Bangladesh J. Bot. **49**(3): 787-798, 2020 (September) Special

EFFECTS OF DIFFERENT RESTORATION MEASURES ON SOIL ORGANIC CARBON COMPONENTS IN A CLEAR-CUTTING CHINESE PINE FOREST

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Keywords: Restoration measures, Chinese pine forest, Soil carbon component

Abstract

In order to analyze effects of different restoration measures on the composition and stability of soil carbon pool, restoration communities in Chinese pine plantations of the Loess Plateau after clear-cutting were investigated. There were 3 types of restoration community (shrub land, abandoned forestland and young plantation land) and no clear-cutting forest as control (CK). The results showed that the soil total organic carbon (SOC), the high activity component (C1), the middle activity component (C2) and the content of stability component (C4) in the upper soil decreased firstly and then increased with the change of restoration measure, reaching the minimum value at SL, and had little effect on the SOC and its components of the lower soil. Restoration measures had little effect on the distribution ratio of different carbon components in total organic carbon and the activity coefficient of soil carbon pool, and C4 has the largest proportion among the four components, reaching 81.4 - 83.6%. C1 and C2 components can more sensitively reflect the effect of restoration measures on soil carbon pool. After clear-cutting, different restoration measures will affect the pH of soil and the content of ammonium nitrate nitrogen, thus affecting the components in the upper soil, and the properties of the lower soil will change with the leaching and other effects, thus affecting the active carbon components. Based on the stability of soil carbon pool, this study analyzed the effect of Restoration measures on the carbon pool composition in the forest soils in the loess hilly region, which is conducive to the understanding of the impact of forestry management measures on soil carbon pool processes.

Introduction

Soil organic matter (SOM), an important indicator for evaluating soil fertility and soil quality (Harrison-Kirk *et al.* 2014), plays an important role in promoting the formation of good soil structure, improving soil fertility and cushioning, and promoting nutrient supply. As an important part of the soil, it can also provide nutrient sources for plants and also provide energy sources for microbial life activities (Li 2015). As a part of soil organic matter, soil organic carbon (SOC) refers to the content of carbon in organic matter in soil, and its change is affected by SOC stability and fractions. Soil organic carbon stability refers to the ability of soil organic matter to resist interference and change to the original level under current conditions (Wu *et al.* 2005), which were determined by the interaction between the nature of the soil and the external environmental factors (Chen *et al.* 2007). Soil organic carbon can be divided into different carbon fractions according to the nature and degree of decomposition (Franzluebbers *et al.* 2001). The changes in SOC content and composition affect the soil fertility and the carbon exchange balance between soil and atmosphere (Chen *et al.* 2007). It has been studied that SOC is divided into four components according to the oxidative decomposition ability, namely C1, C2, C3 and C4. Among

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the components, C1 and C2 are mainly light group organic carbon, which is closely related to the effective use of soil nutrients and the formation of large aggregates, and belonging to the active organic carbon (C-active) (Maia *et al.* 2007, Zhang 2018), C3 and C4 components consist of more stable compounds, which are inert organic carbon (C-passive). Therefore, C-passive is difficult to be affected by microbial activity (Howarth 1991, Sherrod *et al.* 2005), further based on the reducibility and stability of each component. Soil quality was assessed using the proportion of active organic carbon and inert organic carbon in the soil (Janzen 1987, Blair *et al.* 1995, Rangel *et al.* 2008). Soil organic carbon pool dynamics play an important role in soil nutrient flow and soil intrinsic productivity.

Forest ecosystems are an important part of the global carbon cycle, with 70 to 73% of the global soil organic carbon pool being forest soil organic carbon (Birdsey *et al.* 1993). A weak change in forest soil carbon pools can result in significant changes in atmospheric CO_2 (Sundquist 1993). Study of forest soil active organic carbon, an important part of SOC, can reveal the dynamic process of forest soil carbon pool and provide reference for exploring global carbon cycle (Xiang *et al.* 2010). The main problems in forest soil active organic carbon are that the impact factors and the change process are not clear, which is the main reason for not accurately predicting atmospheric CO_2 changes (Zhou *et al.* 2005).

