EFFECTS OF DIFFERENT RICE PLANTING DURATION ON ORGANIC CARBON COMPONENTS AND CARBON POOL MANAGEMENT INDEX OF SALINE-ALKALINE SOIL IN WESTERN JILIN PROVINCE, CHINA

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Abstract. The soil carbon pool management index is an important quantitative index to characterize soil carbon change. It is of great significance to study the change process of easily oxidized organic carbon in the soil and carbon pool management index can be used in the case of saline-alkali fields of western Jilin province to understand the evolution of soil quality and evaluate its effects during ecological restoration. The temporal and spatial evolution characteristics of soil organic carbon (SOC), readily oxidized organic carbon (ROOC), non-readily oxidized organic carbon (NROOC) and carbon pool activity (A), carbon pool activity index (AI), carbon pool management index (CMI) and carbon pool index (CPI) in saline-alkali paddy fields in western Jilin, China were analyzed. The results showed that the soil layer and rice growth stage were the main factors affecting the changes in soil carbon pool, and the CPI and CMI increased with the increase of cultivation time. The soil ROOC, NROOC is closely related to SOC and is an important part of soil SOC, and obviously depends on the input, fixation, transformation and decomposition of surface carbon sources.
Keywords: *saline-alkali rice field, rice growth stages, easily oxidized organic carbon, carbon pool management index, influencing factors*

Introduction

Soil readily oxidizable organic carbon is an important component of soil carbon pool, and is easily degraded by oxidation in soil (Ya et al., 2013). The temporary fluctuation of soil organic matter mainly occurred in the easily oxidized part, and the ratio of Rooc to organic carbon could indicate the soil quality and the rate of soil organic carbon oxidation (Cao et al., 2019). Therefore, Rooc is an important index of soil fertility change, which can indicate the dynamic change of soil organic matter. It was found that the organic carbon that could be oxidized by 333 mmol·L^{-1} KMnO$_4$ changed the most when growing crops, and the organic carbon that could be oxidized by 333 mmol·L^{-1} KMnO$_4$ was called active organic carbon, while the organic carbon that could not be oxidized was called inactive organic matter (Zhao et al., 2019). Active organic carbon can be used as an indicator of early changes in organic carbon, while non-active organic carbon can be used as an indicator of soil long-term accumulation and carbon sequestration (Liu et al., 2019). Soil carbon pool management index is a quantitative index to characterize soil carbon change. It is based on soil total organic carbon and easily oxidized organic carbon (Lefroy et al., 1993). The soil carbon pool management index is obtained by calculation. Ever since the concept of carbon management index was put forward, it has often been used to monitor the effectiveness of soil carbon pool dynamics and evaluate the management level of soil quality (Tang et al.,

2014). The effects of different land use (Qiu et al., 2009), tillage management (Lv et al., 2014) etc. on soil carbon pool have been widely used. Therefore, under the background of the sharp change of global climate and the sharp increase of greenhouse effect, it is of great significance to clarify the change characteristics and evolution law of the management index of easily oxidized organic carbon and carbon pool in saline-alkali paddy soil for the rational utilization of saline-alkali soil, soil fertilization and soil carbon sequestration. The saline-alkali land is widely distributed throughout the world, covering more than 30 countries on six continents, with a total area of about 9.56×10^9 ha. Australia accounted for 37%, the former Soviet Union for 18% and China for 10%. The saline-alkali land of Songnen Plain is the concentrated distribution area of saline-alkali land in China. The west of Jilin Province is located on the south side of Songnen Plain, which is a serious disaster area of soda-alkaline desertification. In order to promote the development and utilization of saline-alkali land, rice was planted in part of the land to improve saline-alkali land. (Zhang et al., 2016a). At present, there are few studies on soil carbon pool index of saline-alkalized paddy field under different rice cultivation years. Therefore, the change characteristics of soil carbon pool management index and its evolution law during the maturation of saline-alkali rice field are discussed.

