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Research Article

Responses of Soil Organic Carbon to Long-Term Understory Removal in Subtropical *Cinnamomum camphora* Stands

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We conducted a study on a 48-year-old *Cinnamomum camphora* plantation in the subtropics of China, by removing understory gradually and then comparing this treatment with a control (undisturbed). This study analyzed the content and storage soil organic carbon (SOC) in a soil depth of 0–60 cm. The results showed that SOC content was lower in understory removal (UR) treatment, with a decrease range from 5% to 34%, and a decline of 10.16 $g\cdot kg^{-1}$ and 8.58 $g\cdot kg^{-1}$ was noticed in 0–10 cm and 10–20 cm layers, respectively, with significant differences ($P < 0.05$). Carbon storage was reduced in UR, ranging from 2% to 43%, with a particular drastic decline of 15.39 $t\cdot hm^{-2}$ and 11.58 $t\cdot hm^{-2}$ in 0–10 cm ($P < 0.01$) and 10–20 cm ($P < 0.01$) layers, respectively. Content of SOC had an extremely significant ($P < 0.01$) correlation with soil nutrients in the two stands, and the correlation coefficients of CK were higher than those of UR. Our data showed that the presence of understory favored the accumulation of soil organic carbon to a large extent. Therefore, long-term practice of understory removal weakens the function of forest ecosystem as a carbon sink.

1. Introduction

The soil carbon storage, changes, and regulation mechanism of forest ecosystem, which is one of the most important terrestrial ecosystems, have been the focus of carbon cycling study in natural and plantation forests. Owing to its huge amount (soil carbon storage in forest ecosystems accounts for about 39% in global soil carbon storage [1]), any minor change may result in the release of a great amount of CO_2 into the atmosphere, causing global climate changes through greenhouse effect and the nutrients supply of vegetation, which will instigate the alteration of distribution, composition, structure, and the function of the terrestrial ecosystems [2]. Content of SOC, a major indicator for soil quality in a forest, can directly influence forest productivity. At the same time, forest ecosystems have been suffering more serious interference from human and nature itself. For this reason, it is of great importance to strengthen the study of SOC pool in forest ecosystems under the circumstances of global change and anthropogenic interference.

Compared with the natural forest, plantation is one kind of ecosystems controlled by human and its management plays an important role in the balance of carbon budget [3]. Soil carbon pool of the plantation is a major part of the whole carbon pool in ecosystem and even its subtle changes after afforestation can significantly influence the terrestrial carbon budget [4–6]. Understory removal is an efficient measure for tree growth in plantation management, and at present most studies on understory removal focus on its effects on soil nutrients [7–12]. In addition, the studies of its effects on soil microorganisms [13–15], soil physicochemical properties [16–18], and litter decomposition [19] have been conducted and reported. However, the effects of understory removal on soil organic carbon content and carbon storage in plantation ecosystem have not been thoroughly investigated and are still largely unknown. For this reason, studies need to be carried out to evaluate its effects and to improve our understanding on the performance of plantation as a carbon sink, particularly in subtropical areas. We conducted this study in a *Cinnamomum camphora* plantation, by gradually removing undergrowth and then comparing this treatment with a control (undisturbed), to evaluate its effects on soil organic carbon, soil carbon storage, and soil nutrients.

Table 1: General characteristics of experimental plots (mean ± SD, $n = 10$).

Stand type	Main plant species	Tree height (m)	DBH (cm)	Stem density (trees·hm^{-2})	Stand age (year)	Canopy density	Slope aspect	Understory vegetation
UR	*Cinnamomum camphora*	13.5 ± 1.07	18.96 ± 1.98	917 ± 88	48	0.9	south	With few shrubs and a few herbs
CK	*Cyclobalanopsis glauca* and *Loropetalum chinensis*	10.0 ± 0.59	10.58 ± 2.62	1658 ± 300	48	0.9	south	With lots of shrubs and herbs

UR: understory removal; CK: control; DBH: diameter at breast height (the same as below).

Table 2: Characteristics of the two stands.

