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The Entangled Phenology of the Olive Tree: A Compiled Ecological Calendar of *Olea Europaea* L. Over the Last Three Millennia With Sicily as a Case Study

Vincenza Ferrara[1,2] **and Dominic Ingemark**[1]

[1]Department of Archaeology and Ancient History, Uppsala University, Uppsala, Sweden, [2]Department of Human Geography, Stockholm University, Stockholm, Sweden

Key Points:

- The compiled ecological calendar of the olive tree shows phenological stability over the last three millennia
- Land use is entangled with temporal plant behavior and place geography. Derived knowledge is adaptive, relational and transformative
- Cultural diversity and ecological disturbances have not, so far, undermined stability over the long term

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

V. Ferrara,
vincenza.ferrara@arkeologi.uu.se

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Abstract Seasonal cycles in plants and animals drive key timings of human practices in an agrosystem like the best time for harvest, planting, or pruning. Within the framework of historical phenological studies, we attempt a reconstruction of the olive (*Olea europaea* L.) phenology along millennia. Thanks to its extraordinary longevity, the olive tree is a living proxy from the past and embodies a still uncollected long-term memory of ecological behaviors. A cultural keystone species, olive cultivation has more and more played a crucial role for biodiversity conservation, livelihood of rural communities and their enrooted cultural identity in the whole Mediterranean. By compiling traditional phenological knowledge from historical written sources and oral traditions, and using it as historical bio-indicator of the linkage between human ecological practices and seasonal changes of plant behavior, we compiled a monthly ecological calendar of the olive tree covering the last ~2800 years. As a case study, we chose a special place: Sicily, unique for its position in the Mediterranean, geomorphology and legacies in the form of cross-temporal accumulated eco-cultures. Such a sui generis ecological calendar provides an additional case study to explore the intertwining of plant behavior and human adaptation strategies and the interplay between cultural diversity, ecological disturbance and phenological stability. All of this, in turn, can inform action for the present and future sustainable management of these millennial trees.

Plain Language Summary Sicily is a unique island for its geographic location, richness of biodiversity and long-lasting history of cultural cross-fertilization. On the island, it is still possible to find ancient olive trees many centuries old. Local traditional ecological practices are a key factor in their longevity, thus they represent an extremely important biocultural heritage. In the attempt to understand how the olive trees and humans have co-adapted along history, we looked at this plant behavior according to changing seasons over the last three millennia and how humans' accumulated body of experimental knowledge, lying behind their land use practices, has helped them develop adaptation strategies. How far we can ensure the olive biocultural continuity today and in the future depends on how much we can learn from our own past.

1. Introduction

Phenology is the study of the timing of recurring biological events (Lieth, 1974). By looking at seasonal life cycles in plants and animals (Bastian & Bayliss Hawitt, 2022), phenology studies the complex temporal interactions of living beings with each other, and with the temporalities of other surrounding environmental elements (such as, for instance, temperature, light, etc.). Phenology tries to understand how the many and different forms of ecological timing of an organism or populations interact and intersect with the timing of particular components of their environment (Forrest & Miller-Rushing, 2010), making shared life in an ecosystem possible. Phenology spans over a range of analytical approaches at different spatial scales, from macro level (landscape) to meso (ecological communities) and individual level (stands), including statistical methods, interpretation of long-term phenological data, modeling and physiological analysis, with many different forms of data collection (e.g., using remote sensing with satellites and/or phenocams, analysis of time-series photos). An important focus in phenological studies is recording dates of typical conventional phenophases, such as flowering or bud burst in plants, conducted via long-term observations (Bastian & Bayliss Hawitt, 2022).

Humans, to plan what to do next, have always used phenological indicators. Phenological times of plant and animals are connected with the local environmental context, and key timings of human activities, such as the best time for harvest, planting, or pruning for instance are always decided taking into consideration such aspects

rather than arbitrary fixed dates (Bastian & Bayliss Hawitt, 2022). In other words, human communities integrate their practices into the rhythms and seasons of the cross-species ecological relationships they observe, while being at the same time an integral and entangled part of them. Changes in phenological stages are considered ecological fingerprints of environmental and climate change, being driven by seasonal and weather shifts (Fitchett et al., 2015), and regularly incorporated in future climate modeling (Schwartz, 2003). In such respect, historical observations of plant phenology are important to extend our understanding of climatic variations and their potential effects on ecosystems. A first attempt to conduct phenological studies looking at the past was made by Rutishauser et al. (2007), who looked at a multicentennial record (1702–2005) of phenological observations for fruit trees in Switzerland. Other historical observations of phenology have been done with herbarium-based methods (Lavoie & Lachance, 2006; Morellato et al., 2016). Functional paleoecology, which reconstructs vegetation functional dynamics over long time scales using paleoecological data (Napier & Chipman, 2021), offers a promising new approach to understand evolutionary dynamics in response to past disturbance (Brussel & Brewer, 2021; Carvalho et al., 2019).

In the present paper, we attempt a reconstruction of the olive (*Olea europaea* L.) plant behavior along millennial time-scales. For the first time, a long-term view on the phenological dynamics of this species is displayed, from three thousand years ago until the present. We engage with ancient olive trees as living archeological records (*sensu* Rackham, 2018) and their phenology as bio-indicator of humans-trees-environment interactions through time, stored in historical cultural archives (local ecological knowledge). By integrating environmental and cultural records in such a way, we wear a new lens to look at how the material and socio-cultural implications of the relatedness of people and plants along history may inform our action for the present and the future of these ecosystems.

Olive trees are extraordinary and unique plants. Thanks to their longevity, they could be considered living proxies from the past and embody a still uncollected long-term memory of ecological behaviors and dynamics. Despite considered secondary to other crops, in the Mediterranean countries the olive has become nearly a "sacred" tree for locals who, thanks to a continuous careful management, have ensured its survival for centuries (Rühl et al., 2011). With time, the olive has become a cultural keystone species (Garibaldi & Turner, 2004), and its cultivation has more and more played a crucial role for biodiversity conservation, the livelihood of rural communities and their deeply enrooted cultural identity. Today under critical pressure due to global market forces and climate change (Fraga et al., 2021), these long-lasting trees may offer insights on how to manage agrobiodiversity sustainably in the future.

The focus of our research is on the way human ecological practices (as for instance pruning or harvesting) have interlinked naturally with seasonal changes of the olive tree behavior, and how such has taken shape in a very special geographic setting characterized by cross-cultural influences and ecological disturbances: the island of Sicily.