The forest ecosystem on the Loess Plateau is relatively fragile and vulnerable to changes from the external environmental factors. Studies related to the clear cutting, important forest management measures, have shown that soil organic carbon varies after deforestation, and the effects of different vegetation communities recovered from clear cutting on soil organic carbon components are still unclear (Qi *et al.* 2013). This program offered an opportunity for the current study on SOC sequestration and its stability under different vegetation restoration programs. In this study, sites with *Pinus tabulaeformis* forest, which is the most widely distributed in vegetation restoration on the Loess Plateau were selected, to evaluate the distribution characteristics of soil organic carbon and its different components in different vegetation communities (young woodlands, shrub lands and fallow lands) restored after clear-cutting. The hypotheses are that: (i) in the process of vegetation restoration, the increment of the active organic carbon component is higher than the fraction of the inactive organic carbon component, resulting in the decrease of SOC stability; (ii) the SOC stability affected by vegetation restoration is larger in the upper layer (0 - 20 cm) than in the lower layer (20 - 40 cm); and (iii) different restoration measures will affect soil components by affecting soil pH and available nutrients.

Materials and Methods

The experiment was carried out in the forest farm of Tielongwan (Fig. 1), Yichuan County, Yan'an City. The area is located at the eastern edge of Huanglongshan Forest Area (35°39′N, 110°06′E). The altitude is 860 ~ 1200 m, the slope is 20° ~ 25°, the annual average temperature is 9.8°C, the annual average precipitation is 574.4 mm, and the soil is Taupe forest soil. The soil pH value under the forest was 8.6, the cation exchange capacity was 13.01 g/100 kg dry soil, and the soil surface organic matter content was rich. The total nitrogen (N) and total phosphorus (P) contents were 0.39 and 0.63 g/kg, respectively.

The *Pinus tabulaeformis* plantation was established in 1963, and is now stored at 1400 ~ 1800 trees/plants/hm^2. The average canopy density in the area is 0.7, the breast diameter is 10.0 cm, and the tree height is 11.2 m. The stock volume of forest stands is 75.5 m^3/hm^2; the leaf area index is 6.34. The biomass of arbor layer is 112.96 t/hm^2; the biomass of shrub layer is 3.56 t/hm^2; the biomass of herb layer is 8.28 t/hm^2. The community diversity index is 0.51 (calculated by the Simpson method), and there are more than 20 plant populations. Undergrowth shrubs mainly include *Elaeagnus pungens* Thunb., *Rosa xanthina* Lindl., *Spiraea Salicifolia* L., *Lonicera japonica* Thunb., *Viburnum dilatatum* Thunb., etc., covering 30%; the herbaceous plant is mainly *Carex lanceolata* Boott., covering 30 ~ 50%.

Fig. 1. Location map of the Tielongwan forest farm.

In 1999, some plots of the *Pinus tabulaeformis* plantation was cleared, and the control treatment (CK) was carried out with no artificial disturbance of *Pinus tabulaeformis* plantation. The experimental treatments were three different restoration measures after clear cutting of *Pinus tabulaeformis* plantation, including young pine forest (YL), shrub forest (SL) and clear cutting and ploughing (AF). Three plots were set for each treatment, each plot of 5×10 m^2, surrounded by wire.

Soil samples were collected in October, 2015. Following the principle of random, equal-quantity and multi-point mixing, six locations randomly selected from 0 - 20 cm and 20 - 40 cm soil layers in each plot were mixed into a composite sample. The soil samples were thoroughly mixed after removing the roots, litter and stone particles. Soils were dried in the shade, sieve after 0.25 mm and 1 mm sieve for the determination of the basic physical and chemical properties of the soil and different active organic carbon components.

The physical and chemical properties of the soil were determined by standard methods (Bao 2000). Soil total organic carbon (SOC) was determined by potassium dichromate oxidation-external heating method, total nitrogen (TN) by Kjeldahl method, pH value by potentiometry (water: soil = 2.5 : 1), soil nitrate nitrogen (NO_3^--N) and ammonium nitrogen (NH_4^+-N) were measured by colorimetric method of phenol disulfonic acid and 2 mol/l KCl extraction - indophenol blue colorimetric method. Determination of different active organic carbon content was done by modified $KMnO_4$ oxidation method (Loginow *et al.* 1987). According to the change of $KMnO_4$ concentration (33, 167 and 333 mmol/l), the soil SOC was divided into high active component (C1), medium active component (C2), the low active component (C3) and the stabilizing component (C4), and the sum of the components C1, C2 and C3 constitute an easily oxidizable organic carbon (COC). C_{active} (activated carbon component) = C1 + C2, $C_{passive}$ (inert carbon component) = C3 + C4. The activity coefficient (Eq.1) was obtained in conformity with Chan *et al*. (2001).

$$\text{Activity coefficient} = (C1/COC)*3 + (C2/COC)*2 + (C3/COC)*1 \qquad \text{(Eq. 1)}$$

Data collection and drawing are based on Excel 2010. All data were analyzed by one-way ANOVAs. Duncan's test at a probability level of $p < 0.05$ was used to perform multiple comparisons. All statistical analyses were performed using SPSS 20.0. Differences were considered statistically significant at $p < 0.05$ using Canoco (4.5) software for different active organic carbon fractions and soil pH, soil total organic carbon (SOC), soil total nitrogen (TN), nitrate nitrogen (NO_3^--N) and ammonium nitrogen (NH_4^+-N). A correlation analysis was performed between soil properties with SOC fractions.