Materials and methods

Study description

The saline-alkali soil area in western Jilin of China was once a large inland lake basin in geological history, and the lake water was abundant and withered many times, which made the soluble salt in the parent rock of the highland in the basin converge with the runoff in the closed-flow lowland, forming a large area of saline-alkali soil deposition (Tang et al., 2012a). Rice plantation is adopted as the main method for the improvement as well as repair and utilization of saline alkali land in this area. Here, the Qianguoerluos County Irrigation District (123°35′-125°18′E, 44°17′-45°28′N) is one of the four major irrigation districts in Northeast China. The annual average number of sunny days is 110 days, the annual average sunshine hours is 2879 h, the annual average temperature is 4.5 °C. The initial frost period is generally in the middle and late September, the final frost period is generally from the end of April to the beginning of May, and the frost-free period is 130-140 days. The average annual precipitation is 400-500 mm. The annual evaporation is more than 1200 mm (Tang et al., 2011). Time series study is a powerful tool to understand the change and evolution of soil texture, so in order to make the sample land more representative and the test results more universal, according to the soil type map and the land use type map, combined with the field investigation, according to the paddy field tillage history, and to determine the management method, soil properties basically involved 5 different cultivation years, one year (S1), 10 years (S2), 20 years (S3), 30 years (S4), 50 years (S5), were determined as test plots based on soil type maps and land use type maps, combined with field surveys and based on paddy field tillage history (*Fig. 1*). The plots were unified into single-planted rice soil, and the management of each plots was consistent. The base fertilizer was urea, phosphate and potash.

Sample collection and analysis

Soil sampling was carried out at different growth stages (seedling stage, tillering stage, heading stage, seed setting stage, mature stage) of rice growth. The soil samples

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of 0-10, 10-20, 20-30, 30-40, 40-50 cm soil layer were collected according to the S sampling method, 180 sampling points were set. The samples of the same soil layer at each sampling point were mixed to remove plant residues and roots from the soil and placed in plastic bags. Then the soil samples were stored in the incubator under 4 °C conditions. After all the soil was collected, the soil was brought back to the laboratory for testing.
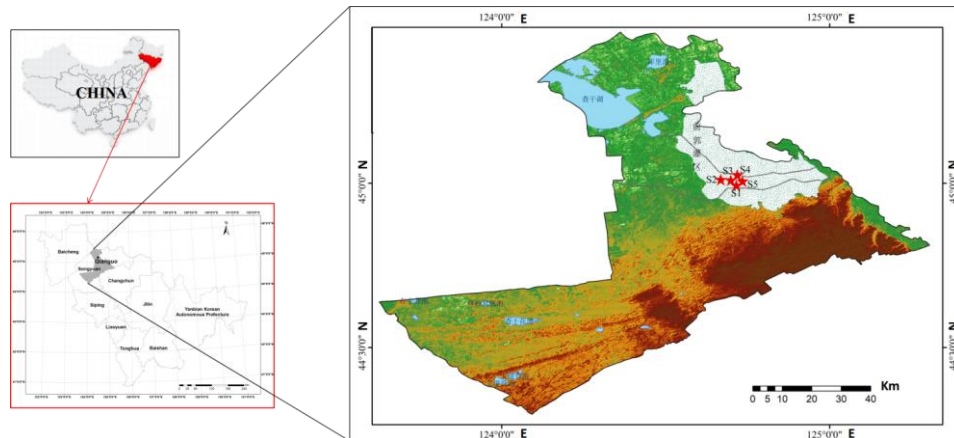

Figure 1. *The location of the study area and the distribution of the sampling points*

Soil organic carbon (SOC) was determined by potassium dichromate external heating (Bao, 2000). Readily oxidized organic carbon (ROOC) was determined by $KMnO_4$ oxidation method (Zhou et al., 2019).

The management index of carbon pool is calculated by Blair and Lefroy, and the calculation formula is as follows:

$$NROOC = SOC - ROOC \tag{Eq.1}$$

$$A = ROOC / NROOC \tag{Eq.2}$$

$$AI = TSOCa / RSOCa \tag{Eq.3}$$

$$CPI = TSOC / RSOC \tag{Eq.4}$$

$$CMI = AI \times CPI \times 100 \tag{Eq.5}$$

where SOC is soil organic carbon, ROOC is readily oxidized organic carbon, NROOC is non-readily oxidized organic carbon, A is carbon pool activity, AI is carbon pool activity index, TSOCa is tillage soil carbon pool activity, RSOCa is reference soil carbon pool activity, CPI is carbon pool index, TSOC is tillage soil organic carbon, RSOC is reference soil organic carbon, CMI is the carbon pool management index (Blair et al., 1995).

Statistical analysis

One-way ANOVA method is used to analyze the influence of three factors on soil carbon composition and carbon pool management index under single condition.

