

Article

# The Influence of Soil Physico-Chemical Properties and Enzyme Activities on Soil Quality of Saline-Alkali Agroecosystems in Western Jilin Province, China

Qing Zhao <sup>1,2</sup>, Jie Tang <sup>1,2,\*</sup>, Zhaoyang Li <sup>1</sup>, Wei Yang <sup>1</sup> and Yucong Duan <sup>1</sup>

<sup>1</sup> College of Environment and Resources, Jilin University, Changchun 130000, China; zhaqing15@mails.jlu.edu.cn (Q.Z.); zhaoyang@jlu.edu.cn (Z.L.); yangwea@jlu.edu.cn (W.Y); duanyc17@mails.jlu.edu.cn (Y.D.)

<sup>2</sup> Key Laboratory of Groundwater Resources and Environment, Ministry of Education, Jilin University, Changchun 130000, China

\* Correspondence: tangjie@jlu.edu.cn; Tel.: +86-0431-8850-2441

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**Abstract:** Soil organic carbon (SOC) plays a critical role in carbon cycling and soil quality of agroecosystems. Understanding the factors influencing SOC and the main indicators for soil quality can help in better soil management and sustainable agriculture. In this study, we selected three upland fields (U1, U2 and U3) and three paddy fields (P1, P2 and P3) of saline-alkali agroecosystems to study the impacts of soil physico-chemical properties (soil pH, exchangeable sodium percentage, electrical conductivity and bulk density) and enzyme activities (soil amylase, invertase, catalase and polyphenol oxidase) on SOC dynamics. The soil pH and exchangeable sodium percentage (ESP) had profoundly negative effect on SOC. Soil amylase and invertase activities were significantly positively correlated with SOC in both upland and paddy fields. Catalase promoted the accumulation of paddy SOC and polyphenol oxidase led to the acceleration of decomposition of upland SOC. Additionally, we combined SOC contents, soil physico-chemical properties and soil enzyme activities together to obtain the main indicators of soil quality. The results suggested that, in upland sites, the main factors affecting the soil quality were soil pH, ESP and SOC. As for paddy sites, the main indicators of soil quality were soil pH, amylase and invertase. By comparing the soil quality indicators between upland and paddy fields, it was observed that the inhibiting effect of ESP on paddy soil quality was not as significant as on upland soil quality due to the irrigation practice of rice planting, which could reduce the degree of soil alkalization. Therefore, paddy development has been widely used to improve the saline-alkali land in western Jilin Province of China.

**Keywords:** soil organic carbon; physic-chemical properties; enzyme activities; soil quality indicators; saline-alkali agroecosystems

## 1. Introduction

Soils, acting as an important component in terrestrial ecosystem, contain the largest organic carbon sink [1,2]. According to previous studies [3–5], the global soil organic carbon (SOC) pool is more than twice that of the terrestrial vegetation carbon pool and nearly three times that of atmospheric carbon pool, thus any small variation of SOC could affect the global carbon cycling and climate change [6]. SOC is a key attribute in maintaining soil tilth and quality and energy source for microorganisms in soils. It also influences other soil functions, such as the charge characteristics, aggregate stability, water holding capacity, and so on [7,8]. Various factors could affect SOC dynamics, while soil enzyme

activities and soil physico-chemical properties are more important among these factors and more easily determined [9–11].

Soil enzymes are involved in nutrient cycling in soil ecosystems [12,13]. The types and quantity of enzymes depend on the soil quality and environmental conditions; hence, enzyme activities may be used as good indicators for soil fertility in different ecosystems. In addition, the formation and decomposition of SOC are regulated by almost all enzymes, so they are comparatively vital in soil carbon cycling [14,15]. Amylase and invertase can catalyze hydrolysis of polysaccharides and release monosaccharides to provide labile carbon and energy sources for supporting microbial living [16–19]. Catalase and polyphenol oxidase belong to soil oxidoreductases and they are the kind of enzymes that can carry out redox reaction in soil, participating in the cycling of carbon [20]. Previous works reported that SOC had significant positive relation with the activities of soil amylase, invertase [21] and catalase [22]. It was found that polyphenol oxidase was an enzyme capable of degrading protein polyphenol complexes, thus having a strong effect on carbon mineralization [23,24].

Soil physico-chemical properties are basic indicators for estimating the level of soil nutrient contents and characteristics. It was observed that available nutrient balance in soil was influenced by soil pH, moreover phytotoxicity of aluminate was reported in alkaline soil (with pH greater than 9) [25,26]. The ESP is also an important property of soil and it has a great impact on soil structure, porosity and permeability [27]. Soil electrical conductivity can serve as a measurement of soluble nutrients and it is useful in monitoring the mineralization of organic matter in soil [28,29]. Besides, Islam et al. [30] pointed out that the SOC sequestration responded to the difference of soil physico-chemical properties and concluded that bulk density had a significant negative correlation with carbon sequestration. Additionally, soil enzyme activities are commonly influenced by soil pH, and the relation between soil pH and enzyme activities also has control on SOC [31–33]. In general, soil physico-chemical properties and soil enzymes do great effort on SOC dynamics together.

Previous studies about SOC and its influencing factors mostly focused on forests, wetlands, grasslands and so on [34–36]. However, the subject about saline-alkali agriculture ecological systems has not been extensively studied. Western Jilin Province (in northeast China) is one of the three major saline-alkali regions in the world and it belongs to the Northeast China Transect of IGBP Terrestrial Transects [37]. After several decades of cultivation development, this region has formed special saline-alkali agroecosystems and also become an important agricultural production base in China. These agroecosystems are cultivated with maize and rice. We selected saline-alkali agroecosystems as our research subject and studied: (1) the variation of SOC in different soil layers, growing periods of crops and sampling sites; (2) the effect of physico-chemical properties and enzyme activities on SOC dynamics; and (3) the main indicators for soil quality among all selected factors. Understanding the factors influencing SOC and the main indicators for soil quality of the saline-alkali agroecosystems is important for soil resource conservation, environmental management and sustainable agricultural development in western Jilin Province of China.

## 2. Materials and Methods

### 2.1. Study Sites and Sampling Design

The study area was located in western Jilin Province (43°22′–46°18′ N, 121°38′–126°11′ E) (Figure 1) of northeast China where climate is semi-arid and sub-humid continental monsoon with four distinct seasons. Mean annual precipitation of this area is 558.3 mm with maximum mean monthly temperature (23.5 °C) in July (Figure 2). Three upland farmlands (U1, U2, and U3) as well as three paddy farmlands (P1, P2, and P3) differing in soil characteristics were chosen for the research (Table 1), and three parallel sample points were randomly selected at each site. Topsoil (T, 0–30 cm) and subsoil (S, 30–60 cm) samples were taken from study sites during the growing periods of maize and rice in 2016, respectively, in May, July and September, corresponding to the seedling stage (I), tillering to heading stage (II) and fructificative stage (III) for rice, and the seedling stage (I), jointing to heading stage

(II) and ripening stage (III) for maize, respectively. Stainless steel rings (5 cm height, 5 cm diameter) were used to collect undisturbed soil for bulk density (BD) measurement.