Sicily, unique for its position in the Mediterranean, geomorphology and ecological legacies (Médail, 2017), has been the crossroad of diverse ethnic and cultural groups for millennia. These groups include the Sikels, Sikans, Elymians, Phoenicians (Leighton, 1999, 2000; Tusa, 1994), Greeks and Romans (Fischer-Hansen, 1995); Byzantines, Vandals and Goths, Arabs (Chiarelli, 2011), Swabians, Normans (Carver et al., 2019; Davis-Secord, 2010, 2017; Nef & Ardizzone, 2014), Spanish, French and Italians (Aymard & Giarrizzo, 1987), who have settled on the island at different points in time, in many cases introducing their own political, social and cultural institutions. The cultivation of the olive has been practiced in Sicily for at least the latest three millennia (Ferrara et al., 2019). The Greco-Roman author Diodorus Siculus—a native Sicilian—is the first written reference attesting the presence of cultivated trees in the distant past Siculus (1933). This source has been validated by archeobotanical evidence of early cultivation (De Angelis, 2003; Reitsema et al., 2020; Sadori et al., 2016; Stika et al., 2008) for olive oil production, dated back to Bronze Age (Caracuta, 2020). In the case of Sicily, the persistence of the olive tree (Ferrara et al., 2019; Pasta et al., 2020) as a biocultural refugia (Barthel et al., 2013; Breton et al., 2006), is connected with the geopolitical disruptions and eco-cultural "disturbances" on the island along the centuries, being the result of a long-term *tacit* negotiation process between the ecological knowledge of locals and the practices introduced by all the different new settlers at different points in time.

A detailed description of the methodological framework adopted and the different types of evidence used to reconstruct the ecological calendar of the olive tree over the last three millennia, using Sicily as a case study area, is provided in the Methods and Materials section. The Results present the final main outcome of our work,

the compiled ecological calendar of the olive tree over the last ~2800 years, visually shown both as a linear and cyclical monthly calendar. Such a unique historical compilation of different cross-temporal eco-cultures is a significant scholarly contribution in its own, no ever attempted before. It reveals key elements related to plant behavior and agricultural practices, illustrated in the Results section and further developed in the Concluding discussions, where they provide an innovative perspective on the correlation between cultural diversity, ecological disturbance and phenological stability.

2. Methods and Materials

We reconstructed the long-term memory of the olive tree phenology using an unconventional archive, the Traditional Phenological Knowledge of the different cultural and ethnic groups crossing the island of Sicily through history. Traditional Phenological Knowledge (TPK) is defined by the ethnobotanist Gary Nabhan as "the cultural perception of the timing of recurrent natural history events" (Nabhan, 2010, p. 1). Within the broader concept of Traditional Ecological Knowledge (TEK) (Berkes et al., 2000), TPK may allow to understand phenological changes at the (human) community and local ecosystem interface. Sicily, in particular, represents a unique case for studying the ecological legacies of a cultural melting pot process ongoing for millennia. Present-day remnants of Traditional Ecological or Phenological Knowledge are the result of different stratified and merged knowledges (De Sousa Santos et al., 2007), in which existing cultures and their ecological knowledge have both shaped the newcomers and merged with the new practices brought from outside. Traditional Ecological and Phenological Knowledge, emerging from a deep connectivity with the habitat, are cumulative over generations and empirically based, and can be accessed through ecological calendars. Ecological calendars are an expression of a situated and always optimized knowledge on seasonal changes and relational timings, derived from living in, working and experiencing a specific ecosystemic context, based essentially of a complex connectivity of interrelationship between all its forces and forms (Kassam, 2021; Ullmann & Kassam, 2022).

Adopting a retrogressive approach (Karsvall, 2013), we compiled a single ecological calendar of the olive tree in Sicily over the last approx. 2800 years. We traced back in time all the available sources that could provide evidence on the phenological behavior of the olive tree, compiling such information within a theoretical framework which merges temporal and spatial elements. Phenological behavior cannot be understood if separated from the spatial context, since phenological events are based on spatial interactions and relationships with other species, environmental features and abiotic elements. In such respect, plant phenological behavior is the expression of contextual relationships. At the same time, it is expression of relational timings (Bastian & Bayliss Hawitt, 2022), connecting ecosystem cyclical changes and patterns of human activities (Kassam et al., 2021) embedded in non-linear temporal frameworks.

To compile the olive ecological calendar covering the period from Prehistory to present-day Sicily, different types of sources have been combined: (a) original written sources on agricultural practices and ecological calendars; (b) archeobotanical and paleoecological evidence, to cross-reference olive cultivation in Sicily; (c) Traditional Ecological and Phenological Knowledge (TEK & TPK), collected directly through interviews and published collections of proverbs in the local Sicilian dialect.

1. **Original written sources.** The primary sources used are documentary works on agricultural practices (agricultural handbooks, ecological calendars) from different historical periods (Greek, Roman and Muslim). So far, archeological evidence has not been able to attest a structured practice of olive cultivation in prehistory (see Reitsema et al., 2020; Stika et al., 2008), even though there is evidence of early cultivation and use of *Olea europaea* L. for wood and fruits (Olson, 1939; Romano et al., 2021). Moreover, the obvious absence of written sources or other type of documentation from prehistory makes it impossible to reconstruct the timing of seasonal works related to the olive. However, a potential agricultural calendar for Sicily in the Archaic period has been reconstructed (see Fitzjohn, 2013), supported by literary evidence (mainly based on the Greek author Hesiod) and paleobotanical records (Stika et al., 2008). At a more general level, Håland (2012) reconstructed the agricultural year of the olive for ancient Greece. An interesting early phenological description and explanation of the olive ripening process could be found in the Hellenistic expert of botany (and Aristotle's follower) Theophrastus, when saying that in early autumn "*the fruit gets no increase of oil beyond the amount it received in summer, and that at this time the stone also gets hard, after which date the trees are no longer able to turn their fluid to oil*" (Theophrastus, 6.8.1). Written sources of antique date, above all Roman, contain valuable evidence to reconstruct the ecological calendar of the olive between ca 200 BCE and

400 CE. Moreover, they constantly refer to previous agricultural authors as, for instance, Pliny the Elder who, in his Natural History (Pliny the Elder, 17.30.127–129), mentions the Punic writer Mago, whose works are unfortunately lost. Here lies the great value of such sources: apart from providing ecological information per se, they are expression of an ongoing process of cultural accumulation, integration and transmission, which is a recurrent aspect found in later sources along history.

Between the ninth and the eleventh century CE, Sicily was under Muslim political and military control, and had strong connections with all the other parts of the Islamic world (Kapitaikin, 2013). The new settlers brought into the island their native agroecological knowledge on plants and ecosystems (Bresc, 1972; Ruggles, 2008), which continued even when the Islamic rule ended with the Norman invasions in the last part of the eleventh century (Bresc, 1972). They had so significant impacts on land use practices that the debate remains quite vivid today about its degree of radical influence on current practices of the time (see Fuks et al., 2020; Glick, 1974; Lundy et al., 2021; Watson, 1974). Simultaneously, Islamic agriculturalists learned from local knowledge and incorporated that into their own science, making constantly reference also to previous agricultural works from the classic tradition.