Multivariate ANOVA was used to analyze the comprehensive differences of carbon composition and carbon pool management index caused by three factors: rice cultivation, soil layer and rice growth stage. Pearson correlation analysis is used to analyze the correlation between soil carbon components and carbon pool management indicators.

Results

Distribution of soil carbon content

As can be seen from *Figure 2,* the soil SOC content showed a decreasing trend: S5 > S4 > S3 > S2 > S1. The SOC content of S5 was significantly higher than S1 ($p < 0.05$), and the soil SOC content of S5 increased gradually with the extension of rice cultivation, the results showed that longer rice growing period and lower salt-alkali stress were beneficial to soil SOC accumulation. During the rice growing stage, the soil SOC content decreased firstly and then increased, and the soil SOC content was the lowest in tillering stage.
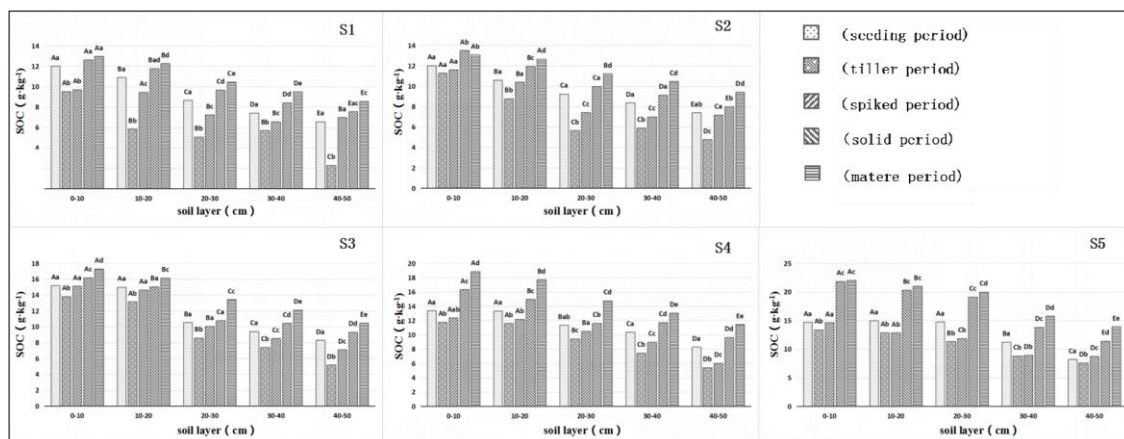

