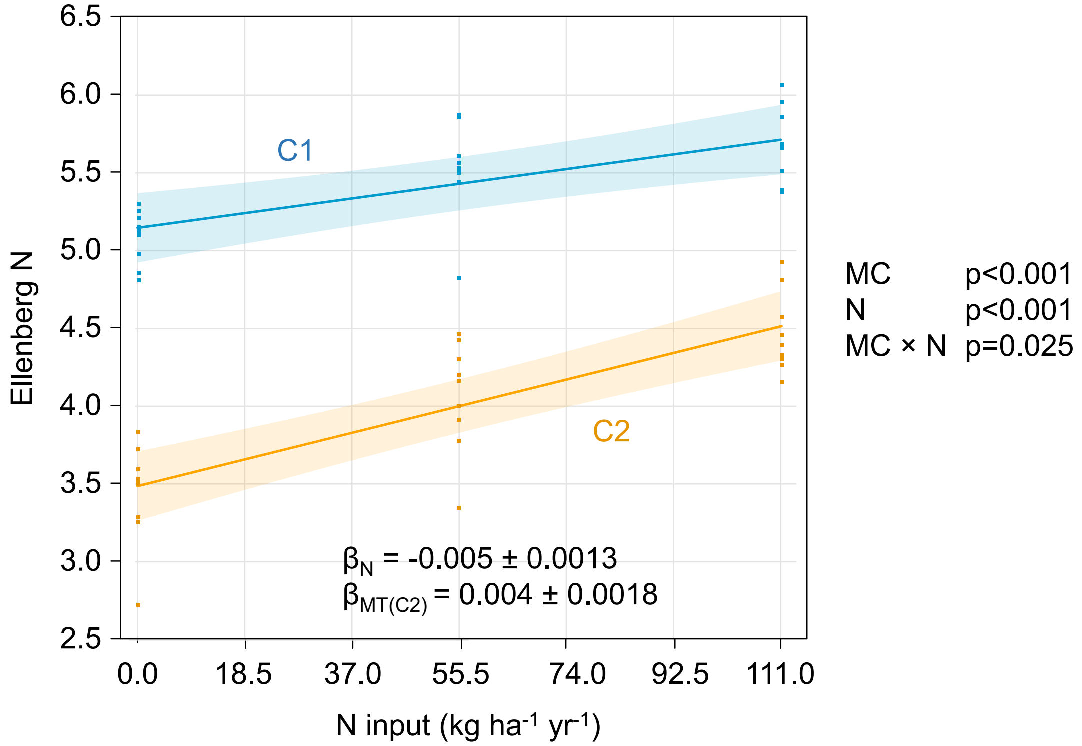


Fig. S7. Predicted values, 95%-confidence intervals and partial residuals of Ellenberg nutrient indicator computed as weighted mean on the cover of vascular plant species at the time of the first cut in the investigation year (2022) depending on meadow class and N input (n=27). Estimated slope parameters (β) ± SE of the reference level (βN) and the difference for level C2 (βMT(C2)) are reported on the transformed scale. MC = meadow class, N = nutrient input, C2 = moderately species-poor, C1 = moderately species-rich.

6.10 Appendix Chapter 3

A brief exposition of pictures taken during my stay: the soil sampling and the laboratory analyses.

Soil sampling

Soil sampling at C2 Montal/Mantena (46º 42' 33,4"N 11º 55' 3,1" E) on August 24th, 2022.

Soil sampling at C1 Montal/Mantena (46º 42’ 33,8’’ N 11º 55’ 5,0" E) on September 17th, 2022.

Soil sampling at C1 Radsberg/Monterota (46º 44’ 46,7 N 12º13’ 19,9" E) on August 24th, 2022.

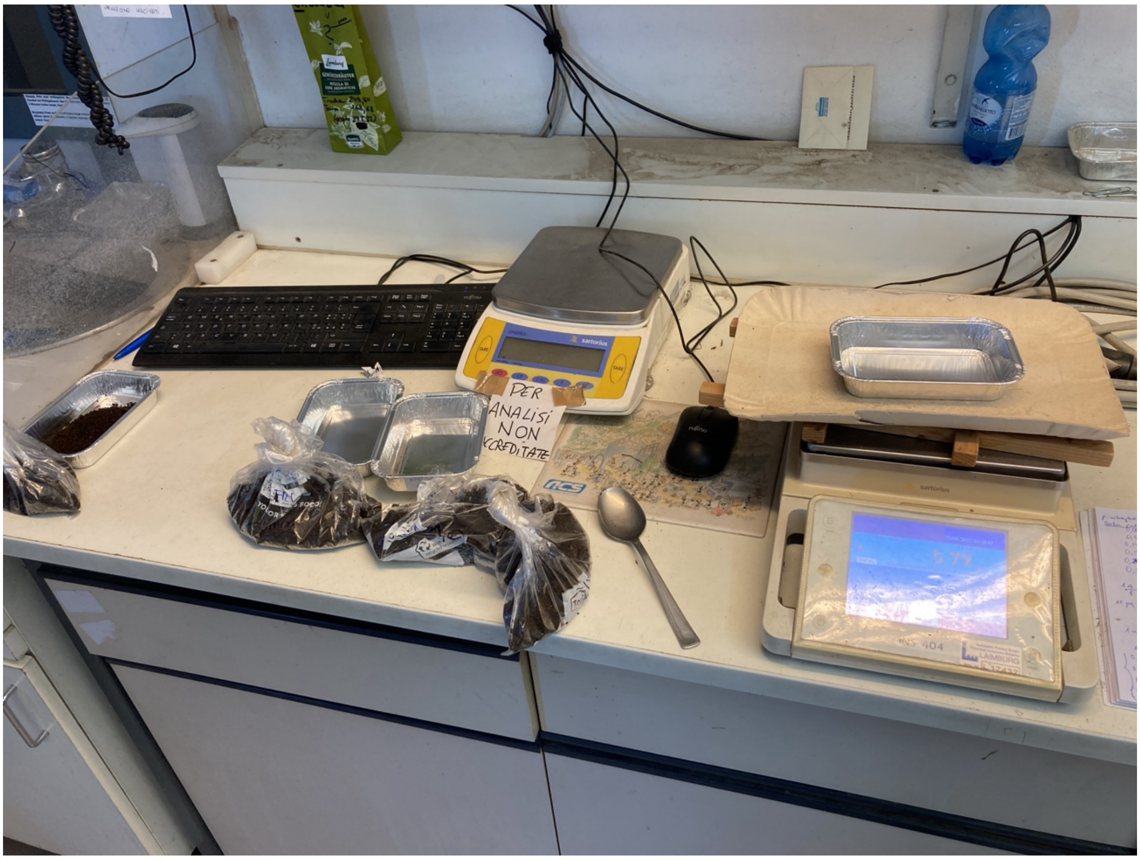
Soil sampling at C2 Radsberg/Monterota (46º 45’ 7,0 N 12º12’ 27,7" E) on September 18th, 2022.

Soil sampling at C1 Radsberg/Monterota (46º 35’ 6,1’’ N 11º 55’ 36,8" E) on September 12th, 2022.

Soil sampling at C2 Radsberg/Monterota (46º 35’ 8,6‘’ N 11º 55’ 35,3'' E) on September 12th, 2022.

Laboratory analyses

Physicochemical parameters



Fresh soil samples were sieved to 5mm in the laboratory of Soil and Plant Analysis at Laimburg Research Centre from August 24th to September 16th, 2022.

Soil moisture analyses in the laboratory of Soil and Plant Analysis at Laimburg Research Centre from August 24th to September 23rd, 2022.