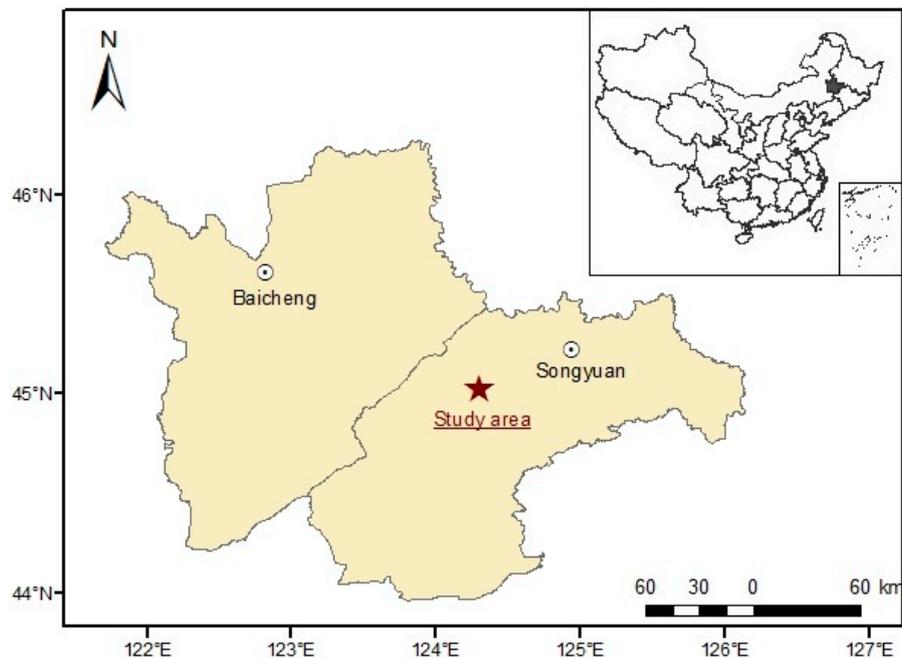


Figure 1. Location of study area.

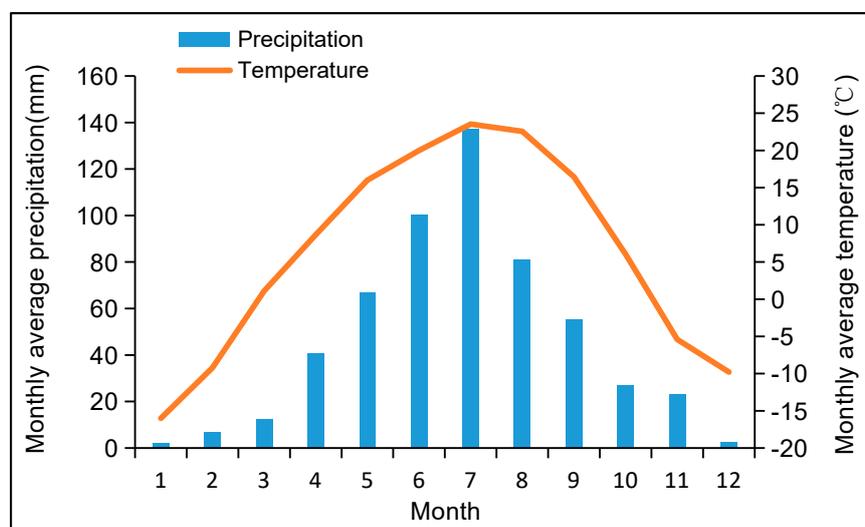


Figure 2. Mean precipitation and temperature in the study area in 2016.

Table 1. Background information of sampling sites.

Sampling Sites	U1	U2	U3	P1	P2	P3
Soil classification	Loam	Silty loam	Sandy loam	Loam	Silty loam	Sandy loam
Clay (%)	14.03	8.52	7.94	14.07	10.75	4.58
Silt (%)	40.73	73.48	24.98	40.18	67.33	31.30
Sand (%)	45.24	18.00	47.08	45.75	21.92	64.12
Fertilization treatment	N, P and K	N, P and K	N, P and K	N, P and K	N, P and K	N, P and K
Experimental area	95 m × 100 m	100 m × 100 m	90 m × 100 m	100 m × 100 m	95 m × 95 m	95 m × 100 m
Type of crop	Maize	Maize	Maize	Rice	Rice	Rice

## 2.2. Soil Analysis

Soil samples were air dried after animal and plant residues and stones were removed, and then sieved (2 mm) for soil properties (except for BD) and enzymes analysis, and further ground (0.149 mm) for SOC assay.

### 2.2.1. Physico-Chemical Analysis of Soil

The measurement of soil physico-chemical properties followed the methods by Zheng [38]. Soil pH and electrical conductivity (EC) were determined by pH meter (soil: distilled water = 1:5) and BD was measured through oven-drying method. Soil BD was calculated as:

$$BD = m/V \quad (1)$$

where  $m$  is the mass of oven-dried soil sample (g) and  $V$  is the volume of stainless steel ring ( $\text{cm}^3$ ).

Exchangeable sodium percentage (ESP) was calculated as:

$$ESP = \text{Na}^+ / \text{CEC} \times 100\% \quad (2)$$

where  $\text{Na}^+$  is the concentration of exchangeable sodium ( $\text{cmol}(\text{Na}^+) \text{kg}^{-1}$ ) and CEC is cation exchange capacity ( $\text{cmol kg}^{-1}$ ).

CEC was measured through the EDTA-ammonium acetate salt exchange method and exchangeable  $\text{Na}^+$  concentration was assayed by using flame photometry (Shimadzu optical double beam atomic absorption spectrophotometer, Shanghai).

### 2.2.2. Soil Enzymes Activities

Amylase (AMY, EC 3.2.1.2.) and invertase (INV, EC 3.2.1.26) activities were both determined by the method of 3, 5-dinitrosalicylic acid colorimetry [39]. Briefly, the soil samples were incubated in a solution containing phosphate buffer (pH = 5.5, 10 mL for amylase and 15 mL for invertase) and adequate substrate (10 mL 1% starch solution added for amylase and 5 mL 8% sucrose solution for invertase) at 37 °C in darkness for 24 h. The amylase and invertase activities were quantified according to the colorimetric analysis (both at 508 nm) of the products released by the samples after incubation and expressed as  $\text{mg g}^{-1} 24 \text{ h}^{-1}$ .

Catalase (CAT, EC 1.11.1.6) activity was measured via potassium permanganate titration as following steps [39]: 2 g soil were mixed with 5 mL 0.3%  $\text{H}_2\text{O}_2$  and 40 mL distilled water and then vibrated for 20 min. The mixture should be filtered immediately and added with 5 mL 3 N  $\text{H}_2\text{SO}_4$  afterwards. After that, 25 mL filtrate was taken to titration by using 0.1 N  $\text{KMnO}_4$ . The catalase activity was calculated after blank subtraction according to the volume of consuming of  $\text{KMnO}_4$  standard solution and described as  $\text{mL 0.1 N KMnO}_4 \text{ g}^{-1}$ . Polyphenol oxidase (PPO, EC 1.10.3.1) was also determined by colorimetric method [40]. The substrate was 1% pyrogallol and the buffer was citric acid phosphate buffer (pH = 4.5). The mixture was first incubated at 30 °C for 2 h, and then extracted through ethyl ether. The amount of released purpurogallin in ethyl ether phase was measured at 430 nm and the enzyme activity was calculated according to standard curves of potassium dichromate standard solution ( $\text{mg g}^{-1}$ ).

### 2.2.3. SOC Assay

The SOC content was determined by using a total organic carbon analyzer (Shimadzu TOC-V, Japan) with the SSM-5000A module. Soil samples were delivered into sample boats of TC (total carbon) and IC (inorganic carbon) reaction chambers. The content of total carbon and inorganic carbon was calculated separately and the difference was reported as the SOC (%).

### 2.3. Statistical Analysis

Statistical significance in soil physico-chemical properties and enzyme activities were determined by one-way analysis of variance (ANOVA) followed by Fisher Least Significant Difference (LSD) test. Differences of SOC between different soil layers, in different sampling sites (U1, U2 and U3 for upland fields and P1, P2 and P3 for paddy fields) and different growing periods of crops were tested using multi-factor ANOVA. Pearson correlation analysis was used to estimate relations between SOC and soil physico-chemical properties and soil enzyme activities. Principal component analysis (PCA) was applied for using data of soil physico-chemical properties, enzyme activities and SOC, to identify the important indicators for soil quality. Statistical analyses were performed using SPSS software (version 19.0).

