Effects of Clear-Cutting and Burning on Soil CO2 Flux at Different Depths in Subtropical Forests (Postprint)

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Abstract

Evaluating CO2 flux from soils at different depths is an important approach for studying soil carbon dynamics. Currently, research on the impacts of clear-cutting and burning on forest soil carbon emissions has been limited to surface soil, with few reports on the effects on soil carbon emissions at different depths. This study took a Castanopsis carlesii secondary forest (control) and its clear-cut burned site as research objects, measured soil CO2 concentration using a non-dispersive infrared CO2 sensor, and estimated soil CO2 flux at different depths (0-80 cm) by combining Fick' s first law of diffusion. The results showed: (1) Clear-cutting and burning altered the apparent CO2 flux emitted from soil to the atmosphere; within 2 months after clear-cutting and burning, the apparent soil CO2 flux was significantly higher than that of the control by 68%; after 2 months, the apparent soil CO2 flux was lower than that of the control by 37%. (2) After clear-cutting and burning, except for the CO2 flux at 10-20 cm which increased, the CO2 flux at all other depths (0-10, 20-40, 40-60 cm, and 60-80 cm) decreased. Simultaneously, clear-cutting and burning changed the contribution rates of different soil layers to soil respiration, decreasing the contribution rate of the 0-10 cm soil layer while increasing that of the 10-20 cm soil layer. (3) In the control plot, only the soil CO2 flux at 0-10 cm showed a significant exponential correlation with temperature, whereas the CO2 flux at 10-40 cm depth showed a significant linear correlation with soil moisture content. After clear-cutting and burning, soil CO2 flux at both 0-10 cm and 10-20 cm showed exponential correlations with temperature. This indicates that clear-cutting and burning altered the response of soil CO2 flux at different depths to environmental factors. Therefore, to accurately assess and predict the impacts of clear-cutting and burning on carbon exchange between soil and atmosphere, temporal changes in soil CO2 flux after clear-cutting and burning, as well as

the responses of soil CO2 flux at different depths to clear-cutting and burning, should be considered.

Full Text

The Impact of Clear-Cutting and Slash Burning on Soil CO Flux at Different Soil Depths in a Subtropical Forest

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Abstract

Measuring soil CO flux at different depths is a critical approach for investigating soil carbon dynamics. Currently, research on the impacts of clear-cutting and slash burning on forest soil carbon emissions has focused primarily on surface soils, while their effects on carbon emissions at various soil depths remain poorly understood. This study measured CO flux along a soil profile (0–80 cm) in an uncut secondary *Castanopsis carlesii* forest and a clear-cut, slash-burnt stand in Sanming, Fujian. Using a scattered infrared CO detector combined with Fick' s laws of diffusion, we estimated soil CO flux at different depths. Our results showed that: (1) Slash burning significantly altered the apparent CO flux. Within two months after burning, soil surface CO flux increased by 68% compared to the control, but decreased by 37% two months later. (2) After slash burning, soil CO fluxes at depths of 0–10, 20–40, 40–60, and 60–80 cm decreased, with the exception of an increase at 10–20 cm depth. Meanwhile, slash burning reduced the contribution rate of the 0–10 cm soil layer to total CO flux while increasing that of the 10–20 cm layer. (3) In the control plot, soil CO flux at 0–10 cm depth showed a significant exponential relationship with temperature, while fluxes at other depths were linearly correlated with soil moisture. After slash burning, soil CO fluxes at 0–10 cm and 10–20 cm depths were exponentially correlated with soil temperature, indicating that slash burning altered how CO flux at different depths responds to environmental factors. Therefore, to accurately estimate and predict the impact of clear-cutting and slash burning on carbon exchange between soil and atmosphere, it is necessary to consider temporal changes in soil CO flux after slash burning and the differential responses of soil CO flux at various depths.