Figure 2. The soil SOC content and distribution characteristics

Figures 3 and *4* show that, Soil ROOC and NROOC content increased significantly with planting years. The soil ROOC content of S1, S2, S3, S4 and S5 were 0.47-4.16 g·kg^{-1}, 1.31-5.41 g·kg^{-1}, 2.10-7.89 g·kg^{-1}, 2.05-7.47 g·kg^{-1} and 2.24-7.91 g·kg^{-1}, respectively. The soil ROOC content increased with the increase of rice cultivation years, the soil ROOC content of S5 was significantly higher than S1, the soil ROOC content of S4 was slightly lower than S3. The soil NROOC content was lower than ROOC. The soil NROOC content of S1, S2, S3, S4 and S5 were 1.83-8.94 g·kg^{-1}, 3.46-8.51 g·kg^{-1}, 3.09-9.75 g·kg^{-1}, 3.38-11.39 g·kg^{-1} and 4.75-14.45 g·kg^{-1}, respectively. The soil NROOC content of S5 was significantly higher than S1, and characteristics of small differences between S3 and S4 were observed. The soil NROOC content was lower in tillering stage and higher in spike-pumping stage, and its distribution law was basically consistent with the distribution characteristics of SOC. The results showed that the soil NROOC content of rice was higher in surface soil, the NROOC content of 0-10 cm soil layer was close to 2 times that of 40-50 cm soil layer, and the NROOC content of 10-20 cm soil layer was slightly lower than 0-10 cm, but the decrease was not large.
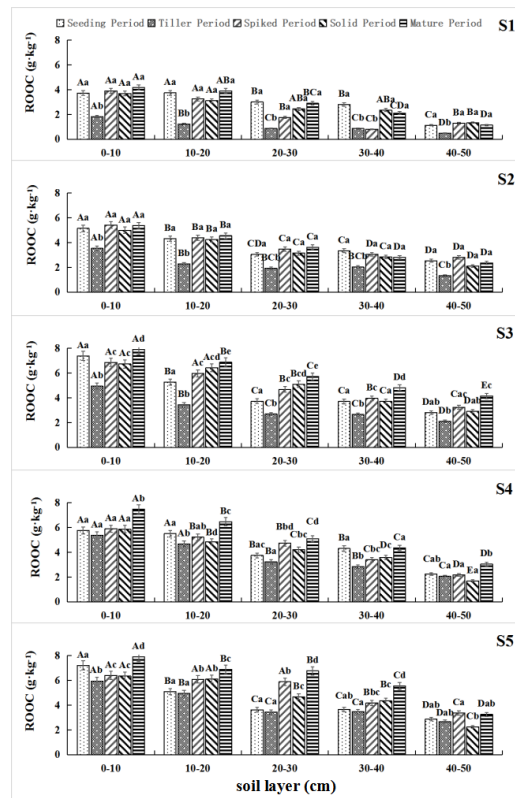
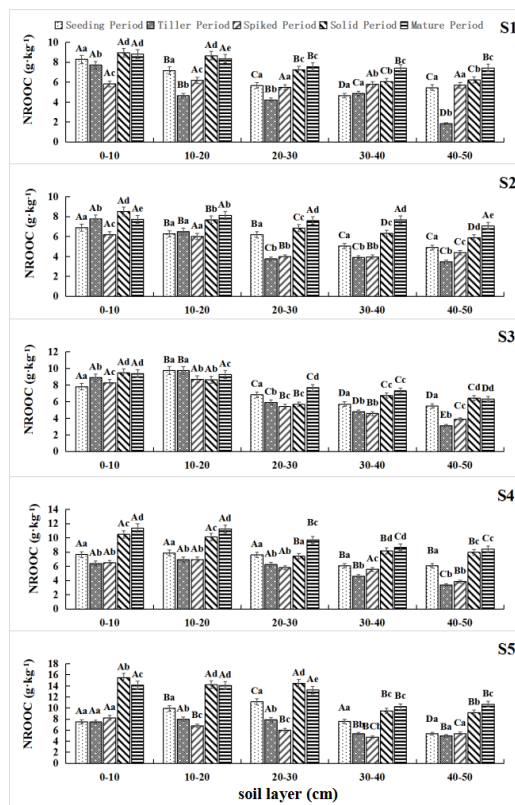*Figure 3. The soil ROOC content and distribution characteristics*

Figure 4. The soil NROOC content and distribution characteristics

Changes in soil carbon pool management indicators

Using saline-alkali wasteland soil in Qianguo County as reference soil, the carbon pool activity (A), carbon pool activity index (AI), carbon pool index (CPI) and carbon pool management index (CMI) of paddy field soil with different rice cultivation years were calculated by space-time substitution method. The results are shown in *Figures 5, 6, 7* and *8.*
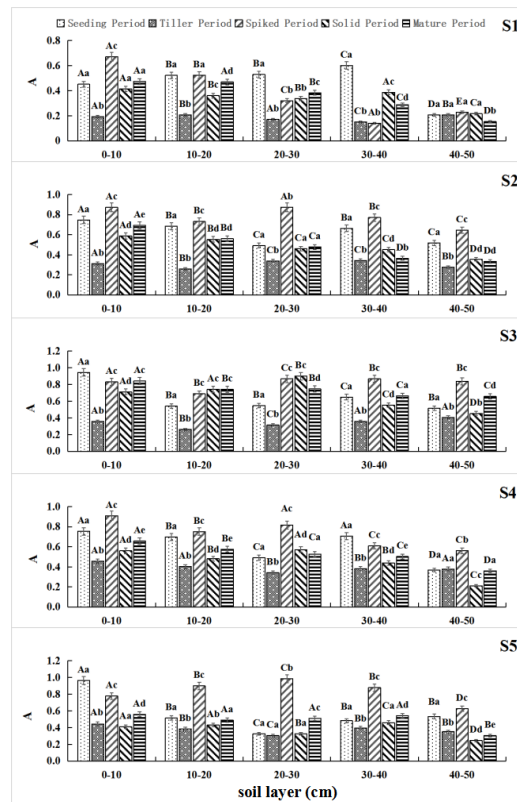

Figure 5. Distribution of A in rice during different growing stages

The soil A index values of S1, S2, S3, S4 and S5 were 0.14-0.67, 0.26-0.87, 0.26-0.94, 0.34-0.91 and 0.30-0.96, respectively. During the rice growing stage, the soil A index value ranged from 0.56 to 0.98 at the rice heading stage, which was the highest value in the whole growing stage and more than twice the value of the soil A index at the tillering stage. The change of A index value of S1 soil in rice growing stage is different from other years. This may be closely related to the time of rice planting and human disturbance, a preliminary change in the nature of the land, so that the soil to undertake root exudates type changes. As a result, the formation of soil carbon pool activity will be different (Guo et al., 2014).