We reviewed all the available original sources, in order to extract and collect the Traditional Phenological Knowledge related to the olive tree: the ancient Greek (**Hesiod**, ca 700 BCE; **Theophrastus**, 372/1 or 371/70–288/7 or 287/6 BCE; **Theocritus**, early third cent. BC) and Roman (**Cato the Elder**, 234–149 BCE; **Varro**, 116–27 BCE; **Lucretius**, 94–55/51 BCE; **Diodorus Siculus**, fl. 60–30 BCE; **Virgil**, 70–19 BCE; **Columella**, fl. 50 CE; **Pliny the Elder**, 23 CE/4–79; **Palladius**, c. mid-fifth cent. CE). These are all sources mentioning agricultural practices along the year. In addition, we included the only available Muslim-Andalusian agricultural calendars and handbooks translated from the original language into French, from the agriculturalist scientists ʻArīb ibn Saʻd (1961) (c. 912—c. 980 CE), Abū ʾl-Khayr ash-Shajjār al-Ishbīlī (1946) (fl. second half 11th cent. CE) and Ibn al-ʻAwwām (d. 1145 CE). Moreover, the phenological information extracted directly from the original ancient texts have been integrated with evidence from existing reviews and commentaries (Amari, 1857; Butzer, 1994; Carrara, 2006; Dufourcq, 1978; Foxhall, 2007; Håland, 2012; Harissis & Harissis, 2009; Hollander, 2019; Hollander & Howe, 2021; Irby, 2016; Lindsell, 1937; Lundy et al., 2021; Olson, 1939; Ruggles, 2008; Sansavini, 2014; Semple, 1928a, 1928b).

The focus of all these original written works is in the description of plant phenological behavior and related agricultural practices, from direct observations or collected transmitted knowledge, regardless of a specific geographic location. Thus, even though characterized by the broad and vague geographic coverage of those times (cf., Figure 1), this written evidence is the only available that can allow to cover such a long period of time when it comes to historical phenological reconstructions. Moreover, in the Mediterranean region, long-term and shorter-term variability in hydro-climate over the last 10,000 years has been documented in multiple records from natural archives, with a dominant south/east versus north/west Mediterranean climate dipole throughout the Holocene (Finné et al., 2019). Sicily is part of the palaeoclimate sub-region, which includes Southern Iberia, southern Italy, the Balkans and northern Greece, which has had a similar climate (Labuhn et al., 2018). Such relative uniformity of climate in Mediterranean subregions allows us to assume that the ancient sources, even though they do not specify the precise location of their observations, refer to phenological behavior of the olive happening in similar climatic and geographic conditions.

2. **Archeological and archeobotanical cross-reference.** Local olive cultivation in Sicily has been cross-referenced by evidence from archeological sites of different periods: Prehistory (Dolce, 2008; Fitzjohn, 2013; Stika et al., 2008; van Dommelen & Bellard, 2008), Hellenistic (Reitsema et al., 2020; Wilson & Leonard, 1980), Roman (Montecchi & Mercuri, 2018) and Medieval (Carver et al., 2019; Montecchi & Mercuri, 2018; Primavera, 2018). As cross-reference we included also the only available published botanical surveys, dating to the 19th century (Cleghorn, 1870), and the most recent but limited archeobotanical evidence coming from several sites site (Mercuri et al., 2019; Michelangeli et al., 2022; Sadori et al., 2016; Tanasi, 2020) and a review on archeogenetics and landscape dynamics in Sicily during the Holocene (Romano et al., 2021).

3. **Traditional Ecological/Phenological Knowledge.** To access the "pockets" of TEK/TPK still surviving locally, we looked at collection of local proverbs in dialect and interviewed locals who, in their everyday work, observed plant behavior and developed quite a complex body of botanical knowledge. Agroecological practices have always been part of an informal body of knowledge, passed down orally from peasant to peasant, and materialized and transformed through customary practices (Glick, 1974). Sicilian dialect is an

