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Effects of forest fire disturbance on carbon density of eucalyptus forest ecosystem in Guangdong Province

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ABSTRACT

Forest fire, as a discontinuous ecological factor of forest, causes the changes of carbon storage and carbon distribution in forest ecosystem, and affects the process of forest succession and national carbon capacity. Taking the burned land with different forest fire interference intensity as the research object, using the comparison method of adjacent sample plots, and taking the combination of field investigation sampling and indoor test analysis as the main means, this paper studies the influence of different forest fire interference intensity on the carbon pool of forest ecosystem and the change and spatial distribution pattern of ecosystem carbon density, and discusses the influence mechanism of forest fire interference on ecosystem carbon density and distribution pattern. The results showed that forest fire disturbance reduced the carbon density of vegetation ($P < 0.05$). The carbon density of vegetation in the light, moderate and high forest fire disturbance sample plots were 67.88, 35.68 and 15.50 t·hm^{-2}, which decreased by 15.86%, 55.78% and 80.79% respectively compared with the control group. In the light, moderate and high forest fire disturbance sample plots, the carbon density of litter was 1.43, 0.94 and 0.81 t·hm^{-2}, which decreased by 28.14%, 52.76% and 59.30% respectively compared with the control group. The soil organic carbon density of the sample plots with different forest fire disturbance intensity is lower than that of the control group, and the reduction degree gradually decreases with the increase of soil profile depth. The soil organic carbon density of the sample plots with light, moderate and high forest fire disturbance is 103.30, 84.33 and 70.04 t·hm^{-2} respectively, which is 11.670%, 27.899% and 40.11% lower than that of the control group respectively; the carbon density of forest ecosystem was 172.61, 120.95 and 86.35 t·hm^{-2} after light, moderate and high forest fire disturbance, which decreased by 13.53%, 39.41% and 56.74% respectively compared with the control group; forest fire disturbance reduced the carbon density of eucalyptus forest, which showed a law of carbon density decreasing with the increase of forest fire disturbance intensity. Compared with the control group, the effect of light forest fire disturbance intensity on the carbon density of eucalyptus forest was not significant ($P > 0.05$), while the effect of moderate and high forest fire disturbance intensity on the carbon density of eucalyptus forest was significant ($P < 0.05$).

Keywords: Forest Fire Disturbance; Forest Ecosystem; Vegetation Carbon Pool; Regulated Litter Carbon Pool; Soil Organic Carbon Pool

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1. Introduction

Forest carbon pools play an important role in the global carbon cycle[1], of which vegetation carbon pool is an indispensable part. Vegetation carbon pool is an important source of carbon elements for other carbon pools, and it is one of the symbols of carbon sequestration capacity, which plays an important role in carbon sink effect. As a hub connecting the vegetation carbon pool and soil organic carbon pool, the fallout carbon pool plays an important role in the ecosystem carbon cycle. Soil organic carbon pool plays a role of source, sink and hub in the global carbon cycle, and has an important carbon sink effect. Forest fire disturbance significantly reduces the coverage of canopy by consuming forest biomass, changes the structure and function of terrestrial ecosystem, and then affects the redistribution of its nutrient cycle[2,3], promoting the composition of forest vegetation and national carbon capacity. Therefore, quantifying the ecological process of forest fire disturbance on forest ecosystem carbon sink is an important basis for balancing ecosystem carbon budget. Further understanding the carbon exchange mechanism between terrestrial ecosystem and atmosphere will help forest fire managers predict the ecosystem recovery response after fire and provide a scientific basis.

Forest fire disturbance can release nutrients into the soil through the immediate and high-concentration CO_2 emissions generated by biomass combustion[4], which can directly affect the soil carbon cycle, and indirectly affect the carbon balance and carbon cycle of the forest ecosystem in the process of forest restoration and forest succession after forest fire disturbance[5,6], thereby causing various ecological environmental problems. About 1% of the world's forests are burned every year (the burned area can reach 3.3×10^7 ~ 4.3×10^7 hm^2) was disturbed by forest fires[7-10], and its carbon loss exceeded 2–4 Pg[5,11]. More and more attention has been paid to the research on carbon sink function and ecological civilization of forest ecosystem, which has become the hotspot of experts and scholars[8,9,10,12]. Increasing forest carbon density can improve the potential of forests in mitigating climate change[13]. The increase of energy released in the process of forest fire interference accelerates the loss of carbon through the decomposition of coarse wood residues, and further affects the carbon sequestration capacity and carbon balance of forests[14,15]. However, the impact of forest fire disturbance is usually not considered when measuring the carbon storage of each carbon pool in the forest ecosystem.

