agronomy

MDPI

Article

Straw Application Strategy to Optimize Nutrient Release in a Southeastern China Rice Cropland

Weiqi Wang [1,2,*], Jordi Sardans [3,4,*], Chun Wang [1,2], Ting Pan [1,2], Congsheng Zeng [1,2], Derrick Y. F. Lai [5], Mireia Bartrons [3,4] and Josep Peñuelas [3,4]

1 Institute of Geography, Fujian Normal University, Fuzhou 350007, China; wangchun821314@163.com (C.W.); panting@hbu.edu.cn (T.P.); cszeng@fjnu.edu.cn (C.Z.)
2 Key Laboratory of Humid Subtropical Eco-geographical Process, Ministry of Education, Fujian Normal University, Fuzhou 350007, China
3 CSIC, Global Ecology CREAF-CSIC-UAB, Cerdanyola del Valles, 08193 Barcelona, Catalonia, Spain; mireiabartrons@gmail.com (M.B.); Josep.penuelas@uab.cat (J.P.)
4 CREAF, Cerdanyola del Valles, 08193 Barcelona, Catalonia, Spain
5 Department of Geography and Resource Management, and Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China; dyflai@cuhk.edu.hk
* Correspondence: wangweiqi@fjnu.edu.cn (W.W.); j.sardans@creaf.uab.cat (J.S.)

Received: 25 October 2017; Accepted: 7 December 2017; Published: 15 December 2017

Abstract: The management and improvement of paddy soils fertility are key factors for the future capacity of rice production. The return of rice straw to paddy soils is the best alternative to the application of industrial fertilizers for rice production sustainability. The best strategy for applying rice straw to improve soil nutritional capacity during rice growth has not yet been investigated. We compared straw decomposition in the ditches and ridges in paddy fields subjected to a typical crop management in southeastern China. Straw spread on the ridges provided lower residual straw carbon (C) concentration and mass, lower nitrogen:phosphorus ratio N:P, C:N, and C:P ratios, and lower soil salinity, as well as higher temperature, and higher N- and P-release capacity during the rice crop in comparison to the straw spread in the ditches. Therefore, applying rice straw to the ridges is better strategy than applying it to ditches to enhance rice production.

Keywords: China; decomposition; habitats; nitrogen; nutrient release; paddy field; phosphorus; rice straw; stoichiometry

1. Introduction

Rice is one of the most important food crops globally, with more than half of the world population fed with rice [1]. Global rice production is projected to increase from 473 million tonnes in 1990 to at least 781 million tonnes by 2020 [2]. Paddy fields in China account for 23% of all cultivated land and nearly 20% of the global rice production [3]. High doses of chemical fertilizers have been used in rice cultivation to increase production in order to meet the increasing demand [4]. The long-term use of chemical fertilizers, however, acidifies the soil and compromises the sustainability of paddy production [5]. The excessive use of fertilizers also increases the risk of pollution [6] and may generate nutrient imbalances in soils and crops, particularly between nitrogen (N) and phosphorus (P) [7]. The use of green fertilizers such as farmyard manure [8] and crop straw [9] has been strongly promoted in recent years as substitutes for, or to reduce the use of, industrial fertilizers in an effort to develop a more sustainable rice production. The return of crop straw has particularly been promoted, because straw is an economical and important source of organic matter and nutrients [10]. The biotic and abiotic decomposition of straw cellulose and hemicellulose releases N, P, and potassium [11]. The application of straw can also increase soil carbon (C) storage [12] to help mitigate global climate change [13].

Straw is currently returned to farmland soil after harvesting, but this practice of soil fertilization and amendment can be problematic. If rice straw decomposes slowly, its residual presence can impede the growth of rice shoots after transplantation to paddies [14] and can affect the total production of the paddies. Optimal strategies for straw application must thus be determined for sustaining nutrient supplies for rice growth and for reducing the inhibition of rice seedlings [15]. Various practices of straw application and incorporation into the soil have been tested, including incorporation with tillage at different depths [16], various proportions of straw incorporation with conventional fertilizers [17], and straw incorporation combined with water-management strategies [10]. These practices, however, have not accounted for the different properties of paddy ridges and ditches.

Plant growth in Chinese wetlands is generally N limited [18]. Nutrient limitation is especially significant in paddy fields, likely because the periodic inundation of the soil limits the access of plants to soil nutrients by the effects of anoxia on root growth [19], the reduction of mineralization rates [20], and the increase in leaching, particularly of N [21]. Rice and vegetable crops are commonly rotated in many provinces of China, such as Fujian, Jiangxi, and Zhejiang. Studying the relationship between crop rotation and the return of rice straw is thus very important. The cultivation of a vegetable crop after a late rice harvest usually requires the construction of a ridge and ditch structure on the soil surface, which potentially generates two different microenvironments where rice straw can be applied. The decomposition of the straw and the release of nutrients will thus likely differ between these microenvironments due to potential differences in soil temperature and salinity, but these differences are not yet known. The elucidation of these unknowns could substantially improve rice production with sustainable practices. In southern China, the common practice consists of growing one crop in each of three growing seasons, including two successive rice crops (early and late) followed by a vegetable (lettuce) crop, with intervening periods of drainage [22]. This management is applied to 56% of the 0.3 million km^2 of China rice croplands [3]. This management system with rotation systems is also widely used in all South Asia, mainly in sites with a pronounced dry season. Thus, a change in rice straw management to improve fertilization has great potential for enhancing rice production.

This study determined (i) the changes in the C:N:P stoichiometry and mass of the residual rice straw and their relationships with other soil variables (temperature, pH, and salinity) during decomposition in the ridges and ditches, and (ii) the capacity of the straw applied at the beginning of the crop rotational cycle to release N and P in the ridges and ditches during rice growth.

2. Results

2.1. Straw Mass Remaining, Nutrient Concentration and Stoichiometry, and Soil Traits

During the straw-decomposition experiment, the proportion of the mass of the straw that remained in the nylon bag, the straw nutrient concentrations, the straw stoichiometry, the proportion of residual nutrients in the straw, and the soil traits all varied seasonally, apart from P concentration and soil pH and salinity (Figures 1, 2 and A2, Tables A1 and A2). The rate of loss of straw mass was highest during the vegetable crop, with similar residual masses in the ridges and ditches (Figure 2).

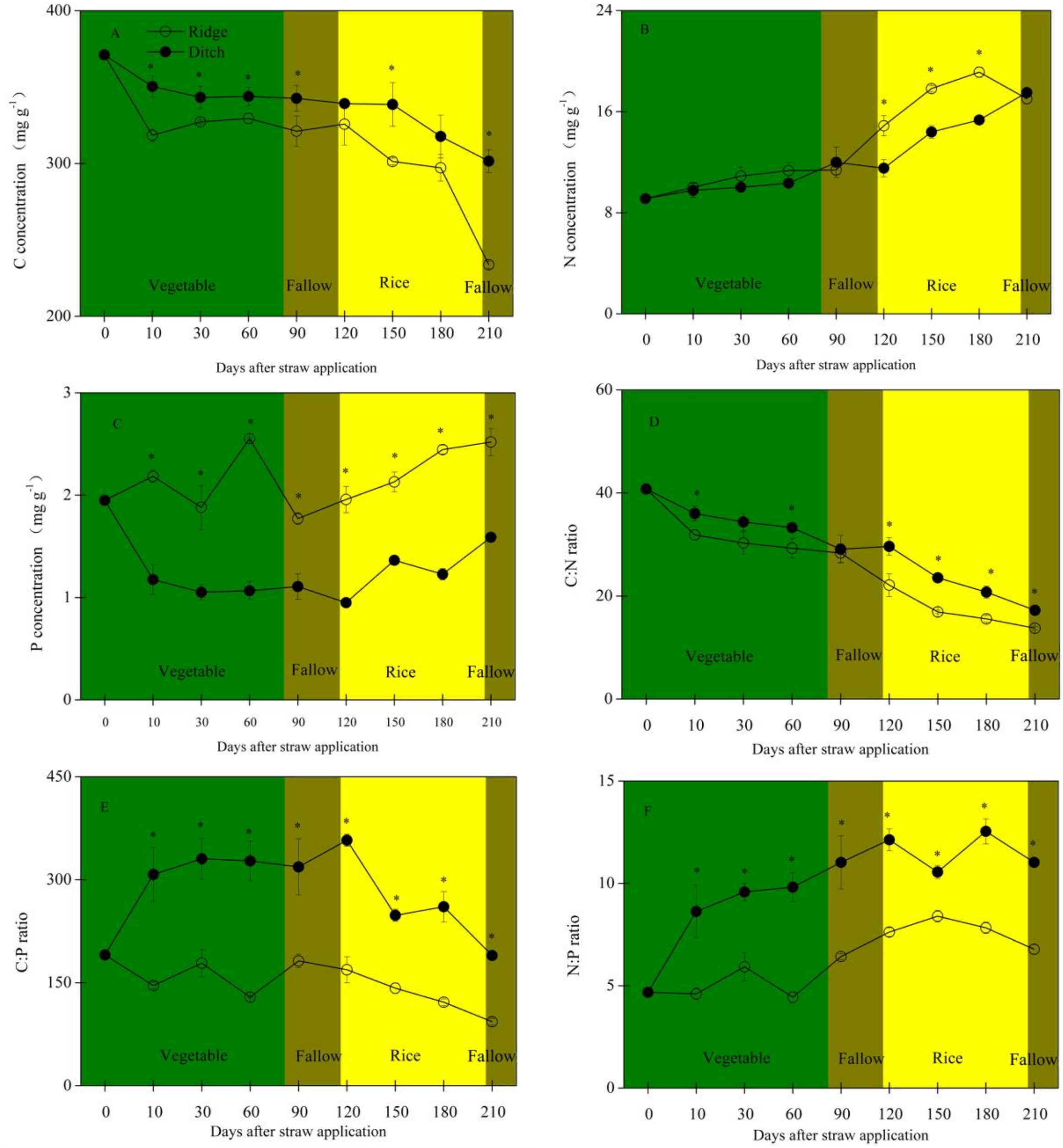

Figure 1. Variation in carbon (C) (**A**); nitrogen (N) (**B**); and phosphorus (P) (**C**) concentrations and C:N (**D**); C:P (**E**); and N:P ratios (**F**) during rice straw decomposition. Statistically significant differences ($p < 0.5$) between ridges and ditches in each sampling date are highlighted with (*).