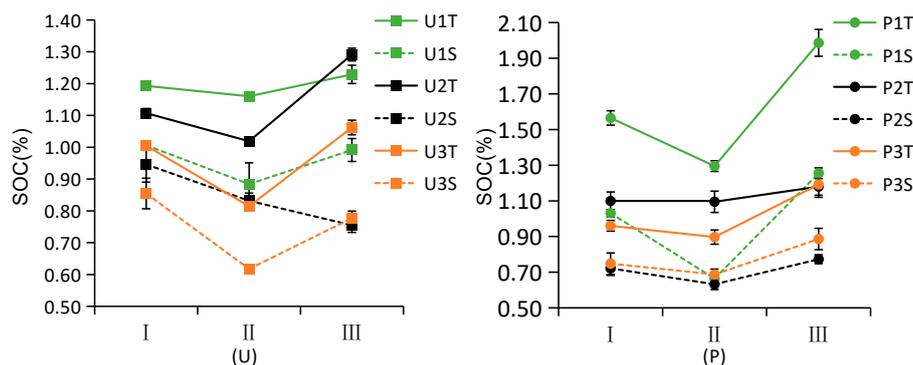
## 3. Results

### 3.1. Soil Organic Carbon Content

The SOC content of topsoil was significantly higher than the content of subsoil no matter at which sampling sites and crop growing periods (Table 2), moreover the SOC content of upland sites and paddy sites averagely decreased 21.82% and 34.40% with the depth of soil layers, respectively. During the different growing periods of crops, a drastic decrease of SOC content was observed in the Stage II maize and rice and showed an increase trend to the third period for all topsoil samples and most subsoil samples (Figure 3 and Table 2). Furthermore, all the possible interactions among influence factors (soil layers  $\times$  sampling sites, soil layers  $\times$  growing periods and sampling sites  $\times$  growing periods) showed significant effect on SOC ( $P < 0.05$ ), except for the triple interaction (soil layers  $\times$  sampling sites  $\times$  growing periods), which showed no significant effect in paddy soil ( $P > 0.05$ ).

**Table 2.** Probability levels of the effects of soil layers (topsoil versus subsoil), sampling sites (U1, U2, and U3 for upland sites and P1, P2, and P3 for paddy sites), and growing periods (I, II and III) were determined by multi-factor analysis of variance. (SOC = soil organic carbon).

	SOC	
	Upland Soil	Paddy Soil
Soil Layers (SL)	$P < 0.01$ T > S	$P < 0.01$ T > S
Sampling sites (SS)	$P < 0.01$ U1 > U2 > U3	$P < 0.01$ P1 > P2 > P3
Growing periods (GP)	$P < 0.01$ III = I > II	$P < 0.01$ III > I > II
SL $\times$ SS	$P < 0.01$ U1T > U1S U2T > U2S U3T > U3S	$P < 0.01$ P1T > P1S P2T > P2S P3T > P3S
SL $\times$ ST	$P < 0.01$ IT > IS IIT > IIS IIIT > IIIS	$P < 0.05$ IT > IS IIT > IIS IIIT > IIIS
SS $\times$ GP	$P < 0.01$ IU1 > IU2 > IU3 IIU2 > IIU1 > IIU3 IIIU1 > IIIU2 > IIIU3	$P < 0.01$ IP1 > IP2 > IP3 IIP1 > IIP2 > IIP3 IIIP1 > IIIP3 > IIIP2
SL $\times$ SS $\times$ GP	$P < 0.01$	$P > 0.05$



**Figure 3.** SOC content during different growing periods in different sites. (U): Upland sites; (P): Paddy sites. Error bars are the standard deviation of the mean values (T = topsoil and S = subsoil).

For the upland soil, significant difference was found among different sampling sites, and the SOC value was the highest at U1 and the lowest at U3 (Table 2), which was in contrast to the trend for soil pH and ESP. However, when taking sampling times into account, U2 became the site containing the highest SOC content in the Stage II maize.

As for paddy soil, the value of SOC was the highest at P1 and the lowest at P3 (Table 2). Due to the interaction effect of “SS × GP”, P2 became the site containing the lowest SOC content instead of P3, in the Stage III rice.

### 3.2. Soil Physico-Chemical Properties

The soil physico-chemical properties of six plots are summarized in Table 3. Mean values of soil pH in upland fields were lowest at U1 (8.54), medium at U2 (8.99), and highest at U3 (9.32). In paddy soil, the mean pH values were lowest at P1 (8.22), medium at P2 (9.00) and highest at P3 (9.10). These trends (in both upland and paddy fields) were positively related with the values of ESP in different fields, as the soil of U1 had the lowest ESP value of 5.42%, and U3 had the highest value of 15.73%. In paddy fields, the lowest ESP was recorded at P1 (5.85%) and the highest at P3 (13.43%). When comparing different soil layers, it was found that topsoil showed lower pH, ESP and BD than the subsoil in both upland fields and paddy fields. For upland fields, EC in topsoil was lower than that in subsoil. In comparison, for paddy fields, EC in topsoil was greater than the subsoil.

**Table 3.** Physico-chemical properties of soil at six sampling sites. The data are mean values of three crop growing periods, respectively in topsoil (T) and subsoil (S). Significant differences analyses between different soil layers were based on one-way ANOVA followed by the Fisher LSD test. Letters mean difference significant at  $P < 0.05$  between different soil layers within each site. (ESP, exchangeable sodium percentage; EC, electrical conductivity; and BD, bulk density).

Soil Properties		U1	U2	U3	P1	P2	P3
pH	T	8.23b	8.82b	9.03b	8.07b	8.90b	9.02b
	S	8.85a	9.16a	9.60a	8.38a	9.11a	9.17a
ESP (%)	T	5.22b	5.51b	13.51b	5.70b	6.29b	12.64b
	S	5.63a	10.20a	17.95a	6.00a	6.47a	14.22a
EC (ms cm <sup>-1</sup> )	T	0.14b	0.26b	0.22a	0.40a	0.28a	0.50a
	S	0.20a	0.46a	0.25a	0.30b	0.23a	0.40b
BD (g cm <sup>-3</sup> )	T	1.16b	1.26b	1.30b	1.25b	1.12b	1.39b
	S	1.27a	1.31a	1.40a	1.32a	1.20a	1.45a

### 3.3. Soil Enzyme Activities

Values of amylase, invertase, catalase and polyphenol oxidase activities in upland soil varied from 0.96 to 1.87 mg g<sup>-1</sup> 24 h<sup>-1</sup>, 3.81 to 9.30 mg g<sup>-1</sup> 24 h<sup>-1</sup>, 1.41 to 2.45 mL g<sup>-1</sup> and 0.82 to 2.51 mg g<sup>-1</sup>,

respectively, at topsoil; and the ranges of four enzyme activities at subsoil are 0.46 to 1.24  $\text{mg g}^{-1} 24 \text{ h}^{-1}$ , 0.44 to 4.94  $\text{mg g}^{-1} 24 \text{ h}^{-1}$ , 1.19 to 2.29  $\text{mL g}^{-1}$ , and 0.50 to 3.05  $\text{mg g}^{-1}$ , respectively. In the paddy soil, the results are 1.41–2.29  $\text{mg g}^{-1} 24 \text{ h}^{-1}$ , 3.17–12.02  $\text{mg g}^{-1} 24 \text{ h}^{-1}$ , 2.09–2.53  $\text{mL g}^{-1}$  and 0.12–0.65  $\text{mg g}^{-1}$  at topsoil; and 1.00–1.76  $\text{mg g}^{-1} 24 \text{ h}^{-1}$ , 1.76–8.34  $\text{mg g}^{-1} 24 \text{ h}^{-1}$ , 0.77–2.33  $\text{mL g}^{-1}$  and 0.23–0.63  $\text{mg g}^{-1}$  at subsoil (values of amylase, invertase, catalase and polyphenol oxidase activities, respectively). When comparing soil enzyme activities at different soil layers, ANOVA revealed significant difference ( $P < 0.05$ ) between different soil layers with higher values of topsoil than that of subsoil, whether in upland or in paddy fields (Figure 4a–c), except for polyphenol oxidase. The polyphenol oxidase activities at topsoil are less than the subsoil in most plots and growing periods (Figure 4d). In the meantime, the difference of polyphenol oxidase activities between soil layers was not as significant as the other three enzymes, especially in paddy fields ( $P > 0.05$ ).