In recent years, the intensification of climate change has changed the cycle period and intensity of forest fire disturbance[16], and the distribution mode of vegetation composition and carbon storage may also be affected, changing the net carbon storage of forest ecosystem. The prediction model shows that the probability of forest fire will increase by 140% by the end of the 21st century[17,18]. Forest fire disturbance increases soil temperature and soil respiration, and affects the potential of forest ecosystem to accumulate carbon sinks. Quantitative research on the impact of forest fire disturbance on forest carbon pools is conducive to reducing the uncertainty in the estimation of global carbon balance. This study makes a quantitative analysis of the changes in carbon density of the eucalyptus forest ecosystem in Guangdong Province after forest fire disturbance, discusses the impact of forest fire disturbance on the carbon storage of each carbon pool in the ecosystem, and clarifies its impact mechanism on each carbon pool in the forest, which is helpful for people understanding the carbon cycle and carbon distribution process of each carbon pool in the forest ecosystem, and it is of great significance to formulate scientific and reasonable forest fire management measures aimed at mitigating global change.

2. Research area and research method

2.1 Overview of the study area

Located at the southernmost tip of Chinese Mainland, Guangdong Province is a province with large natural resources (20°09'N–25°31'N, 109°45'E–117°20'E). The land area is adjacent to Fujian in the East, Hunan and Jiangxi in the north, Guangxi in the west, the vast South China Sea in the south, Hainan Province in the southwest across the Qiongzhou Strait, and the Tropic of Cancer runs across the province from the line that links South Australia—Conghua—Fengkai. The climate of Guangdong Province belongs to the East Asian monsoon region, and the climate zone is divided into tropical monsoon, south subtropical monsoon and mid subtropical monsoon from south to north. The province has abundant precipitation, with an average annual precipitation of 1,777 mm. The annual average temperature is 22.3 ℃, and July is the hottest month in all regions. The average temperature is about 28–29 ℃, and the average sunshine duration is 1,745.8 h. It is an area with sufficient heat, and has the basic characteristics of warm and humid climate at the same time. Guangdong is located in the low latitude. Under the interaction of biological factors and climatic factors, the whole territory has formed zonal soils mainly constitute of lateritic red soil, latosol, red soil, yellow soil and so on. These soil types not only occupy a relatively large distribution area, but also reflect the characteristics of soil conditions in some typical vegetation types distribution areas in the province.

Affected by subtropical and tropical monsoon climate, Guangdong Province has a high degree of visibility, with the distribution of forest vegetation similar to tropical rainforest. In general, the vegetation components of Leizhou Peninsula are mainly tropical components such as saparicaceae, Annonaceae, myrtle and dipterocarpaceae, and the vegetation types are diverse. In the subtropical part of the mainland of the province, the vegetation components are mainly tropical and subtropical components such as barrier family, Camellia family, Fagaceae, Magnoliaceae and Bambusoideae, forming subtropical evergreen seasonal rainforest, subtropical evergreen broad-leaved forest and other vegetation types, which respectively constitute the tropical vegetation zone and subtropical vegetation zone of the province with the characteristics of zonal forest vegetation. Due to the interference of human factors, the floristic components also changed. First, the plains and hilly areas are cultivated, and secondary vegetation (coniferous sparse shrubs, grass slopes) and various artificial vegetation are planted instead. The artificial forests are dominated by pure forests such as *Eucalyptus robusta*, *Pinus Massoni Ana*, *Cunninghamia lanceolata*, *Casuarina equisetifolia*, *Schima superba* and *Phyllostachys pubescens*. Secondly, artificial cultivation has introduced some other economic plants. According to the statistical results of forest fire data in Guangdong Province from 1990 to 2017, a total of 6,275 forest fires occurred in the province, with an annual average of 224.11. The total area of the fire was 86,684.45 hm^2, with an annual average of 3,095.87 hm^2.

2.2 Forest fire interference intensity division and sample plot setting

Table 1 shows the division of forest fire interference intensity[19-22]. In this paper, the burned land in Fogang County, Guangdong Province on April 4, 2017 is selected as the research object. Within one week after the fire, the forest fire interference intensity (light, moderate and high forest fire interference intensity) is basically the same (see **Table 2** for the basic situation of the forest fire interference sample land), and take the land of the specification of 20 m × 20 m that repeated 3 times in the burned land and the control sample land (adjacent non burned forest stand) respectively. A total of 12 fixed standard plots are selected, that is, 12 standard plots = (3 kinds of forest fire interference intensity + 1 control plot) × 3 repetitions. Field investigation and experimental sample collection were carried out one year after the fire, and vegetation biomass, falling biomass and soil samples were collected.