Fresh soil samples were air-dried and sieved to 2mm in the laboratory of Soil and Plant Analysis at Laimburg Research Centre from August 24th to September 27th, 2022.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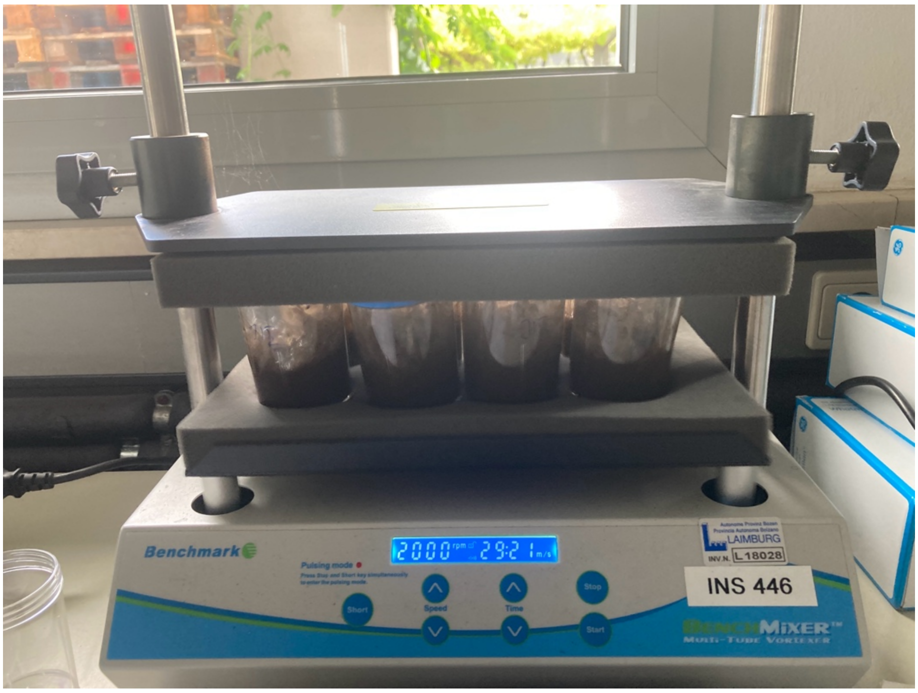
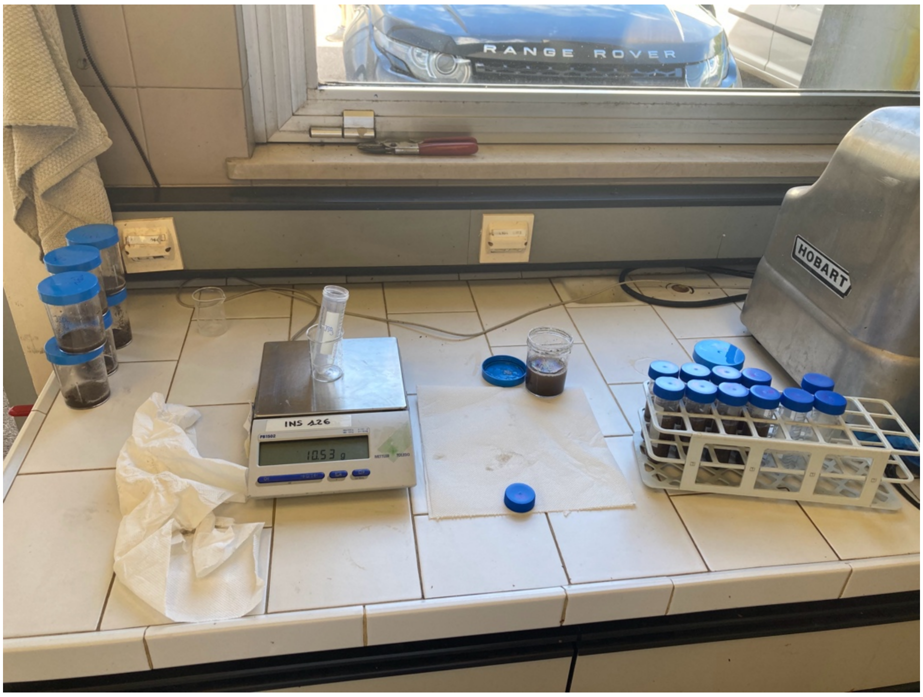
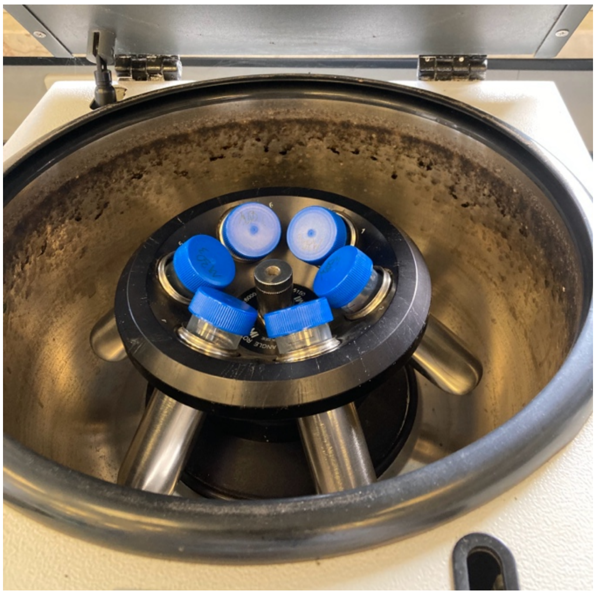
EXPLORER
Toppits


LAIMBURG
L.17996
39.2°C

APase activity assay in the laboratory of Food and Vegetable Processing and Food Technology at Laimburg Research Centre from August 30th to September 23rd, 2022.


Benchmark
INS 446
LAIMBURG
L18028
BenchMixer™

RANGE ROVER
HOBART



Phosphorus in soil extract using malachite green assay in the laboratory of Residues and Contaminants at Laimburg Research Centre from September 27th to October 3rd, 2022.

7. General discussion

The Earth's land area exceeds 10 million hectares, with approximately 37% classified as agricultural by the FAO. Agricultural land is divided into arable land (28% of the global agricultural area), permanent crops (3%), and permanent meadows and pastures (69%), which constitute the largest part of the world's agricultural area (FAO, 2013). Essentially, half of the world's croplands grow crops for direct human consumption and a large amount is allocated to biofuels, industrial goods, and primarily, animal feed (Poore and Nemecek, 2018).

Soil plays a crucial role in supporting essential ecosystem functions (Dominati et al., 2010), and, in particular soil enzymes, are instrumental in initiating and maintaining the biochemical cycles of major nutrients like C, N, P and K, as well as secondary nutrients such as Ca, Mg and S, and micronutrients like B, Cl, Cu, Fe, Mn, Mo and Zn. They facilitate the cycling of C, N, P, and K by converting complex organic compounds into inorganic forms which are then accessible to microorganisms, fauna, and plants for their growth and development (Allison et al., 2011). This underscores the essential role of soil enzymes in providing the necessary fertility to support healthy plant growth (Dotaniya et al., 2019).

Phosphorus is a vital macronutrient for cell development in all organisms (Wrage et al., 2010), being part of nucleic acids (DNA, RNA), which are essential for reproduction and protein synthesis, and it plays a crucial role in energy-storing molecules like adenosine triphosphate (ATP) and cytidine triphosphate (CTP), which drive powering various cellular processes (Malhotra et al., 2018). When focusing on agricultural production, only about 0.1% of soil P is in an assimilable inorganic form for plants, significantly limiting crop growth across ecosystems (Zhu et al., 2018, Peñuelas et al., 2013). The availability of P is intricately linked to management practices, as fertilizers and manures serve as the primary sources of P in agricultural production (Lu and Tian, 2017). However, substantial amounts of P commonly used in agriculture can leach into water when sediments wash off fertilized or manured lands, leading to environmental issues such as eutrophication (Del Rossi et al., 2023) becoming a problem of environmental pollution. For this reason, effective soil and fertilizer management can mitigate these P losses, reducing the need for non-renewable and relatively costly mineral P fertilizers (Schnitkey et al., 2022) and the significant role of APase activity could ensure that this nutrient supply aligns more closely with nutrient demand (Allison et al., 2010) considerably reducing environmental pollution.