The soil AI index value of different rice cultivation years was slightly higher in heading period, but with the extension of rice cultivation years, the fluctuation of AI index was more intense, the law was not obvious, and there was no obvious law between soil layers.

The soil CPI index increased gradually with the increase of rice cultivation years. The values of CPI of S1, S2, S3, S4 and S5 were 0.28-1.04, 0.53-1.10, 0.58-1.36, 0.56-1.44 and

0.68-1.54, respectively. During the rice cultivation years, the CPI values of mature soil were higher, and those of tillering soil were lower. In addition, the CPI values of 10-20 cm soil layers of S2 and S3 were higher than that of other soil layers, the CPI value of 20-30 cm soil layer of S4 and S5 were higher than that of other soil layers.

The soil CMI index of S1, S2, S3, S4 and S5 were 16.56-222.48, 26.91-323.25, 31.07-130.67, 37.02-129.08 and 27.01-91.65, respectively. With the growing of rice, the soil CMI index of S2 was higher than S1, and the soil CMI index of S3 was similar to S4. The results showed that the soil CMI index of saline-alkali rice field fluctuated greatly. In this study, the maximum value of soil CMI index was reached when rice was planted to 20-30 years, and then began to decrease slowly. During rice growth stages, the soil CMI index of heading stage was higher than that of other growth stages.

Coupling relationship between soil SOC, ROOC and NROOC and carbon pool management index

Table 1 shows the correlation among organic carbon, readily oxidizable organic carbon, steady-state carbon and carbon pool management indicators. The soil SOC, ROOC and NROOC of S1, S2, S3, S4 and S5 were significantly correlated with CMI index, and there were no significant correlation between the soil ROOC and index A. The soil ROOC of S2, S3, S4 and S5 were significantly correlated with index A ($P < 0.05$), and the correlation coefficient was greater between the soil ROOC and index A with the extension of rice cultivation years. The soil SOC of S4 and S5 were significantly correlated with CPI ($P < 0.05$).

Table 1. *Correlation analysis of soil SOC, ROOC, NROOC and carbon reservoir management index*

Sample number	Index	A	AI	CMI	CPI
S1	SOC	-0.240	0.313	-0.402*	-0.419*
	ROOC	-0.080	0.255	-0.473*	-0.529**
	NROOC	0.284	-0.316	0.887**	0.299
S2	SOC	0.311	-0.430*	0.764**	-0.150
	ROOC	0.522**	-0.212	0.502*	0.032
	NROOC	-0.050	-0.447*	0.827**	-0.126
S3	SOC	0.335	0.026	0.629**	0.325
	ROOC	0.645**	0.397*	0.460*	0.499*
	NROOC	0.021	-0.251	0.667**	0.095
S4	SOC	0.314	0.110	0.620**	0.517**
	ROOC	0.672**	0.462*	0.423*	0.465*
	NROOC	0.042	-0.092	0.735**	0.443*
S5	SOC	-0.136	-0.275	0.895**	0.588*
	ROOC	0.883**	0.324	0.413*	0.643**
	NROOC	0.013	-0.312	0.443*	-0.450*