Keywords: clear-cutting and slash burning; CO flux; soil vertical profile; soil temperature; soil moisture

Introduction

Soil respiration represents the second-largest carbon flux in terrestrial ecosystems and plays a crucial role in regulating soil carbon pools and ecosystem carbon cycling [1-3]. Forest conversion driven by human activities reduces ecosystem carbon storage, making converted forestlands a carbon source in the near term. Studies indicate that nearly one century of carbon emissions from land-use change originated from forest conversion [4]. As the primary method of commercial forest conversion in southern China, clear-cutting and slash burning significantly affect soil respiration rates and their feedback to climate change [5]. Investigating the impacts and mechanisms of clear-cutting and slash burning on soil respiration is essential for accurately assessing ecosystem carbon balance.

Although numerous studies have examined the effects of clear-cutting and slash burning on soil respiration [6–7], most have focused on disturbances to apparent CO flux and environmental factors [7–8], with few reporting impacts on CO flux at different soil depths. The diffusion of total CO production (from autotrophic and heterotrophic respiration) through soil profiles is influenced by biological factors and environmental conditions at various depths. Evaluating soil CO flux at different depths effectively reflects the carbon dynamics of CO production emission to the atmosphere. However, substantial uncertainty remains in assessing soil-atmosphere carbon exchange responses to anthropogenic disturbance and climate change, primarily because research has focused on how environmental factors like temperature and moisture affect biological processes of CO production, while CO flux patterns at different depths require further investigation [9].

Fire strongly alters physical and chemical properties at different soil depths, thereby affecting both CO production and diffusion rates. Previous studies have shown that after clear-cutting and slash burning, the contribution of deep soil layers to apparent CO flux increases as surface CO flux decreases [10]. Water availability has been identified as a key factor affecting soil CO flux [11]. This study continuously monitored soil CO flux at different depths in a subtropical evergreen broadleaf secondary *Castanopsis carlesii* forest to analyze the impacts of clear-cutting and slash burning, providing a basis for more accurately assessing how human-induced forest conversion affects ecosystem carbon cycling.

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1. Study Area Overview

The study site is located at the Sanming Forest Ecosystem and Global Change Research Station in Fujian Province (26°19 N, 117°36 E) at 330 m elevation. The region features low hilly terrain and a mid-subtropical monsoon climate, with an average annual precipitation of 1749 mm and mean annual temperature of 19.1°C. The soil, developed from biotite granite, is red soil with a thickness exceeding 80 cm.

Pre-treatment vegetation consisted of a secondary *Castanopsis carlesii* forest regenerated after selective logging, with a stand density of 1970 stems/ha, mean height of 19.7 m, and mean DBH of 13.5 cm. The dominant tree species was *Castanopsis carlesii*, with main understory species including *Ilex pubescens*, *Tricalysia dubia*, *Itea chinensis*, and *Woodwardia japonica*. Annual litterfall was 5.81 t/hm², and soil organic carbon stock in the 0–80 cm layer was 85.34 t/hm².

In October 2011, the *Castanopsis carlesii* secondary forest was clear-cut. Each standard plot (20 m × 20 m) was completely cleared of trees. After stem removal, logging residues were evenly distributed on the surface to dry. In April 2012, all residues and litter were burned. The burn duration was one day. Adjacent *Castanopsis carlesii* secondary forests were retained as control treatments (CT).

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2. Plot Setup

In July 2012, weeding was conducted in the slash-burned plots.

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3. Soil Apparent CO Flux Measurement

To validate the applicability of the diffusion model in this study area, we used Li-8100 chamber measurements of soil apparent CO flux. In each standard plot, PVC collars (20 cm × 10 cm) were inserted 3–5 cm into the soil. Chamber measurements of apparent CO flux were conducted between 9:00–10:00. From June 2012 to May 2013, we selected observation points with average soil apparent CO flux in both slash-burned and control plots for long-term monitoring. The observation interval was every two months.