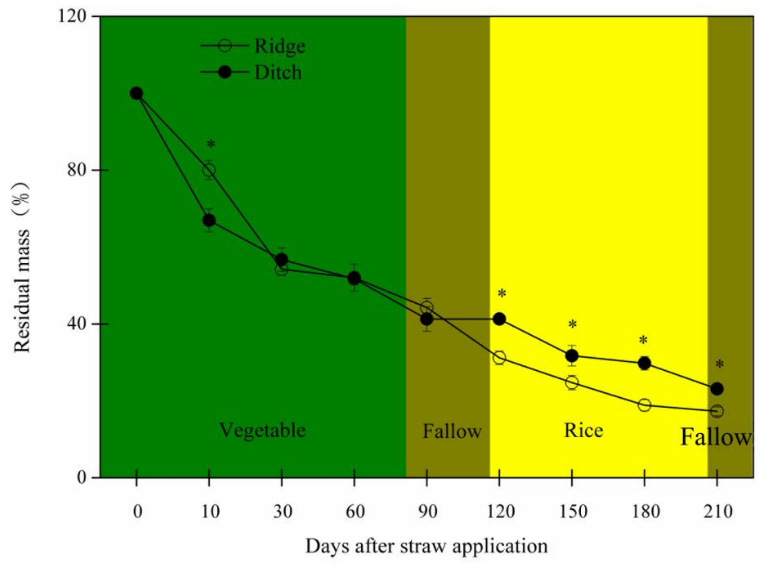

Figure 2. Residual straw mass during rice straw decomposition. Statistically significant differences ($p < 0.5$) between ridges and ditches in each sampling date are highlighted with (*).

Soil salinity also varied considerably between the ridge and ditch habitats along all the studied periods, and soil temperature was higher in ridges than ditches during the rice crop period (Figure A2). Soil temperature, straw N concentration, straw P concentration, and the proportion of residual P in the straw were higher in the ridges than the ditches (Figures 1, 3 and A2), but soil salinity, straw C concentration, C:N ratio, C:P ratio, N:P ratio, and the proportion of residual C in the straw were lower in the ridges than the ditches (Figure 1, Tables A1 and A2). The interactions between period and habitat also differed significantly for most variables, with the exception of straw stoichiometry. Also, the fast loss of 50% of the straw mass in the first 30 days of decomposition was observed.

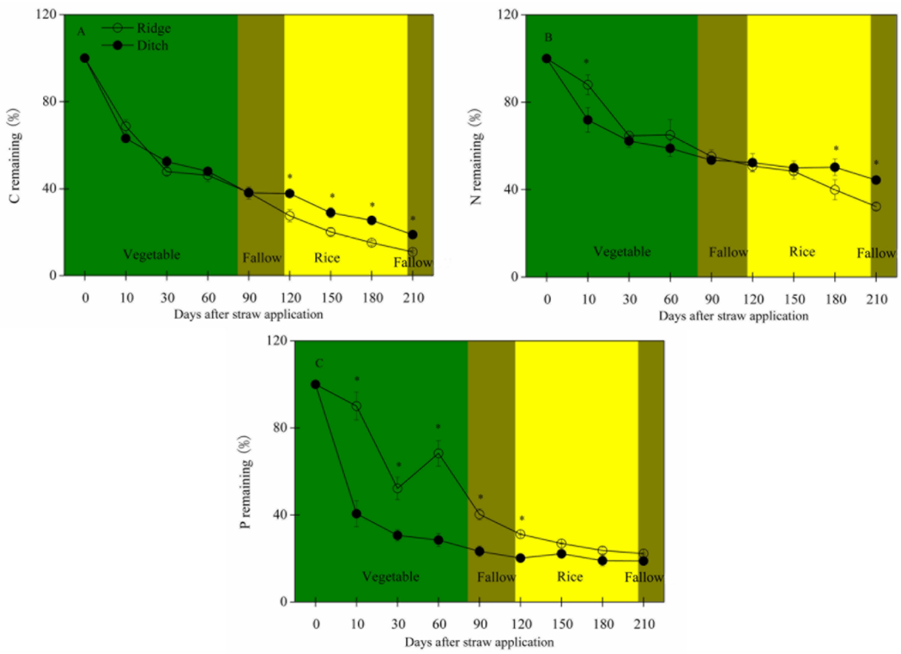

Figure 3. The dynamic changes of residual carbon (C) (**A**); residual nitrogen (N) (**B**); and residual phosphorus (P) (**C**) concentrations during rice straw decomposition. Statistically significant differences ($p < 0.5$) between ridges and ditches in each sampling date are highlighted with (*).

2.2. Residual Straw Mass and Nutrients, Nutrient Release, and Influencing Factors

The mass of the straw that remained in the nylon bag (% of the initial content) was correlated negatively with soil temperature ($R = -0.85$, $p < 0.001$), straw N concentration ($R = -0.88$, $p < 0.001$), and straw N:P ratio ($R = -0.36$, $p = 0.006$), and positively with soil salinity ($R = 0.32$, $p = 0.014$), straw C concentration ($R = 0.53$, $p < 0.001$), straw C:N ratio ($R = 0.86$, $p < 0.001$), and straw C:P ratio ($R = 0.28$, $p = 0.025$) (Table A3).

The proportions of residual C, N, and P in the straw (% of the initial content) were correlated negatively with temperature ($R = -0.86$, $p < 0.001$; $R = -0.72$, $p < 0.001$; $R = -0.62$, $p < 0.001$; respectively), straw N concentration ($R = -0.90$, $p < 0.001$; $R = -0.69$, $p < 0.001$; $R = -0.51$, $p < 0.001$; respectively), and straw N:P ratio ($R = -0.28$, $p = 0.025$; $R = -0.33$, $p = 0.010$; $R = -0.77$, $p < 0.001$; respectively), but positively with the proportion of residual mass ($R = 0.99$, $p < 0.001$; $R = 0.93$, $p < 0.001$; $R = 0.76$, $p < 0.001$; respectively) and straw C:N ratio ($R = 0.90$, $p < 0.001$; $R = 0.67$, $p < 0.001$; $R = 0.43$, $p = 0.001$; respectively) (Table A3). The proportion of residual C and N in the straw were positively correlated with soil salinity ($R = 0.35$, $p = 0.008$; $R = 0.31$, $p = 0.016$; respectively) and straw C concentration ($R = 0.62$, $p < 0.001$; $R = 0.47$, $p < 0.001$; respectively). The proportion of residual C in the straw was negatively correlated with straw P concentration ($R = -0.23$, $p = 0.019$). The proportion of residual N in the straw was positively correlated with litter P concentration ($R = 0.43$, $p = 0.001$). Finally, the straw C:P ratio was correlated positively with the proportion of residual C in the straw ($R = 0.38$, $p = 0.004$), but negatively with the residual N in the straw ($R = -0.36$, $p = 0.006$).

More N and P were released during the rice crop (% of the initial content) from the straw in the ridges than from the straw in the ditches; the straw applied to the ridges released 18% of the initial N contents and 9% of the initial P contents, whereas the straw applied to the ditches released 8% of the initial N contents and 2% of the initial P contents (Figure 4).

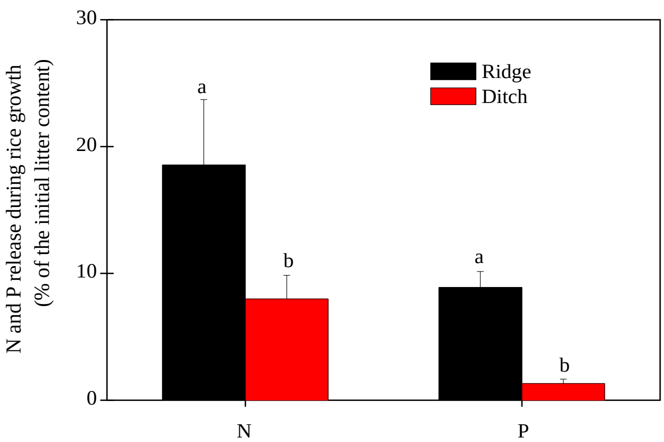

Figure 4. Comparison of nitrogen (N) and phosphorus (P) release during rice growth. Different letters mean statistical differences ($p < 0.05$) of the corresponding variables between ridges and bridges.