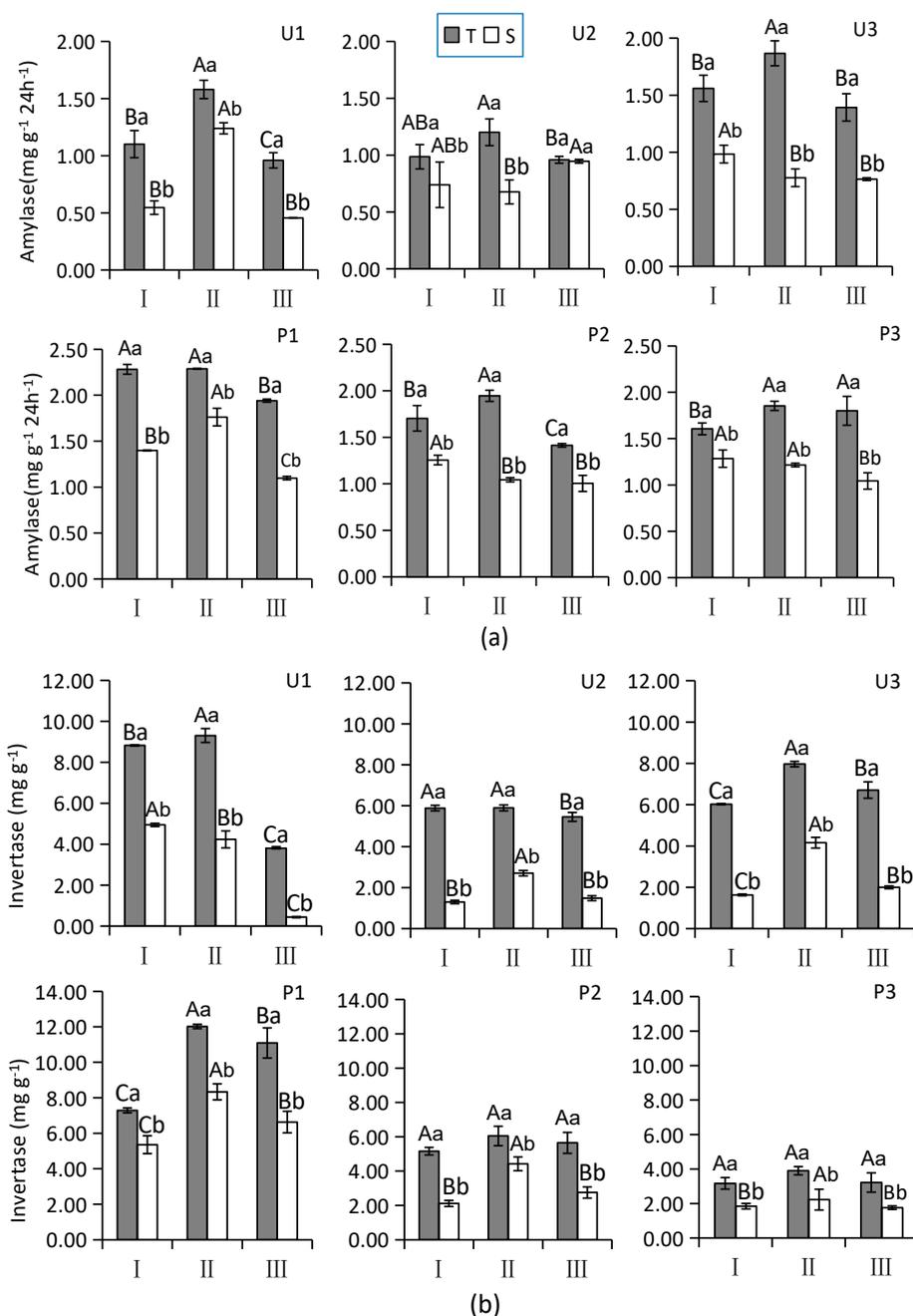
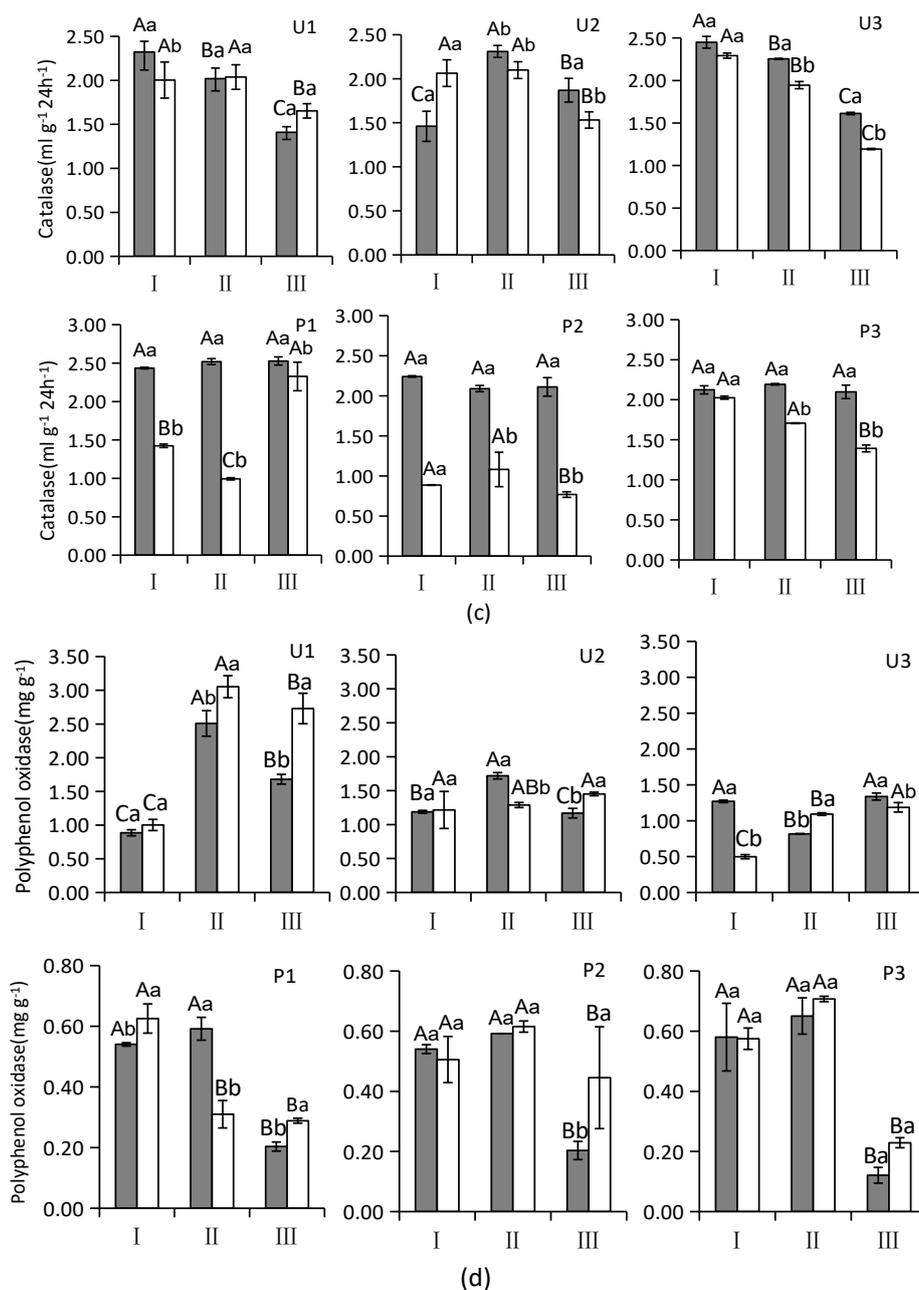


Figure 4. Cont.