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4. Soil Profile CO Concentration Measurement

In each standard plot, we excavated three standard soil profiles with depths of 0–80 cm. At depths of 10, 20, 40, 60, and 80 cm, we horizontally inserted perforated tubes (80 cm × 2.0 cm) and connected each layer' s tubes using a three-way connector to mix CO concentrations from specific depths and reduce spatial heterogeneity. To minimize disturbance effects, measurements began one week after installation. The CO concentration observation system consisted of a Vaisala GMT220 detector with novel silicon-based non-dispersive infrared (NDIR) technology, capable of continuous measurement unaffected by dust or water vapor. The instrument recorded data every 30 minutes, with internal storage for temperature and concentration data.

In June and December 2012, soil samples were collected to determine total carbon, total nitrogen, and microbial biomass. Table 1 presents the baseline soil properties.

Table 1 Soil properties of control treatment (CT) and slash burning (SB)

Soil depth (cm)	Total C (g/kg)	Total N (g/kg)	C/N ratio	Microbial biomass C (mg/kg)
0–10	16.33±0.40 Aa	1.46±0.01 Aa	9.49±0.10 Ab	202.3±1.24 Aa
10–20	10.85±0.10 Ab	1.15±0.01 Ab	6.42±0.13 Ac	142.48±3.52 Ab
20–40	5.70±0.03 Bc	0.81±0.01 Bc	4.33±0.16 Ac	108.61±4.19 Ac
40–60	3.81±0.07 Ac	0.76±0.01 Ac	0.91±0.01 Ac	60.00±2.93 Bd
60–80	2.93±0.09 Ac	0.69±0.01 Ac	0.84±0.01 Ac	54.75±1.04 Ad

Note: Different uppercase letters indicate significant differences between treatments for the same soil layer (P<0.05). Different lowercase letters indicate significant differences among soil layers for the same treatment (P<0.05). Values are means ± SE.

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5. Calculation of Soil Profile CO Flux and Contribution Rate

Based on Fick' s first law of diffusion, soil CO flux was calculated using the effective gas diffusion coefficient in soil [13]. The apparent soil CO flux at different depths was estimated from concentration gradients:

$$F_S = D_S \frac{dC}{dz}$$

where D_S is the CO diffusion coefficient in soil (m²/s), C is CO concentration, and z is depth. The flux represents apparent soil CO flux calculated from concentration gradients between the surface and soil depth (0–10 cm), between 10–20 cm, etc.

The diffusion coefficient D_S was calculated using the Moldrup 2000 model, which our previous research found most suitable for this region [17]:

$$D_S = \varepsilon D_a$$

where ε is the relative gas diffusion coefficient and D_a is the free atmospheric diffusion coefficient (1.47×10 m²/s at 20°C, 293.15 K, and 1.013×10 Pa).

Soil layer CO production was estimated from net flux across the layer—the difference between upper and lower boundary fluxes—while stored CO within the layer was negligible [18]. The contribution rate was calculated as [13]:

$$\text{Contribution rate} = \frac{F_{\text{layer}}}{F_{\text{total}}} \times 100\%$$

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6. Soil Profile Temperature and Moisture Observation

Soil profile temperature and moisture sensors (ECH O Model EC-5, Decagon) were installed in each standard plot at the same depths as CO measurements.

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7. Data Processing

Data processing and graphing were performed using SPSS 19.0 and Origin 9.0. All data were pre-processed and tested for normal distribution and homogeneity of variance. Significance differences in CO flux and influencing factors between treatments for the same soil layer were analyzed using t-tests. Differences among depths for the same treatment were analyzed using ANOVA with q-tests (S-N-K). Exponential models were used to fit relationships between soil profile CO flux and temperature/moisture.

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1. Soil CO Concentration Dynamics at Different Depths

Soil CO concentrations in both slash-burned and control plots showed unimodal annual curves, increasing with soil depth. In the control plot, the timing of peak concentrations was delayed with increasing depth: 10 cm (June), 20 cm (July), 40 cm (August), 60 cm (September), and 80 cm (October). Except at 10 cm depth, CO concentrations in the slash-burned plot were significantly lower than in the control plot throughout the year (20–68% lower). At 10 cm depth, concentrations were significantly lower in the slash-burned plot only from June to August 2012, with no significant difference thereafter.