7.1 Factors influencing APase activity in agricultural soils: Effects of climatic parameters, physicochemical and biological properties of the soil, management systems and crop yields

I reviewed the relationship between both APase activity and soil biophysicochemical properties, agro-ecosystem management, soil pollutants, climate factors and crop yields (Chapter 1). This comprehensive review, both qualitative and quantitative has not been conducted before due to the volume of published data and the complexity of factors influencing their activity in agricultural soils. Then, I performed a global analysis in croplands using four different models for each APase activity (Chapter 2). The results showed an effect of climate variables, crop species and management practices on APase activity and a relationship between the activity of both APase and crop yield.

In terms of climate factors, the results in Chapter 1 showed that APase activity responds positively when MAT and MAP increase. Warmer temperatures accelerate plant growth and enhance plant P acquisition (Sardans and Peñuelas, 2004), while increased rainfall can elevate topsoil nutrient losses (Yao et al., 2021). Seasonality also impacts APase activity, with lower levels observed during drier cropping periods although soil microbes can adapt to soil drying conditions (Landesman and Dighton, 2010). However, in Chapter 2, I found that elevated temperatures initially cause a decline in the activity of both ACP and ALP activity, contrary to findings in other ecosystems (Margalef et al., 2017). The temperature sensitivity of APase activity, along with the influence of pH on that sensitivity, can determine the relative availability of bioavailable resources sourced from these enzymes. In natural ecosystems, the bioavailability of resources derived from APase activity may transition from N to P limitation with warming, primarily due to slight enhancements in P release from decomposing organic matter (Souza and Billings, 2021). This phenomenon is less common in croplands as the decomposition of organic matter by soil microbes and vegetation is contingent upon management practices. Moreover, soil multifunctionality is low in higher temperatures due to immobilization of soil enzymes and reduction of substrate and enzyme diffusion rates (Sünnemann et al., 2023). On the other hand, extreme low precipitation, such as drought, notably reduces microbial biomass C, N, and P, thereby decreasing the activity of P-acquiring enzymes like ACP (Qu et al., 2023) which is aligned with previous research (Margalef et al., 2021). However, the response of ALP activity is more complex. In colder climates with high precipitation and weaker evapotranspiration, increased infiltration and higher leaching lead to elevated ALP activity, compared to low precipitation levels (Riddle et al., 2018). Conversely, in warmer environments with lower precipitation, ALP activity tends to be relatively high, indicating the ability of soil microbes (e.g., plant growth promoting bacteria) to promote plant growth under less watered conditions (Rubin et al., 2017).

Physical properties, like soil pH and soil depth, also play a significant role; acidic pH favours ACP activity while reducing ALP activity (Juma and Tabatabai, 1978) and ACP activity decreases with increasing soil depth because substrate concentrations are lower in depth, and there is less competitive interaction (Stone and Plante, 2014). When considering soil biological properties, the abundance of soil microorganisms (Gelsomino and Azzellino, 2011), MBC, MBN (Hatti et al., 2018) and MBP, which serve as the nutrient pool for ecosystem nutrient cycling (Angers et al., 1993), positively influence APase activity. On the other hand, when soil physicochemical properties are enhanced, they generally have positive effects on ACP and ALP activity. For example, clay content can preserve enzyme activity long-term (Nedyalkova et al., 2020), and soil organic C content is positively linked to APase substrates like organic P (Tipping et al., 2016) or N content, due to its high N mineralization rates which promotes APase activity (Cattaneo et al., 2014). On the contrary, low soil P content tends to enhance APase activity, as enzymes seek to meet or even surpass plant P demands (Tarafdar and Claassen, 1988).

In terms of management, the combined results of Chapter 1 and 2, show that these agro ecosystem strategies positively influence the activity of both APase:

i) That agricultural land is managed as ungrazed grasslands, meadows, and pastures compared to croplands. These land-use types experience less intensive human disturbance, and they support plants and microorganisms in transforming soil organic P into inorganic forms, which aids in nutrient availability (da Cunha et al., 2021). Moreover, grazing and livestock management increase soil biophysiochemical properties such as MBC, organic matter content, and available N, among others (Galindo et al., 2020).

ii) In general, techniques like crop rotation, intercropping, cover cropping, and reduced/zero tillage which enhance biological (e.g., MBC) and physiochemical properties (e.g., C, K, and Mg) of soil (Borase et al., 2020; Redel et al., 2007). In particular, crop rotation contributes to P cycling (Yu et al., 2021), with a positive effect on ACP activity, while no significant effect was found on ALP activity. This lack of effect on ALP activity may be due to the primary influence of tillage, which affects P distribution in the soil profile and alters the soil microorganism environment (Khan et al., 2023; Lv et al., 2023). Reduced and zero tillage practices positively impact the activity of both APase by creating favourable conditions, such as increased organic C, total N, and total bacterial and fungal abundance (Swedrzynska et al., 2013). Additionally, under zero tillage, soils contain a higher abundance of fungi, bacteria, and actinomycetes compared to conventional tillage (Kumar et al., 2017). Furthermore, if they are combined with proper irrigation practices which positively influence P storage in soil, they contribute to nutrient retention and availability (Zhang et al., 2019).

iii) Choosing different crop species. The literature shows that certain crops, like maize and lupine, exhibit higher activity of ACP in their soils, contributing to nutrient availability (Dou et al., 2016) because the type of species impact soil N content, C sequestration, and P accumulation in long-term cropping systems. Both ACP and ALP activity were strongly influenced by the crop species at the family level since plants have the ability to enhance P-mining strategies through APase exudation, although this varies between species (Cong et al., 2020). Significant differences in APase activity were observed at the family level, often aligned with soil pH requirements. For example, families like Rubiaceae, Oleaceae, and Sapindaceae, which thrive in acidic soils, exhibited higher ACP activity (von Uexküll and Mutert, 1995). Management practices, such as using Fabaceae as an intercrop or in crop rotation, have also been shown to influence APase activity (Simpson et al., 2011). It can be challenging to isolate the specific impact of these plants on APase activity, as they constitute only a portion of the vegetation present in those soils, as well as to evaluate the interaction between management practices and crop species families.

iv) Utilization of organic fertilizers, especially manures, and the combination of organic and inorganic fertilizers. Numerous articles have provided insight into the fertilization effect of N and P on APase activity as well as meta-analyses (Chen et al., 2023; Margalef et al., 2021). In the long-term, their use improves soil quality and nutrient availability such as labile C, N, and P through mineralization, as well as increased microbial biomass and abundance (Chatterjee et al., 2021; Dhanker et al., 2021). The positive link between organic fertilization and the activity of both ALP and ACP is well documented (Miao et al., 2019). However, the negative effect observed from inorganic fertilization in croplands (Jian et al., 2016; Margalef et al., 2021) was unexpected and it can be explained by the inhibition of APase activity by inorganic P additions and its stimulation under P-deficient conditions (Janes-Bassett et al., 2022; Nannipieri et al., 2011). Thus, long-term inorganic fertilizer additions may mitigate P soil deficiencies. The combination of organic fertilization with crop rotation causes a significant effect on ACP activity, indicating a positive interaction effect between crop rotation and nutrient management (Borase et al., 2021). Similarly, ALP activity is enhanced by the combination of reduced or zero tillage with organic fertilization, resulting in less soil disturbance and a positive effect on establishment and P solubilization by microorganisms (Shahane et al., 2020). Finally, fertilized irrigated croplands exhibit higher ACP activity, whereas for ALP activity was higher in rainfed crops, without any interaction with fertilizer type (Blaise and Rao, 2004; Kumar et al., 2021), indicating the microbial response to irregular water supply (Abddalla and Lager, 2009).

v) The use of crop residues, which contribute positively to P transformation rates and the availability of plant-accessible P in soil (Singh et al., 2018). The combined use of crop residues and/or plant-beneficial microbes, such as phosphate solubilizing bacteria, aid in converting insoluble forms of P into accessible forms for plant uptake, thereby enhancing nutrient availability (Wang et al., 2022).