**Figure 4.** Soil enzyme activities during different growing periods in different sites (T = topsoil and S = subsoil): (a) Amylase; (b) Invertase; (c) Catalase; and (d) Polyphenol oxidase. The data are mean values of three parallel samples ( $n = 3$ ). The bars represent the standard deviation of mean values. Capital letters mean significant difference among different growing periods (in the same soil layer) and lowercase letters mean difference between different soil layers within each growing stage ( $P < 0.05$ ).

For the whole growing periods, the amylase and invertase of topsoil showed highest activities at Stage II in all the plots, besides, significant difference was found at most plots when comparing different periods of these two enzyme activities ( $P < 0.05$ ). However, the amylase and invertase of subsoil had no consistent changing trends, although the activities are different among the periods. Soil catalase and polyphenol oxidase activities were diverse during different periods, but with no obvious trend.

### 3.4. The Effect of Soil Physico-Chemical Properties on SOC

Pearson's correlation analysis was used to understand the relation between soil properties and SOC content. The results (Table 4) showed that in upland fields soil pH ( $r = -0.653$ ,  $P < 0.01$ ), ESP ( $r = -0.620$ ,  $P < 0.01$ ) and BD ( $r = -0.419$ ,  $P < 0.01$ ) were significantly negatively correlated with SOC. There was no significant correlation between soil EC and SOC ( $P > 0.05$ ). For paddy soil (Table 4), negative correlations were similarly found among soil properties and SOC (pH:  $r = -0.523$ ,  $P < 0.01$ ; ESP:  $r = -0.533$ ,  $P < 0.01$ ; BD:  $r = -0.358$ ,  $P < 0.05$ ), except for EC ( $P > 0.05$ ). These results illustrated that soil pH and ESP are the most important physico-chemical factors negatively influencing the variation of SOC in both upland and paddy soil of our study sites. In addition, soil BD also negatively affected SOC content, but not as significant as the former two.

**Table 4.** Pearson correlation coefficient ( $r$ ) between soil physico-chemical properties and enzyme activities and SOC in upland and paddy fields (ESP, exchangeable sodium percentage; EC, electrical conductivity; BD, bulk density; AMY, amylase; INV, invertase; CAT, catalase; and PPO, polyphenol oxidase).

		pH	ESP	EC	BD	AMY	INV	CAT	PPO
SOC	Upland	-0.653 **	-0.620 **	-0.165	-0.419 **	0.282 *	0.430 **	0.017	-0.401 **
	Paddy	-0.523 **	-0.533 **	0.148	-0.358 **	0.524 **	0.677 **	0.662 **	0.136

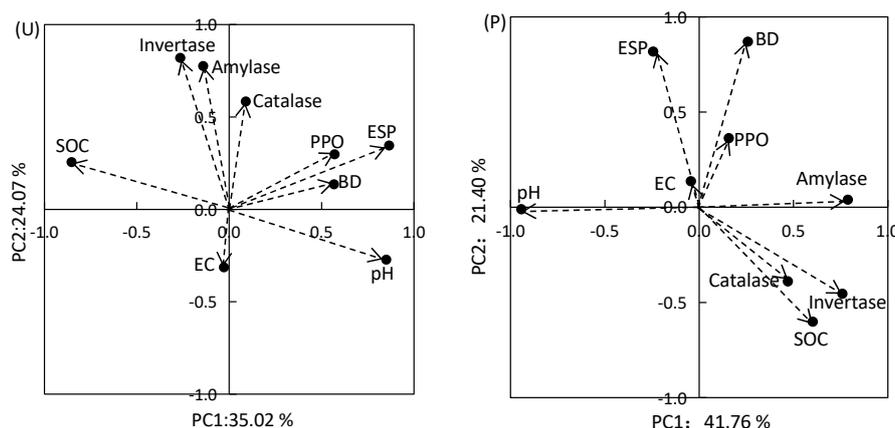
\* Correlation is significant at 0.05 level (2-tailed); \*\* Correlation is significant at 0.01 level (2-tailed).

### 3.5. The Effect of Soil Enzymes Activities on SOC

Significant positive correlations were observed between activities of amylase and invertase and SOC in upland soil ( $r = 0.282$ ,  $P < 0.05$ ;  $r = 0.430$ ,  $P < 0.01$ , respectively) (Table 4), which explained that the SOC was positively responded to these two enzymes. Nevertheless, polyphenol oxidase had negative correlation with SOC ( $r = -0.411$ ,  $P < 0.01$ ) and there were no significant correlations between catalase and SOC ( $P > 0.05$ ). As for rice farmlands (Table 4), amylase, invertase and catalase were all highly positively correlated with SOC ( $r = 0.524$ ,  $P < 0.05$ ;  $r = 0.677$ ,  $P < 0.01$ ;  $r = 0.662$ ,  $P < 0.01$ , respectively) except for polyphenol oxidase, which had no significant correlations with SOC. The absolute values of the Pearson correlation coefficient between the invertase and polyphenol oxidase and the SOC were much larger than those between the other two enzymes and the SOC in upland soil, and this implied that the invertase had greater positive effect on SOC and polyphenol oxidase had greater negative effect on SOC. Likewise for paddy soil, we could observe that invertase and catalase had more important positive effect on SOC. In summation, the selected enzymes all had effect on SOC content, yet the impact depended on different types of crop cultivation.

### 3.6. The Main Indicators of Soil Quality

Principal components analysis (PCA) from upland soil indicated that the first two principal components (PCs) explained 59.09% of the variance (PC1:35.02%, PC2:24.0%). In paddy data, the first two PCs accounted for 63.16% of the variability (PC1:41.76%, PC2:21.40%). When the absolute value of factor loading scores is closer to 1, the variables are more strongly correlated to the relevant PCs. As a result (Figure 5), in upland sites, PC1 was significantly positively correlated with soil pH and ESP and negatively correlated with SOC. PC2 had significant positive correlation with amylase and invertase. With regard to paddy sites, PC1 was significantly positively correlated to amylase and invertase, and negatively correlated to soil pH. PC2 was significantly positively correlated to soil ESP, BD and negatively correlated to SOC.



**Figure 5.** Principal component analysis of the factor loading scores of SOC, soil physico-chemical properties and enzyme activities on PC1 and PC2, respectively. (U): Upland sites; (P): Paddy sites. (ESP, exchangeable sodium percentage; EC, electrical conductivity; BD, bulk density; and PPO, polyphenol oxidase).

#### 4. Discussion

The results obtained in this study demonstrated higher SOC contents in the topsoil comparing to those of the subsoil and this general trend has also been reported by Teng et al. [41]. The distribution of plant roots directly affects SOC contents, due to a large number of decayed roots providing a rich source of carbon for soil [42], while the roots of rice and maize mainly concentrated in topsoil and hard to penetrate into the deeper layer (>30 cm) [43,44]. On the other side, returning litter is also an important carbon source of surface SOC and therefore topsoil contained more SOC. The growth of crops has also caused SOC dynamics. Previous studies, such as by Aon and Colaneri [45], pointed out that SOC differed significantly along the soybean growth cycle. In our study, during the tillering to heading stage for rice and jointing to heading stage for maize, exuberant growing activities of crops required numerous nutrients and the decomposition of SOC accelerated, and consequently a temporarily decrease in SOC content occurred. In addition, we found that the variability in SOC content were also affected by different sampling sites, mainly because different sites varied in physico-chemical characteristics and enzyme activities.

As shown in our results, the soil of selected farmlands in western Jilin Province was alkaline and sodic. The salts such as sodium bicarbonate and sodium carbonate, present in high concentrations, make the soil alkaline, resulting in high ESP. For this reason, ESP is positively correlated with pH, and sodic soils are likely to have a higher pH [46]. The effect of soil pH on SOC is relatively complicated, because the soil texture, soil microbial biomass and community structure as well as the production and secretion of enzymes are all influenced by pH [47–49]. In general, the optimum pH condition of most actinomycetes and bacteria are 6.5–8, and fungi is 5–6 [50], so within the alkaline soil environment (pH > 8), microbe would become less active as pH rises, which may slow down the humification of litters and then result in the decrease of SOC content. Additionally, in an environment where pH is too high (or too low), the enzymes that play an important role in the transformation of nutrients and the formation of humus would be inactivated [51], which also leads to the loss of soil fertility and SOC content in the study area. A soil is considered to be sodic when the ESP is too high, and obvious changes could be found in soil properties. For example, the excess of exchangeable sodium would replace other cations and micronutrients absorbed on soil, such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , Cu, Zn and Mn [52], leading to the deterioration of soil fertility and quality. Furthermore, swelling and dispersion of soil with high ESP would reduce the soil porosity and permeability, and increase soil strength, resulting in restriction of water storage, nutrient uptake and root elongation and expansion [27,53].