Results and Discussion

The forest management practices have an impact on soil organic carbon and its fractions, but the response of different fractions and the same SOC fractions from different soil depth was different (Fig. 2). In 0 - 20 cm, C1 and C3 both had lowest values at SL, with 0.76 and 0.20 mg/kg, respectively. However, C2 and C4 had maximum numerical value at SL, with 1.00 and 14.86 mg/kg. In 20 - 40 cm layer, C1, C2 and C4 fractions contents did not show significant difference. In 20 - 40 cm layer, C3 numerically maximum and minimum values at AF and SL, with 0.55 and 0.19 mg/kg, respectively.

The distribution of different fractions in total organic carbon also varied among forest management practices treatments (Table 1). In 0 - 20 cm layer, except C3/SOC, C1/SOC, C2/SOC and C4/SOC all showed significant difference among different treatments. C1/SOC first increased and then decreased, with highest values at AF in 0 - 20 cm. Only C1/SOC in 20 - 40 cm reached a significant level, and the C1/SOC of the three measures were significantly lower than CK, and YL reached the lowest value. Among the four fractions, C4 accounted for the highest SOC ratio, reaching 80.02 - 88.99% in 0 - 20 cm layer. Active carbon accounted for 8.58 - 15.92% of SOC. The three treatments increased the C_{act}/SOC in 0 - 20 cm, but did not significantly change those in 20 - 40 cm. Passive carbon accounted for 84.08 - 91.42% of the SOC. The forest management practices did not significantly change the soil carbon pool activity coefficient (Fig. 3).

A correlation analysis (Tables 2, 3) and redundancy analysis (Fig. 4) were conducted to reveal the relationship between soil organic carbon components and environmental factors. According to correlation analysis, in 0 - 20 cm layer, C1 was positively correlated with pH, however, C4 was significantly negative correlattion with pH. In 20 - 40 cm layer, C1 was positively correlated with NO_3^--N and SOC. C3 was also positively correlated with TN and C4 was positively correlation

Table 1. Distribution of different carbon components in SOC.

Soil depth (cm)	Treat-ments	C1/SOC (%)	C2/SOC (%)	C3/SOC (%)	C4/SOC (%)	COC/SOC (%)	C_{active}/SOC (%)	$C_{passive}$/SOC (%)
0 - 20	CK	7.32 ± 0.57b	1.26 ± 0.61b	4.25 ± 1.36a	87.17 ± 1.63a	12.83 ± 1.63c	8.58 ± 0.47c	91.42 ± 0.47a
	YL	7.86 ± 0.11b	3.13 ± 0.01b	5.20 ± 1.09a	83.82 ± 1.18b	16.18 ± 1.18b	10.99 ± 0.10b	89.01 ± 0.10b
	AF	9.67 ± 0.90a	6.25 ± 2.31a	4.06 ± 2.38a	80.02 ± 0.85b	19.98 ± 0.85a	15.92 ± 1.74a	84.08 ± 1.74c
	SL	4.50 ± 1.04c	6.04 ± 1.57a	1.20 ± 0.09b	88.99 ± 0.46a	11.74 ± 0.84c	10.54 ± 0.94b	90.19 ± 0.38ab
20 - 40	CK	7.85 ± 0.30a	4.85 ± 1.55a	7.80 ± 1.12a	79.50 ± 0.81a	20.50 ± 0.81a	12.70 ± 1.84a	87.30 ± 1.84a
	YL	4.75 ± 0.13c	5.44 ± 2.59a	3.53 ± 2.41a	86.28 ± 5.09a	13.72 ± 5.09a	10.19 ± 2.68a	89.81 ± 2.68a
	AF	5.75 ± 0.78b	3.81 ± 1.72a	8.68 ± 6.53a	81.76 ± 4.41a	18.24 ± 4.41a	9.56 ± 2.13a	90.44 ± 2.13a
	SL	6.00 ± 0.53b	3.76 ± 2.43a	4.32 ± 1.67a	85.93 ± 0.67a	14.07 ± 0.67a	9.76 ± 2.33a	90.24 ± 2.33a

Table 2. Correlation coefficients of contents and stoichiometry between different carbon components and soil chemical properties in the 0 - 20 cm.