On the other hand, some agro-ecosystem practices negatively influence the activity of both APase. For instance, plant protection products, such as herbicides, fungicides, and insecticides, can alter soil function and health, impacting soil respiration and biomass. This often leads to a decrease in APase activity, although recovery can occur beyond 30 days after application (Mahapatra et al., 2017; Meher et al., 2021). Soil pollutants like heavy metals (e.g., Pb, As, Cr, Cd, Ba, Ag) can also negatively affect APase activity (Aponte et al., 2020). However, in soils with high organic matter content, this impact is relatively low due to the positive association between APase and soil C abundance (de Santiago-Martín et al., 2013).

Interestingly, the literature reviewed in Chapter 1 did not find any clear association between APase activity and crop yield. However, as a novelty, I highlight the positive association between ACP and ALP activity with crop yield found in Chapter 2. The results indicated that as ACP activity doubles from 100 to 200 mg pNP kg-1h-1, crop yield increases by more than two-fold, which is not previously demonstrated in croplands. Furthermore, there is a positive effect of the combination of ACP activity with crop rotation on crop yield as cited in the literature (Jain et al., 2018; Rao et al., 1995). Additionally, conventional tillage practices combined with ACP activity have also been found to enhance crop yield, although there were more available studies for incorporation in the database using conventional tillage than reduced or zero tillage and it may have introduced bias. However, establishing a clear effect on the yield of ACP and ALP activity is challenging due to various factors, with particular importance given to considering crop yield variability depending on the species and different soil factors such as total N, soil organic matter, pH, and total P (Qaswar et al., 2019). Furthermore, climatic conditions, variations in amendment composition, and irrigation water quality may act as confounding factors (Chocano et al., 2016). In this case, further research would be needed to determine whether certain crop species, various climatic parameters, soil parameters and combined management practices can significantly influence APase activity in a global agricultural land context.

7.2. Factors influencing APase activity in grasslands: the particular case of organically fertilized permanent meadows

The experimental work was conducted in one of the most common forms of agriculturally managed grasslands in Europe (Schils et al., 2022). The results indicated that ACP and ALP activity were influenced by pH; negatively for ACP activity and positively for ALP activity, which aligns with several meta-analyses (Janes-Bassett et al., 2022; Sun et al., 2020).

In this experiment, meadow class C2, attributed to higher species diversity, exhibited higher APase activity compared to C1 with lower species diversity. The effect of species on the activity of both APase was aligned with previous studies demonstrating a positive influence of plant diversity and soil organic C (Shi et al., 2020; Pokharel et al., 2020). This increase in APase activity in C2 may be due to the community-level combinations of conservative and acquisitive traits (White and Hammond, 2008), where a variety of N and P acquisition strategies coexist.

However, the effect of N input using organic manures on ACP activity was unexpected. At the time of sampling, the activity decreased with increasing N input only in the treatment combining farmyard manure and manure effluent, while it remained unaffected by N input using other manures. The complex mechanism governing the response of ACP activity is not readily explicable in this study, and further data, such as additional sampling data during the permanent meadow's growth and available soil macronutrient ratios, would be required.

In the case of available P, it increased only with increasing N input when organic fertilization was done with farmyard manure. This type of manure had the highest P and C content, contributing to organic P cycling, and increasing P content and availability in soils (Kidd et al., 2017). Although no influence of ACP activity on available P was observed, we identified a significant positive effect of ALP activity, likely associated with increased microbial biomass resulting from the application of farmyard manure (Langer and Klimanek, 2006). Moreover, the association between soil K content and P availability requires further investigation, particularly regarding the mechanisms by which K and P interact and are mobilized into soluble and accessible forms (Sardans et al., 2023).

Analyzing the forage yield, we found no influence of APase activity and available P on the forage yield of the permanent meadow's last growth cycle or on the annual yield. This suggests that P was not a limiting factor at the time of sampling and the results revealed that organic fertilization under these experimental conditions is the primary determinant of forage yield.

7.3 Knowledge gaps, perspectives and limitations of the thesis

Throughout the thesis, several hypotheses have been proposed and addressed over the course of four years of research. However, new questions have emerged, further contributing to the limitations of the investigations conducted thus far.

The response of APase activity in croplands differs greatly from what has been published so far related to MAT and MAP. A limitation of my study is that seasonality has not been taken into account to provide a better explanation for the model results. Hence, future studies would incorporate more variables to provide more accurate results at local scale; for instance, include altitudes or climate types, two parameters closely linked to climatological variables that they would provide valuable insights into how climatology influences APase activity in croplands, thereby aiding in the improvement of agricultural practices. Moreover, the integration of climatic parameters with soil variables at a local scale could yield promising results, offering a more comprehensive understanding of environmental processes. For instance, by incorporating detailed soil data such as texture, soil moisture or physiochemical parameters along with local climatic conditions, more precise insights can be gained into how these factors interact and affect APase activity. It is important to note that this integration may pose challenges, especially regarding data availability and sample size. Since multiple parameters are being considered, the number of observations could decrease due to the need to collect specific and detailed soil data. However, this limitation can be addressed with a careful approach to selecting representative study sites and using appropriate statistical techniques to optimize data analysis. Ultimately, the combination of climatic and soil parameters at a small scale could enhance the predictive capacity of APase activity models, providing more robust and evidence-based explanations for its response. This could have significant implications for cropland management and decision-making in agriculture.

The model based on crop species family is the one that has highlighted more knowledge gaps, generating further questions on how plants, in combination with microorganisms, can, even under management, increase APase activity. The results obtained have some limitations, especially when it comes to applying the results to agricultural management. The direct relationship between crop species, grouping them by taxonomical affiliation at the family level, and APase activity is clear, but the lack of understanding of why this relationship occurs and how it can influence current agricultural practices is a significant challenge. My observation regarding the variability within crop families highlights the need for greater precision in the models. Considering plant biology, soil morphology, and agricultural management practices could improve the accuracy and applicability of the results. The question of the possibility of implementing this approach on a global scale is intriguing. It would be a significant challenge, but if achieved, it could lead to novel and useful results that have not yet been evaluated. However, it would require significant collaboration and coordination globally, as well as a deep understanding of regional differences in plant biology, soil characteristics, and agricultural practices

Moreover, other soil biological parameters such as soil bacterial diversity (measured by the Shannon diversity index), phoD gene abundance and richness, and earthworm abundance and biomass, the relationship with ACP and ALP activity is inconclusive in the qualitative analysis. Additionally, although ALP activity has been proposed as an early indicator of change in soil biological status (Angers et al., 1993), it does not show a strong association with specific soil bacterial community composition which needs further investigation. Regarding soil structure, conclusive results are lacking to evaluate whether microaggregates significantly contribute to the transformation of soil P via APase activity, leading to lower concentrations of phosphate monoesters and diesters (Wei et al., 2014).