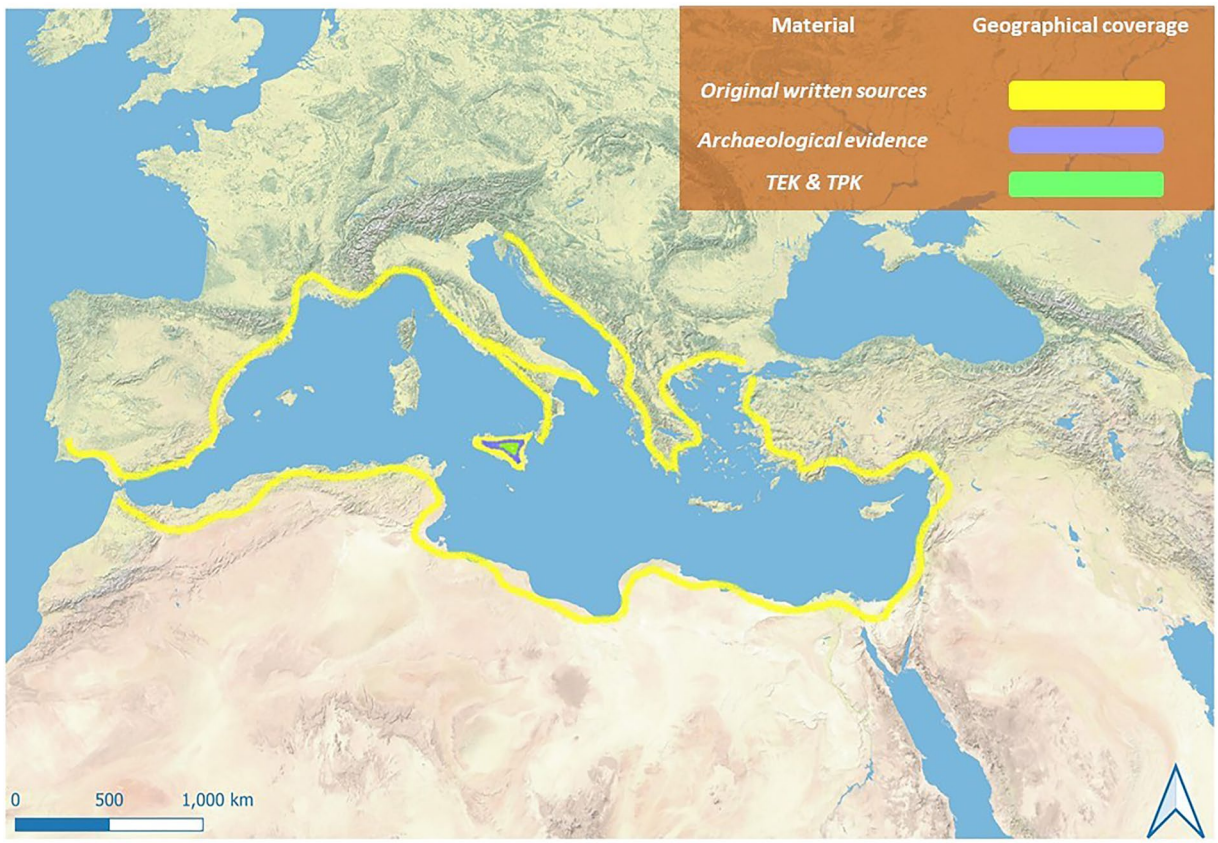

Figure 1. Geographical coverage of the different types of material reviewed and compiled.

old stratified non-written language, used by local communities as fundamental vehicle for the transmission of ecological knowledge over time. In order to access this knowledge, we adopted an "ethno-anthropological and ethnobotanical" approach, combining a large body of local agricultural proverbs in dialect (Alfieri, 2015; Dispenza, 1985; Frattallone, 1991; Giacomarra, 2016), some of them traced back to the nineteenth century and published in early works compiled by the Sicilian ethnographer Giuseppe Pitrè (1880) and the botanist Francesco Minà Palumbo (1854). We looked also at collections of Sicilian folk tales (Zipes & Gonzenbach, 2004) and local folklore (Guggino, 1983; Napoli, 2008).

Ultimately, we reconstructed the olive ecological calendars of the recent past (last century) directly with local communities, conducting semi-structured interviews and focus groups in 2020 and 2021, within the framework of the ERC project "LICCI. Local Indicators of Climate Change Impacts" (FP7-771056-LICCI) (Ferrara, 2022). Data were collected in three towns (Villarosa, Villapriolo, and Calascibetta) of the Morello Valley, study area of current geo-archeological survey under the Vetenskapsrådet (Swedish Research Council) research project "Oliven och Siciliens bio-kulturella arv." The semi-structured interviews (total number of participants: 25) were carried out as two parts. In the first, local livelihoods, timeline events, and seasonal calendar were covered. The selection of informants followed judgmental or convenience sampling (cf., protocol for data collection in Labeyrie et al. (2021) and Reyes-García et al. (2021)), with the aim to interview the most knowledgeable people (local experts). The second part covered local knowledge on the olive tree and its phenology, perceived changes and their correlation with environmental or climatic conditions. In every village, a Focus Group was conducted to discuss and validate in a larger group the topics emerged from the semi-structured interviews. The total number of participants in the Focus Groups was eighteen (18) people. In this case, the participants were selected through convenience sampling, aiming to capture a diversity in terms of livelihood activities and expertise (with special preference given to elders). Methodologically, when collecting information on local ecological memory and on agricultural practices related to the olive tree, we explored the relationship between crop phenophases and spatiotemporal dimension of human practices over the long term.

3. Results

3.1. The Compiled Ecological Calendar of the Olive Tree Over the Last ~2800 Years

The phenological behavior of the olive tree from ca 800 BCE until today is here unfolded. By reconstructing a single unified ecological calendar that can incorporate all the available traditional phenological knowledge from different periods of the past, we traced correlations between olive plant phenophases and ecological processes back in time, including human practices. Our reconstruction covered not only the timing of the olive tree phenology (season variations as blooming, ripening, etc.), but as well the timing of related agricultural works (e.g., pruning, grafting). It is first of all a calendar of plant behavior, second a calendar of human practices and stratified ecological memory along millennia. Per each month and different historical periods, the compiled calendar (Table 1) shows plant phenological stages and human activities performed in those phenological stages. Where the calendar rows are colored green, there is a cross-temporal uniformity of phenological stages and human behavior, and the same practices performed along the centuries are marked in bold. Light blue in the rows indicates a mismatch across different historical periods or lack of data.

3.2. Three Millennia of Cumulative Plant Behavior, Agricultural Time-Space, and Adapted Knowledge

The compilation in just one single calendar, comprehensive of the different traditional ecological and phenological knowledges on the olive tree brought by the various cultural groups crossing Sicily at many points in time, gives a cross-temporal overview of the olive phenology, allowing a number of key elements to emerge in connection to agricultural practices and adaptation strategies.

3.2.1. Plant Behavior and Agricultural Time

Agricultural time is relational, since it is defined after observing phenological non-linear cyclical behavior of the plant. The accumulated knowledge on the temporal relations in the ecological dynamics of an ecosystem allows communities to synchronize their livelihood activities within such ecological context (Kassam et al., 2018, 2021), and therefore to define the timing of their agricultural activities. Such relational nature between phenology and agricultural time in the olive tree management is well embodied by some specific activities, as *pruning*, *planting* and *transplanting*. Pruning is done twice a year: ground sprouts in summer, crown branches in late autumn after the harvest or in early spring before blooming. Nonetheless, while pruning of sprouts is carried out every year, crown pruning is done every few years (Columella, 1941, 5.9.5–7, 5.9.13, 5.9.15; Pliny the Elder, 17.30.127–129; Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, pp. 471–473; Ferrara, 2022). Moreover, even though sprouts pruning takes place annually, in some years it is not done integrally but some sprouts are left with the intentional purpose to be constituent of the tree in the future years (Palladius, 11.8.2; Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 473; Ferrara, 2022). This last practice shows how human agricultural time is cognitively co-constructed (Bastian & Bayliss Hawitt, 2022), since it takes into account the present and, furthermore, future phenological cycles of the plant. Following the same relational logic, cultivation and transplanting practices are usually done in October or March, in a process lasting a few years at least: "*during the first year the nursery ought to be hoed over (…). In the following and subsequent years, when the rootlets of the plants have gained strength, they should be cultivated with rakes; but for the first 2 years, it is best to abstain from pruning, and in the third year, two little branches should be left on each plant, and the nursery should be frequently hoed. In the fourth year, the weaker of the two branches should be cut away. Thus cultivated the small trees are fit for transplantation in 5 years*" (Columella, 1941 5.9.5–6). The example of the transplanting practice is an emblematic expression of the cumulative knowledge people had collected, by experimentation, empirical learning, and trial and error, about plant phenological behavior across different temporal cycles. Such cumulative knowledges help people decide about the different timing of detailed agricultural practices: when to hoe the nursery, when to cultivate using rakes, when and what to prune according to the age of the young plant (Figure 2). The compiled ecological calendar of the olive tree clearly shows that agricultural times are made in situ, across the multiple interactions and experiences humans have with the plant at different temporal scales.