We measured four enzyme activities related to soil carbon cycling, comprising hydrolase (amylase and invertase) and oxidoreductase (catalase and polyphenol oxidase). In this study, enzyme activities (except for polyphenol oxidase) decreased with soil depth and the findings are similar to Lemanowicz and Krzyżaniak [54], Biró et al. [55] and Das et al. [56]. No consistent temporal trends were observed among soil enzyme activities, however, at the second crop growing stage, i.e., in July (summer in study area), most soil enzymes appeared higher activities, probably because soil enzyme activities increase with the rise of soil temperature [57]. Shao et al. [58] also concluded that alkaline phosphatase, urease and invertase showed higher activities in summer. The correlation analysis in our study claimed that both in paddy and upland fields, soil amylase and invertase activities were positively correlated with SOC, which agreed with Xie et al. and Zhang et al. [22,59]. Furthermore, the activity of catalase was significantly correlated with SOC in paddy soil, yet no significant correlation was found in upland fields. Greater activities of catalase are able to catalyze the decomposition of hydrogen peroxide, which is beneficial to preventing the toxicity of hydrogen peroxide on organisms and good for the accumulation of SOC [39]. In this study, paddy sites were under flooded conditions from mid-May to early September, leading to the aggregation of hydrogen peroxide, as a result, paddy soil relied more on catalase than upland soil. From our results, the average activity of PPO in upland soil ( $1.45 \text{ mg g}^{-1}$ ) was more than three times that of paddy soil ( $0.44 \text{ mg g}^{-1}$ ) in that PPO is less active in the absence of oxygen [60]. Since the paddy soil contained low activity of PPO and the correlation between PPO and SOC was not significant, there were no distinct interactions between them. On the contrary, the results in upland soil showed that PPO activities had remarkable effect on SOC. PPO was reported to be one of the most important factors in the decomposition of SOC and it promotes the degradation of recalcitrant phenolic compounds [61]. Moreover, the toxicity of some aromatic compounds are likely to inhibit the activities of hydrolases, while PPO can catalyze the oxidation of phenolics in soil, thus PPO also has an important role in releasing extracellular hydrolases from phenolics [62]. Overall, PPO can both directly and indirectly accelerate the decomposition of SOC.

To find the main impact factors for soil quality in the study area, soil physico-chemical properties, enzyme activities and SOC were analyzed through PCA. The PCA analysis suggested that, in upland sites, PC1 mainly contained soil pH, ESP and SOC, and, consequently, they had larger impact on upland soil quality. Additionally, SOC was the positive factors of soil quality, yet pH and ESP were the negative ones. As for paddy sites, PC1 mainly represented soil pH, amylase and invertase. That means the principal positive influence factors of paddy soil quality were amylase and invertase, while soil pH was the dominant negative one. By comparing the main soil quality indicators between upland fields and paddy fields, we could notice that the constraint of ESP on paddy soil quality was not as much as on upland soil. This might be attributed to the farming practices of rice planting that perennial irrigation condition contribute to reducing the alkalization of soil [63,64]. Actually, rice cultivation has been adopted to be an effective method to amend saline-alkaline lands in western Jilin Province since the 1950s. Nevertheless, this method for saline-alkaline lands remediation still needs to be further studied and ameliorated, for instance, combining with fertilization, drainage and vegetation recovery [65–67].

## 5. Conclusions

Our study was conducted to understand the impacts of soil physico-chemical properties and enzyme activities on SOC content of three saline-alkali upland fields (U1, U2 and U3) and three saline-alkali paddy fields (P1, P2 and P3) in western Jilin Province. The content of SOC changed with different soil layers, crop growing periods and sampling sites. In general, SOC decreased along with soil depth as well as appeared lower content at the second growing stage of crops. The trend for SOC content was  $U1 > U2 > U3$  in upland fields, and  $P1 > P2 > P3$  in paddy fields. Among the determined physico-chemical properties, soil pH and ESP had profoundly negative impacts on SOC. Soil BD also had negative correlation with SOC content, but not as significant as the former two. For enzyme activities, amylase and invertase were significantly positively correlated with SOC in both upland

and paddy fields. Catalase played an important role in the accumulation of paddy SOC through catalyzing the decomposition of hydrogen peroxide when the soil was under flooded conditions, however, it had less influence on upland SOC. The PPO activities did not have significant correlation with paddy SOC, but had significantly negative correlation with upland soil, leading to the acceleration of decomposition of SOC in upland fields. Finally, we combined selected physico-chemical properties and enzyme activities and SOC together to obtain the main indicators for soil quality by means of PCA. In upland sites, the main indicators of soil quality were pH, ESP and SOC. Soil pH and ESP were the negative factors, yet SOC was the positive one. In paddy sites, amylase and invertase play critical positive roles in soil quality, and soil pH had extensively adverse influence on it. It is noted that the main indicators of the soil quality were different between paddy soil and upland soil, especially for the effect of soil ESP. The inhibiting influence of ESP on paddy soil quality was not as significant as on upland soil quality, and this may be due to the distinction of farming practices. The perennial irrigation methods are conducive to reducing the degree of soil alkalization. Therefore, paddy fields development has been widely used to improve saline-alkali land in western Jilin Province.

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## References

1. Heimann, M.; Reichstein, M. Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature* **2008**, *451*, 289–292. [[CrossRef](#)] [[PubMed](#)]
2. Štursová, M.; Baldrian, P. Effects of soil properties and management on the activity of soil organic matter transforming enzymes and the quantification of soil-bound and free activity. *Plant Soil* **2011**, *338*, 99–110. [[CrossRef](#)]
3. Wei, Y.; Córdoba, P.; Caramanna, G.; Maroto-Valer, M.; Nathaniel, P.; Steven, M.D. Influence of a CO<sub>2</sub> long term exposure on the mobilisation and speciation of metals in soils. *Chem. Erde Geochem.* **2015**, *75*, 475–482. [[CrossRef](#)]
4. Falkowski, P.; Scholes, R.J.; Boyle, E.; Canadell, J.; Canfield, D.; Elser, J.; Gruber, N.; Hibbard, K.; Höglberg, P.; Linder, S.; et al. The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System. *Science* **2000**, *290*, 291–296. [[CrossRef](#)] [[PubMed](#)]
5. Jenkinson, D.S.; Adams, D.E.; Wild, A. Model estimates of CO<sub>2</sub> emissions from soil in response to global warming. *Nature* **1991**, *351*, 304–306. [[CrossRef](#)]
6. Van Groenigen, K.J.; Qi, X.; Osenberg, C.W.; Luo, Y.; Hungate, B.A. Faster decomposition under increased atmospheric CO<sub>2</sub> limits soil carbon storage. *Science* **2014**, *344*, 508–509. [[CrossRef](#)] [[PubMed](#)]
7. Lal, R.; Griffin, M.; Apt, J.; Lave, L.; Morgan, M.G. Ecology. Managing soil carbon. *Science* **2004**, *304*, 393. [[CrossRef](#)] [[PubMed](#)]
8. Gregorich, E.G.; Carter, M.R.; Angers, D.A.; Monreal, C.M.; Ellert, B.H. Towards a minimum data set to assess soil organic matter quality in agricultural soils. *Can. J. Soil Sci.* **1994**, *74*, 367–385. [[CrossRef](#)]
9. Chandra, L.R.; Gupta, S.; Pande, V.; Singh, N. Impact of forest vegetation on soil characteristics: A correlation between soil biological and physico-chemical properties. *3 Biotech* **2016**, *6*, 1–12. [[CrossRef](#)] [[PubMed](#)]
10. García-Ruiz, R.; Ochoa, V.; Viñepla, B.; Hinojosa, M.B.; Peña-Santiago, R.; Liébanas, G.; Linares, J.C.; Carreira, J.A. Soil enzymes, nematode community and selected physico-chemical properties as soil quality indicators in organic and conventional olive oil farming: Influence of seasonality and site features. *Appl. Soil Ecol.* **2009**, *41*, 305–314. [[CrossRef](#)]
11. Robertson, F.; Crawford, D.; Partington, D.; Oliver, I.; Rees, D.; Aumann, C.; Armstrong, R.; Perris, R.; Davey, M.; Moodie, M. Soil organic carbon in cropping and pasture systems of Victoria, Australia. *Soil Res.* **2016**, *54*, 64–77. [[CrossRef](#)]