* indicates significant difference (P < 0.05), ** represents a very significant difference (P < 0.01). SOC, organic carbon; ROOC, readily oxidized organic carbon, NROOC, non-readily oxidized organic carbon, A, carbon pool activity, AI, carbon pool activity index, CPI, carbon pool index, CMI, carbon pool management index
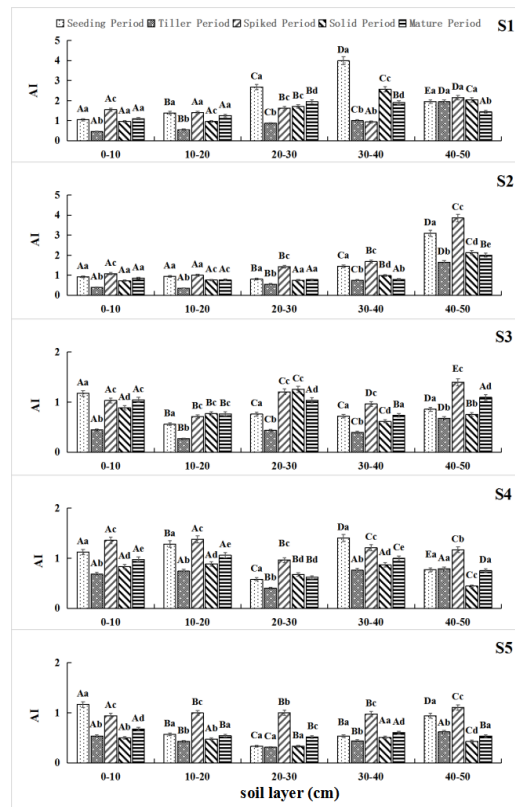
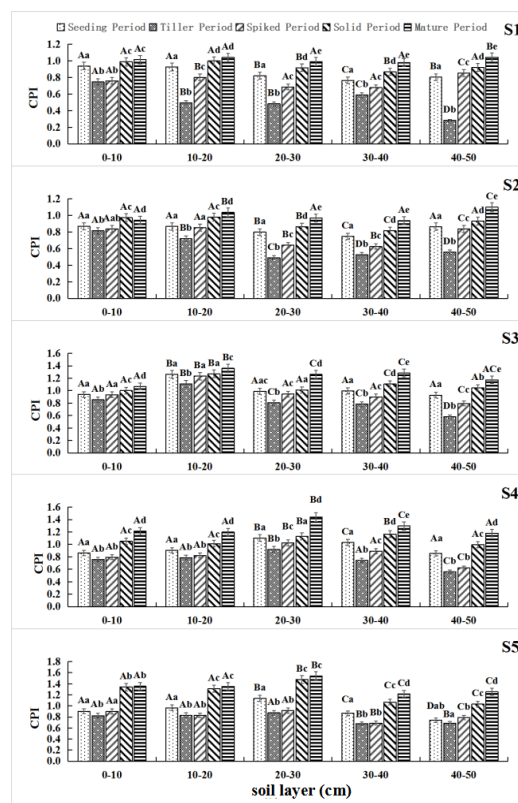*Figure 6. Distribution of AI in rice during different growing stages*

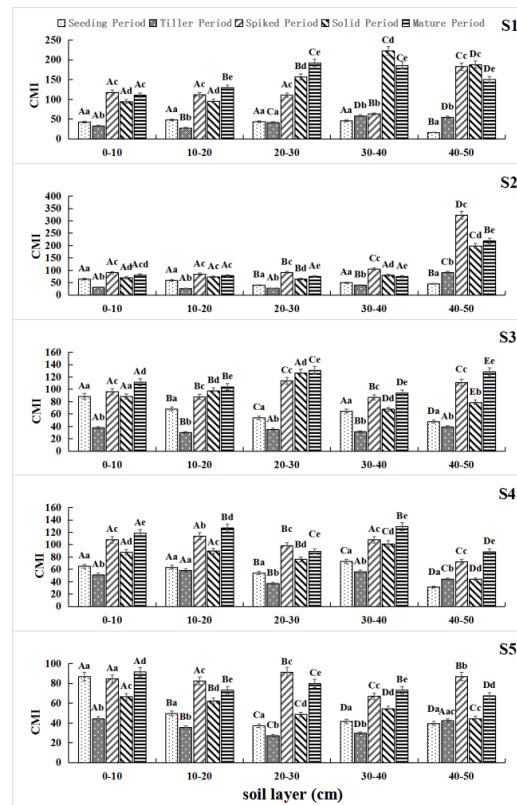*Figure 7. The soil CPI content and distribution characteristics*

Figure 8. The soil CMI content and distribution characteristics

Factors influencing the management index of carbon pool

Table 2 shows the effects of soil layer, the rice cultivation years and rice growth stages on the carbon pool management index. The results showed that soil layer as an independent source of variation had a significant effect on AI and CMI ($P < 0.001$), and the number of rice cultivation years and rice growth stages as the independent source of variation had a significant effect on soil management indexes ($P < 0.001$).

