Postprint: Soil Respiration Response to Defoliating Insect Outbreak in a Typical Deciduous Broad-Leaved Forest at Jigong Mountain

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Abstract

Soil respiration is one of the key components of the carbon cycle in terrestrial ecosystems. With the increasing frequency of extreme climate events, the frequency and intensity of forest pest outbreaks also tend to increase, and forest pest outbreaks have become an important natural disturbance affecting the carbon cycling processes in forest ecosystems. Whether the outbreak of insect disasters in typical forest ecosystems of climate transition zones affects soil carbon emission processes remains unclear. This study took advantage of a large-scale outbreak of leaf-feeding pests in a mixed Quercus acutissima-Liquidambar formosana forest in the Jigong Mountain area to compare soil carbon emission fluxes between the outbreak year (2014) and a normal year (2015), in order to elucidate the impact of forest pest outbreaks on soil carbon emission fluxes. The results showed that in July, August, September, and October of the outbreak year, the average soil temperature was 0.26, 0.51, 0.83, and 0.07 °C higher than the corresponding months in the normal year, respectively, and soil respiration increased significantly by 129.9%, 77.1%, 61.6%, and 58.9%, respectively. The average soil respiration during the growing season in the outbreak year was 3.55 mol m-2 s-1, which was 36.2% higher than that in the normal year (2.77 mol m-2 s-1); the average soil heterotrophic respiration during the growing season increased by 29.7% compared to the normal year. This study indicates that the outbreak of leaf-feeding pests in forests can lead to a significant increasing trend in forest soil carbon emissions, at least in the short term, thereby exerting an important influence on soil carbon pool accumulation in forest ecosystems. Therefore, a comprehensive understanding of the disturbance and impact of pests and diseases on forest ecosystems will contribute to the accurate estimation and modeling of carbon cycles in terrestrial ecosystems.

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Preamble

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Effect of a Defoliator Plague on Soil Respiration in a Typical Deciduous Broadleaf Forest on Jigong Mountain

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Abstract

Soil respiration is a critical pathway of carbon (C) cycling in terrestrial ecosystems. As extreme climate events become more frequent, forest pest outbreaks have emerged as a significant natural disturbance affecting carbon cycling processes in forest ecosystems. The frequency and intensity of these outbreaks are projected to increase. However, it remains unclear whether pest outbreaks in typical forest ecosystems within climate transition zones will affect soil carbon emission processes. This study capitalized on a large-scale outbreak of defoliating pests in a *Quercus acutissima–Liquidambar formosana* mixed forest in the Jigong Mountain region to compare soil carbon emission fluxes between the outbreak year (2014) and a normal year (2015), thereby elucidating the impacts of forest pest outbreaks on soil carbon emissions.

During the outbreak year, soil temperatures in July, August, September, and October were 0.26°C, 0.51°C, 0.83°C, and 0.07°C higher, respectively, than in the corresponding months of the normal year. Soil respiration rates increased significantly by 129.9%, 77.1%, 61.6%, and 58.9% during these same months. The mean soil respiration during the growing season in the outbreak year was 3.55 mol m ^{2} s ^{1}, which was 36.2% higher than that observed in the normal year (2.77 mol m ^{2} s ^{1}). Heterotrophic respiration during the growing season in the outbreak year increased by 29.7% compared to the normal year. These results demonstrate that defoliating pest outbreaks can significantly increase soil CO emissions, at least in the short term, thereby exerting important effects on soil

carbon pool accumulation in forest ecosystems. A better understanding of pest disturbance impacts on forest ecosystems is essential for accurate estimation and modeling of terrestrial ecosystem carbon cycling.

Keywords: oak forest; climate transitional zone; soil CO emission; heterotrophic respiration; soil temperature

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Introduction

Forest ecosystems represent the plant community with the largest carbon storage in the terrestrial biosphere and play a crucial role in regulating global carbon cycling processes [1-2]. The soil carbon content in forest ecosystems is equivalent to 75–98 Pg C annually, making it the largest carbon pool in terrestrial ecosystems [4-5]. Soil respiration is a key component of terrestrial ecosystem carbon cycling, releasing approximately 75–98 Pg C to the atmosphere each year—substantially more than the amount emitted from burning fossil fuels [4-6]. The magnitude of soil respiration is regulated by both abiotic factors such as temperature, moisture, and nutrients [6-8], and biotic factors including soil microorganisms and plant metabolism [9-10].

In recent years, forest pest outbreaks have become one of the most important disturbances affecting forest ecosystem services and sustainable forestry development [11-12]. Globally, approximately 34×10 hectares of forest are affected by pests, with the severity increasing due to intensifying climate change [13]. China is among the countries most severely affected, with total pest-disturbed forest area reaching 3.152×10 hectares—nearly double the area affected in previous years [13]. The scale and intensity of forest pest outbreaks have become important factors influencing regional and global carbon budget patterns and the carbon sink role of forests [14].