12. Burns, R.G.; DeForest, J.L.; Marxsen, J.; Sinsabaugh, R.L.; Stromberger, M.E.; Wallenstein, M.D.; Weintraub, M.N.; Zoppini, A. Soil enzymes in a changing environment: Current knowledge and future directions. *Soil Biol. Biochem.* **2013**, *58*, 216–234. [CrossRef]
13. Hill, B.H.; Follstad Shah, J.J.; Sinsabaugh, R.L. Ecoenzymatic stoichiometry of microbial organic nutrient acquisition in soil and sediment. *Nature* **2009**, *462*, 795–798.
14. Theuerl, S.; Buscot, F. Laccases: Toward disentangling their diversity and functions in relation to soil organic matter cycling. *Biol. Fertil. Soils* **2010**, *46*, 215–225. [CrossRef]
15. Song, Y.; Song, C.; Yang, G.; Miao, Y.; Wang, J.; Guo, Y. Changes in labile organic carbon fractions and soil enzyme activities after marshland reclamation and restoration in the Sanjiang Plain in northeast China. *Environ. Manag.* **2012**, *50*, 418–426. [CrossRef] [PubMed]
16. Luo, L.; Meng, H.; Gu, J.-D. Microbial extracellular enzymes in biogeochemical cycling of ecosystems. *J. Environ. Manag.* **2017**, *197*, 539–549. [CrossRef] [PubMed]
17. Sinsabaugh, R.L.; Lauber, C.L.; Weintraub, M.N.; Ahmed, B.; Allison, S.D.; Crenshaw, C.; Contosta, A.R.; Cusack, D.; Frey, S.; Gallo, M.E.; et al. Stoichiometry of soil enzyme activity at global scale. *Ecol. Lett.* **2008**, *11*, 1252–1264. [CrossRef] [PubMed]
18. Gundi, V.A.K.B.; Viswanath, B.; Chandra, M.S.; Kumar, V.N.; Reddy, B.R. Activities of cellulase and amylase in soils as influenced by insecticide interactions. *Ecotoxicol. Environ. Saf.* **2007**, *68*, 278–285. [CrossRef] [PubMed]
19. Zhang, C.; Liu, G.; Xue, S.; Wang, G. Soil bacterial community dynamics reflect changes in plant community and soil properties during the secondary succession of abandoned farmland in the Loess Plateau. *Soil Biol. Biochem.* **2016**, *97*, 40–49. [CrossRef]
20. Burns, R.G.; Dick, R.P.; Burns, R.G.; Dick, R.P. *Enzymes in the Environment: Activity, Ecology, and Applications*; CRC Press: Boca Raton, FL, USA, 2002; Volume 84, pp. 106–107.
21. Wan, Z.; Song, C. In Seasonal dynamics of soil active carbon and its response to soil enzyme activity in a freshwater marsh of northeast China. In Proceedings of the International Conference on Remote Sensing, Environment and Transportation Engineering, Nanjing, China, 24–26 June 2011; pp. 5299–5302.
22. Zhang, W.; Qiao, W.; Gao, D.; Dai, Y.; Deng, J.; Yang, G.; Han, X.; Ren, G. Relationship between soil nutrient properties and biological activities along a restoration chronosequence of *Pinus tabulaeformis* plantation forests in the Ziwuling Mountains, China. *Catena* **2017**, *161*, 85–95. [CrossRef]
23. Bartosz, A.; Veikko, K.; Aino, S. Polyphenol oxidase, tannase and proteolytic activity in relation to tannin concentration in the soil organic horizon under silver birch and Norway spruce. *Soil Biol. Biochem.* **2009**, *41*, 2085–2093.
24. Wurzburger, N.; Hendrick, R.L. Rhododendron thickets alter N cycling and soil extracellular enzyme activities in southern Appalachian hardwood forests. *Pedobiologia* **2007**, *50*, 563–576. [CrossRef]
25. Kinyangi, J. Soil Health And Soil Quality: A Review. 2007. Available online: <http://www.worldagroforestrycentre.org/Portals/0/PDFarchive/2007/000/00001122.pdf> (accessed on 20 December 2017).
26. Ma, G.; Rengasamy, P.; Rathjen, A.J. Phytotoxicity of aluminium to wheat plants in high-pH solutions. *Anim. Prod. Sci.* **2003**, *43*, 497–501. [CrossRef]
27. Rengasamy, P.; Chittleborough, D.; Helyar, K. Root-zone constraints and plant-based solutions for dryland salinity. *Plant Soil* **2003**, *257*, 249–260. [CrossRef]
28. Ingole, S.P. A Review on Role of Physico-Chemical Properties in Soil Quality. *Int. J. Chem. Stud.* **2015**, *3*, 29–32.
29. Sde, N.; Jvande, S.; Hartmann, R.; Hofman, G. Using time domain reflectometry for monitoring mineralization of nitrogen from soil organic matter. *Eur. J. Soil Sci.* **2000**, *51*, 295–304.
30. Islam, K.K.; Anusontpornperm, S.; Kheoruenromne, I.; Thanachit, S. Relationship between carbon sequestration and physico-chemical properties of soils in salt-affected areas, Northeast Thailand. *Kasetsart J. Nat. Sci.* **2014**, *48*, 560–576.
31. Bueis, T.; Turrión, M.B.; Bravo, F.; Pando, V.; Muscolo, A. Factors determining enzyme activities in soils under *Pinus halepensis* and *Pinus sylvestris* plantations in Spain: A basis for establishing sustainable forest management strategies. *Ann. For. Sci.* **2018**, *75*, 34. [CrossRef]
32. Wan, Z.; Wu, J. Study progress on factors affecting soil enzyme activity. *J. Northwest Sci-Tech Univ. Agric. For.* **2005**, *33*, 87–91.