2.3. Multivariate Analyses

We performed multivariate statistical analyses by using general discriminant analysis (GDA) to determine the overall differences between the ridges and ditches in the changes of total soil C, N, and P concentrations; soil C:N, C:P, and N:P ratios; straw mass; residual C, N, and P concentrations; and soil salinity, pH, and temperature during straw decomposition. We used sampling day as an independent categorical variable and habitat as the categorical dependent variable. GDA is an appropriate tool for identifying the variables most responsible for the differences among groups while controlling the component of the variance due to other categorical variables (see Materials and Methods). This analysis indicated statistical differences among the variables between the ditches and ridges (Figure A3, Table A4).

2.4. SEM

We used structural equation modeling (SEM) to analyze the factors explaining the maximum variability of the biomass; residual straw C, N, and P concentrations; soil C, N, and P concentrations; and C:N, C:P, and N:P ratios throughout the study period as functions of the habitat and the other soil traits. This analysis provides information on the direct, indirect, and total effects of the variables (see Materials and Methods). The structural model that best represented the variance of the residual mass of straw in the litter bags contained habitat and soil temperature, through the direct and indirect effects on either straw N:P or straw C:N (Figure 5). The best structural model for P concentration contained habitat and soil salinity (R^2 = 0.78) (Figure 6), and the best structural models for C and N concentrations contained habitat and soil temperature (Figure 6).

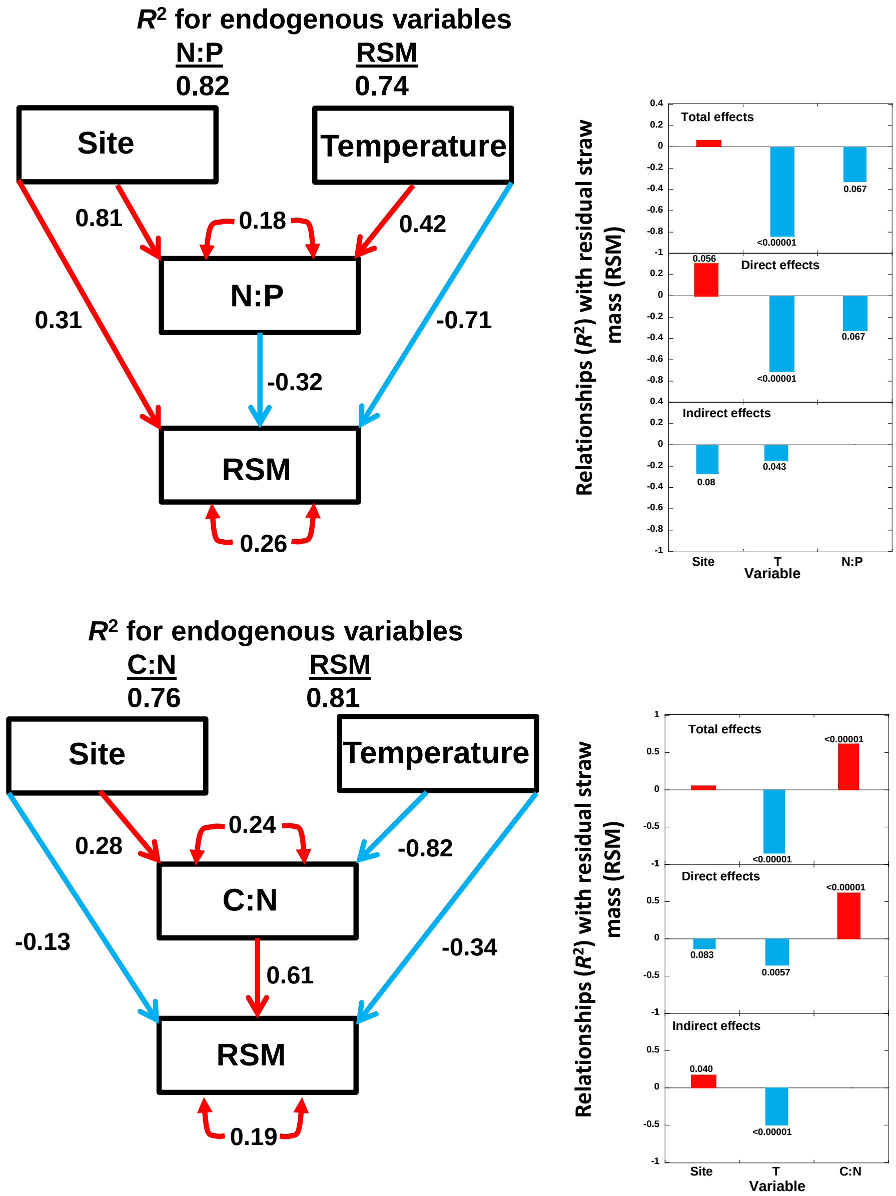

Figure 5. Diagrams of the structural equation models that best explained the maximum variance of the residual mass (RSM) with habitat (ridges and ditches) and soil traits as exogenous factors and the elemental composition and stoichiometric variables of the straw as endogenous variables. MRe, residual mass. Positive relationships are indicated by blue arrows and negative relationships with red arrows.

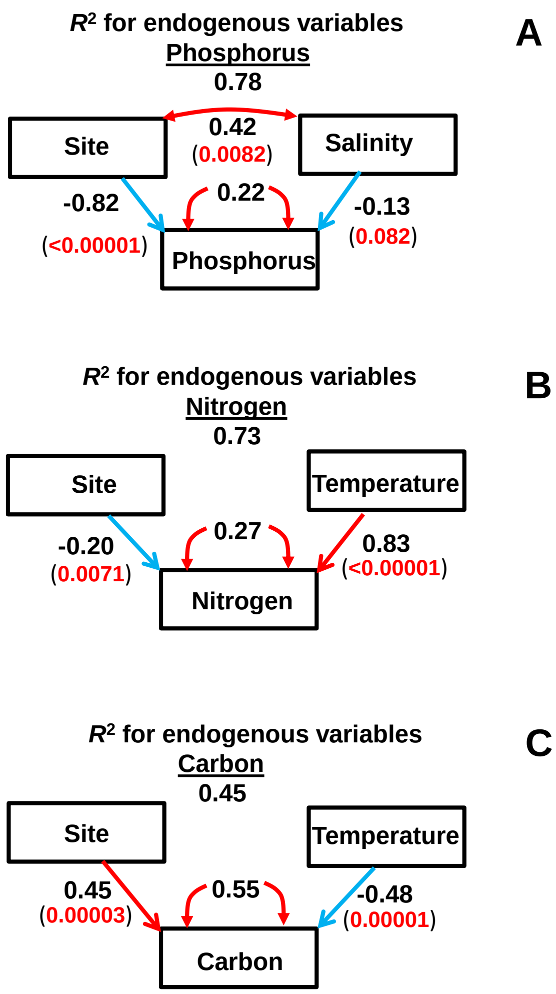

Figure 6. Diagrams of the structural equation models that best explained the maximum variance of the elemental composition of the straw during decomposition with habitat (ridges and ditches) and Phosphorus (**A**); Nitrogen (**B**); and Carbon (**C**) concentrations in residual litter as exogenous factors. Positive relationships ware indicated with blue arrows and negative relationships with red arrows.

3. Discussion

3.1. The Impacts of Different Methods of Straw Application on Straw Decomposition

The straw mass loss for the two straw treatments was high during the first 30 days of the experiment (approximately 50%). This result is consistent with a previous study reporting that water-soluble substances and easily soluble carbohydrates are rapidly leached and degraded in the first weeks of plant litter decomposition [23]. In our experiment, nutrient concentrations changed with decomposition time. The negative correlation between the residual mass and nutrient (N and P) concentrations suggested that N and P were not limiting for the decomposition by soil microorganisms during the first 30 days. Winter at the study site, however, began 30 days after the application of the straw. The decrease in temperatures coincided with the observed slowing of straw decomposition. In spring, after the first 120 days of decomposition, litter mass loss remained constant, despite the fact that this period coincided with a gradual increase in temperatures. These low rates of straw decomposition may also in part be due to the accumulation of lignin, cellulose, and other recalcitrant substances in the straw [24].

The straw decomposition rate was higher in the ditches than the ridges during the first 10 days, which may have been due to the initial higher impacts on the ridges of the plastic sheeting covering the ridges at the beginning of the vegetable crop.