3.2.2. Olive Phenology and the Spatial Element

In the management of the olive tree, the timing of agricultural practices is not only strictly correlated to plant phenophases, but also to spatial considerations that follow well-defined ecological logics. In other words, agricultural time is place-centered and co-constructed along phenological cycles. In such, the environmental context is vital, and thus the spatial element itself becomes constituent of the ecological relationship between humans, the plant and the habitat as a whole (Kassam et al., 2011).

Table 1
The Compiled Ecological Calendar of the Olive Tree Over the Last ~2800 Years (Monthly Linear Time)

Olive Ecological Calendar	"Archaic, Classical and Hellenistic Greek periods" [ca 800–200 BC]	"Roman period" [ca 200 BC–400 AD]	"Muslim period" [ca AD 800–1100]	Proverbs (dialect) & TEK/TPK [ca 1800- today]
January	**Harvest**	**Harvest**	**Harvest** in the mountains Crown pruning Setting props for new trees on the ground	(General for the winter) If the year is snowy, it is a year of olives **Harvest**
February	Harvest	Planting/making nurseries and manuring Establishing olive orchards		2nd Ploughing after the harvest Crown pruning
March	Harvest **Ploughing** **Grafting**	**Ploughing** for olive nurseries, **planting** and **grafting** **Pruning** **Transplanting** before the plant comes into buds and in rich soils Fertilising	**Grafting** **Planting** in colder regions before the plant starts budding	2nd **Ploughing** after the harvest **Pruning** **Grafting**
April	Ploughing	**Pruning**, till mid-April **Grafting** Transplanting before the plant comes into buds	**Olive trees blossom** **Grafting**	Early development of olive pests **Grafting** on land facing south **Pruning** and manuring **Olive blooming**
May	Watering young trees		Olives begin to take shape	Development of olive pests Grafting on land facing north Clear the previous-year grafts from the wild component Olive blooming
June	Watering of young trees			Development of olive pests Clearing the land under the trees from grasses, improve water retain, etc. and sprouts pruning
July	Watering of young trees			Attack from olive pests Clearing the land under the trees from grasses, improve water retain, etc. and sprouts pruning
August	**Watering** of young trees	**Dig trenches** around the olive trees (**for water retain**) and manure	**Watering** **Sprouts pruning**	Clearing the land under the trees from grasses, **improve water retain**, etc. and **sprouts pruning**
September	**Watering** of young trees	**Dig trenches** around the olive trees (for **water retain**) and manure them **Sprouts pruning**	Olives start turning black	Clearing the land under the trees from grasses, **improve water retain**, etc. It is time to visually evaluate the state of the olives´ ripening
October	**Harvest**, pressing, **trenching**, **manuring** and pruning begins	Dig **trenches** around the olive trees (for water retain) and **manure** them **Planting/making nurseries** and **transplanting in hot places** Remove of suckers (some) **Harvest** and make of green oil	The olive **harvest** is evaluated and picking commences **Planting in warmer regions** **Manuring**	It is time to visually evaluate the state of the **olives´ ripening** Clearing the land under the trees **Harvest** **Planting**
November	Olives are mature, **harvest**	**Pruning**, dig trenches around the olive trees (for water retain) and **manure** them Planting in hot and dry areas **Harvest**	**Pruning** **Manuring**	**Harvest** 1st Ploughing after the harvest, **manuring** **Pruning**
December	**Harvest** Trenching, **manuring** and **pruning**	**Harvest** of the ripe olives	**Harvest** and **pruning**	**Harvest and Pruning** 1st Ploughing after the harvest, **manuring**

A first geographical description of vegetation, olives included, present in the lowland meadows and foothills of an ancient landscape around Syracuse, is found in the Sicilian Greek poet Theocritus (ca 300–260 BCE) (Theocritus, 4.43–44; 5.100–101. See Lindsell (1937) for a critical reconstruction of the botanical and geographical references of Theocritus' work). The Roman poet and philosopher Lucretius reports of the use of olive trees as markers to

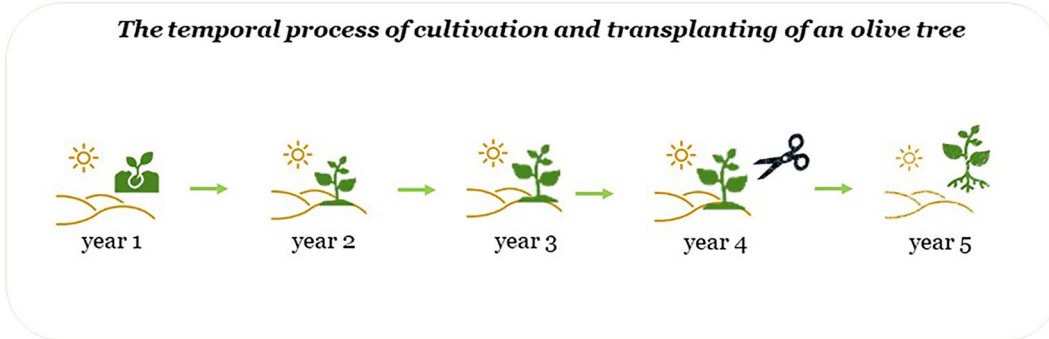

Figure 2. The temporal process of cultivation and transplanting of an olive tree according to the compiled sources.

delimit borders in intercropped fields of hills and valleys, thus referring explicitly to their spatial function in the landscape (Lucretius, 1924, 5.1373–1378).