[Figure 1: see original paper] **Figure 1 Inter-annual dynamics of soil vertical profile CO concentrations in the SB (plain line) and CT (dashed line) plots from June 2012 to May 2013**

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2. Effects of Slash Burning on Soil CO Flux and Contribution Rate at Different Depths

Linear regression analysis between Li-8100 chamber measurements and diffusion-method calculations showed strong correlation ($R^2 = 0.94$), confirming the Moldrup 2000 model' s suitability for this region.

Apparent CO Flux: Within two months after slash burning, apparent soil CO flux in the burned plot was significantly higher than in the control (68% increase). However, two months later, the burned plot flux was significantly lower (37% decrease), with no significant difference between treatments during the intervening period.

[Figure 2: see original paper] **Figure 2 Correlation between soil surface CO flux measured with Li-8100 chambers (horizontal axes) and CO fluxes calculated according to the gradient-based diffusion model using the Moldrup et al. (2000) model (vertical axes)**

[Figure 3: see original paper] **Figure 3 Soil surface CO fluxes of SB (plain line) and CT (dashed line) directly measured with Li-8100 chambers within two months after SB**

Profile CO Flux: Slash burning significantly reduced CO flux at 0–10, 20–40, 40–60, and 60–80 cm depths, while increasing flux at 10–20 cm depth. The annual dynamics showed unimodal patterns in both treatments.

[Figure 4: see original paper] **Figure 4 Inter-annual dynamics of soil vertical profile CO flux in the SB (plain line) and CT (dashed line) plots from June 2012 to May 2013**

Contribution Rates: Slash burning altered the relative contributions of different soil layers to total CO flux. In the control plot, the 0–10 cm layer contributed 58% of total flux, while 10–20, 20–40, 40–60, and 60–80 cm layers contributed 31%, 2%, 6%, and 2%, respectively. After slash burning, the 0–10 cm contribution decreased to 31%, while the 10–20 cm contribution increased to 58%. Other layers showed no significant changes.

[Figure 5: see original paper] **Figure 5 Annual carbon fluxes of CO at different layers of SB and CT**

[Figure 6: see original paper] **Figure 6 Soil vertical profile CO flux contribution at different layers of SB and CT plots**

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3. Effects of Slash Burning on Temperature and Moisture at Different Depths

Both treatments showed similar annual temperature trends, gradually increasing from June to August 2012 and decreasing from September 2012 to January 2013. Soil temperature decreased with depth during warm months but increased with depth during cold months. Slash-burned plots had higher temperatures than control plots at all depths, with annual averages ranging from 7-31°C (mean ~21°C).

Soil moisture trends were also similar between treatments, though slash burning reduced moisture by 3-25% across all depths. The reduction was most pronounced in the 0–20 cm layer. Moisture increased with soil depth in both treatments.

[Figure 7: see original paper] **Figure 7 Inter-annual dynamics of soil vertical profile temperature and water content in the SB (plain line) and CT (dashed line) plots from June 2012 to May 2013 at each depth**

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4. Relationships Between CO Flux and Temperature/Moisture at Different Depths

Exponential models fitting soil CO flux to temperature showed that in the control plot, only the 0–10 cm layer was significantly correlated with temperature (P<0.05). In the slash-burned plot, both 0–10 cm and 10–20 cm layers showed significant exponential relationships with temperature.

Linear models fitting flux to moisture revealed that in the control plot, only the 10–20 cm and 20–40 cm layers showed significant negative correlations with soil moisture. In the slash-burned plot, the 10–20 cm and 20–40 cm layers also showed significant linear correlations with moisture, while other layers showed no significant relationships.