Table 1. Forest fire disturbance intensity classification

Forest fire disturbance intensity	Division standard of forest fire disturbance intensity
Light forest fire disturbance: Part of the shrub under the forest was burned (≤50%), and part of the litter was burned (≤50%)	Fire burned wood less than 30% Live standing timber (including burned wood) > 70% or more Tree blackening height ≤ 2 m
Moderate forest fire disturbance: The shrubs under the forest were almost burned (>50%), and the litter was almost burned (>50%)	Fire burned wood ≥ 30%-70% Live standing timber (including burned wood) ≥ 30%–70% Tree blackening height is 2–5 m
High forest fire disturbance: The shrubs under the forest were all burned, and the litter is burned out	Fire burned wood ≥ 70%–100% Standing timber (including burned wood) is below 30% Tree blackening height ≥ 5 m

Table 2. Basic situation of forest fire disturbance in *Eucalyptus robusta* forests (mean ± SD)

Sample plot	Ages (a)	Mean DBH (cm)	Mean height (m)	Stem density (plant·hm^{-2})	Canopy openness	Slope (°)	Slope position	Aspect	Altitude (m)	Soil type	Forest type
Control plot CK	8 ~ 9	14.36 ± 3.24	17.26 ± 3.24	1687 ± 318	0.80	10–20	Mid-slope	South slope	245–280	Latosolic red soil	Plantation
Light forest fire disturbance L	8 ~ 9	14.36 ± 3.24	17.26 ± 3.24	1687 ± 318	0.75	10–20	Mid-slope	South slope	245–280	Latosolic red soil	Plantation
Moderate forest fire disturbance M	8 ~ 9	14.36 ± 3.24	17.26 ± 3.24	1435 ± 176	0.65	10–20	Mid-slope	South slope	245–280	Latosolic red soil	Plantation
High forest fire disturbance H	8 ~ 9	14.36 ± 3.24	17.26 ± 3.24	1021 ± 102	0.50	10–20	Mid-slope	South slope	245–280	Latosolic red soil	Plantation

Note: CK, L, M and H represent control, light forest fire disturbance, moderate forest fire disturbance and high forest fire disturbance respectively. The same below

2.3 Biomass survey

Investigate the tree species, canopy density, stand growth status, etc. in the fixed standard sample plot, and measure the DBH and tree height; set five small quadrats, each 2 m × 2 m, on the diagonal of the fixed standard sample plot according to the vegetation distribution characteristics, especially the uniformity. Investigate shrubs, herbs and falling objects in the quadrat, and weigh the collected samples and take samples back to the laboratory. See **Table 2** for the basic information of the forest fire disturbance sample plot.

Table 3. Effect of forest fire disturbance on soil bulk density (mean ± SD, g·cm^{-3})

Soil layer (cm)	Contrast CK	Light forest fire disturbance L	Moderate forest fire disturbance M	High forest fire disturbance H
0–10	1.20 ± 0.025	1.23 ± 0.039	1.41 ± 0.041	1.43 ± 0.022
10–20	1.23 ± 0.026	1.27 ± 0.021	1.46 ± 0.042	1.49 ± 0.032
20–30	1.27 ± 0.038	1.32 ± 0.033	1.48 ± 0.040	1.49 ± 0.024
30–40	1.31 ± 0.024	1.36 ± 0.026	1.51 ± 0.029	1.52 ± 0.029
40–60	1.35 ± 0.024	1.39 ± 0.026	1.52 ± 0.025	1.53 ± 0.012
60–80	1.38 ± 0.024	1.41 ± 0.013	1.52 ± 0.023	1.54 ± 0.031
80–100	1.41 ± 0.023	1.42 ± 0.024	1.53 ± 0.013	1.54 ± 0.030

2.4 Collection and treatment of soil samples

In the standard sample plot, three soil profiles (lateritic red soil) are selected along the "S" shape, and each soil profile is divided into seven levels (0–10, 10–20, 20–30, 30–40, 40–60, 60–80 and 80–100 cm) for sampling. The soil bulk density was determined with the soil ring knife (100 cm^3) method (drying to constant weight at 105 ℃) (**Table 3**). Take 500 g soil samples at different sampling points and take them back to the laboratory for experimental analysis, which is used to analyze and determine the content of soil organic carbon. Five soil samples were taken from each fixed standard sample plot in the burned area, with three kinds of forest fire interference intensity, and a total of 105 samples were taken from seven soil layers (5 sampling points for each standard sample plot × 3 kinds of forest fire interference intensity levels × 7 soil layers). A total of 35 soil samples were collected from the control sample plots (5 sampling points for each standard sample plot × 7 soil layers). Using a soil drill with an inner diameter of 10 cm, collect 5 soil cores with diameters of 0–10, 10–20, 20–30 and 30–40 cm respectively according to the root system with root diameters ≤2 mm, and bag them in layers. Through the processes of rinsing and sieving with running water, select the fine roots, weigh them after drying, dry them to constant weight, save the samples, and test the moisture content.