In ancient texts, there are several precise references to the geometric distance to consider when planting olive trees, always related to environmental features of the landscape and (local) climatic conditions, which, in turn, play an important role on plant behavior. Cato the Elder, in Cato and Varro (1934) explains this: "*In heavy, warm soil plant olives—those for pickling, the long variety, the Sallentine, the orcites, the posea, the Sergian, the Colminian, and the waxy-white; choose especially the varieties which are commonly agreed to be the best for these districts. Plant this variety of olives at intervals of twenty-five or thirty feet. Land which is suitable for olive planting is that which faces the west and is exposed to the sun; no other will be good. Plant the Licinian olive in colder and thinner soil. If you plant it in heavy or warm soil the yield will be worthless, the tree will exhaust itself in bearing, and a reddish scale will injure it.*" (Cato the Elder, in Cato and Varro (1934), 6.1–6.3; see also Varro, in Cato and Varro (1934), 1.24.1–2 on the Licinian olive in cold and thin soils). This passage also shows how people accumulated empirical knowledge on the interrelation between spatiality and olive phenology: first, we have a clear indication of the geographical aspect to prefer for planting (in this case west-facing, cf., Figure 3). And the same is mentioned by Pliny the Elder, when referring to what learned from the Punic author Mago: "*Mago recommends that on sloping ground and in dry positions and in a clay soil they should be planted between autumn and the middle of winter, but in heavy or damp or watery soil between harvest and the middle of winter—though it must be understood that he gave this advice for Africa. Italy at any rate, at the present time, does its planting chiefly in spring, but if one chooses to plant in autumn as well, there are only 4 days of the forty between the equinox and the setting of the Pleiades on which it injures olives to be planted"* (Pliny the Elder, 17.30.127–129). Moreover, as in Cato the Elder, in Cato and Varro (1934), reference to the alignment of the rows toward the west can be found also in Palladius, 3.18.5, when talking about the time (February) when to plant olive trees (Figure 3), together with precise specification about the distance between each tree according to the soil type (in grain-land 40 feet, 25 feet in thin soils, being a Roman foot around 0.3 m). Second, from Cato's and Varro's passages we have information on different *local* varieties of olive trees to choose depending on soil characteristics (i.e., the Licinian for colder and thinner soils).

The need to take into account locality and soil characteristics are also confirmed by other authors later on in history (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 135, 187–188, 222–223; Abū 'l-Khayr ash-Shajjār al-Ishbīlī, 1946, p. 341), as specifications on the distance between each tree (Cato the Elder, in Cato and Varro (1934), 6.1–6.3; Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 193, the distance between olive trees should be 15 to 20 cubits, 1 cubit = 0.461 m). Another good example of the connection between spatiality of human practices, physical environmental features and plant behavior is found in Ibn al-'Awwām Yaḥyá ibn Muḥammad (1983), who provides a detailed explanation about why a specific spatial arrangement is so important to make positive use of a natural element, the wind action: "*The olive tree has affection for the earth which looks at the sea and which is humid; it grows there rapidly, and the vegetation is more brilliant in this region than anywhere else. Agronomists are unanimous (…) that the wind is favorable to the olive tree; it must therefore be planted on the mountains and hillsides, (…) where the snow does not fall in too great quantity, and that it is not exposed (…) to cold and icy winds, nor to an excessive heat*" (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 209), providing furthermore a detailed explanation about why a specific spatial arrangement is so

Figure 3. Spatial considerations (slope aspect, wind blowing, tree alignment) when transplanting and designing an olive orchard.

important to make positive use of the wind action "*The lines must be in the direction from the east to the sunset and from south to north, and equally spaced. (…) thus arrayed the orchard, the east wind and the south wind find easy passage for entry and exit, and, under the influence of their breath, the plantation will be preserved in a satisfactory condition*" (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 215) (cf., Figure 3).

Spatial optimization is very important as well (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 135), such as the practice to plant olives in rows, which enhances the production and improves the overall esthetic appearance of a farm (Varro, in Cato and Varro (1934), 1.4.1–2; Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 137). "*Ognuno si tira u so filaru*" (literally "everyone draws his own row of vineyards or olives", Dispenza, 1985, Ferrara, 2022) is still today one of the most popular proverbs in the Sicilian dialect. Clearly referring to a precise spatial agricultural practice, the proverb is a metaphor to mean that everyone, after all, first and foremost, cares about his own business. The connection between spatial optimization, plant behavior and timing of human practices is skillfully explained by Columella (1941). Since the olive makes fruits at alternate years, he suggests virtually dividing the olive grove in two parts and practicing alternate pruning and intercropping every year, so to have a production every year (Columella, 1941, 5.9.11–12). This practice is still popular today (Ferrara, 2022) (Figure 4).

Even the grafting has a correlation to space, as when Ibn al-'Awwām Yaḥyá ibn Muḥammad (1983) suggests not to graft when the wind is blowing from the north (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 387), or Abū al-Khayr mentioning a special root grafting technique to restore plant fertility: "*the foot is uncovered, on the southern side, then a small trench is dug in the northern direction. We then take two shoots of a very productive tree*"(Abū 'l-Khayr ash-Shajjār al-Ishbīlī, 1946, p. 342).

Lastly, plant association is a recurrent theme in the written sources, clearly expressing the awareness of cross-species interactions at the ecosystemic level. We have already mentioned the strategic use of olive trees as boundary markers and wind protectors for other crops (Lucretius, 1924, 5.1373–1378; Cato the Elder, in Cato and Varro (1934), 6.1–6.3), and their intercropping with underneath crops used as fertilizers (Columella, 1941, 5.9.11–12). Muslim authors give precise indications about the most suitable plant associations for the olive: first of all for the wild olive, playing the pollinator role (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 541); good associations are with the

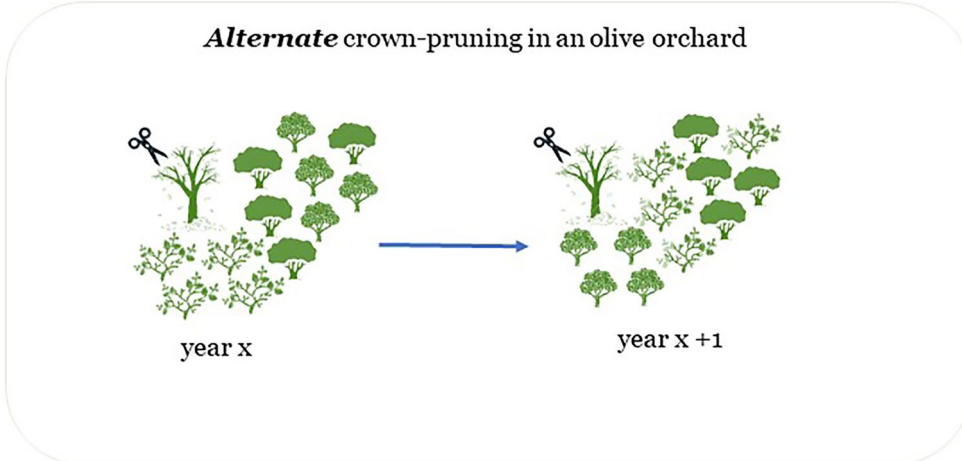

Figure 4. Example of different spatial configurations in an olive orchard due to the practice of yearly alternate crown-pruning.

grape (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 519), pomegranate (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 525), apple and sea squill (*Drimia maritima* L.) (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 520), fig tree (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, p. 542). These plant associations were quite widely used in Sicily until 50 years ago (Ferrara, 2022 and Focus Groups) and their spatial patterns are remnants that can still be seen today (Ferrara & Wästfelt, 2021). The last 50 years have been a period that has witnessed major changes, characterized by a different concept of spatial intensification in the olive orchards: from spatial arrangements resembling agroforestry and polyculture ("*Around the borders of the farm and along the roads plant elms and some poplars, so that you may have leaves for the sheep and cattle; and the timber will be available if you need it",* Cato the Elder, 6.1–6.3) to a more agrarian system in which the process of intensification leads to an increase in the density of olive trees, a reduction in accessory species and the total disappearance of grazing animals (Ferrara, 2022 and Focus Groups). In other words, from a spatial arrangement taking into account and advantage of cross-species biological diversity and interactions in the agroecosystem to drastic homogenizations.