3.2. The Variability of C, N, and P Concentrations and C:N:P Stoichiometry during Straw Decomposition

Several studies have also shown that the N:P ratio is an important factor during litter decomposition and can provide information on the most limiting nutrient [25]. The relative demand of a nutrient during decomposition, such as C, N, and P, may control the stoichiometric C:N:P dynamics in decomposing litter [26]. In our study, the residual straw mass was not significantly correlated with P concentration, but was negatively and significantly correlated with the N:P ratio. This result suggested that straw decomposition is N limited in this area, consistent with the low N:P ratios of soils at this study site, around 1.1 in mass basis, when the global average reported by Cleveland and Liptzin [27] is 5.9, and further suggesting a general N limitation in this ecosystem that may be associated with higher N than P uptake by decomposers. Soil total N and P concentrations at this site were reported as 1.2 and 1.1 mg g^{-1}, respectively [28].

Wang et al. [29] also reported a similar molar N:P ratio of 2.42 in the soils of other ecosystems in the same wetland where the studied rice crop was located. This ratio is much lower than the average of 28 for various wetlands around the world [30], providing strong evidence of the N limitation of this wetland. Moreover, the P concentration in the straw varied more than the C and N concentrations during decomposition, similar to the litter decomposition in a natural wetland in the same area [31]. Indeed, changes in nutrient levels during litter decomposition have been associated with a large variation in microbial P contents [32].

The N and especially the P concentrations of the straw located on ridges tended to be higher in ridges than in ditches during the first 120 days of decompositions. In the more aerobic environment of ridges, P is proportionally more retained than N in straw in comparison with the more anaerobic environment of ditches. The application of straw on ridges thus tended to release decomposition products with a higher N:P ratio than the application of straw in ditches. This result was consistent with the proposal that organisms in a medium poor in N should invest more effort to take up the limiting element to maintain a more equilibrated N:P ratio [33]. Organisms will release or absorb nutrients to or from the environment to maintain an optimum stoichiometry of C, N, P, and other elements [33]. The rate of litter decomposition in the first 120 days was higher in the well-oxygenated and warmer ridge habitats than in the ditch habitats. The ridges had more favorable environmental conditions (temperature, oxygen, and salinity) for increasing the nutrient-use efficiency, carbon use, and respiration, so more C can be used without the need for as much N and P [34]. Water conditions were quite different between ridges and ditches during vegetable growth; the decomposition of rice straw was more aerobic in the ridges than in the ditches. Water conditions (time of flooding and soil water content) were also underlying the differences in temperature and salinity between ridges and ditches. So, the differences in straw decomposition observed in the study may mainly result from the different water status between ridges and ditches. The higher temperatures of the ridges were in fact correlated with lower litter C:N ratios and higher N concentrations. This trend was not observed for litter P concentration, which, in contrast, was negatively correlated with salinity. Similar results have been reported in the decomposition of *Kandelia candel* litter under different salinity conditions in laboratory experiments, with lower litter P concentrations occurring under conditions of high salinity [35]. Consistent with these results and within the framework of the Growth Rate Hypothesis [33], environments with high salinity should favor microbial communities with high N:P demands, so P should be released from litter more slowly than other nutrients, such as C and N. The evolution of C and N concentrations and contents in litter during decomposition should thus be more dependent than litter P concentration on environmental factors such as temperature or salinity that affect soil microorganisms.

The straw in the ridges thus had lower C:N and C:P ratios and less residual mass at the beginning of the rice crop (120 days after straw application). These results were consistent with the higher release of N and P during the rice crop (120–210 days of decomposition), because the highest rates of decomposition and soil respiration of organic matter are correlated with lower C:N and C:P ratios under the same environmental conditions [36]. The C:N and C:P ratios of the straw in the ridges during the rice crop, however, tended to converge with those of straw in the ditches, which were correlated with the higher release of N and P from straw in the ridges. These results are consistent with the long-term decomposition of different types of litter under similar environmental conditions reported by a previous study [37].

In summary, the release of nutrients from the straw differed between the ridges and ditches due to the different environmental conditions of these two habitats. Carbon release was higher, whereas N and P release and released C:N, C:P and N:P ratios from straw were lower in the ridges than in the ditches at the beginning of the decomposition period during the vegetable crop and the first fallow period. The straw in the ridges thereafter released more N and P during the rice crop. The application of straw on the ridges thus allowed a better release of N and P during the rice crop and produced less residual straw mass than the application of straw in the ditches. Both of these factors can enhance rice growth.

4. Materials and Methods

4.1. Study Site

All field experiments were performed in the Wufeng Agronomy Field of the Fujian Academy of Agricultural Sciences (26.1° N, 119.3° E; Figure 7) in subtropical southeastern China. This field was managed following the common practice of growing one crop in each of three growing seasons, including two successive rice crops (early and late) followed by a vegetable (lettuce) crop, with intervening periods of drainage [22]. The early rice crop is grown from March-April to June-July, the late rice crop is grown from July-August to November-December, and the vegetable crop is grown from November–December to February-March. During this last period ditches are flooded during some periods, whereas ridges are never flooded. Moreover, during this period plastic sheeting is used to cover the ridges but not the ditches. This practice increases the temperature and reduces the weed impact, thus improving the vegetable growth. Chemical fertilizer (N, P_2O_5, and K_2O at a rate of 200, 158, and 141 kg ha^{-1}, respectively) was applied once to the vegetable crop on 17 December 2011. Fertilizer was applied to dry soil. The other two additional fertilizations were applied to flooded water. Chemical fertilizers were applied in three splits with different nutrient loadings using a mix of complete fertilizer (N:P_2O_5:K_2O = 16%:16%:16%, Keda Fertilizer Co., Ltd., Jingzhou, China) and urea fertilizers (46% N). Chemical fertilizer (including N, P_2O_5, and K_2O at a rate of 95, 70, and 70 kg ha^{-1}, respectively) was applied to the rice crops before transplantation, at the tillering stage, and at the panicle-formation stage. The three dates of fertilization were 8 April 2012, 20 April 2012, and 12 June 2012. The field was ploughed to a depth of 15 cm with a moldboard plow. The plough dates for the vegetable crop and the early rice crop were 10 December 2011 and 8 April 2012. The rice variety was Hesheng 10, which is the rice variety commonly cultivated in southeast China, and the lettuce variety was Kexing 5, also frequently used in southeast China. The spacing between individual plants was 14 × 28 and 40 × 60 cm, respectively.

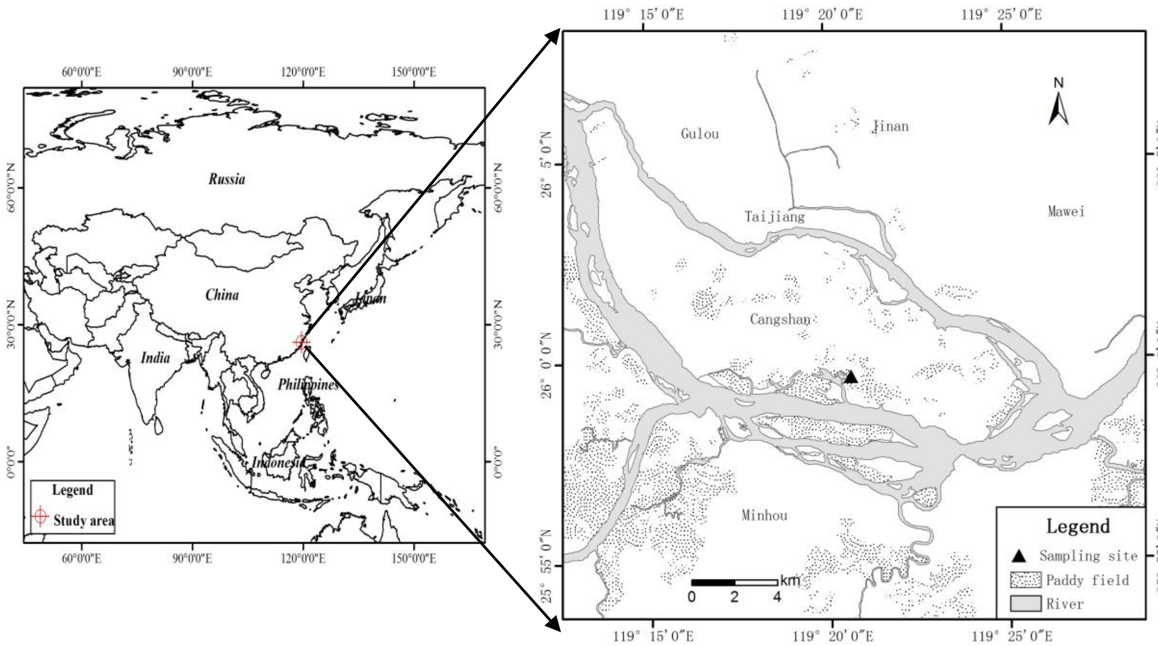

Figure 7. The location of the study area and sampling site in Fujian province, southeastern China.