Initially, the hypotheses proposed regarding management have been confirmed, corroborating the findings of individual experimental studies and previous global analyses. It has been demonstrated that agricultural practices oriented towards sustainable and less aggressive soil management favour APase activity. This is certainly an area that I would like to devote more time to in the future. It is important to consider variables such as species, climate, and non-categorical parameters like fertilizer quantity in management. The study represents a first step, but further work with more complex and elaborate analysis techniques is required to address the questions that farmers have about if the increase of APase activity based on species can play a fundamental role in reducing costs and increasing yields.

The complexity of the plant-microorganisms-animals-soil relationship is evident in this study, considering that croplands have received and continue to receive management that tends to be of high intensity and disturbance. Nevertheless, at the same time, these findings can help evaluate how APase activity contributes to understanding the P stock status and addressing deficiencies in soil P availability for crop growth and productivity. This association can significantly reduce many of the costs related to both mineral and organic fertilizations (organic fertilization, although involving nutrient recirculation, requires the use of machinery that increases carbon footprint) and simultaneously benefit degraded ecosystems with intensive agriculture practiced achieving high yields.

I have observed that yield is directly related to APase activity, further emphasizing the importance of transferring and applying researchers' work for the benefit of farmers.

However, it remains uncertain whether yield acts as a cause or effect in its relationship with APase activity, so this should be investigated in future experiments.

Evidently, new questions have arisen for me upon completing Chapter 1 and 2:

i) can the farmer enhance soil resilience based on the activity of APase in short term?

ii) does soil health increase substantially when sustainable, ecological, and low-carbon footprint agricultural practices are carried out, or is it also possible with sustainable intensive agriculture?

iii) why have species like legumes shown such a low response compared to other species used in intensive agriculture?

iv)) does water availability due to soil retention capacity play a significant role when specific species like legumes are used, or is it solely determined by climatic factors?

iii) why is ACP activity in sites that are unfertilized with crop rotation similar to those with organic fertilization? Does this imply that if crop rotation is used, additional P input is unnecessary?

v) why does a reduction in tillage practice increase ALP activity when a combination of mineral and organic fertilizers is used? Is this result not incompatible with the decrease in soil microorganism diversity caused by long-term mineral fertilization?

In Chapter 3, the results of the APase activity evaluated at the end of the growing season in mountain permanent meadows were not sufficiently clear to determine whether organic fertilization was increasing its activity throughout the growing season or not and its role in forage yield. Although sampling was done correctly, with samples taken as far away as possible from the last fertilization event in all the plots, additional sampling throughout the other specific stages of the growing season could have helped elucidate its true role in this experiment.

Moreover, the laboratory analyses of the parameters I conducted were not fully sufficient to see the connection between APase activity and other soil parameters, such as MBC, MBN, MBP, C:N:P ratios, and those corresponding to K. The role of K content in the soil related to the activity of APase is still unknown. This knowledge gap persists despite attempts to seek an explanation through experimental design. Potassium turned out to be an important element linked to available P, which opens the door to evaluating this macroelement as a determinant for stimulating soil P availability and as a result, how it enhances or decreases the activity of ACP and ALP.

Natural permanent meadows are an example of high biodiversity with minimal management (Peeters et al., 2014) and enhancing the activity of ACP and ALP activity can be of vital importance. For this reason, the results obtained raise new questions:

i) how can soil quality be improved if there were a conversion of some pastures to permanent meadows to prioritize biodiversity conservation and sustainable ecosystem management?

ii) how does climate change affect species that are part of species-rich meadows and play an important role in increasing APase activity?

iii) using APase activity values, could we evaluate if permanent meadows in environmentally degraded areas improve their biodiversity and thus play a role in biodiversity conservation?

iv) can sustainable artificial grasslands be managed to enable APase activity to play an important role in meeting production needs and alleviate pressure on natural grasslands?

v) could a field analysis method for APase activity, that is accessible to farmers and technicians, be evaluated, allowing on-the-spot decision-making based on the response to the management practices being implemented?

7.4 References

Abdalla, M.A., Langer, U. 2009. Soil Enzymes Activities in Irrigated and Rain-Fed Vertisols of the Semi-Arid Tropics of Sudan. International Journal of Soil Science 4: 67-79. https://scialert.net/abstract/?doi=ijss.2009.67.79.

Allison, S.D., Weintraub, M.N., Gartner, T.B., Waldrop, M.P., 2011. Evolutionary-Economic Principles as Regulators of Soil Enzyme Production and Ecosystem Function, in: Shukla, G., Varma, A. (Eds.), Soil Enzymology. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 229–243. https://doi.org/10.1007/978-3-642-14225-3_12.

Angers, D.A., Bissonnette, N., Legere, A., Samson, N., 1993. Microbial and biochemical changes induced by rotation and tillage in a soil under barley production. Canadian Journal of Soil Science 73, 39–50. https://doi.org/10.4141/cjss93-004.

Aponte, H., Meli, P., Butler, B., Paolini, J., Matus, F., Merino, C., Cornejo, P., Kuzyakov, Y., 2020. Meta-analysis of heavy metal effects on soil enzyme activities. Science of the Total Environment 737, 139744. https://doi.org/10.1016/j.scitotenv.2020.139744.

Blaise, D., Rao, M.R.K., 2004. ß-glucosidase and alkaline phosphatase activity as affected by organic and modern method of cotton (Gossypium hirsutum) cultivation of the rainfed Vertisols. Indian Journal of Agricultural Sciences 74, 276–278.

Borase, D.N., Nath, C.P., Hazra, K.K., Senthilkumar, M., Singh, S.S., Praharaj, C.S., Singh, U., Kumar, N., 2020. Long-term impact of diversified crop rotations and nutrient management practices on soil microbial functions and soil enzymes activity. Ecological Indicators 114, 106322. https://doi.org/10.1016/j.ecolind.2020.106322.

Borase, D.N., Murugeasn, S., Nath, C.P., Hazra, K.K., Singh, S.S., Kumar, N., Singh, U., Praharaj, C.S., 2021. Long-term impact of grain legumes and nutrient management practices on soil microbial activity and biochemical properties. Archives of Agronomy and Soil Science 67, 2015–2032. https://doi.org/10.1080/03650340.2020.1819532.

Cattaneo, F., Gennaro, P.D., Barbanti, L., Giovannini, C., Labra, M., Moreno, B., Benitez, E., Marzadori, C., 2014. Perennial energy cropping systems affect soil enzyme activities and bacterial community structure in a South European agricultural area. Applied Soil Ecology 84, 213–222. https://doi.org/10.1016/j.apsoil.2014.08.003.

Chatterjee, D., Nayak, A.K., Mishra, A., Swain, C.K., Kumar, U., Bhaduri, D., Panneerselvam, P., Lal, B., Gautam, P., Pathak, H., 2021. Effect of Long-Term Organic Fertilization in Flooded Rice Soil on Phosphorus Transformation and Phosphate Solubilizing Microorganisms. Journal of Soil Science and Plant Nutrition 21, 1368–1381. https://doi.org/10.1007/s42729-021-00446-8.

Chen, Y., Xia, A., Zhang, Z., Wang, F., Chen, J., Hao, Y., Cui, X., 2023. Extracellular enzyme activities response to nitrogen addition in the rhizosphere and bulk soil: A global meta-analysis. Agriculture Ecosystems & Environment 356. https://doi.org/10.1016/j.agee.2023.108630.

Chocano, C., García, C., González, D., Aguilar, J.M. de, Hernández, T., 2016. Organic plum cultivation in the Mediterranean region: The medium-term effect of five different organic soil management practices on crop production and microbiological soil quality. Agriculture, Ecosystems & Environment 221, 60–70. https://doi.org/10.1016/j.agee.2016.01.031.