Table 4. Regression equation and regression coefficient of *Eucalyptus robusta* forests

Component	Regression equation	*a*	*b*	Coefficient of determination (R^2)	Number of samples (*N*)
Trunk	$Y = a(D^2H)^b$	0.0513	0.8902	0.9689	30
Branch	$Y = a(D^2H)^b$	0.0013	1.7895	0.8894	30
Leaf	$Y = a(D^2H)^b$	0.0201	0.2356	0.9569	30
Bark	$Y = a(D^2H)^b$	0.0098	0.7856	0.9235	30

2.5 Experimental methods

2.5.1 Determination of biomass

Generally, the relative growth method is used to estimate the biomass of trees. According to the "Allometric" equation proposed by Huxley[23], the formula is[22,24,25]:

$$Y = a(D^2H)^b \tag{1}$$

Where: *Y* is biomass, *D* is DBH, *H* is tree height, *a*, *b* are the coefficients. See **Table 4** for the regression equation and regression coefficient of the biomass of the arbor layer of the eucalyptus forest in Guangdong Province. The biomass of shrubs, herbs and fallout is measured mainly by measuring the moisture content. Vegetation biomass includes the sum of the biomass of trees, shrubs and herbs. See **Table 5** for the impact of different forest fire disturbances on vegetation biomass and regulated litter biomass.

2.5.2 Determination of carbon content

Determination of carbon content in vegetation, fallout and soil organic carbon: grind the vegetation and falling object samples dried and collected into 60 mesh (0.25 mm) and store them in glass bottles. The soil samples were sieved for 100 mesh (0.15 mm) and stored in glass bottles. MultiN/C3100 analyzer (MultiN/C3100, Analytik Jena AG, Jena, Germany) combined with solid module was used to determine the carbon content of vegetation, fallout and soil samples.

Table 5. Effect of forest fire disturbance on vegetation/litter biomass of *Eucalyptus robusta* forests (mean±SD, t·hm^{-2})

Treatment	Vegetation	Litter
Control CK	163.73 ± 12.80	4.30 ± 0.30
Light forest fire disturbance L	137.78 ± 18.86	3.09 ± 0.21
Moderate forest fire disturbance M	72.56 ± 9.05	2.03 ± 0.28
High forest fire disturbance H	31.71 ± 5.53	1.75 ± 0.28

2.5.3 Calculation method of carbon density per unit area

(1) Biomass carbon density per unit area. Biomass carbon density (t·hm^{-2}) is represented by *M*, biomass carbon content (g·kg^{-1}) is represented by *F*, and 1,000 is the unit of carbon content converted into the coefficient of carbon content (%). The formula can be expressed as:

$$C_t = M \times F_c/100 \tag{2}$$

(2) Soil organic carbon density per unit area. The calculation formula of organic carbon density in a certain soil layer per unit area is:

$$SOC_d = \sum_{i=1}^{n} T_i \times \theta_i \times C_i \times (1 - \delta_i\%)/10 \tag{3}$$

Where, SOC_d is the density of soil organic carbon (t·hm^{-2}); *i* is the number of soil layers, *n* = 7; T_i is the thickness of soil layer *i* of soil profile (cm), that is, the interval in 1–4 layers is 10 cm, and the interval in 5–7 layers is 20 cm; θ_i is the soil bulk density of layer *i* of soil profile (g·cm^{-3}); C_i is the organic carbon content of layer *i* of soil profile (g·kg^{-1}); δ_i% is the gravel content coefficient of soil profile with diameter greater than 2 mm; 10 is the coefficient that converts the unit of SOC into t·hm^{-2}.

2.6 Data analysis

Data statistical analysis was processed with Microsoft Excel 2016 and SPSS 25.0 software. SPSS 25.0 software was used for one-way ANOVA to compare the difference of carbon density (LSD test) between sample plots with different forest fire interference intensity and control sample plots, and the significance level setting α = 0.05. Draw the chart with OriginPro 2019b.

3. Results and analysis

3.1 Impact of forest fire disturbance on vegetation carbon density

3.1.1 Carbon content of vegetation

As shown in **Table 6**, the order of carbon content of different components of vegetation from high to low is: arbor (493.24 g·kg^{-1}) > shrub (472.19 g·kg^{-1}) > herb (482.27 g·kg^{-1}), and the average carbon content of eucalyptus forest vegetation is 482.57 g·kg^{-1}. It reflects the difference of carbon sequestration capacity of vegetation components in the eucalyptus forest in photosynthesis.