The soil of the paddy field was moist, poorly drained, and had a sand:silt:clay content of 28:60:12 [28]. The bulk density of the soil prior to this study was 1.1 g cm^{-3}. The soil pH (1:5 with H_2O) was 6.5, and the concentrations of organic carbon, total N, and total P were 18.1, 1.2, and 1.1 g kg^{-1}, respectively [28]. The water level was maintained at 5–7 cm above the soil surface in the rice crops before the late tillering stage, and then drained for the control of non-productive tillering [38]. After about one week, the paddy field was re-flooded, kept alternately wet and dry, and then drained again two weeks before rice harvest.

4.2. Experimental Design

The rice straw used in the experiment was collected from the late rice crop. The straw-decomposition experiment used nylon-mesh bags [39]. Each bag was 20 × 20 cm with a pore size of 1 mm and contained 13 g of straw, and the bags were placed on top of the soil. The experiment began on 17 December 2011 during the vegetable crop season. The field contained two microhabitats during this period, the ditches and ridges, which provided the two treatments of this decomposition experiment (Figure A1), with three replicates each. The ridges were 40 cm apart with heights and widths of 15 cm, which is typical for this area. Straw samples were collected 10, 30, and 60 days after straw application during the vegetable crop (17 December 2011 to 8 March 2012); 90 days after straw application during the first fallow period (8 March to 11 April 2012); 120, 150, and 180 days after straw application during the early rice crop (11 April to 13 July 2012); and 210 days after straw application during the second fallow period (13 July to 31 July 2012). The experiment thus consisted of two treatments (habitats) × eight sampling times × three replicates = 48 sample bags.

4.3. Sample Collection and Analysis

Three samples (one from each replicate) were randomly collected from each treatment on each sampling date. The litter from each nylon bag was gently washed with water and subsequently oven-dried to a constant mass (65 °C for 24–36 h) and weighed. These dried and cleaned samples were then finely ground in a ball mill. The C and N concentrations of the dried litter were determined using a Vario EL III Elemental Analyzer (Elemental Scientific Instruments, Hanau, Germany). The P concentration of the litter was measured using the molybdate-blue reaction [40] with a UV-2450 spectrophotometer (Shimadzu Scientific Instruments, Kyoto, Japan).

Soil salinity (mS cm^{-1}), pH, and temperature were measured in situ on each sampling date at a depth of 20 cm. Soil pH and temperature were measured with a pH/temperature meter (IQ Scientific Instruments, Carlsbad, CA, USA), and soil salinity was measured using a 2265FS EC Meter (Spectrum Technologies Inc., Paxinos, PA, USA).

4.4. Statistical Analyses

We analyzed the changes in elemental composition and stoichiometry during litter decomposition in the two habitats (ridges and ditches) at the various sampling times (after 10, 30, 60, 90, 120, 150, 180, and 210 days). Litter C, N, and P concentrations; C:N, C:P, and N:P ratios; and C, N, and P remaining (% of initial respective amount) during the studied period of litter decomposition were the dependent variables, while habitat (ridges and ditches) represented the fixed independent factor with repeated measures along time of sampling and plots as random factors. We used the "nlme" [41] R package with the "lme" function. We chose the best model for each dependent variable using Akaike information criteria. We used the MuMIn [42] R package in the mixed models to estimate the percentage of variance explained by the model.

We also studied the effect of time by the crop period (vegetable: from 0 to 60 days, fallow: 90 days, rice crop: from 120 to 180 days, fallow: 210 days). Pearson correlation analyses identified the relationships among the rate of litter decomposition and nutrient release with C, N, and P concentrations; C:N, C:P, and N:P ratios; and soil factors. These univariate analyses were performed using SPSS 13.0 (SPSS Inc., Chicago, IL, USA).

We also performed multivariate statistical analyses by using general discriminant analysis (GDA) to determine the overall differences between ridges and ditches in the changes of total soil C, N, and P concentrations; soil C:N, C:P, and N:P ratios; straw mass; residual C, N, and P concentrations; and soil salinity, pH, and temperature during straw decomposition. We also assessed the component of the variance due to the sampling day as an independent categorical variable. GDA is thus an appropriate tool for identifying the variables most responsible for the differences among groups while controlling the component of the variance due to other categorical variables. This analysis used the Squared Mahalanobis Distance statistic that depends on the Euclidean distance in the model between two sets of samples; if the sets were closer or less different, the squared Mahalanobis distance would be lower, and if the sets were more distant or more different, and the squared Mahalanobis distance would be higher [43]. Soil C:N, C:P, and N:P ratios were calculated as mass ratios. GDA was performed using Statistica 6.0 (StatSoft, Inc., Tulsa, OK, USA).

We used structural equation modeling (SEM) to analyze the factors explaining the maximum variability of the biomass; residual straw C, N, and P concentrations; soil C, N, and P concentrations; and soil C:N, C:P, and N:P ratios throughout the study period as functions of the habitat and the other soil traits. This analysis provides information on the direct, indirect, and total effects of the variables. We fit the models using the sem R package [44] and acquired the minimally adequate model using the Akaike information criterion. Standard errors in addition to the significance levels of the direct, indirect, and total effects were calculated by bootstrapping (1200 repetitions).

5. Conclusions

1. Straw mass decreased faster and C, N, and mainly P concentrations remained higher during the vegetable crop and fallow periods in the ridges than the ditches. C:N, C:P, and N:P ratios of the residual straw were thus lower in the ridges. The straw in the ridges thus had less residual mass and higher N and P concentrations at the beginning of the rice crop period.
2. N and P concentrations and contents decreased more in the straw in the ridges than the straw in the ditches during rice growth, so the straw in the ridges provided more N and P than the straw in the ditches.

3. Temperature played a key role in the changes of straw C and N concentrations during decomposition, whereas soil salinity had more of an effect on the changes of straw P concentrations.
4. The application of straw in the ridges thus allowed a better release of N and P during the rice crop period and produced less residual straw mass than the application of straw in the ditches. Both processes can enhance rice yield in the subtropical rice croplands of China and southeast Asia that use this management system.

Acknowledgments: The authors would like to thank Yongyue Ma, Linmei Ouyang, and Xianbiao Lin for their assistance with field sampling. Funding was provided by the National Science Foundation of China (41571287; 31000209), Natural Science Foundation Key Programs of Fujian Province (2018R1101006-1), Fujian Provincial Outstanding Young Scientists Program (2017), and by the Spanish Government grant CGL2013-48074-P, the Catalan Government grant SGR 2014-274, and the European Research Council Synergy grant ERC-SyG-2013-610028, IMBALANCE-P.

Author Contributions: W.W. and C.Z. designed the experiment; W.W. and C.W. performed the experiment; W.W., J.S., provided data analyses; and W.W., J.S., M.B., T.P., D.Y.F.L. and J.P. co-wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Results of the mixed repeated measures (time) models with habitat (ridges versus ditches) as the fixed independent variable, plot the as random variable, and the different litter and soil studied variables.

Variable	Model Type	R^2 Model	lme (Variable~Site * Day, Data = Dades, Random = ~1 | Day/Plot, Method = "REML")		
			Site (Fixed)	Time (Repeat)	Site ˆ Time
Mass remaining (% of initial)	lme	0.94	$F = 6.86$ $p = 0.016$	$F = 59.8$ $p = 0.0002$	$F = 18.6$ $p = 0.0003$
Carbon remaining (% of initial)	lme	0.95	$F = 0.906$ $p = 0.35$	$F = 94.8$ $p = 0.0001$	$F = 16.0$ $p = 0.0006$
Nitrogen remaining (% of initial)	lme	0.89	$F = 20.3$ $p = 0.0002$	$F = 19.3$ $p = 0.0046$	$F = 27.8$ $p < 0.0001$
Phosporus remaining (% of initial)	lme	0.88	$F = 118$ $p < 0.0001$	$F = 4.70$ $p = 0.073$	$F = 47.9$ $p < 0.0001$
Carbon concentration in litter	lme	0.76	$F = 2.43$ $p = 0.13$	$F = 5.71$ $p = 0.054$	$F = 4.60$ $p = 0.043$
Nitrogen concentration in litter	lme	0.85	$F = 0.695$ $p = 0.41$	$F = 56.4$ $p = 0.0003$	$F = 2.34$ $p = 0.14$
Phosphorus concentration in litter	lme	0.87	$F = 79.7$ $p < 0.0001$	$F = 2.82$ $p = 0.14$	$F = 0.036$ $p = 0.85$
Litter C:N ratio	lme	0.88	$F = 7.36$ $p = 0.13$	$F = 120$ $p < 0.0001$	$F = 0.33$ $p = 0.57$
Litter C:P ratio	lme	0.85	$F = 87.6$ $p < 0.0001$	$F = 10.4$ $p = 0.018$	$F = 4.06$ $p = 0.056$
Litter N:P ratio	lme	0.84	$F = 54.9$ $p < 0.0001$	$F = 8.06$ $p = 0.030$	$F = 0.075$ $p = 0.79$
Soil pH	lme	0.83	$F = 1.52$ $p = 0.23$	$F = 0.827$ $p = 0.40$	$F = 1.27$ $p = 0.27$
Soil salinity	lme	0.90	$F = 37.7$ $p < 0.001$	$F = 0.967$ $p = 0.363$	$F = 4.61$ $p = 0.043$
Soil temperature	lme	0.98	$F = 0.638$ $p = 0.43$	$F = 32.6$ $p = 0.0012$	$F = 0.015$ $p = 0.91$

(*) Represents the fact that the model contained the effects of both independent factor and also their interaction.
ˆ Represents the interaction between the two dependent factors in the model.