	Soil relative moisture (%)	Soil temperature (°C)	Soil respiration (μmolCO_2·m^{-2}·s^{-1})	Litter (t·hm^{-2}·a^{-1})
UR	17.00	18.72	2.97	6.62
CK	17.60	16.98	3.17	8.14

2. Materials and Methods

2.1. Study Site. This study was performed in a forest farm in the Institute of Subtropical Forestry (Chinese Academy of Forestry) (119°57′E, 30°03′N). The climate of the region is northern subtropical monsoon with an annual precipitation of 1464 mm, an annual average temperature of 16.2°C, and 237 frost-free days per year. The soil originally developed from quartz and arkose is slightly acidic red soil. Historically, the region has been a forest zone with predominant vegetation consisting of subtropical evergreen deciduous broad-leaved forests. The region is composed of mountainous and hilly areas. Due to the increasing demand for timber and firewood and the frequently increased agricultural activities, most of the naturally virgin forests were destroyed and gradually transformed into secondary forests, agricultural fields, or plantations. *Cinnamomum camphora* plantation in the study site was afforested into a space of 4 m × 4 m through the clear cutting of secondary forest in the winter of 1964. Considering the safety of the residence located at the bottom of the afforested hill, understory was removed at specific areas of the forest (along the contour at the bottom of the slope of the afforested hill) once every 4 or 5 years. Except for the understory removal practice and natural disasters, the forest has been free from any human interference. Thus far, after 48 years of multiple forest protection practice, stands with understory removal (UR) treatment have remained a pure *Cinnamomum camphora* plantation, while the control (CK) ones have developed into mixed forest of *Cinnamomum camphora*, *Cyclobalanopsis glauca,* and *Loropetalum chinensis*. The basic characteristics of the experimental plots are shown in Table 1.

2.2. Site Investigation and Soil Sampling. In spring 2012, ten experimental plots (20 m × 20 m) were installed at the bottom of the hill in UR. Meanwhile, ten plots (20 m × 20 m) of similar characteristics (south aspect, slope gradient, slope position, and soil parent material) were installed in CK, located five meters away from UR.

In July 2012, five sampling points were set in an "S" shape in each plot of the two stands. At each sampling point, soil samples were collected in six different layers (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, and 50–60 cm) after the surface litter was removed. Then soil samples from the same layer of each plot were mixed up, brought back to the laboratory, immediately cleared of gravel and roots, and then left to air-dry. SOC was determined by potassium dichromate oxidation spectrophotometric method and soil nutrients (total N, available N, available P, available K, exchangeable Ca, and exchangeable Mg) were determined by national standard methods [20]. In addition, soil respiration was measured using Automated Soil CO_2 Flux System (Licor-8150, USA) since July 2009, once every 30 minutes and 2 minutes for each measurement. At the same time, soil temperature and soil relative moisture at 5 cm depth were recorded every 30 minutes using ECH$_2$O probe. Litter productivity was calculated based on the recent three years' data from the forest farm. Characteristics of the two stands are listed in Table 2.

2.3. Data Analysis. The formula used for the computation of the soil carbon storage is as follows.

Soil carbon storage = $\sum_{i=1}^{n}(C_i \times d_i \times D_i)$, in which i corresponds to soil layer, C_i to SOC content, d_i to soil bulk density, and D_i to soil depth.

The data were computed with SPSS 16.0. To test the significance of difference, the method of independent-samples t-test was adopted. At the same time, Pearson's correlation coefficients were used to determine the correlation of SOC and soil nutrients.

3. Results and Discussion

3.1. Comparison of SOC Content in Different Stands. The SOC content UR was lower than that of CK in all the six layers, with decrease ranging from 5% to 34% (Table 3). Among the six layers, content of 0–10 cm and 10–20 cm layers decreased by 28% and 34%, respectively, with significant differences

Table 3: Comparison of SOC content in different stands (mean ± SD, $n = 30$).

	Soil layer					
	0–10 cm	10–20 cm	20–30 cm	30–40 cm	40–50 cm	50–60 cm
UR ($g{\cdot}kg^{-1}$)	26.08 ± 3.79^{a}	16.56 ± 3.01^{a}	13.42 ± 1.40	12.38 ± 1.36	11.32 ± 2.02	11.52 ± 2.26
CK ($g{\cdot}kg^{-1}$)	36.24 ± 3.71^{b}	25.14 ± 3.79^{b}	18.84 ± 3.93	15.84 ± 4.96	13.49 ± 4.27	12.10 ± 4.20
Difference relative to CK (%)	28.04	34.13	28.77	21.84	16.09	4.79
Annual variation ($g{\cdot}kg^{-1}{\cdot}y^{-1}$)	−0.21	−0.18	−0.11	−0.07	−0.05	−0.01

Values within the same column with different lowercase letters are significantly different at $P < 0.05$.