3.1.2 Impact of forest fire disturbance on vegetation carbon density

After forest fire disturbance of different intensity, the vegetation carbon density of the eucalyptus forest is different from that of the control sample (**Figure 1(A)**). Only moderate and high forest fire disturbance significantly reduced the carbon density of vegetation ($P < 0.05$). Under the same intensity of forest fire disturbance, the change of carbon density of each component of vegetation is the largest in arbors, which presents as control > light forest fire disturbance > moderate forest fire disturbance > high forest fire disturbance, while forest fire disturbance significantly improves the carbon density of herbs ($P < 0.05$), which presents as high forest fire disturbance > moderate forest fire disturbance > light forest fire disturbance > control (**Figure 1(B)**). Compared with the control plots, the carbon density of vegetation in the light forest fire disturbance, moderate forest fire disturbance and high forest fire disturbance plots was 15.50–80.69 t·hm^{-2}, which decreased by 15.86%, 55.78% and 80.79% respectively, and the difference was significant only after the moderate and high forest fire disturbance ($P < 0.05$). The arbor carbon density of the eucalyptus forest showed a downward trend compared with the control sample after different forest fire interference, but the difference was significant only after moderate and high forest fire interference ($P < 0.05$); compared with the control plots, the shrub carbon density first decreased and then increased after different forest fire disturbances. After moderate and high forest fire disturbances, the shrub carbon density significantly increased ($P < 0.05$), and the herb carbon density increased after different forest fire disturbances compared with the control plots, and the difference was significant ($P < 0.05$), that is, the forest fire disturbances significantly increased the herb carbon density.

3.2 Effect of forest fire interference on carbon density of litter

3.2.1 Carbon content of litter

The carbon content of regulated litter in the eucalyptus forest is smaller than the average carbon content of vegetation, which is 462.53 g·kg^{-1}, indicating that the carbon content of each component of the forest is arbor > shrub > herb > litter, and the difference may be related to site conditions, climate, vegetation carbon content and the composition of regulated litter.

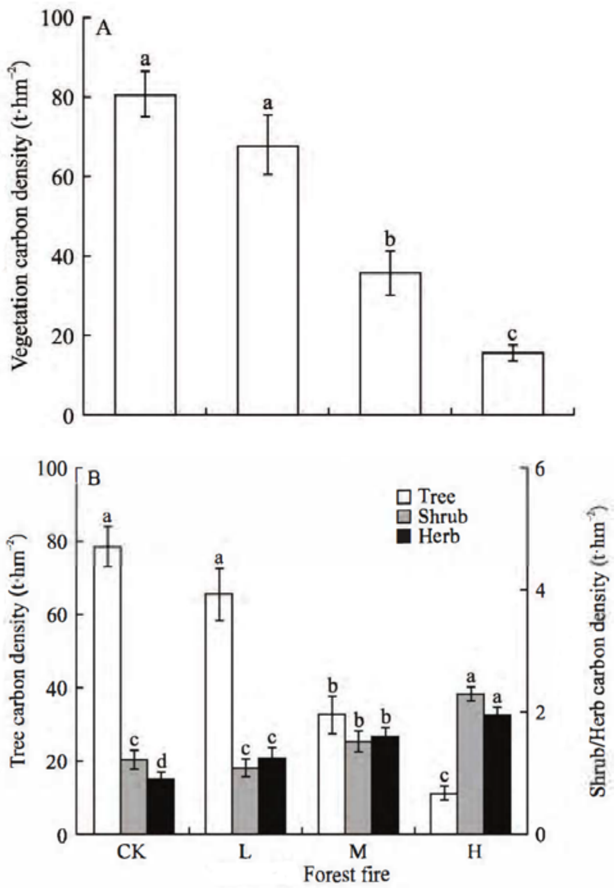

Figure 1. Effect of forest fire disturbance on vegetation carbon density of *Eucalyptus robusta* forest.
Note: Different small letters indicate significant difference between different forest fire disturbance intensity and control plot s in the same forest type at $P < 0.05$ Level. The same below.

Table 6. Vegetation carbon contents of *Eucalyptus robusta* forest (mean ± SD, g·kg^{-1})

Forest type	Carbon content
Tree	493.24 ± 78.20
Shrub	482.27 ± 67.20
Herb	472.19 ± 68.60
Mean	482.57 ± 71.34

3.2.2 Effect of forest fire interference on carbon density of fallout

It can be seen from **Figure 2** that different forest fire interference intensities have significantly reduced the carbon density of falling objects (P < 0.05), and the reduction degree increases with the increase of forest fire interference intensity. Compared with the control group, the carbon density of litter after light, moderate and high forest fire disturbance was 1.43, 0.94 and 0.81 t·hm^{-2}, which decreased by 28.14%, 52.76% and 59.30% respectively. The carbon density of litter after high forest fire disturbance reduced the most, which was consistent with the overall change of vegetation carbon density.