Table 2 Parameters of two models of CO flux in relation to soil temperature and soil moisture content at different soil depths

Treatment	Depth (cm)	Temperature Model	Moisture Model
		R^2	Q
CT	0–10	0.578	1.665
	10–20	0.051	1.047
	20–40	0.037	1.184
	40–60	0.232	0.086
	60–80	0.269	-0.159
SB	0–10	0.689	3.544
	10–20	0.310	2.165
	20–40	0.282	1.045
	40–60	0.095	1.209
	60–80	0.133	1.487

Note: indicates significance at P<0.05; ** indicates significance at P<0.01; ns = not significant.*

1. Effects of Slash Burning on Apparent Soil CO Flux

The impact of slash burning on soil CO flux was time-dependent. Within the first two months, flux was higher in burned plots—consistent with Wüthrich et al.'s [19] findings in Switzerland and Ma et al.'s [5] research showing that burning promotes soil respiration. This initial increase resulted from: (1) increased soil temperature due to reduced vegetation cover, (2) abundant easily decomposable carbon from ash residues, (3) enhanced microbial growth, and (4) improved soil aeration from destroyed aggregates releasing protected carbon [19,21,22].

The subsequent decrease in apparent CO flux below control levels likely occurred because: (1) easily decomposable organic carbon was exhausted, reducing heterotrophic respiration, (2) surface soil organic carbon decreased, (3) root respiration declined, and (4) reduced litter input lowered organic matter availability [23,25].

2. Effects of Slash Burning on Soil CO Flux at Different Depths

Slash burning altered vertical CO flux patterns. Compared to the control, flux decreased at all depths except 10–20 cm, where it increased. The contribution of different layers to total flux also changed: the 0–10 cm layer' s contribution decreased from 58% to 31%, while the 10–20 cm layer' s contribution increased from 31% to 58%.

The 0–10 cm layer' s high CO production typically results from abundant soil organic carbon and available carbon substrates [26]. After slash burning, the complete combustion of surface litter and significant reduction in soil carbon content decreased heterotrophic respiration, reducing this layer' s contribution [27]. Reduced root respiration in the 0–10 cm layer also contributed to its decreased contribution.

The increased contribution of the 10–20 cm layer can be attributed to: (1) enhanced gas exchange due to destroyed soil structure in the overlying layer, (2) increased atmospheric CO diffusion into this layer, stimulating microbial activity [31], and (3) greater heat transfer raising soil temperature and microbial activity [5]. For depths below 20 cm, reduced root respiration likely caused the observed flux decreases, despite moisture conditions that might otherwise promote heterotrophic respiration.

3. Response of CO Flux at Different Depths to Temperature and Moisture

Soil temperature and moisture are key regulators of soil respiration [32]. In control plots, apparent CO flux showed a highly significant exponential relationship with temperature, while subsurface fluxes were primarily moisture-controlled. The 10–40 cm layers showed significant negative linear correlations with moisture, indicating that in this moisture-sufficient subtropical region, higher water content inhibits rather than promotes CO flux, likely by impeding gas diffusion and creating anaerobic conditions [34–36].

Slash burning changed these relationships. The 0–20 cm layers showed significant exponential temperature relationships, possibly because burning reduced moisture content, eliminating water limitation and allowing temperature to become the dominant control. The 10–20 cm and 20–40 cm layers maintained significant moisture relationships, but the nature of these relationships was altered by burning.

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4. Conclusion

(1) As an important forest management practice in subtropical regions, slash burning' s effects on soil respiration are time-dependent. Within two months post-burn, apparent CO flux exceeds control levels, but subsequently falls below them. Accurate assessment requires considering these temporal dynamics.

(2) Slash burning differentially affects CO flux across soil depths, decreasing flux in the 0–10 cm layer while increasing the 10–20 cm layer's contribution to total flux. This redistribution significantly alters the vertical pattern of soil carbon emissions.

(3) Slash burning modifies how CO flux at different depths responds to environmental factors. To accurately evaluate slash burning' s impact on soil-atmosphere carbon exchange, both temporal changes in CO flux and depth-specific responses must be considered.

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Note: Figure translations are in progress. See original paper for figures.