33. Dick, R.P.; Rasmussen, P.E.; Kerle, E.A. Influence of long-term residue management on soil enzyme activities in relation to soil chemical properties of a wheat-fallow system. *Biol. Fertil. of Soils* **1988**, *6*, 159–164. [[CrossRef](#)]
34. Nitsch, P.; Kaupenjohann, M.; Wulf, M.; Nitsch, P.; Kaupenjohann, M.; Wulf, M.; Nitsch, P.; Kaupenjohann, M.; Wulf, M. Forest continuity, soil depth and tree species are important parameters for SOC stocks in an old forest (Templiner Buchheide, northeast Germany). *Geoderma* **2018**, *310*, 65–76. [[CrossRef](#)]
35. Zhang, Z.; Lu, X.; Song, X.; Guo, Y.; Xue, Z. Soil, C, N and P stoichiometry of *Deyeuxia angustifolia* and *Carex lasiocarpa* wetlands in Sanjiang Plain, Northeast China. *J. Soils Sediments* **2012**, *12*, 1309–1315. [[CrossRef](#)]
36. Lu, Y.; Xu, H. Distribution characteristic of soil organic carbon fraction in different types of wetland in Hongze Lake of China. *Sci. World J.* **2014**, *2014*, 487961. [[CrossRef](#)] [[PubMed](#)]
37. Li, Z. *The Response Mechanism of Soil Microbes and Enzyme Activity on Carbon Variations of Paddy Soil in Western Jilin*; Jilin University: Changchun, China, 2014.
38. Zheng, B.Z. *Technical Guide for Soil Analysis*; China Agriculture Press: Beijing, China, 2013.
39. Guan, S.Y. *Soil Enzyme and Its Research Methods Beijing*; Agriculture Press: Beijing, China, 1986.
40. Lin, X.G. *Principles and Methods of Soil Microbiology Research*; Education Press: Beijing, China, 2010.
41. Teng, M.; Zeng, L.; Xiao, W.; Huang, Z.; Zhou, Z.; Yan, Z.; Wang, P. Spatial variability of soil organic carbon in Three Gorges Reservoir area, China. *Sci. Total Environ.* **2017**, *599–600*, 1308–1316. [[CrossRef](#)] [[PubMed](#)]
42. Jobbagy, E.G.; Jackson, R.B. The Vertical Distribution Of Soil Organic Carbon And Its Relation To Climate And Vegetation. *Ecol. Appl.* **2000**, *10*, 423–436. [[CrossRef](#)]
43. Liu, X.; Zhang, X.; Chen, S.; Sun, H.; Shao, L. Subsoil compaction and irrigation regimes affect the root–shoot relation and grain yield of winter wheat. *Agric. Water Manag.* **2015**, *154*, 59–67. [[CrossRef](#)]
44. Rostamza, M.; Richards, R.A.; Watt, M. Response of millet and sorghum to a varying water supply around the primary and nodal roots. *Ann. Bot.* **2013**, *112*, 439–446. [[CrossRef](#)] [[PubMed](#)]
45. Aon, M.A.; Colaneri, A.C. Temporal and spatial evolution of enzymatic activities and physico-chemical properties in an agricultural soil. *Appl. Soil Ecol.* **2001**, *18*, 255–270. [[CrossRef](#)]
46. Seelig, B. *Salinity and Sodicy in North Dakota Soils*; Extension Publications; North Dakota State University: Fargo, ND, USA, 2000.
47. Hartman, W.H.; Richardson, C.J.; Vilgalys, R.; Bruland, G.L. Environmental and Anthropogenic Controls over Bacterial Communities in Wetland Soils. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 17842–17847. [[CrossRef](#)] [[PubMed](#)]
48. Baath, E.; Berg, B.; Lohm, U.; Lundgren, B.; Lundkvist, H.; Rosswall, T.; Soderstrom, B.; Wiren, A. Effects of experimental acidification and liming on soil organisms and decomposition in a Scots pine forest. *Pedobiologia* **2009**, *20*, 85–100.
49. Tabatabai, M.A. *Methods of Soil Analysis: Microbiological and Biochemical Properties*; Soil Science Society of America: Madison, WI, USA, 1994.
50. Zhou, Q.D. *Microbiology Course*; Higher Education Press: Beijing, China, 2011.
51. Frankenberger, M.T., Jr.; Desheng, Z. Effect of pH on the Stability of Soil Enzymes. *Adv. Soil Sci.* **1985**, *6*, 39–42. [[CrossRef](#)]
52. Pistocchi, C.; Ragaglini, G.; Colla, V.; Branca, T.A.; Tozzini, C.; Romaniello, L. Exchangeable Sodium Percentage decrease in saline sodic soil after Basic Oxygen Furnace Slag application in a lysimeter trial. *J. Environ. Manag.* **2017**. [[CrossRef](#)] [[PubMed](#)]
53. Rengasamy, P.; Olsson, K.A. Sodicy and soil structure. *Aust. J. Soil Res.* **1991**, *29*, 935–952. [[CrossRef](#)]
54. Lemanowicz, J.; Krzyżaniak, M. Vertical distribution of phosphorus concentrations, phosphatase activity and further soil chemical properties in salt-affected Mollic Gleysols in Poland. *Environ. Earth Sci.* **2015**, *74*, 1–10. [[CrossRef](#)]
55. Biró, B.; Toscano, G.; Horváth, N.; Matics, H.; Domonkos, M.; Scotti, R.; Rao, M.A.; Wejden, B.; French, H.K. Vertical and horizontal distributions of microbial abundances and enzymatic activities in propylene-glycol-affected soils. *Environ. Sci. Pollut. Res. Int.* **2014**, *21*, 9095–9108. [[CrossRef](#)] [[PubMed](#)]
56. Das, C.; Aditya, P.; Datta, J.K.; Mondal, N.K. Soil enzyme activities in dependence on tree litter and season of a social forest, Burdwan, India. *Arch. Agron. Soil Sci.* **2014**, *60*, 405–422. [[CrossRef](#)]
57. Wallenstein, M.; Allison, S.D.; Ernakovich, J.; Steinweg, J.M.; Sinsabaugh, R. *Controls on the Temperature Sensitivity of Soil Enzymes: A Key Driver of In Situ Enzyme Activity Rates*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 245–258.

58. Shao, X.; Yang, W.; Wu, M. Seasonal Dynamics of Soil Labile Organic Carbon and Enzyme Activities in Relation to Vegetation Types in Hangzhou Bay Tidal Flat Wetland. *PLoS ONE* **2015**, *10*, e0142677. [[CrossRef](#)] [[PubMed](#)]
59. Xie, X.; Pu, L.; Wang, Q.; Zhu, M.; Xu, Y.; Zhang, M. Response of soil physicochemical properties and enzyme activities to long-term reclamation of coastal saline soil, Eastern China. *Sci. Total Environ.* **2017**, *607–608*, 1419–1427. [[CrossRef](#)] [[PubMed](#)]
60. Yakushev, A.V.; Kuznetsova, I.N.; Blagodatskaya, E.V.; Blagodatsky, S.A. Temperature dependence of the activity of polyphenol peroxidases and polyphenol oxidases in modern and buried soils. *Eurasian Soil Sci.* **2014**, *47*, 459–465. [[CrossRef](#)]
61. Kunito, T.; Akagi, Y.; Park, H.D.; Toda, H. Influences of nitrogen and phosphorus addition on polyphenol oxidase activity in a forested Andisol. *Eur. J. For. Res.* **2009**, *128*, 361–366. [[CrossRef](#)]
62. Toberman, H.; Laiho, R.; Evans, C.D.; Artz, R.R.E.; Fenner, N.; Straková, P.; Freeman, C. Long-term drainage for forestry inhibits extracellular phenol oxidase activity in Finnish boreal mire peat. *Eur. J. Soil Sci.* **2010**, *61*, 950–957. [[CrossRef](#)]
63. Xue, B.X.; Kang, X.F.; Wei, L. Study on the Saline-Alkaline Land Reclamation in Daqing. *Adv. Mater. Res.* **2012**, *518–523*, 6034–6037. [[CrossRef](#)]
64. Yu, R.; Wang, J. Evaluation of the environmental sustainability of farmers' land use decisions in the saline-alkaline areas. *Environ. Monit. Assess.* **2015**, *187*, 182. [[CrossRef](#)] [[PubMed](#)]
65. Qadir, M.; Noble, A.D.; Qureshi, A.S.; Gupta, R.K.; Yuldashev, T.; Karimov, A. Salt-induced land and water degradation in the Aral Sea basin: A challenge to sustainable agriculture in Central Asia. *Nat. Resour. Forum* **2009**, *33*, 134–149. [[CrossRef](#)]
66. Xu, H.; Huang, X.; Zhong, T.; Chen, Z.; Yu, J. Chinese land policies and farmers' adoption of organic fertilizer for saline soils. *Land Use Policy* **2014**, *38*, 541–549. [[CrossRef](#)]
67. Ranatunga, K.; Nation, E.R.; Barodien, G. Potential use of saline groundwater for irrigation in the Murray hydrogeological basin of Australia. *Environ. Model. Softw.* **2010**, *25*, 1188–1196. [[CrossRef](#)]



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