3.3 Effect of forest fire disturbance on soil organic carbon density

3.3.1 Soil organic carbon content

The content of soil organic carbon in each soil layer (0–100cm) with different forest fire interference intensities and in control plots varied in the range of 26.50–247.45 and 33.10–306.40 g·kg^{-1} respectively. The same soil layer showed a downward trend with the increase of forest fire interference intensity, and gradually decreased with the increase of soil profile depth (**Figure 3**). However, light forest fire disturbance had a significant effect on the density of soil organic carbon in the surface layer (0–20 cm) (P < 0.05), while moderate and high forest fire disturbance had a significant difference on the content of soil organic carbon in the surface layer and shallow layer (2,040 cm) of eucalyptus forest soil (P < 0.05).

3.3.2 Effect of forest fire disturbance on soil organic carbon density

After light forest fire disturbance, moderate forest fire disturbance and high forest fire disturbance in the eucalyptus forest, the soil organic carbon density of each soil layer (0–100 cm) was 103.30, 84.33 and 70.04 t·hm^{-2}, which decreased by 11.67%, 27.89% and 40.11% respectively compared with the control sample (**Figure 4(A)**). Light forest fire disturbance had no significant effect on soil organic carbon density (P > 0.05), while moderate and high forest fire disturbance significantly reduced soil organic carbon density (P < 0.05). The density of soil organic carbon in the surface layer (0–10 cm) decreased by 17.22%, 36.99% and 46.68% respectively, and the density of soil organic carbon in the sub surface layer (10–20 cm) decreased by 21.08%, 45.489% and 59.09% respectively. After the three kinds of forest fire interference intensity, the density of soil organic carbon in the surface layer decreased significantly (P < 0.05) (**Figure 4(B)**). The density of soil organic carbon in shallow soil (20–40 cm) decreased by 6.26%, 27.73% and 42.84% respectively. Only moderate and severe forest fire disturbance significantly reduced the density of soil organic carbon in shallow soil (P < 0.05). The density of soil organic carbon in deep layer (40–100 cm) decreased by 3.89%, 6.37% and 18.13% respectively. Only high forest fire disturbance had a significant effect on the density of soil organic carbon in deep layer (P < 0.05), while moderate forest fire disturbance had a significant effect on the density of soil organic carbon in deep layer (40–60 cm) (P < 0.05), while light and moderate forest fire disturbance had no significant effect on the density of soil organic carbon in deep layer (P > 0.05).

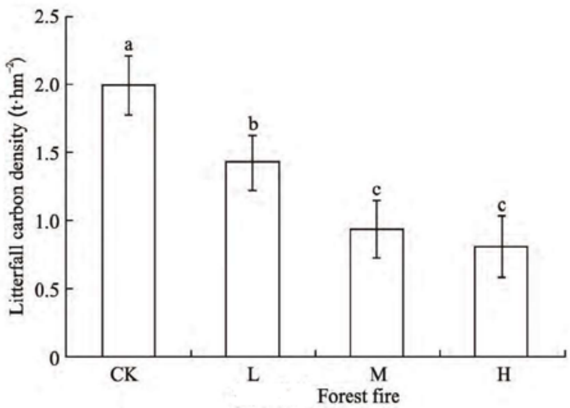

Figure 2. Effect of forest fire disturbance on litter carbon density of *Eucalyptus robusta* forest.

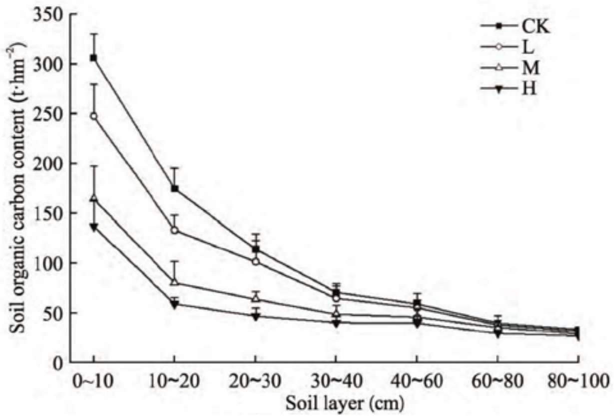

Figure 3. Effect of forest fire disturbance on soil organic carbon content of *Eucalyptus robusta* forest.
Note: For the sake of illustration, the results of the data of soil depth (40–60, 60–80 and 80–100 cm) is divided by 2. The same below.