Table A2. Residual mass, nutrient characteristics of the straw, and physical soil traits (mean ± SE) in each crop period.

Variable	Residual Mass (%)	Soil Temperature (°C)	Soil Salinity (mS cm^{-1})	Soil pH
Residual mass and soil properties				
Vegetable crop (both habitats)	60.29 ± 2.63a	12.70 ± 0.32a	0.36 ± 0.05a	6.33 ± 0.05a
First fallow period (both habitats)	42.78 ± 1.90b	22.07 ± 0.41b	0.23 ± 0.06ab	6.00 ± 0.03a
Rice crop (both habitats)	29.62 ± 1.77c	27.81 ± 0.44c	0.40 ± 0.04ac	6.22 ± 0.16a
Second fallow period (both habitats)	20.22 ± 1.48d	29.80 ± 0.28d	0.25 ± 0.02a	6.17 ± 0.05a
Crop period	$F = 141.319$ $p < 0.001$	$F = 2643.159$ $p < 0.001$	$F = 61.305$ $p < 0.001$	$F = 37.587$ $p < 0.001$
Ridges	40.34 ± 4.24	21.90 ± 1.57	0.27 ± 0.04	6.21 ± 0.10
Ditches	42.84 ± 2.97	21.46 ± 1.51	0.42 ± 0.03	6.24 ± 0.07
Habitat	$F = 3.401$ $p = 0.139$	$F = 11.646$ $p = 0.027$	$F = 2245.267$ $p < 0.001$	$F = 0.159$ $p = 0.711$
Crop period × habitat	$F = 6.809$ $p < 0.001$	$F = 48.211$ $p < 0.001$	$F = 5.733$ $p < 0.001$	$F = 2.418$ $p = 0.045$
Nutrient concentration	C (mg g^{-1})	N (mg g^{-1})	P (mg g^{-1})	
Vegetable crop (both habitats)	335.47 ± 3.25a	10.40 ± 0.21a	1.65 ± 0.15a	
First fallow period (both habitats)	331.90 ± 7.58ab	11.69 ± 0.58a	1.44 ± 0.16a	
Rice crop (both habitats)	319.99 ± 5.39b	15.52 ± 0.62b	1.68 ± 0.13a	
Second fallow period (both habitats)	267.66 ± 15.56c	17.27 ± 0.21c	2.05 ± 0.22a	
Crop period	$F = 18.234$ $p < 0.001$	$F = 62.068$ $p < 0.001$	$F = 9.660$ $p < 0.001$	
Ridges	306.81 ± 6.55	14.06 ± 0.72	2.18 ± 0.07	
Ditches	334.67 ± 4.18	12.61 ± 0.58	1.19 ± 0.05	
Habitat	$F = 29.715$ $p = 0.006$	$F = 31.669$ $p = 0.005$	$F = 623.082$ $p < 0.001$	
Crop period × habitat	$F = 2.710$ $p = 0.028$	$F = 5.286$ $p = 0.001$	$F = 3.439$ $p = 0.009$	

Table A2. *Cont.*

Variable	Residual Mass (%)	Soil Temperature (°C)	Soil Salinity (mS cm^{-1})	Soil pH
Nutrient stoichiometry	C:N ratio	C:P ratio	N:P ratio	
Vegetable crop (both habitats)	32.51 ± 0.77a	236.57 ± 22.73a	7.16 ± 0.60a	
First fallow period (both habitats)	28.70 ± 1.44a	250.26 ± 35.94a	8.73 ± 1.18ab	
Rice crop (both habitats)	21.42 ± 1.20b	216.54 ± 20.25ab	9.85 ± 0.51b	
Second fallow period (both habitats)	15.48 ± 0.83c	141.53 ± 21.77b	8.90 ± 0.96ab	
Crop period	F = 44.704 p < 0.001	F = 7.700 p < 0.001	F = 10.184 p < 0.001	
Ridges	23.51 ± 1.50	145.18 ± 6.79	6.50 ± 0.30	
Ditches	27.98 ± 1.40	292.60 ± 13.31	10.66 ± 0.34	
Habitat	F = 35.419 p = 0.004	F = 329.071 p < 0.001	F = 127.838 p < 0.001	
Crop growth × habitat	F = 0.967 p = 0.474	F = 1.484 p = 0.213	F = 1.369 p = 0.257	
Residual nutrients	C (%)	N (%)	P (%)	
Vegetable crop (both habitats)	54.36 ± 2.21a	68.46 ± 2.81a	51.69 ± 5.57a	
First fallow period (both habitats)	38.13 ± 1.37b	54.36 ± 1.38b	31.75 ± 4.11b	
Rice crop (both habitats)	25.80 ± 1.82c	48.63 ± 1.59b	23.82 ± 1.10b	
Second fallow period (both habitats)	14.86 ± 1.88d	38.32 ± 2.84c	20.53 ± 0.82b	
Crop period	F = 178.055 p < 0.001	F = 25.644 p < 0.001	F = 47.704 p < 0.001	
Ridges	34.32 ± 3.87	55.55 ± 3.56	44.33 ± 4.87	
Ditches	39.05 ± 2.94	55.44 ± 1.97	25.37 ± 1.69	
Habitat	F = 13.407 p = 0.022	F = 0.002 p = 0.965	F = 94.171 p = 0.001	
Crop growth × habitat	F = 4.914 p = 0.001	F = 3.110 p = 0.015	F = 14.328 p < 0.001	

Different letters within a column for each variable indicate significant differences (p < 0.05).

Table A3. Pearson correlations among the residual mass in the straw bag (%), nutrient concentrations (mg g^{-1}) and ratios, and physical soil traits. Bold type indicates significant differences ($p < 0.05$).

	Temperature	pH	Salinity	Litter C	Litter N	Litter P	Litter C:N	Litter C:P	Litter N:P	Residual C	Residual N	Residual P
Residual mass	**$R = -0.848$ $p < 0.001$**	**$R = 0.199$** $p = 0.088$	**$R = 0.316$ $p = 0.014$**	**$R = 0.525$ $p < 0.001$**	**$R = -0.876$ $p < 0.001$**	**$R = -0.220$** $p = 0.067$	**$R = 0.859$ $p < 0.001$**	**$R = 0.284$ $p = 0.025$**	**$R = -0.357$ $p = 0.006$**	**$R = 0.992$ $p < 0.001$**	**$R = 0.925$ $p < 0.001$**	**$R = 0.756$ $p < 0.001$**
Temperature		**$R = -0.169$** $p = 0.125$	**$R = 0.029$** $p = 0.421$	**$R = -0.491$ $p < 0.001$**	**$R = 0.835$ $p < 0.001$**	**$R = 0.144$** $p = 0.164$	**$R = -0.827$ $p < 0.001$**	**$R = -0.262$ $p = 0.036$**	**$R = 0.397$ $p = 0.003$**	**$R = -0.857$ $p < 0.001$**	**$R = -0.718$ $p < 0.001$**	**$R = -0.624$ $p < 0.001$**
pH			**$R = 0.416$ $p = 0.002$**	**$R = 0.231$** $p = 0.057$	**$R = -0.314$ $p = 0.015$**	**$R = -0.196$** $p = 0.091$	**$R = 0.287$ $p = 0.024$**	**$R = 0.241$ $p = 0.049$**	**$R = 0.006$** $p = 0.484$	**$R = 0.223$** $p = 0.064$	**$R = 0.147$** $p = 0.159$	**$R = 0.037$** $p = 0.400$
Salinity				**$R = 0.330$ $p = 0.011$**	**$R = -0.251$ $p = 0.043$**	**$R = -0.474$ $p < 0.001$**	**$R = 0.297$ $p = 0.020$**	**$R = 0.500$ $p < 0.001$**	**$R = 0.363$ $p = 0.006$**	**$R = 0.348$ $p = 0.008$**	**$R = 0.311$ $p = 0.016$**	**$R = -0.023$** $p = 0.439$
Litter C					**$R = -0.628$ $p < 0.001$**	**$R = -0.638$ $p < 0.001$**	**$R = 0.753$ $p < 0.001$**	**$R = 0.708$ $p < 0.001$**	**$R = 0.272$ $p = 0.031$**	**$R = 0.616$ $p < 0.001$**	**$R = 0.472$ $p < 0.001$**	**$R = 0.106$** $p = 0.236$
Litter N						**$R = 0.431$ $p = 0.001$**	**$R = -0.969$ $p < 0.001$**	**$R = -0.508$ $p < 0.001$**	**$R = 0.200$** $p = 0.086$	**$R = -0.897$ $p < 0.001$**	**$R = -0.688$ $p < 0.001$**	**$R = -0.505$ $p < 0.001$**
Litter P							**$R = -0.503$ $p < 0.001$**	**$R = -0.952$ $p < 0.001$**	**$R = -0.770$ $p < 0.001$**	**$R = -0.299$ $p = 0.019$**	**$R = -0.123$** $p = 0.203$	**$R = 0.426$ $p = 0.001$**
Litter C:N								**$R = 0.600$ $p < 0.001$**	**$R = -0.110$** $p = 0.229$	**$R = 0.901$ $p < 0.001$**	**$R = 0.670$ $p < 0.001$**	**$R = 0.432$ $p = 0.001$**
Litter C:P									**$R = 0.712$ $p < 0.001$**	**$R = 0.376$ $p = 0.004$**	**$R = 0.152$** $p = 0.151$	**$R = -0.358$ $p = 0.006$**
Litter N:P										**$R = -0.284$ $p = 0.025$**	**$R = -0.334$ $p = 0.010$**	**$R = -0.770$ $p < 0.001$**
Residual C											**$R = 0.918$ $p < 0.001$**	**$R = 0.694$ $p < 0.001$**
Residual N												**$R = 0.788$ $p < 0.001$**

Table A4. Statistical significance of the independent variables in the general discriminant analysis with the habitat (ridge or ditch) of rice straw decomposition as the dependent categorical variable. Bold type indicate significant differences ($p < 0.05$).