3.2.3. Cumulative Adaptive Knowledge: An Ongoing Transformative Look at Plant Agency in Space-Time

The compiled ecological calendar of the olive tree shows that, along the millennia, humans not only took into account the place-centered/contextual seasonality of the plant and its cycles of growth, but that plants have their own "agency" in responding to and shaping their environments in different ways (Taxel, 2023; van deer Veen, 2014). Through observations and empirical gained knowledge, humans have come to know plant agency in both time and space, thus they have adapted their practices accordingly. This is the case, for instance, of the *planting* practice, suggested along the centuries to be done in autumn as the best period since, in that season, the olive tree growth is concentrated in its root system. Another reason is that autumn guarantees best soil conditions for roots' growing (Columella, 1941, 5.9.6–7; Palladius, 11.8.1; Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, pp. 149–153; Ferrara, 2022). Another excellent example of how humans look at plant phenology and plant agency to decide the timing of their practices is embodied by the practice of *grafting*: as explained by Ibn al-'Awwām Yaḥyá ibn Muḥammad (1983), "*the (opportune) moment to practice grafting (…) is when the subject on which you want to take grafts is about to open (its buds) and show its flowers*" (Ibn al-'Awwām Yaḥyá ibn Muḥammad, 1983, pp. 404–405).

From a human perspective, the collected body of ecological and phenological knowledge related to the olive phenological behavior becomes a Cumulative Adaptive Knowledge (Ullmann & Kassam, 2022), since it implies an ongoing look at the relational agency that this plant has in both space and time and the consequent synchronization of the human practice (Figure 5).The case of the *transplanting* practice provides a good example. As seen above, transplanting has been done preferably in autumn (if the soil is a dry one, with little moisture), but also in spring (if the soil is rich and damp) before the plant is budding. Nonetheless, the transplanting process does not

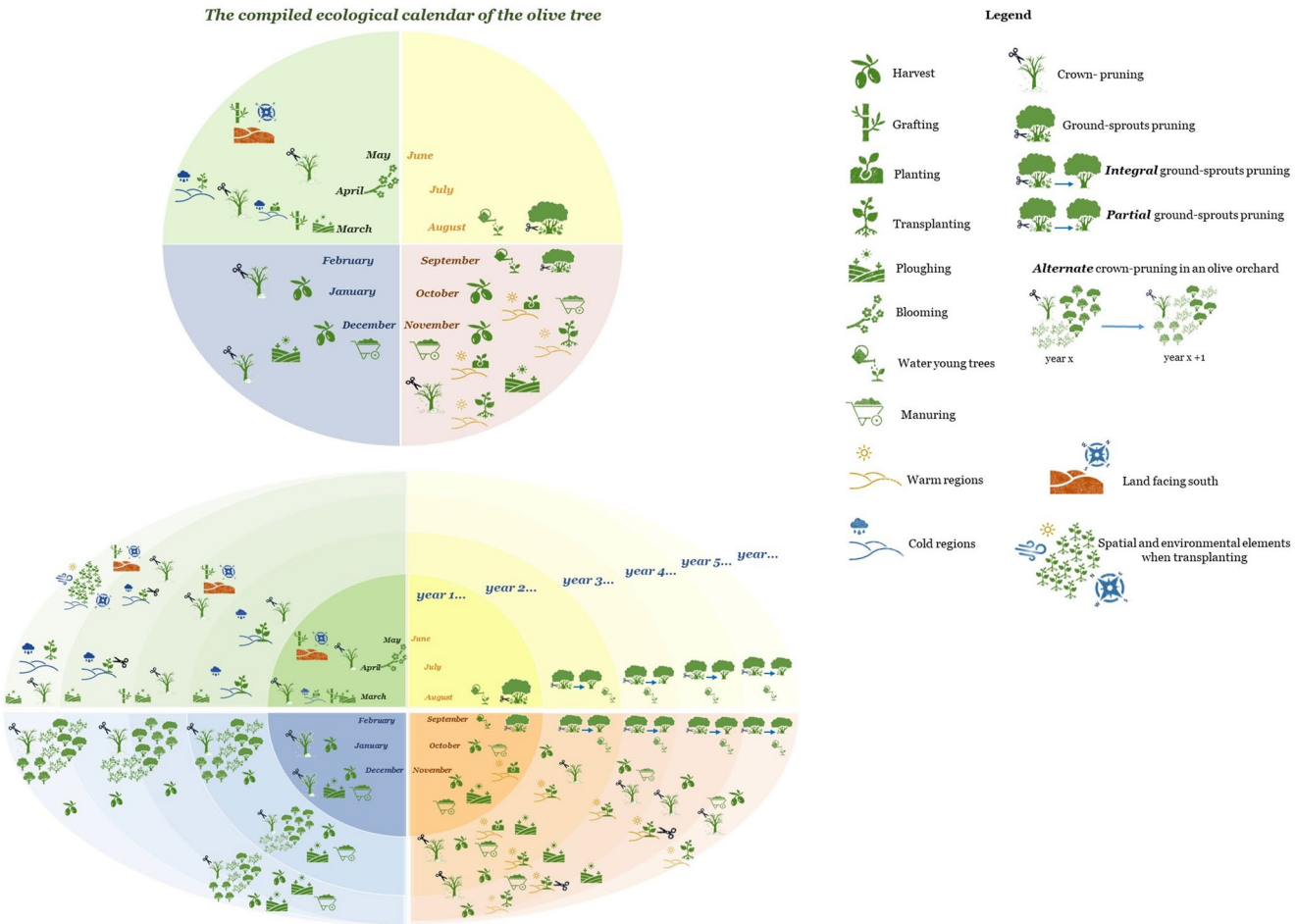

Figure 5. The compiled ecological calendar of the olive tree over the last ~2800 years. Yearly seasonal cyclical time (top left), legend (right), multi-year seasonal cyclical time (down left).