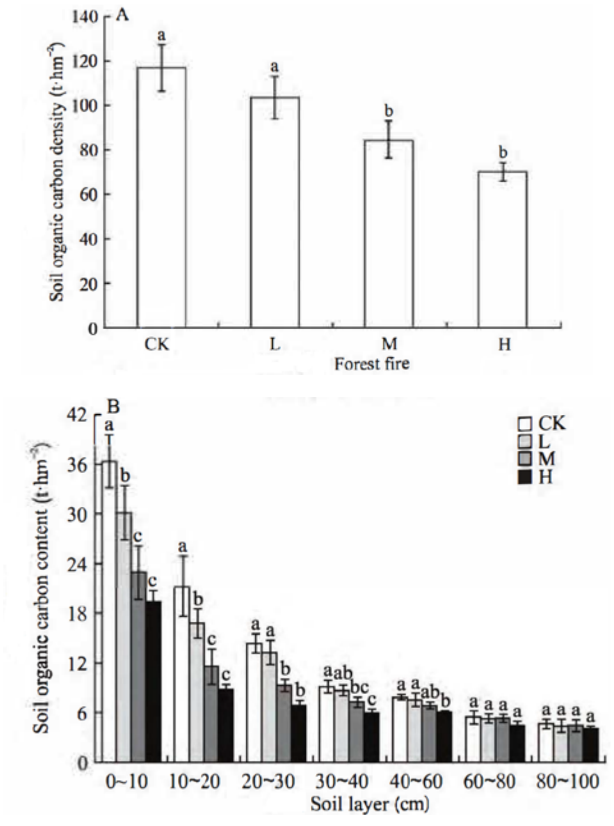

Figure 4. Effect of forest fire disturbance on soil organic carbon density of *Eucalyptus robusta* forest.

3.3.2 Effect of forest fire disturbance on soil organic carbon density

After light forest fire disturbance, moderate forest fire disturbance and high forest fire disturbance in the eucalyptus forest, the soil organic carbon density of each soil layer (0–100 cm) was 103.30, 84.33 and 70.04 $t \cdot hm^{-2}$, which decreased by 11.67%, 27.89% and 40.11% respectively compared with the control sample (**Figure 4(A)**). Light forest fire disturbance had no significant effect on soil organic carbon density ($P > 0.05$), while moderate and high forest fire disturbance significantly reduced soil organic carbon density ($P < 0.05$). The density of soil organic carbon in the surface layer (0–10 cm) decreased by 17.22%, 36.99% and 46.68% respectively, and the density of soil organic carbon in the sub surface layer (10–20 cm) decreased by 21.08%, 45.489% and 59.09% respectively. After the three kinds of forest fire interference intensity, the density of soil organic carbon in the surface layer decreased significantly ($P < 0.05$) (**Figure 4(B)**). The density of soil organic carbon in shallow soil (20–40 cm) decreased by 6.26%, 27.73% and 42.84% respectively. Only moderate and severe forest fire disturbance significantly reduced the density of soil organic carbon in shallow soil ($P <$ 0.05). The density of soil organic carbon in deep layer (40–100 cm) decreased by 3.89%, 6.37% and 18.13% respectively. Only high forest fire disturbance had a significant effect on the density of soil organic carbon in deep layer ($P < 0.05$), while moderate forest fire disturbance had a significant effect on the density of soil organic carbon in deep layer (40–60 cm) ($P < 0.05$), while light and moderate forest fire disturbance had no significant effect on the density of soil organic carbon in deep layer ($P > 0.05$).

Table 7. Effect of forest fire disturbance on fine root biomass of *Eucalyptus robusta* forests ($t \cdot hm^{-2}$)

Soil layer (cm)	Contrast CK	Light L	Moderate M	High H
0–10	4.04 ± 0.39 a	3.22 ± 0.32 b	2.56 ± 0.47 b	1.98 ± 0.22 b
10–20	3.12 ± 0.45 a	2.16 ± 0.35 b	1.59 ± 0·26 c	1.10 ± 0.11 c
20–30	2.18 ± 0.39 a	1.85 ± 0.47 a	1.04 ± 0.26 b	0.83 ± 0.18 b
30–40	0.94 ± 0.14 a	0.93 ± 0.19 a	0.67 ± 0.11 ab	0.57 ± 0.21 b

Note: Different small letters on the same line indicate significant differences between the same soil layer processing (P < 0.05)

3.3.3 Effect of forest fire disturbance on soil fine root biomass

It can be seen from **Table 7** that the fine root biomass of forest soil after forest fire interference is lower than that of the control sample, and the change trend is presented as high forest fire interference > moderate forest fire interference > light forest fire interference. After the disturbance of forest fires, the fine root biomass of the soil surface (0–10 cm) decreased significantly ($P < 0.05$), decreasing by 20.30%, 36.63% and 50.99% respectively; the soil fine root biomass in the sub surface layer (10–20 cm) decreased significantly ($P < 0.05$), decreasing by 30.77%, 49.04% and 64.74% respectively; the fine root biomass in shallow soil (20–40 cm) decreased by 8.10%, 40.51% and 47.98% respectively, and only the high and moderate forest fire disturbance decreased significantly ($P < 0.05$); the decrease of fine root biomass in shallow soil (20–40 cm) was smaller than that in surface soil (0–20 cm).