Discussion

Characteristics and contribution of carbon accumulation in soil steady state during saline-alkali rice maturing

The dynamic balance of soil carbon pool is closely related to crop growth and fertilization management and directly affects soil fertility and crop yield (Cuo et al., 2014). Actually, agricultural production (e.g. years of soil tillage, management of fertilization, return of plant residues or organic materials, etc.) causes the initial changes in the soil carbon pool mainly by easy decomposition and mineralization. Currently, some scholars have tried to use soil organic carbon sublibrary to indicate total carbon change (Ma et al., 2019; Sun et al., 2015). The change of soil carbon pool mainly occurs in the active carbon pool (Kong et al., 2019). Therefore, they are important for soil carbon conversion, and it is closely related to soil productivity. Dalal and others think that it is better to use unstable carbon (Labile C) to indicate the change of soil carbon pool (Dalal et al., 1986). According to Su Jing and other studies,

the main increase is inactive organic carbon content (Su et al., 2005). Distribution of NROOC in general soils is between 75 and 85%, and different ecosystems have different NROOC contents in soil (Ma et al., 2019; Li et al., 2006). In this study, during the rice growth stage, the proportion of the soil NROOC in saline-alkali paddy fields with different rice cultivation years was about 52.4-87.72. With the extension of rice, the soil ROOC and NROOC are increasing, and the NROOC content is higher than ROOC. In the process of rice cultivation years, most of the main carbon in the soil is converted into inactive parts and stored in soil (Mao, 2019). The soil NROOC content of different rice cultivation years also showed seasonal variation law, because of the difference of exogenous carbon input and soil microbial activity in different rice cultivation years.

Table 2. Multifactorial variance analysis of carbon bank management index

Index	Source of variation	Sum of squares	Degree of freedom	Mean square	F	P
A	Soil layer	0.558	4	0.139	38.124	0.001
	Reclamation time	1.159	4	0.29	79.2	*
	Growth stage	1.992	4	0.498	136.148	*
	Soil layer * Reclamation time	0.077	15	0.005	1.402	0.377
	Reclamation time * Growth stage	0.293	16	0.018	5.002	0.042
	Soil layer * Growth stage	0.517	16	0.032	8.834	0.012
	Soil layer * Reclamation time * Growth stage	0.555	60	0.009	2.531	0.15
AI	Soil layer	7.321	4	1.83	168.896	*
	Reclamation time	13.354	4	3.339	308.083	*
	Growth stage	7	4	1.75	161.483	*
	Soil layer * Reclamation time	11.159	15	0.744	68.653	*
	Reclamation time * Growth stage	1.895	16	0.118	10.931	0.008
	Soil layer * Growth stage	3.551	16	0.222	20.48	0.002
	Soil layer * Reclamation time * Growth stage	6.266	60	0.104	9.637	0.009
CPI	Soil layer	0.282	4	0.071	11.138	0.011
	Reclamation time	1.123	4	0.281	44.291	*
	Growth stage	3.309	4	0.827	130.548	*
	Soil layer * Reclamation time	0.72	15	0.048	7.574	0.017
	Reclamation time * Growth stage	0.166	16	0.01	1.634	0.308
	Soil layer * Growth stage	0.336	16	0.021	3.313	0.095
	Soil layer * Reclamation time * Growth stage	0.192	60	0.003	0.504	0.906
CMI	Soil layer	18296.604	4	4574.151	62.369	*
	Reclamation time	24126.885	4	6031.721	82.243	*
	Growth stage	112007.641	4	28001.91	381.81	*
	Soil layer * Reclamation time	46784.172	15	3118.945	42.527	*
	Reclamation time * Growth stage	22854.251	16	1428.391	19.476	0.002
	Soil layer * Growth stage	29025.917	16	1814.12	24.736	0.001
	Soil layer * Reclamation time * Growth stage	32085.276	60	534.755	7.291	0.017

* indicates significant difference (P < 0.001). A, carbon pool activity, AI, carbon pool activity index, CPI, carbon pool index, CMI, carbon pool management index

Response of soil carbon reservoir management index to organic carbon accumulation in saline-alkali paddy field

The change of land use mode can lead to the change of tillage system, which will affect the balance of soil organic matter and change the decomposition rate of soil organic carbon (Tang et al., 2012b; Shen et al., 2000). In this study, the effect of planting years on soil carbon pool management index was obvious, and the soil A index value of different rice cultivation years was different. The soil A index value of 50 years was higher than that of the newly planted rice, which indicated that the carbon of saline-alkali paddy soil did not age, which was beneficial to carbon transformation.