take place randomly, but has a clear spatial logic, correlated to pedological features "*On ground which is rich and fit for growing (…) the space between the rows ought to be sixty feet in one direction and forty in the other: if the soil is poor and not suitable for crops, twenty-five feet"* and how climate interplays with spatiality "*it is proper that the rows should be aligned toward the west, that they may be cooled by the summer-breeze blowing through them*" (Columella, 1941, 5.9.6–7). Another good example is the harvest timing, really depending on entangled crop phenology, spatiality and orography, skilfully explained by Ibn al-'Awwām: "*The best time to harvest trees in the mountains is January (…). The signs by which we recognize that maturity is at its peak is when the liquid contained in the olive has taken on a purple hue. For what is in the plain, especially in seed land, the harvest will be done as soon as the fruit is colored purple, without waiting to turn black, nor to be too ripe. In January, the unctuous part of the olive reaches its complement on the trees planted in the mountains (…)"* (Ibn al-'Awwām, p. 225). Such Cumulative Knowledge is adaptive, in the etymological sense of the term "adaptation": "to act to adjust to." The first part of the adaptation is human knowledge accumulation, emerging from the ecological relationships with their biophysical environment. The second part of the adaptation process is the human capacity to continually refine and recalibrate such knowledge, from season to season and generation after generation, to "navigate" changing environmental circumstances and natural rhythms.

By adapting their practices to plant phenology and harmonizing their livelihood activities with the specific biophysical phenomena observed, humans have had, in turn, long-term impacts on olive plant physiology and behavior. Human practice and its body of Cumulative Adapted Knowledge has thus become **transformative,** in the sense that this knowledge allows humans to continually evolve, or transform, their agricultural practices in the context of their relatedness with the olive plant, in a mutual process in which both plants and people are

changed (van deer Veen, 2014). This concept is brought up immediately by our interviewees, when asked about plant behavior changes in today's olive varieties, which are the result of centuries of grafting and genetic selection done via direct empirical experimentation. The transformative power that this body of accumulated ecological knowledge has on ecosystems was already well-known in antiquity, as Pliny the Elder reports referring retrospectively even to Hesiod, so happening already nearly 2700 years ago, "*who (…) has declared that there was no one who had ever gathered fruit from the olive-tree that had been sown by his own hands, so slow was it in reaching maturity in those times; whereas, now at the present day, it is sown in nurseries even, and if transplanted will bear fruit the following year*" (Pliny the Elder, 15.1, 3. Hesiod, 2018, fragment 227).

3.2.4. Stability and Change

The compilation of the olive ecological calendar along different historical periods, covering as a whole the very long temporal scale of nearly three millennia, makes it possible to trace elements of both stability and variations in the olive phenological stages.

When we look at the overall time scale of our compiled ecological calendar (three millennia), the olive tree appears to have been incredibly stable in its overall phenological trends along the centuries. According to each phenological stage, the timing of related agricultural practices along the year has remained more or less the same as well: crown pruning soon after the harvest and/or in early spring (mainly February and March), grafting in March, blooming in April-May, ground-sprouts pruning in July and August, transplanting in October, harvest starting in October/November. If we zoom in at a shorter timescale, like the past 50 years, significant variations are perceived instead. Interviews with olive farmers make it clear that today climate change poses a threat. The interviewees have witnessed a yearly progressive reduction in the harvest yield caused by a series of unseasonal abrupt climatic events (e.g., sirocco, hailstorms, heavy rains) affecting crops growing patterns by, for instance, destroying flowers or damaging unripe fruits. The threat posed by these recent abrupt climatic events to the long-term stability of the olive tree seasonal behavior should then be an important element to consider when developing present and future management strategies.

4. Concluding Discussions

In this paper, we have deliberately focused on phenology as stored in local ecological knowledge (ecological calendars) and used it as historical archive of humans-trees-environment interactions over a millennial timeframe. The future integration with other relevant methodologies and data sources may set the stage for more accurate investigations on plant-human entanglements, such as aDNA (ancient DNA) research, cross-cultural comparative approaches (sensu Webster, 2008) looking at already published phenological observations in arboreal crops (cf., Primack & Higuchi, 2007) and the influence of genotype × environment interactions on phenology (cf., Navas-Lopez et al., 2019). So far, the compiled ecological calendar of the olive tree shows that, on the island of Sicily, local people relationship with this tree has mainly been a cumulative adaptation process to this plant phenological behavior. An empirical process of ongoing observation, experimentation, accumulation, integration, transmission and improvement of an informal body of ecological knowledge, related to different time dimensions of plant behavior, always seen from a place-centered ecosystemic perspective. In the case of Sicily, this is what has guaranteed the persistence of the olive biocultural heritage.

From our comparison of the different phenological cycles along the centuries, it emerges that climatic variations along millennia did not have significant impacts on olive phenophases. Our analyses also demonstrated that the timing of connected human practices have been more or less stable over time. The extraordinary longevity of these trees and the maintenance of more or less the same practices today, as the ones adopted many centuries ago, reflects both their effectiveness in meeting the needs of local communities and their ability to preserve these agrosystems. Such "stability" can be read as the long-term result guaranteed by a unique anticipatory capacity developed by locals (De Smedt & De Cruz, 2011), based on a singular cumulative adaptive knowledge which is the result of the respect, integration and incorporation of traditional ecological *knowledges* coming from diverse and heterogeneous ethnic groups crossing the island for millennia. In the Sicilian case, these eco-cultural "disturbances" turn out to have been a strength over the long term, allowing locals to better understand connections between seasonal environmental changes and sustainable management of natural resources.

The olive tree may be seen as *la longue durée* of the landscape, representing continuity over time. How far we can ensure it today and in the future depends on how much we can learn from our own past. In compilations of

context-specific ecological calendars, we may find meanings from the changing agrosystems we inhabit and a methodology of hope for their future management. A bird's-eye look at human-nature dynamics over the long term in a case like Sicily could also contribute to teach the ecological value of ethnic diversity.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The audio recordings of the semi-structured interviews and Focus Groups used in this study are stored in DiVA (Digitala Vetenskapliga Arkivet), and accessible via the following link: http://uu.diva-portal.org/smash/record.jsf?pid=diva2:1690733. These data are not publicly available to protect the interviewees' interests, trust and safety. Data collection was conducted according to Uppsala University and its Department of Archaeology and Ancient History compliance procedures to the *CODEX Rules and Guidelines for Research* (http://codex.vr.se/en/omcodex.shtml), the Swedish Research Council´s (VR) Guidelines for Research Ethics (https://publikationer.vr.se/produkt/goodresearch-practice/), the Swedish Research Council's Guidelines relates to the law "Knowing the ethics of research involving humans" (http://www.riksdagen.se/sv/Dokument-Lagar/Lagar/Svenskforfattningssamling/Forordning-20071068-med-ins_sfs-2007-1068/). Informed consent was obtained from all the participants in this study.

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