4. Discussion

In the global carbon cycle, the change of carbon pool in subtropical forest ecosystem is very important. Forest fire disturbance profoundly affects the ecological process of carbon balance in the ecosystem, changing the nutrient utilization rate[3], thereby reducing the carbon density of the forest ecosystem[26]. This is consistent with this study. The proportion of vegetation carbon density in the forest ecosystem in the control group of eucalyptus forest, forest with light, moderate and high forest fire interference is 40.42%, 39.33%, 29.50% and 17.95% respectively. The proportion of litter carbon density in the forest ecosystem is 1.00%, 0.83%, 0.78% and 0.94%, and the proportion of soil organic carbon density in the forest ecosystem is 58.58%, 59.85%, 69.72% and 81.11% respectively. The carbon density of vegetation and litter accounted for 41.42%, 40.15%, 30.28% and 18.89% of the forest ecosystem respectively. It can be seen that with the increase of forest fire interference intensity, the proportion of vegetation and litter carbon density in the ecosystem decreased. After forest fire interference, the carbon density of the ecosystem decreased, and the carbon density decreased with the increase of forest fire interference intensity. In addition, due to the relatively small proportion of litter carbon density, the change of vegetation and soil organic carbon density is the main influencing factor of ecosystem carbon density change[27,28]. Since the moderate and high forest fire disturbance intensity significantly affects the carbon density of eucalyptus forest vegetation ($P < 0.05$) and soil organic carbon density, the moderate and high forest fire disturbance intensity significantly affects the carbon density of eucalyptus forest ecosystem ($P < 0.05$), and the light forest fire disturbance has no significant impact on the carbon density of forest ecosystem ($P > 0.05$).

The overall impact of forest fire disturbance on forest ecosystems is complex and highly variable, ranging from the reduction of aboveground biomass (including vegetation biomass and litter biomass, etc.) to physical, chemical and microbial mediated processes in soil micro ecosystems, but the short-term and long-term impact of forest fire disturbance on underground micro organisms and the ultimate impact on ecosystem sustainability are uncertain, and it requires further study on how forest fire disturbance with different intensity can change the succession of vegetation, and then affect the structure of soil microbial community. The change of underground ecological process will affect the internal mechanism of soil carbon pool circulation, and then affect the carbon sequestration potential and key carbon processes of forest ecosystem. In addition, after the forest fire disturbance, due to the difference in the recovery speed of different vegetation types, in the early stage of vegetation recovery, the input of soil carbon source is reduced due to the reduction of the nutrient cycle process available to plants. It is necessary to systematically carry out a systematic study on "vegetation—litter—soil—microorganism—climate", and explore the interaction mechanism of migration, transformation and storage of carbon pools in different stages after the fire disturbance. The distribution characteristics of each carbon pool and the relationship between energy conversion in a longer period of time should be analyzed, so as to realize the quantitative study of different forest fire interference types on the dynamic changes of forest ecological carbon pool[29].

5. Conclusion

Forest fire disturbance reduced the carbon density of vegetation, the effect of light forest fire disturbance on the carbon density of vegetation was not significant ($P > 0.05$), while moderate and high forest fire disturbance significantly reduced the carbon density of vegetation ($P < 0.05$). Different forest fire disturbance intensities significantly reduced the carbon density of regulated litter ($P < 0.05$), and the reduction amplitude increased with the increase of forest fire disturbance intensity.

Forest fire disturbance reduced the density of soil organic carbon in the same soil layer. The soil organic carbon density of the sample plots with different forest fire interference intensity is lower than that of the control, and the reduction range gradually decreases with the increase of soil profile depth. Light forest fire disturbance only significantly reduced the density of soil organic carbon in the surface layer (0–20 cm) ($P < 0.05$); however, moderate and high forest fire disturbance significantly reduced the density of soil organic carbon in the surface layer and shallow layer (20–40 cm) ($P < 0.05$). After forest fire disturbance, the soil fine root biomass of each forest type was lower than that of the control sample. The effect of light forest fire disturbance on the soil surface fine root biomass was significantly different ($P < 0.05$), while moderate and high forest fire disturbance significantly reduced the soil surface and shallow fine root biomass ($P < 0.05$).

Forest fire disturbance reduced the carbon density of forest ecosystem. With the increase of forest fire disturbance intensity, the carbon density decreased gradually. After forest fire disturbance, it appears as control > light forest fire disturbance > moderate forest fire disturbance > high forest fire disturbance. Compared with the control, the impact of light forest fire disturbance intensity on ecosystem carbon density was not significant ($P > 0.05$), while the impact of moderate and high forest fire disturbance intensity on ecosystem carbon density was significantly different ($P < 0.05$).

Conflict of interest

The authors declared no conflict of interest.

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