Variable	Wilks' Lambda	p
Residual C (%)	0.997	0.765
Residual N (%)	0.969	0.298
Residual P (%)	0.972	0.319
C (%)	0.976	0.361
N (%)	0.990	0.550
P (%)	0.994	0.660
C:N	0.999	0.878
C:P	0.978	0.384
N:P	0.855	0.020
pH	0.802	0.006
Salinity	0.840	0.038
Temperature	0.985	0.474

(**A**)

(**B**)

(**C**)

(**D**)

Figure A1. *Cont.*

(**E**) (**F**)

Figure A1. Photographs of the paddy field at various periods of the crop-rotation system (**A**) preparation of vegetable beds; (**B**) vegetable growth; (**C**) fallow after vegetable harvest; (**D**) preparation of rice beds and transplantation; (**E**) rice growth; and (**F**) fallow after rice harvest.

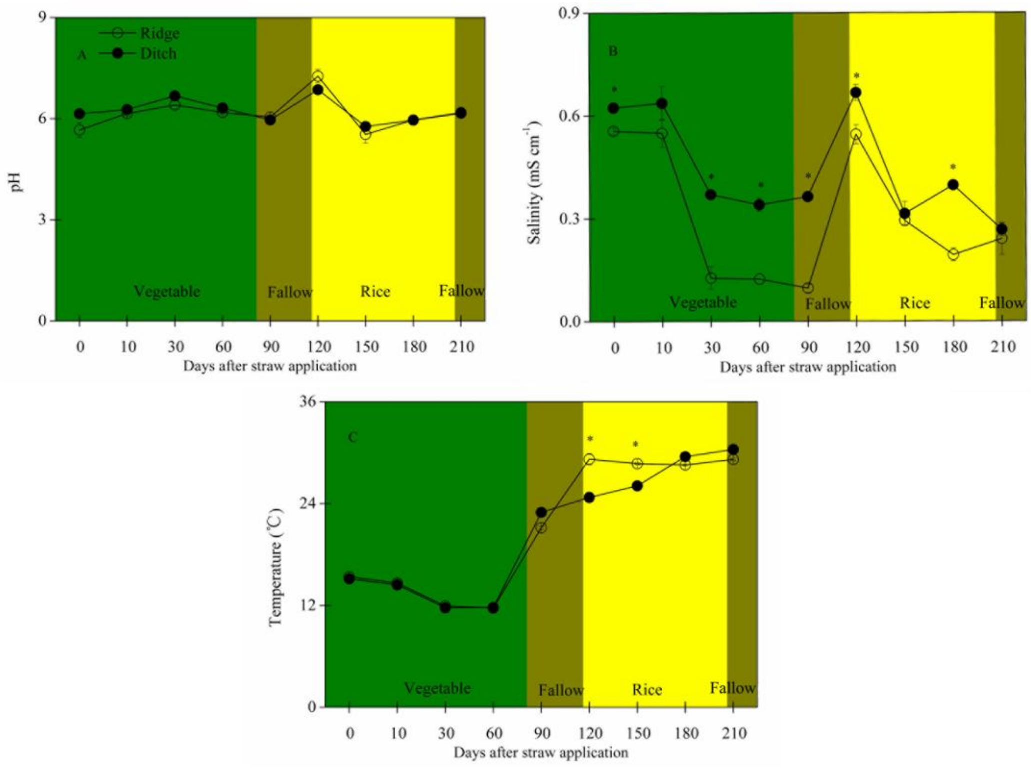

Figure A2. The dynamic changes of soil pH (**A**); temperature (**B**); and salinity (**C**) during rice straw decomposition. Statistically significant differences ($p < 0.5$) between the ridges and ditches in each sampling date are highlighted with (*).

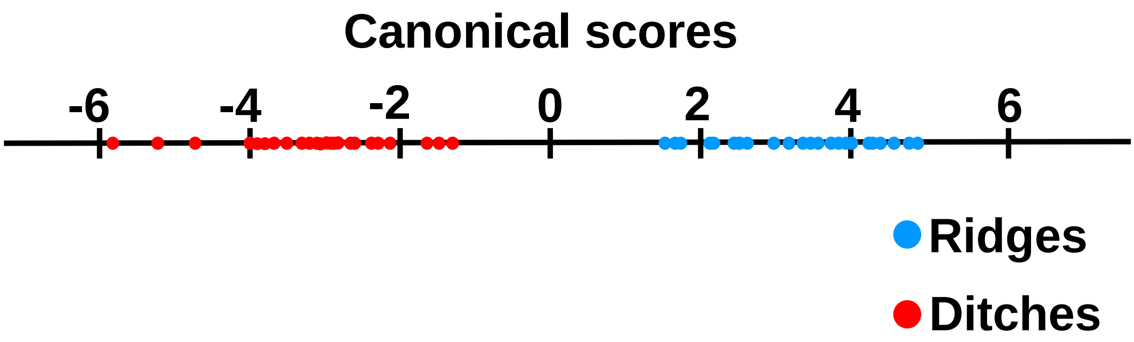

Figure A3. Standardized canonical scores distribution along the root resulting from the discriminant general analysis with the straw and soil variables as independent continuous variables, the days of sampling as an categorical independent variable, and different grouping-dependent factors corresponding to the habitats (ridges and ditches) where straw was applied.

References

1. Seck, P.A.; Diagne, A.; Mohanty, S.; Wopereis, M.C.S. Crops that feed the world 7: Rice. *Food Secur.* **2012**, *4*, 7–24. [CrossRef]
2. International Rice Research Institute (IRRI). *Toward 2000 and Beyond*; IRRI: Los Baños, Philippines, 1989.
3. Frolking, S.; Qiu, J.; Boles, S.; Xiao, X.; Liu, J.; Zhuang, Y.; Li, C.; Qin, X. Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China. *Glob. Biogeochem. Cycles* **2002**, *16*, 1091–1101. [CrossRef]
4. Linquist, B.A.; Adviento-Borbe, M.A.; Pittelkow, C.M.; van Kessel, C.; van Groenigen, K.J. Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Res.* **2012**, *135*, 10–21. [CrossRef]
5. Guo, J.H.; Liu, X.J.; Zhang, Y.; Shen, J.L.; Han, W.X.; Zhang, W.F.; Christie, P.; Goulding, K.W.T.; Vitousek, P.M.; Zhang, F.S. Significant acidification in major Chinese croplands. *Science* **2010**, *327*, 1008–1010. [CrossRef] [PubMed]
6. Zhang, Y.; Wen, M.; Li, X.; Shi, X. Long-term fertilization causes excess supply and loss of phosphorus in purple paddy soil. *J. Sci. Food Agric.* **2014**, *94*, 1175–1183. [CrossRef] [PubMed]
7. Peñuelas, J.; Poulter, B.; Sardans, J.; Ciais, P.; van der Velde, M.; Bopp, L.; Boucher, O.; Godderis, Y.; Llusià, J.; Nardin, E.; et al. Human-induced nitrogen-Phosphorus imbalances alter natural and managed ecosystems across the globe. *Nat. Commun.* **2013**, *4*, 2934. [CrossRef] [PubMed]
8. Singh, J.S.; Pandey, V.C.; Singh, D.P.; Singh, R.P. Influence of pyrite and farmyard manure on population dynamics of soil methanotroph and rice yield in saline rain-fed paddy field. *Agric. Ecosyst. Environ.* **2010**, *139*, 74–79. [CrossRef]
9. Singh, B.; Humphreys, E.; Eberbach, P.L.; Katupitiya, A.; Singh, T.; Kukal, S.S. Growth, yield and water productivity of zero till wheat as affected by rice straw mulch and irrigation schedule. *Field Crops Res.* **2011**, *121*, 209–225. [CrossRef]
10. Wang, J.Y.; Jia, J.X.; Xiong, Z.Q.; Khalil, M.A.K.; Xing, G.X. Water regime–nitrogen fertilizer–straw incorporation interaction: Field study on nitrous oxide emissions from a rice agroecosystem in Nanjing, China. *Agric. Ecosyst. Environ.* **2011**, *141*, 437–446. [CrossRef]
11. Sonnleitner, R.; Lorbeer, E.; Schinner, F. Effect of straw, vegetable oil and whey on physical and microbiological properties of a chernozem. *Appl. Soil Ecol.* **2003**, *22*, 195–204. [CrossRef]
12. Bhattacharyya, P.; Roy, K.S.; Neogi, S.; Adhya, T.K.; Rao, K.S.; Manna, M.C. Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice. *Soil Tillage Res.* **2012**, *124*, 119–130. [CrossRef]
13. Zhang, Z.S.; Song, X.L.; Lu, X.G.; Xue, Z.S. Ecological stoichiometry of carbon, nitrogen, and phosphorus in estuarine wetland soils: Influences of vegetation coverage, plant communities, geomorphology, and seawalls. *J. Soils Sediment.* **2013**, *13*, 1043–1051. [CrossRef]