Table 4: Comparison of soil carbon storage in different stands (mean ± SD, $n = 30$).

	Soil layer						Total
	0–10 cm	10–20 cm	20–30 cm	30–40 cm	40–50 cm	50–60 cm	
UR ($t{\cdot}hm^{-2}$)	25.56 ± 3.72^{A}	15.07 ± 2.74^{a}	12.88 ± 1.34	13.99 ± 1.53	12.23 ± 2.18	11.86 ± 2.33	91.59^{a}
CK ($t{\cdot}hm^{-2}$)	40.95 ± 4.19^{B}	26.65 ± 4.01^{b}	18.09 ± 3.78	18.06 ± 5.65	13.62 ± 4.31	12.10 ± 4.20	129.47^{b}
Difference relative to CK (%)	37.58	43.45	28.80	22.54	10.21	1.98	29.26
Annual variation ($t{\cdot}hm^{-2}{\cdot}y^{-1}$)	−0.32	−0.24	−0.11	−0.08	−0.03	−0.01	−0.79

Values within the same column with different lowercase letters are significantly different at $P < 0.05$.
Values within the same column with different uppercase letters are significantly different at $P < 0.01$.

($P < 0.05$). In both stands, the SOC content in the surface layer was the highest among all other layers. The SOC content began to decrease with the soil depth at different degree. In comparison with CK, the SOC content in the 0–10 cm layer of UR was 0.21 $g{\cdot}kg^{-1}$ less per year and the content of all the layers from 0 to 60 cm decreased within a range from 0.01 $g{\cdot}kg^{-1}$ to 0.21 $g{\cdot}kg^{-1}$ per year.

Compared with CK, organic carbon content situated in the 0–10 cm and 10–20 cm soil layers in UR decreased by 28% and 34%, respectively, and the contents of the other layers were also lower. These results are similar to the ones reported from the Yildiz et al. [18], in which organic carbon content in 0–15 cm decreased by 26% without understory vegetation. In addition, the soil carbon concentration was reduced by 27% under complete understory removal in 5-year-old Douglas-fir experimental plantations [21]. The main factors that affected the SOC content were return amount of litter fall and decomposition rate of litter [22] and SOC inputs were higher in CK than those in UR. Also the present understory vegetation (large amount of shrub biomass, fine root and root exudates, and high rate of root turnover) and the multistory stand in CK made a significant contribution to the input of SOC. Busse et al. [23] deemed that decomposition and the turnover of the root system were the main sources of SOC input. Carbon input was acquired by litter, root, and its exudates when the ground was covered by shrubs and herbs. Besides, the stability of soil organic matter, which led to the formation of humus compound, was another factor that contributed to the increase of the content of SOC [24]. Sun [25] discovered that litter decomposition was accelerated while understory vegetation was present, which favored the accumulation of soil humus. Liu et al. [26] were of the opinion that the return of forest litter and its change of quality were the biggest factors that reduced the content of SOC. Therefore, soil disturbance caused by soil erosion and forest management could accelerate the decomposition or the loss of soil organic matter. A higher biomass of fine root was found in the surface layer when understory vegetation was present in the forest, and the accumulation of SOC was proportional to the amount of fine roots [27]. Thus, to certain extent, the content of SOC was reduced by the practice of understory removal. However, some of the results are not consistent with ours. Tripathi et al. discovered that the contribution of the C inputs to the total in the uppermost layer (0–10 cm deep) was greater in the stands with undergrowth removed than those with intact undergrowth [28]. Zhao et al. concluded that understory removal had no significant effects on soil organic carbon in a plantation of mixed native tree species in southern China [15].

3.2. Comparison of Soil Carbon Storage in Different Stands. After 48 years of growth, the SOC storage of UR was 37.88 $t{\cdot}hm^{-2}$ less than that of CK, reaching a significant level of difference (Table 4). In the soil layers from 0 to 60 cm, carbon storage of UR was lower in comparison with that of CK, with a decrease varying from 2% to 43%. Carbon storage situated in 0–10 cm and 10–20 cm of depth decreased by 38% and 43% with significant ($P < 0.05$) or extremely significant ($P < 0.01$) differences, accounting for 41% and 31%, respectively, of the total reduction amount. In both treatments, carbon storage reached its maximum amount in the 0–10 cm layer, and the carbon storage was mostly concentrated in 0–20 cm layer, accounting for 44% and 52%, respectively, of the overall soil carbon storage. Meanwhile, a declining trend occurred with soil depth in both treatments but the decreasing degree was different. In comparison with CK, the annual loss of carbon storage in 0–10 cm in UR was 0.32 $t{\cdot}hm^{-2}$. The average decrement of soil carbon storage in UR was from 0.01 to 0.32 $t{\cdot}hm^{-2}$ less per year than that in CK in layers from 0 to 60 cm, respectively.