The soil CPI index value increased gradually with the extension of rice cultivation years, which was basically consistent with the research of Wu et al (2015). The results showed that the soil CPI value increased after rice cultivation in dry land and wasteland. It shows that rice cultivation can effectively improve the carbon sink function of saline-alkali soil during the ripening process of saline-alkali rice field.

The soil CMI index value combined with soil carbon pool index and soil activity index, it can be sensitive to reflect and monitor soil organic carbon change index (Xu et al., 2006), and it can reflect external conditions on the quantity and quality of each component in carbon pool. The rise in the carbon pool management index indicates an increase in soil fertility, while a decline indicates a decline in soil fertility (Qiu et al., 2009). According to some studies, the initial change of soil carbon pool caused by agricultural production management measures and land use mode is mainly activated carbon part, which further affects soil carbon pool management index (Zhang et al., 2016b).

In this study, carbon pool activity (A) increases gradually with the rice cultivation years from the carbon pool management indices. During the rice cultivation, the soil carbon pool activity in seedling stage and heading stage is large, it shows that the soil quality improved in the process of soil maturation. The return of straw to the field is beneficial to the improvement of soil active carbon content and carbon pool management index in the tillage layer. The soil carbon pool management index is vulnerable to fertilization and farming years according to Wu Jianfu and other studies (Wu et al., 2013). In this study, the soil CMI index values increased gradually with the increase of rice cultivation, S2 above S1 level, and continued to increase with the extension of rice cultivation years, to show that reasonable rice cultivation can effectively improve soil CPI and CMI, but then the soil CMI began to slow down, because of farming provides a more suitable environment for microbes. As a result, the decomposition rate of soil organic carbon increased (Liu et al., 2017), so S5 soil CMI is lower than S4.

Sun Tao and others simulated the effect of planting years on the change of soil carbon pool in secondary saline-alkali soil based on CENTURY model (Sun et al., 2015). It was found that the total organic carbon of soil experienced a rapid rise, rapid decline and gradual steady change after planting Lycium barbarum. Therefore, the renewal and change of soil carbon pool caused by planting years may continue to be dynamic in the early decades of planting. On the other hand, it is found that the L, CPI and CMI of deep soil (40-50 cm) are lower than that of surface soil (0-10 cm), which is similar to that of Li et al. (2008). It shows that the carbon pool transformation and nutrient cycle of deep soil decrease slowly.

The main factors affecting the change of carbon pool management index were analyzed from three aspects: rice cultivation years, soil layer and rice growing stage.

The results showed that soil layer had only significant effect on AI, CMI ($P < 0.001$), which indicated that the change of carbon pool activity in cultivated soil was obviously affected by section structure. Both rice cultivation years and rice growth stage have significant effects on A, AI, CPI and CMI, indicating that the renewal and evolution of soil carbon pool in saline-alkali rice field is more based on the influence of rice cultivation years and crop growth.

The correlation analysis showed that the soil SOC, ROOC and NROOC content of different rice cultivation years was significantly positively correlated in different rice growth stages, indicating that soil ROOC and NROOC were closely related to SOC, and was an important part of soil SOC, it obviously depended on the input, fixation, transformation and decomposition of surface carbon sources (Zhang et al., 2020). Further, it is clear that soil ROOC is a sensitive index to indicate soil carbon pool, which can reflect the change characteristics of soil organic carbon pool in the short term. Previous studies have shown that the soil CMI index can well indicate the change of soil quality and organic carbon (Zhang et al., 2019). The soil SOC and CMI index showed no significant correlation between tillering stage and heading stage. As a result, the soil CMI index can be used to evaluate the cumulative effect of soil carbon pool in rice cultivation.

Conclusion

The readily oxidized organic carbon to soil rice cultivation years and growing stage is obvious, which indicates that the stability of soil carbon pool is closely related to rice growth. Therefore, the feedback effect of plant and atmosphere on soil material circulation can further be studied, this provides a more comprehensive understanding of the process of the carbon bank cycle.

In the process of maturation of saline-alkali rice field, the content of soil NROOC increased significantly with the extension of rice cultivation years. The soil CMI index and the organic carbon content change obviously, showing that the soil CMI index increases first and then decreases with the extension of rice cultivation years. However, the carbon pool is in dynamic change during the maturation of saline-alkali rice field. The renewal and evolution of soil carbon pool is more based on the influence of rice cultivation and crop growth. Therefore, it is suggested that reasonable rice planting can improve the quality of soil carbon pool in saline-alkali paddy field.

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