Cong, W.-F., Suriyagoda, L.D.B., Lambers, H., 2020. Tightening the Phosphorus Cycle through Phosphorus-Efficient Crop Genotypes. Trends in Plant Science 25, 967–975. https://doi.org/10.1016/j.tplants.2020.04.013.

Cunha, J.R. da, Freitas, R. de C.A. de, Souza, D.J. de A.T., Gualberto, A.V.S., Souza, H.A. de, Leite, L.F.C., 2021. Soil biological attributes in monoculture and integrated systems in the cerrado region of Piauí State, Brazil. Acta Scientiarum - Agronomy 43, 1–9. https://doi.org/10.4025/ACTASCIAGRON.V43I1.51814.

Del Rossi, G., Hoque, M.M., Ji, Y., Kling, C.L., 2023. The Economics of Nutrient Pollution from Agriculture. Annual Review of Resource Economics 15, 105–130. https://doi.org/10.1146/annurev-resource-111820-021317.

De Santiago-Martín, A., Cheviron, N., Quintana, J.R., González, C., Lafuente, A.L., Mougin, C., 2013. Metal contamination disturbs biochemical and microbial properties of calcareous agricultural soils of the Mediterranean area. Archives of Environmental

Contamination and Toxicology 64, 388–398. https://doi.org/10.1007/s00244-012-9842-8.

Dhanker, R., Chaudhary, S., Goyal, S., Garg, V.K., 2021. Influence of urban sewage sludge amendment on agricultural soil parameters. Environmental Technology and Innovation 23, 101642. https://doi.org/10.1016/j.eti.2021.101642.

Dominati, E., Patterson, M., Mackay, A., 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecological Economics 69, 1858–1868. https://doi.org/10.1016/j.ecolecon.2010.05.002.

Dotaniya, M.L., Aparna, K., Dotaniya, C.K., Singh, M., Regar, K.L., 2019. Role of Soil Enzymes in Sustainable Crop Production, in: Enzymes in Food Biotechnology. Elsevier, pp. 569–589. https://doi.org/10.1016/B978-0-12-813280-7.00033-5.

Dou, F., Wright, A.L., Mylavarapu, R.S., Jiang, X., Matocha, J.E., 2016. Soil Enzyme Activities and Organic Matter Composition Affected by 26 Years of Continuous Cropping. Pedosphere 26, 618–625. https://doi.org/10.1016/S1002-0160(15)60070-4.

Fao (2013) – Statistical Yearbook. Table 4. https://www.fao.org/3/i3107e/i3107e.pdf (accessed 18th April 2024).

Galindo, F.S., Delate, K., Heins, B., Phillips, H., Smith, A., Pagliari, P.H., 2020. Cropping system and rotational grazing effects on soil fertility and enzymatic activity in an integrated organic crop-livestock system. Agronomy 10, 1–18. https://doi.org/10.3390/agronomy10060803.

Gelsomino, A., Azzellino, A., 2011. Multivariate analysis of soils: microbial biomass, metabolic activity, and bacterial-community structure and their relationships with soil depth and type. Journal of Plant Nutrition and Soil Science 174, 381–394. https://doi.org/10.1002/jpln.200900267.

Hatti, V., Ramachandrappa, B.K., Sathishand, A., Thimmegowda, M.N., 2018. Soil properties and productivity of rainfed finger millet under conservation tillage and nutrient management in Eastern dry zone of Karnataka. Journal of Environmental Biology 39, 612–624.

Jain, N.K., Jat, R.S., Meena, H.N., Chakraborty, K., 2018. Productivity, Nutrient, and Soil Enzymes Influenced with Conservation Agriculture Practices in Peanut. Agronomy Journal 110, 1165–1172.

Janes-Bassett, V., Blackwell, M.S.A., Blair, G., Davies, J., Haygarth, P.M., Mezeli, M.M., Stewart, G., 2022. A meta-analysis of phosphatase activity in agricultural settings in response to phosphorus deficiency. Soil Biology and Biochemistry 165. https://doi.org/10.1016/j.soilbio.2021.108537.

Jian, S., Li, J., Chen, J., Wang, G., Mayes, M.A., Dzantor, K.E., Hui, D., Luo, Y., 2016. Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. Soil Biology and Biochemistry 101, 32–43. https://doi.org/10.1016/j.soilbio.2016.07.003.

Juma, N.G., Tabatabai, M.A., 1978. Distribution of phosphomonoesterases in soils. Soil Science 126.

Khan, Muzammil Hassan, Liu, H., Zhu, A., Khan, Mudassir Hassan, Hussain, S., Cao, H., 2023. Conservation tillage practices affect soil microbial diversity and composition in experimental fields. Frontiers in Microbiology 14, 1227297. https://doi.org/10.3389/fmicb.2023.1227297.

Kidd, J., Manning, P., Simkin, J., Peacock, S., Stockdale, E., 2017. Impacts of 120 years of fertilizer addition on a temperate grassland ecosystem. PLOS ONE 12, 1–26. https://doi.org/10.1371/journal.pone.0174632.

Kumar, G., Suman, A., Lal, S., Ram, R.A., Bhatt, P., Pandey, G., Chaudhary, P., Rajan, S., 2021. Bacterial structure and dynamics in mango (Mangifera indica) orchards after long term organic and conventional treatments under subtropical ecosystem. Scientific Reports 11, 1–13. https://doi.org/10.1038/s41598-021-00112-0.

Kumar, R., Shambhavi, S., Beura, K., Kumar, S., Singh, R.G., 2017. Soil microbial budgeting as influenced by contrasting tillage and crop diversification under rice based cropping systems in Inseptisol of Bihar. Journal of Pure and Applied Microbiology 11, 539–547. https://doi.org/10.22207/JPAM.11.1.71.

Lambers, H., Raven, J.A., Shaver, G.R., Smith, S.E., 2008. Plant nutrient-acquisition strategies change with soil age. Trends in Ecology & Evolution 23, 95–103. https://doi.org/10.1016/j.tree.2007.10.008.

Landesman, W.J., Dighton, J., 2010. Response of soil microbial communities and the production of plant-available nitrogen to a two-year rainfall manipulation in the New Jersey Pinelands. Soil Biology and Biochemistry 42, 1751–1758. https://doi.org/10.1016/j.soilbio.2010.06.012.

Langer, U., Klimanek, E.M., 2006. Soil microbial diversity of four German long-term field experiments. Archives of Agronomy and Soil Science 52, 507–523. https://doi.org/10.1080/03650340600915554.

Lu, C., Tian, H., 2017. Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. Earth System Science Data 9, 181–192. https://doi.org/10.5194/essd-9-181-2017.

Lv, L., Gao, Z., Liao, K., Zhu, Q., Zhu, J., 2023. Impact of conservation tillage on the distribution of soil nutrients with depth. Soil and Tillage Research 225, 105527. https://doi.org/10.1016/j.still.2022.105527.

Mahapatra, B., Adak, T., Patil, N.K.B., G, G.P.P., Gowda, G.B., Jambhulkar, N.N., Yadav, M.K., Panneerselvam, P., Kumar, U., Munda, S., Jena, M., 2017. Imidacloprid application changes microbial dynamics and enzymes in rice soil. Ecotoxicology and Environmental Safety 144, 123–130. https://doi.org/10.1016/j.ecoenv.2017.06.013.

Malhotra, H., Vandana, Sharma, S., Pandey, R., 2018. Phosphorus Nutrition: Plant Growth in Response to Deficiency and Excess, in: Hasanuzzaman, M., Fujita, M., Oku, H., Nahar, K., Hawrylak-Nowak, B. (Eds.), Plant Nutrients and Abiotic Stress Tolerance. Springer Singapore, Singapore, pp. 171–190. https://doi.org/10.1007/978-981-10-9044-8_7.