	C1	C2	C3	C4	SOC	TN	TP	NO_3^--N	NH_4^+-N	pH	aP
C1	1										
C2	–0.46	1									
C3	0.43	–0.739**	1								
C4	–0514	0.083	–0.565	1							
SOC	–0.484	0.107	–0.576	0.933**	1						
TN	–0.417	0.496	0.369	0.253	0.240	1					
TP	–0.207	0.315	–0.252	0.242	0.291	0.079	1				
NO_3^--N	–0.436	–0.285	–0.097	0.645*	0.616*	–0.238	–0.007	1			
NH_4^+-N	0.140	–0.563	0.145	0.326	–0.294	–0.007	–0.693**	0.453	1		
pH	0.760**	–0.146	0.446	–0.822**	–0.787**	–0.178	–0.310	–0.770**	–0.152	1	
aP	–0.547	0.249	–0.411	0.474	0.470	–0.090	0.561	0.655*	–0.271	–0.661*	1

Table 3. Correlation coefficients of contents and stoichiometry between different carbon components and soil chemical properties in the 20 - 40 cm.

	C1	C2	C3	C4	SOC	TN	TP	NO_3^--N	NH_4^+-N	pH	aP
C1	1										
C2	0.001	1									
C3	0.138	–0.578*	1								
C4	0.645*	0.002	–0.220	1							
SOC	0.730**	–0.008	–0.088	0.986**	1						
TN	0.452	–0.372	0.589*	0.517	0.601*	1					
TP	0.094	0.116	0.001	0.134	0.147	0.280	1				
NO_3^--N	0.854**	0.100	0.064	0.381	0.438	0.129	0.212	1			
NH_4^+-N	–0.512	–0.114	–0.073	–0.316	–0.369	–0.130	0.240	–.342	1		
pH	0.014	–0.325	0.255	0.245	0.252	0.590*	–0.407	–.263	–.135	1	
aP	–0.005	0.223	–0.125	0.207	0.198	0.175	0.411	.023	.124	–.009	1

with SOC. According to RDA, in 0 - 20 cm, RDA1 explained 53.23%, and RDA2 explained 39.53%. SOC, pH had extremely significant effect on SOC fractions (P<0.001). NO_3^--N, C:N and C : P had significant effect on SOC fractions (P < 0.01). In 20 - 40 cm, in 0 - 20 cm, RDA1 explained 48.29%, and RDA2 explained 29.13%. TN, pH and C : N had significant effect on SOC fractions (p < 0.01).

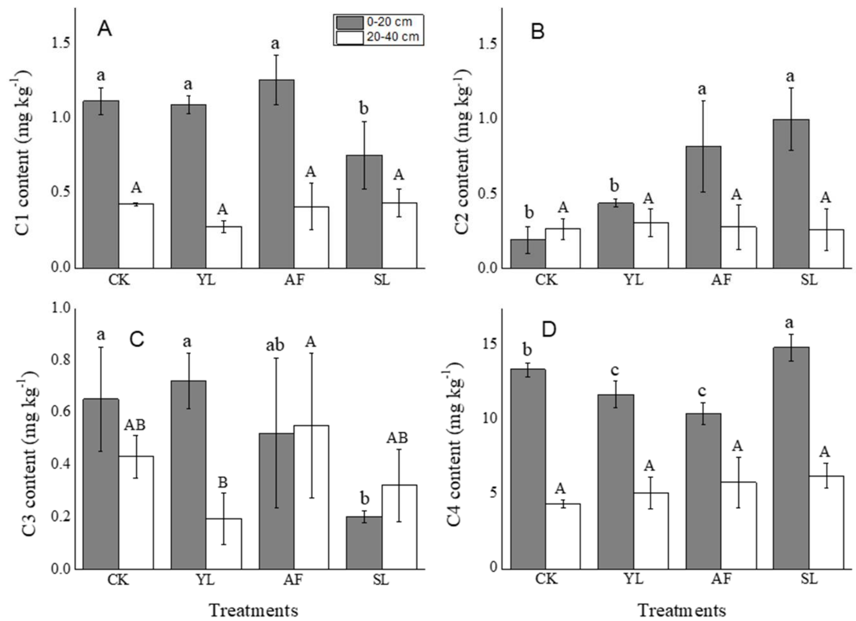

Fig. 2. Effects of different treatments on soil organic carbon components in *Pinus tabulaeformis* forest different letters in the same column refer to significant difference among different treatments (p < 0.05).