Table 5: Comparison of the correlation between SOC and soil nutrients in different stands.

	Soil nutrients					
	Total N	Available N	Available P	Available K	Exchangeable Ca	Exchangeable Mg
UR	0.937**	0.638**	0.550**	0.854**	0.863**	0.787**
CK	0.966**	0.905**	0.858**	0.842**	0.744**	0.841**

**$P < 0.01$.

The SOC storage of the two stands was concentrated especially in the 0–20 cm layer, in accordance with the results from other studies [29, 30]. The SOC storage of each layer in UR was lower than that in CK, and the differences in 0–10 cm and 10–20 cm were significant. The decrease of organic carbon storage in UR was particularly obvious in the 0–20 cm layer, accounting for about 71% of the total decrement situated in the 0–60 cm depth. The balance of three factors determines the soil carbon pool: carbon input, release of carbon decomposition, and loss of carbon into water system [31]. The result of the previous studies [14, 19] indicated that the practice of understory removal could result in a lower rate of litter decomposition. At the same time, understory removal reduced the amount of littler layer by 1.52 $t{\cdot}hm^{-2}{\cdot}y^{-1}$. Both the factors led to a reduced input of organic carbon to some levels. Although understory removal decreased soil respiration by 6%, the carbon released into the atmosphere was far below the level of that transformed from litter into soil (increased by 23% with understory present). According to the study on soil labile organic carbon in this plantation, understory removal significantly or extremely significantly increased the ratio of water soluble organic carbon to SOC (not shown), indicating that SOC in UR was easier to be lost than that in CK. Moreover, the environmental changes within the stands (sunshine, soil temperature, moisture, etc.) due to understory removal [32–35] can indirectly affect the storage of SOC. As listed in Table 2, the data of soil temperature acquired in both UR and CK stands, in accordance with the results of Wang et al. [36] and Liu et al. [19], indicated that understory removal increased soil temperature, promoting microbial activities, and organic matter decomposition. Besides, understory removal reduced soil moisture by 3%, indirectly changing SOC by affecting the quantities and microbial activities [16]. What is more, soil carbon pool is highly related to the change of aboveground biomass, climate, and disturbance (e.g., duration, effect intensity, and mode of action).

3.3. Comparison of Correlation between SOC and Soil Nutrients in Different Stands. The content of SOC was prominently correlated with soil nutrients (Table 5). SOC in CK had a higher correlation coefficient with total N, hydrolysis N, available P, and exchangeable Mg than that in UR, while SOC in UR has a higher correlation coefficient with available K and exchangeable Ca than that in CK. In the two stands, SOC content is most positively correlated with total N. However, SOC content in UR was least positively correlated to available P while SOC content in CK was least positively correlated to exchangeable Ca.

The correlation between SOC and soil nutrients was exceedingly prominent in both stands. The correlation between SOC and soil nutrients (except available K and exchangeable Ca) in UR was lower than that in CK. On one hand, the input of soil organic matter and soil nutrients is reduced by the removal of understory vegetation. On the other hand, antierodibility of the soil is weakened with its surface uncovered by shrubs. All these factors combined to accelerate soil nutrients loss in the surface layer [37]. Understory removal had complex effects on soil nutrients and the effects were various in different situations. When studying the effects of understory removal on soil fertility, Tripathi et al. pointed out that understory (*S. kurilensis*) removal might have ensured greater N availability in the *S. kurilensis* removal stand [38]. Xiong et al. found that understory removal had no significant impacts on soil exchangeable K [39].

4. Conclusion

This study provided an understanding on the long-term effects of understory removal on the content and storage of SOC, which demonstrates the impact of understory vegetation on preserving and increasing SOC pool. In terms of the soil carbon storage in the forest ecosystem, the practice of understory removal weakens the function of the soil carbon pool as carbon sink in global carbon cycling, which, to a certain extent, is detrimental to the mitigation of CO_2 concentration in the atmosphere and the global warming effects.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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