Margalef, O., Sardans, J., Fernández-Martínez, M., Molowny-Horas, R., Janssens, I.A., Ciais, P., Goll, D., Richter, A., Obersteiner, M., Asensio, D., Peñuelas, J., 2017. Global patterns of phosphatase activity in natural soils. Scientific Reports 7(1), 1337. https://doi.org/10.1038/s41598-017-01418-8.

Margalef, O., Sardans, J., Maspons, J., Molowny-Horas, R., Fernández-Martínez, M., Janssens, I.A., Richter, A., Ciais, P., Obersteiner, M., Peñuelas, J., 2021. The effect of global change on soil phosphatase activity. Global Change Biology 27, 5989–6003. https://doi.org/10.1111/gcb.15832.

Meher, S., Saha, S., Tiwari, N., Panneerselvam, P., Munda, S., Mahapatra, A., Jangde, H.K., 2021. Herbicide-Mediated Effects on Soil Microbes, Enzymes and Yield in Direct Sown Rice. Agricultural Research 10, 592–600. https://doi.org/10.1007/s40003-020-00536-6.

Miao, F., Li, Y., Cui, S., Jagadamma, S., Yang, G., Zhang, Q., 2019. Soil extracellular enzyme activities under long-term fertilization management in the croplands of China: a meta-analysis. Nutrient Cycling Agroecosystems 114, 125–138. https://doi.org/10.1007/s10705-019-09991-2.

Nannipieri, P., Giagnoni, L., Landi, L., Renella, G., 2011. Role of Phosphatase Enzymes in Soil, in: Bünemann, E., Oberson, A., Frossard, E. (Eds.), Phosphorus in Action: Biological Processes in Soil Phosphorus Cycling. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 215–243. https://doi.org/10.1007/978-3-642-15271-9_9.

Nedyalkova, K., Donkova, R., Malinov, I., 2020. Acid phosphatase activity under the impact of erosion level in agricultural soils of different type and land use. Bulgarian Journal of Agricultural Science 26, 1217–1222.

Peeters, A., Beaufoy, G., Canals, R., Vliegher, A., Huyghe, C., Isselstein, J., Jones, G., Kessler, W., Kirilov, A., Mosquera-Losada, M.R., Nilsdotter-Linde, N., Parente, G., Peyraud, jean-louis, Pickert, J., Plantureux, S., Porqueddu, C., Rataj, D., Stypinski, P., Tonn, B., Wilkins, R.J., 2014. Grassland term definitions and classifications adapted to the diversity of European grassland-based systems. Proceedings of the

25th European Grassland Federation Conference EGF at 50: The Future of European Grasslands 19, 743–752.

Peñuelas, J., Poulter, B., Sardans, J., Ciais, P., van der Velde, M., Bopp, L., Boucher, O., Godderis, Y., Hinsinger, P., Llusia, J., Nardin, E., Vicca, S., Obersteiner, M., Janssens, I.A., 2013. Human-induced nitrogen–phosphorus imbalances alter natural and managed ecosystems across the globe. Nature Communications 4, 2934. https://doi.org/10.1038/ncomms3934.

Pokharel, P., Ma, Z., Chang, S.X., 2020. Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: a global meta-analysis. Biochar 2, 65–79. https://doi.org/10.1007/s42773-020-00039-1.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216.

Qaswar, M., Jing, H., Ahmed, W., Dongchu, L., Shujun, L., Ali, S., Kailou, L., Yongmei, X., Lu, Z., Lisheng, L., Jusheng, G., Huimin, Z., 2019. Long-term green manure rotations improve soil biochemical properties, yield sustainability and nutrient balances in acidic paddy soil under a rice-based cropping system. Agronomy 9. https://doi.org/10.3390/agronomy9120780.

Qu, Q., Wang, Z., Gan, Q., Liu, R., Xu, H., 2023. Impact of drought on soil microbial biomass and extracellular enzyme activity. Frontiers in Plant Science 14. https://doi.org/10.3389/fpls.2023.1221288.

Rao, A.V., Tarafdar, J.C., Sharma, S.K., Kumar, P., Aggarwal, R.K., 1995. Influence of cropping systems on soil biochemical properties in an arid rain-fed environment. Journal of Arid Environments 31, 237–244. https://doi.org/10.1006/jare.1995.0063.

Redel, Y.D., Rubio, R., Rouanet, J.L., Borie, F., 2007. Phosphorus bioavailability affected by tillage and crop rotation on a Chilean volcanic derived Ultisol. Geoderma 139, 388–396. https://doi.org/10.1016/j.geoderma.2007.02.018.

Riddle, M., Bergström, L., Schmieder, F., Kirchmann, H., Condron, L., Aronsson, H., 2018. Phosphorus Leaching from an Organic and a Mineral Arable Soil in a Rainfall Simulation Study. Journal of Enviromental Quality 47, 487–495. https://doi.org/10.2134/jeq2018.01.0037.

Rubin, R.L., van Groenigen, K.J., Hungate, B.A., 2017. Plant growth promoting rhizobacteria are more effective under drought: a meta-analysis. Plant and Soil 416, 309–323. https://doi.org/10.1007/s11104-017-3199-8.

Sardans, J., Lambers, H., Preece, C., Alrefaei, A.F., Penuelas, J., 2023. Role of mycorrhizas and root exudates in plant uptake of soil nutrients (calcium, iron, magnesium, and potassium): has the puzzle been completely solved? The Plant Journal 114, 1227–1242. https://doi.org/10.1111/tpj.16184.

Sardans, J., Peñuelas, J., 2004. Increasing drought decreases phosphorus availability in an evergreen Mediterranean forest. Plant and Soil 267, 367–377. https://doi.org/10.1007/s11104-005-0172-8.

Schils, R.L.M., Bufe, C., Rhymer, C.M., Francksen, R.M., Klaus, V.H., Abdalla, M., Milazzo, F., Lellei-Kovács, E., Berge, H. ten, Bertora, C., Chodkiewicz, A., Dămătîrcă, C., Feigenwinter, I., Fernández-Rebollo, P., Ghiasi, S., Hejduk, S., Hiron, M., Janicka, M., Pellaton, R., Smith, K.E., Thorman, R., Vanwalleghem, T., Williams, J., Zavattaro, L., Kampen, J., Derkx, R., Smith, P., Whittingham, M.J., Buchmann, N., Price, J.P.N., 2022. Permanent grasslands in Europe: Land use change and intensification decrease their multifunctionality. Agriculture, Ecosystems & Environment 330, 107891. https://doi.org/10.1016/j.agee.2022.107891.

Schnitkey, G., Paulson, N., Zulauf, C., Swanson, K., Baltz, J. 2022. Fertilizer Prices, Rates, and Costs for 2023. farmdoc daily (12):148, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, September 27, 2022. https://farmdocdaily.illinois.edu/2022/09/fertilizer-prices-rates-and-costs-for-2023.html.

Shahane, A.A., Shivay, Y.S., Prasanna, R., 2020. Enhancing phosphorus and iron nutrition of wheat through crop establishment techniques and microbial inoculations in conjunction with fertilization. Soil Science and Plant Nutrition 66, 763–771. https://doi.org/10.1080/00380768.2020.1799692.

Shi, Y., Ziadi, N., Hamel, C., Bélanger, G., Abdi, D., Lajeunesse, J., Lafond, J., Lalande, R., Shang, J., 2020. Soil microbial biomass, activity and community structure as affected by mineral phosphorus fertilization in grasslands. Applied Soil Ecology 146, 103391. https://doi.org/10.1016/j.apsoil.2019.103391.