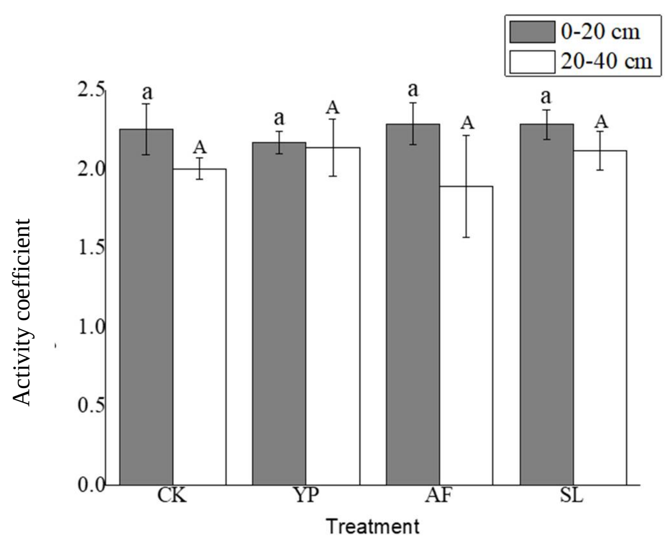

Fig. 3. Effect of different treatments on soil activity coefficient.

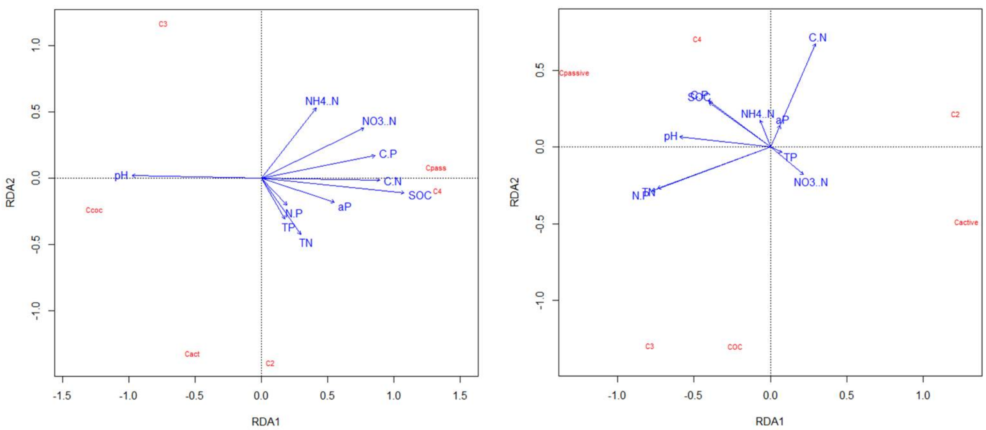

Fig. 4. Redundancy analysis of soil organic carbon composition and environmental factors in the 0 - 20 cm (a) and 20 - 40 cm (b) layers.

Different restoration measures have a series of effects on the ecosystem. Clear cutting has a greater impact on soil carbon storage (Turner *et al.* 2000). SOC content is the result of a dynamic balance between the input of organic matter such as soil biological residues and the loss of organic matter mainly caused by microbial decomposition (Cusack 2013). The results of this study indicate that the soil organic carbon content (SL < YL < CK < AF). In addition, the soil SOC of the young pine forest and shrub land did not change significantly compared with the control, which may be due to the slow return of the litter of the young pine forest and the shrub land. The increase of soil nitrogen, especially the increase of NO_3^--N, enhances microbial activity and accelerates SOC consumption. Through correlation analysis, one can find that SOC has a significant negative correlation with NO_3^--N, which reduces the SOC content, but the soil quality can be improved and continuously improved with the positive succession of the community. The root system was mainly concentrated in the surface soil in the abandoned land, so the SOC of the surface soil was significantly increased compared with that of the blank soil. The surface soil SOC was significantly increased compared to CK. Different restoration measures have little effect on the SOC content of the lower soil, and they have not reached a significant level.