14. Pan, T. The Effect of Straw Application on Soil Carbon Pool, Methane and Nitrous Oxide Emissions in the Paddy Fields of Fuzhou. Ph.D. Thesis, Fujian Normal University, Fuzhou, China, 2014.
15. Sommer, R.; Ryan, J.; Masri, S.; Singh, M.M.; Diekmann, J. Effect of shallow tillage, moldboard plowing, straw management and compost addition on soil organic matter and nitrogen in a dryland barley/wheat-vetch rotation. *Soil Tillage Res.* **2011**, *115*, 39–46. [CrossRef]
16. Yao, S.; Teng, X.; Zhang, B. Effects of rice straw incorporation and tillage depth on soil puddlability and mechanical properties during rice growth period. *Soil Tillage Res.* **2015**, *146*, 125–132. [CrossRef]
17. Qiu, S.J.; Peng, P.Q.; Li, L.; He, P.; Liu, Q.; Wu, J.S.; Christie, P.; Ju, X.T. Effects of applied urea and straw on various nitrogen fractions in two Chinese paddy soils with differing clay mineralogy. *Biol. Fertil. Soils* **2012**, *48*, 161–172. [CrossRef]
18. Zhang, B.; Pang, C.; Qin, J.; Liu, K.; Li, H. Rice straw incorporation in winter with fertilizer-N application improves soil fertility and reduces global warming potential from a double rice paddy field. *Biol. Fertil. Soils* **2013**, *49*, 1039–1052. [CrossRef]
19. Amlin, N.A.; Rood, S.B. Inundation tolerances of riparian willows and cottonwoods. *J. Am. Water Resour. Assoc.* **2001**, *37*, 1709–1720. [CrossRef]
20. Adame, M.F.; Virdi, B.; Lovelock, C.E. Effect of geomorphological setting and rainfall on nutrient exchange in mangroves during tidal inundation. *Mar. Freshw. Res.* **2010**, *61*, 1197–1206. [CrossRef]
21. Kobayashi, T.; Ryder, D.S.; Gordon, G.; Shannon, I.; Ingleton, T.; Carpenter, M.; Jacobs, S.J. Short-term response of nutrients, carbon and planktonic microbial communities to floodplain wetland inundation. *Aquat. Ecol.* **2009**, *43*, 843–858. [CrossRef]
22. Sheng, L.X.; Huang, D.Y.; Xia, H.A.; Xiao, S.Y. The effect of applying economic green manure crops in the paddy field with succession cropping system. *Chin. J. Eco-Agric.* **2004**, *12*, 109–111.
23. Valiela, I.; Teal, J.M.; Allen, S.D.; Van Etten, R.; Goehringer, D.; Volkmann, S. Decomposition in salt marsh ecosystems: The phases and major factors affecting disappearance of above-ground organic matter. *J. Exp. Mar. Biol. Ecol.* **1985**, *89*, 29–54. [CrossRef]
24. Talbot, J.M.; Treseder, K.K. Interactions among lignin, cellulose, and nitrogen drive litter chemistry-decay relationships. *Ecology* **2012**, *93*, 345–354. [CrossRef] [PubMed]
25. Güsewell, S.; Verhoeven, J.T.A. Litter N:P ration indicate whether N or P limits the decomposability of graminoid leaf litter. *Plant Soil* **2006**, *287*, 131–143. [CrossRef]
26. Manzoni, S.; Trofymow, J.A.; Jackson, R.B.; Porporato, A. Stoichiometric controls on carbon, nitrogen, and phosphorus dynamics in decomposing litter. *Ecol. Monogr.* **2010**, *80*, 89–106. [CrossRef]
27. Cleveland, C.C.; Liptzin, D. C:N:P stoichiometry in soil: Is there a "Redfield ratio" for the microbial biomass? *Biogeochemistry* **2007**, *85*, 235–252. [CrossRef]
28. Wang, W.; Lai, D.Y.F.; Li, S.; Kim, P.J.; Zeng, C.; Li, P.; Liang, Y. Steel slag amendment reduces methane emission and increases rice productivity in subtropical paddy fields in China. *Wetl. Ecol. Manag.* **2014**, *22*, 683–691. [CrossRef]
29. Wang, W.; Sardans, J.; Zeng, C.; Zhong, C.; Li, Y.; Peñuelas, J. Responses of soil nutrient concentrations and stoichiometry to different human land uses in a subtropical tidal wetland. *Geoderma* **2014**, *232*, 459–470. [CrossRef] [PubMed]
30. Xu, X.; Thornton, P.E.; Post, W.M. A global analysis of soil microbial biomass carbon, nitrogen, and phosphorus in terrestrial ecosystems. *Glob. Ecol. Biogeogr.* **2013**, *22*, 737–749. [CrossRef]
31. Tong, C.; Liu, B.G. Litter decomposition and nutrient dynamics in different tidal water submergence environments of estuarine tidal wetland. *Geogr. Res.* **2009**, *28*, 118–128.
32. Richardson, A.E.; Simpson, R.J. Soil microorganisms mediating phosphorus availability update on microbial phosphorus. *Plant Physiol.* **2011**, *156*, 989–996. [CrossRef] [PubMed]
33. Sterner, R.W.; Elser, J.J. *Ecological Stoichimetry: The Biology of Elements from Molecules to Biosphere*; Princeton University Press: Princeton, NJ, USA, 2002.
34. Sieger, S.M.; Kristensen, B.K.; Robson, C.A.; Amirsadeghi, S.; Eng, E.W.Y.; Abdel-Mesih, A.; Møller, L.M.; Vanlerberghe, G.C. The role of alternative oxidase in modulating carbon use efficiency and growth during macronutrient stress in tobacco cells. *J. Exp. Bot.* **2005**, *56*, 1499–1515. [CrossRef] [PubMed]
35. Hu, H.Y.; Zhang, Z.C.; Li, X. Influences of salinity on mass and energy dynamics during decomposition of *Kandelia candel* leaf litter. *Chin. J. Plant Ecol.* **2010**, *34*, 1377–1385.

36. Mu, Z.J.; Huang, A.Y.; Ni, J.P.; Xie, D.T. Linking anual N_2O emission in organic soils to mineral nitrogen inputs as estimated by heterotrophic respiration and soil C/N ratio. *PLoS ONE* **2014**, *9*, e96572. [CrossRef] [PubMed]
37. Moore, T.R.; Trofymow, J.A.; Prescott, C.E.; Titus, D.B. Nature and nurture in the dynamics of C, N and P during litter decomposition in Canadian forest. *Plant Soil* **2011**, *339*, 163–175. [CrossRef]
38. Peng, S.; Luo, Y.; Xu, J.; Khan, S.; Jiao, X.; Wang, W. Integrated irrigation and drainage practices to enhance water productivity and reduce pollution in a rice production system. *Irrig. Drain.* **2012**, *61*, 285–293. [CrossRef]
39. Ocio, J.A.; Brookes, P.C.; Jenkinson, D.S. Field incorporation of straw and its effects on soil microbial biomass and soil inorganic N. *Soil Biol. Biochem.* **1991**, *23*, 171–176. [CrossRef]
40. Lu, R.K. *Analysis Methods of Soil Science and Agricultural Chemistry*; Agricultural Science and Technology Press: Beijing, China, 1999.
41. Pinheiro, J.; Bates, D.; DebRoy, S.; Sarkar, D.; Core, T.R. Nlme: Linear and Nonlinear Mixed Effects Models. R Package Version 3.1-126. Available online: http://CRAN (accessed on 12 June 2016).
42. Barton, K. MuMIn: Multi-Model Inference. Available online: https://cran.r-project.org/package=MuMIn (accessed on 12 June 2017).
43. De Maesschalck, R.; Jouan-Rimbaud, D.; Massart, D.L. The Mahalanobis distance. *Chemom. Intell. Lab.* **2000**, *50*, 1–18. [CrossRef]
44. Epskamp, S. semPlot: Unified Visualizations of Structural Equation Models. *Struct. Equ. Model. A Multidiscip. J.* **2000**, *22*, 474–483. [CrossRef]