Simpson, R.J., Oberson, A., Culvenor, R.A., Ryan, M.H., Veneklaas, E.J., Lambers, H., Lynch, J.P., Ryan, P.R., Delhaize, E., Smith, F.A., Smith, S.E., Harvey, P.R., Richardson, A.E., 2011. Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems. Plant and Soil 349, 89–120. https://doi.org/10.1007/s11104-011-0880-1.

Singh, G., Bhattacharyya, R., Das, T.K., Sharma, A.R., Ghosh, A., Das, S., Jha, P., 2018. Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo-Gangetic Plains. Soil and Tillage Research 184, 291–300. https://doi.org/10.1016/j.still.2018.08.006.

Souza, L.F.T., Billings, S.A., 2022. Temperature and pH mediate stoichiometric constraints of organically derived soil nutrients. Global Change Biology 28, 1630–1642. https://doi.org/10.1111/gcb.15985.

Stone, M.M., Plante, A.F., 2014. Changes in phosphatase kinetics with soil depth across a variable tropical landscape. Soil Biology and Biochemistry 71, 61–67. https://doi.org/10.1016/j.soilbio.2014.01.006.

Sun, Y., Goll, D.S., Ciais, P., Peng, S., Margalef, O., Asensio, D., Sardans, J., Peñuelas, J., 2020. Spatial Pattern and Environmental Drivers of Acid Phosphatase Activity in Europe. Frontiers in Big Data 2, 1–13. https://doi.org/10.3389/fdata.2019.00051.

Sünnemann, M., Beugnon, R., Breitkreuz, C., Buscot, F., Cesarz, S., Jones, A., Lehmann, A., Lochner, A., Orgiazzi, A., Reitz, T., Rillig, M.C., Schädler, M., Smith, L.C., Zeuner, A., Guerra, C.A., Eisenhauer, N., 2023. Climate change and cropland management compromise soil integrity and multifunctionality. Communications Earth & Environment 4, 394. https://doi.org/10.1038/s43247-023-01047-2.

Swedrzyńska, D., Małecka, I., Blecharczyk, A., Swedrzyński, A., Starzyk, J., 2013. Effects of various long-term tillage systems on some chemical and biological properties of soil. Polish Journal of Environmental Studies 22, 1835–1844.

Tarafdar, J.C., Claassen, N., 1988. Organic phosphorus compounds as a phosphorus source for higher plants through the activity of phosphatases produced by plant roots and microorganisms. Biology and Fertility of Soils 5, 308–312. https://doi.org/10.1007/BF00262137.

Tipping, E., Somerville, C.J., Luster, J., 2016. The C:N:P:S stoichiometry of soil organic matter. Biogeochemistry 130, 117–131. https://doi.org/10.1007/s10533-016-0247-z.

von Uexküll, H.R., Mutert, E., 1995. Global extent, development and economic impact of acid soils. Plant and Soil 171, 1–15.

Wang, M., Wu, Y., Zhao, J., Liu, Y., Chen, Z., Tang, Z., Tian, W., Xi, Y., Zhang, J., 2022. Long-term fertilization lowers the alkaline phosphatase activity by impacting the phoD-harboring bacterial community in rice-winter wheat rotation system. Science of the Total Environment 821. https://doi.org/10.1016/j.scitotenv.2022.153406.

Wei, K., Chen, Z., Zhu, A., Zhang, J., Chen, L., 2014. Application of 31P NMR spectroscopy in determining phosphatase activities and P composition in soil aggregates influenced by tillage and residue management practices. Soil and Tillage Research 138, 35–43. https://doi.org/10.1016/j.still.2014.01.001.

White, P.J., Hammond, J.P., 2008. Phosphorus nutrition of terrestrial plants. Pp. 51–81 in The Ecophysiology of Plant-Phosphorus Interactions, edited by P. J. White and J. P. Hammond. Dordrecht: Springer Netherlands.

Wrage, N., Chapuis-Lardy, L., Isselstein, J., 2010. Phosphorus, Plant Biodiversity and Climate Change, in: Lichtfouse, E. (Ed.), Sociology, Organic Farming, Climate Change and Soil Science. Springer Netherlands, Dordrecht, pp. 147–169. https://doi.org/10.1007/978-90-481-3333-8_6.

Yao, T., Zhang, W., Gulaqa, A., Cui, Y., Zhou, Y., Weng, W., Wang, X., Liu, Q., Jin, F., 2021. Effects of Peanut Shell Biochar on Soil Nutrients, Soil Enzyme Activity, and Rice Yield in Heavily Saline-Sodic Paddy Field. Journal of Soil Science and Plant Nutrition 21, 655–664. https://doi.org/10.1007/s42729-020-00390-z.

Yu, H., Wang, F., Shao, M., Huang, L., Xie, Y., Xu, Y., Kong, L., 2021. Effects of Rotations With Legume on Soil Functional Microbial Communities Involved in Phosphorus Transformation. Frontiers in Microbiology 12. https://doi.org/10.3389/fmicb.2021.661100.

Zhang, Y., Wang, X., Xu, F., Song, T., Du, H., Gui, Y., Xu, M., Cao, Y., Dang, X., Rensing, C., Zhang, J., Xu, W., 2019. Combining Irrigation Scheme and Phosphorous Application Levels for Grain Yield and Their Impacts on Rhizosphere Microbial Communities of Two Rice Varieties in a Field Trial. Journal of Agricultural and Food Chemistry 67, 10577–10586. https://doi.org/10.1021/acs.jafc.9b03124.

Zhu, J., Li, M., Whelan, M., 2018. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. Science of the Total Environment 612, 522–537. https://doi.org/10.1016/j.scitotenv.2017.08.095.

8. General conclusions

The research included in this thesis leads to the following conclusions:

Chapter 1

- The significance of APase activity in P uptake in agroecosystems underscores its pivotal role in the global P cycle.
- In agricultural land, there is a positive relationship between microbial abundance, biomass, activity, soil clay texture, soil moisture, soil organic carbon, and available forms of N and P and ACP and ALP activity.
- The activity of both enzymes is enhanced by management practices promoting soil health such as optimal irrigation, conservation or no-tillage techniques, crop rotation or intercropping, and cover cropping.
- Organic fertilization through the use of amendments such as organic manures, vermicompost, green manures, crop residue management, biochar, and biostimulants/biofertilizers containing beneficial bacteria and fungi has a positive relationship with ACP and ALP activity.
- ACP and ALP activity have a negative relationship with soil depth, salinity, pesticide and sewage sludge use, and high concentrations of heavy metals or other pollutants in agricultural land.

Chapter 2

- In croplands, ACP and ALP activity is negatively influenced by high temperature. Moreover, ACP activity is positively influenced by precipitation while ALP activity is not.
- Crop taxonomical affiliation (crop species family) clearly influences the activity of both APase.
- ACP activity increases under organic fertilization combined with crop rotation or irrigation.
- ALP activity increases under organic or combination of organic-inorganic fertilization and reduced or zero tillage practices.
- Crop yield is greatly influenced by ACP and ALP activity in croplands.

Chapter 3

- In permanent meadows under organic fertilization, organic N input does not imply an increase in APase activity.
- The combined use of farmyard manure and manure effluent, along with an increasing rate of nutrient input, results in a negative effect on ACP activity, while there is no effect when using farmyard manure alone or slurry.
- ACP activity exhibits higher levels in moderately species-rich meadows, while ALP activity is positively influenced by biological factors such as TOC and the Shannon diversity index of the aboveground vegetation.
- Soil available P increases with pH, TOC, soil moisture, K_2O content, and organic N input from farmyard manure. It is moderately positively affected by ALP activity.
- Forage yield of the last growth cycle is positively affected by organic manure input but negatively affected by TOC. APase activity has no effect on it.
- The annual yield increases with N input, and it is higher in moderately species-poor meadows.

2024