Activated carbon (COC) moves fast, has poor stability, is easily oxidized, and is easy to mineralize and can be absorbed and used by plants as nutrients (Zhang *et al.* 2017). Although it accounts for a small proportion of total carbon, it plays an important role in transformation and nutrient flow, and it can also reflect the changes of soil physical and chemical properties and carbon pool balance more accurately and sensitively than organic matter (Shen *et al.* 1999). Soil COC is mainly composed of microbial biomass carbon, root exudates, soil humus. Although the amount of COC component increased after the tillage in this study, it did not reach a significant level, which may be mainly related to the shorter recovery time after clear cutting; however, it was significantly lower in the shrub land than the CK which was carried out with no artificial disturbance of *Pinus tabulaeformis* plantation. Under the general nitrogen restriction conditions, the nitrogen fixation of plants activates microorganisms, which are easily reduced by micro-organisms and COCs used by plants. The activity of the microorganisms decreased greatly with the increase of soil depth, while the root system of the shrub increased the COC. Different measures only had significant differences on the contents of C1 and C3 in the upper soil, and the trend of C1 and SOC was consistent, indicating that the C1 component can respond more sensitively to the effects of different restoration measures on soil carbon pool balance. There was no significant difference in the underlying soil.

The ratio of soil active carbon fractions to organic carbon is an important indicator reflecting soil carbon activity. The larger the value, the greater the activity of soil carbon and the worse the stability is. The more organic carbon is absorbed and utilized by microorganisms and plants, the higher quality of the soil carbon pool (Qiu *et al.* 2009, Han *et al.* 2012). In this study, the COC/SOC ranged from 10.1 to 14.8%, which was maintained at a low ratio overall, and was lower than that of Han *et al.* (2012), indicating that the content of active organic carbon was low in this region. The decomposition of microorganisms is relatively weak, and the overall soil quality is not good. AF significantly increased COC/SOC. The study also shows that in the upper COC component, the C1 and C2 components were the main components, and different recovery measures reduced the proportion of the two in the COC, indicating that the SOC decomposition ability decreases with different treatments, high and moderate activity. Organic carbon was gradually converted into lower active organic carbon. The lower layer increased the proportion of C1 and C2 in COC, which is mainly related to plant root growth. At the same time, the above results indicate that different active components are more sensitive than COC when reflecting soil carbon activity. The C3/SOC under different recovery measures increased, reaching a significant level at the shrub ground. The proportion of C1 in SOC in abandoned land is higher than that in young woodland and shrub land. The main reason is that most of the fine roots are distributed in the surface soil, releasing a large amount of root secretion, and the herbaceous plants have a short life cycle, the apoptotic biochar is transferred into the soil.

Theoretically, the restoration measures after clear cutting have changed the elemental composition of soil and litter, and the soil quality is improved, which is beneficial to the decomposition of organic matter and the increase of soil activity coefficient. However, the present research did not find that the restoration measures increased the soil activity index. On the contrary, there was a certain degree of reduction in each treatment in the topsoil, where SL was significantly lower than CK, and there was no significant difference in the lower layer. This might be due to the allelopathic effect of oil pine, resulting in a decrease in soil activity coefficient.

In this study, after clear cutting of *Pinus tabulaeformis* plantation in the Loess hilly region, with the change of restoration measures, the content of SOC and its C1, C2 and C4 components in the upper layer decreased first and then increased, and the minimum soil SL reached the minimum soil SOC and its composition changes a little. Different recovery measures after clear cutting have little effect on the distribution ratio of different carbon components in total organic carbon. Among the four components, C4 accounts for the largest proportion, reaching 81.4 - 83.6%, and accounts for the total in the lower soil. The proportion of organic carbon was slightly higher than that of the upper soil. The impact of the restoration measures on the soil carbon pool activity coefficient is relatively small, and the impact is only significant under the surface SL treatment. Studies have shown that restoration measures can change the composition of soil carbon pool, but do not increase soil carbon pool activity, and the C1 and C2 components can more sensitively reflect the impact of nitrogen addition on soil carbon pool. After the clear cutting, different restoration measures will affect the components of the upper soil by affecting the soil pH and ammonium nitrate nitrogen content, and will also affect the activated carbon components by changing the properties of the lower soil along with leaching. However, as the research involves less research on the metabolic mechanism of carbon storage, it is necessary to strengthen related work in the future, such as the role of microorganisms and roots in the process of soil carbon pool conversion.

Acknowledgements

The first author (He) would like to express her gratitude to all those who have helped her during the writing of this manuscript. She gratefully acknowledges the help of her supervisor Professor Sha Xue. She does appreciate her patience, encouragement, and professional instructions during preparing this manuscript.

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(Manuscript received on 29 July 2020; revised on 26 October 2020)