When pest outbreaks occur, tree growth rates slow and some trees may even die, directly reducing ecosystem primary productivity [16]. As pest severity increases, the combination of reduced productivity and increased ecosystem respiration leads to declines in net ecosystem productivity and carbon storage [16-17]. Dead organic matter entering decomposition processes also releases substantial amounts of CO , equivalent to 7–17% of ecosystem gross primary productivity [15]. In addition to direct impacts on aboveground vegetation, forest pests can significantly affect forest soils. For defoliating pests in particular, large-scale outbreaks cause extensive leaf consumption, substantially reducing canopy leaf area index and increasing surface light intensity [11]. Pest frass deposited directly on the forest floor creates a fertilization effect, enhancing soil nutrient availability [18-19] and thereby regulating ecosystem soil carbon and nitrogen cycling processes.

While most research on forest pest impacts has focused on aboveground plant physiological activity and biomass [11, 16], few studies have examined the effects of pest outbreaks on soil carbon emission rates. This study investigated a typical deciduous broadleaf forest in the north subtropical-warm temperate climate transition zone of China. In 2014, the region experienced a massive outbreak of defoliating pests, primarily *Lampronadata cristata* and *Ochrostigma albibasis*, which feed on oak species. By comparing soil carbon emission rates between the outbreak year (2014) and a normal year (2015), this research reveals the impacts of forest pest outbreaks on soil respiration and provides scientific insights into how forest pests affect forest ecosystem carbon cycling.

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1. Study Area Overview

The study site is located in the Jigong Mountain National Nature Reserve in Xinyang, Henan Province (31°46 -31°51 N, 114°01 -114°06 E), a mid-elevation mountain region with elevations ranging from 120–810 m. The area lies in the transition zone between north subtropical and warm temperate climates, with a mean annual temperature of 15.2°C and mean annual precipitation of 1098 mm, concentrated primarily during July–September.

The zonal vegetation consists of deciduous broadleaf forest and evergreen broadleaf-deciduous mixed forest, though most primary vegetation no longer exists and has been replaced by secondary forests. Dominant secondary forest types include *Quercus acutissima*, *Quercus variabilis*, *Liquidambar formosana*, *Pinus massoniana*, *Cunninghamia lanceolata*, and *Cryptomeria fortunei* plantations. Meteorological data show that during the study period, mean air temperatures from July–October were 24.7°C in 2014 and 24.4°C in 2015, with precipitation of 757.2 mm and 794.4 mm, respectively—indicating no significant interannual differences in temperature or rainfall.

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2. Methods

2.1 Sample Plot Selection and Setup

In May 2014, we established three 20 m × 20 m permanent plots in a naturally regenerated *Quercus acutissima*-*Liquidambar formosana* mixed forest on relatively flat terrain with consistent stand characteristics. Plots were spaced at least 50 m apart. Within each plot, we randomly selected two 1 m × 1 m subplots. In one subplot, we installed a soil respiration collar (20 cm diameter, 8 cm height) inserted to a depth of 5 cm to measure total soil respiration. In the other subplot, we trenched around the perimeter to 60 cm depth, inserted nylon mesh (30 m pore size) to block root ingrowth, backfilled the soil, and installed a second respiration collar to estimate heterotrophic respiration.

2.2 Soil Respiration and Temperature-Moisture Measurements

Beginning in June 2014, we measured soil temperature, moisture, and respiration monthly during the growing season (June–October). Soil respiration was measured using a LI-8100 automated soil CO flux system. During each measurement, we simultaneously recorded soil temperature and moisture at 10 cm depth using the system' s integrated probes.

2.3 Pest Outbreak Characterization

In July 2014, a large-scale defoliating pest outbreak occurred in the deciduous broadleaf forest of Jigong Mountain, with *Lampronadata cristata* and *Ochrostigma albibasis* causing severe damage to most deciduous broadleaf trees. By the end of the outbreak, nearly all canopy leaves were consumed. We quantified pest abundance by collecting dead insects and frass in 1 m × 1 m litter traps, yielding (88.3 ± 6.4) insects/m^2 and (417.9 ± 13.2) g/m^2 of frass.

2.4 Data Processing and Analysis

We performed statistical analyses on soil respiration, temperature, and moisture data from both the outbreak year (2014) and normal year (2015). Data were tested for normality and homogeneity of variance to meet ANOVA assumptions. We used one-way ANOVA to determine differences in monthly soil total respiration, temperature, and moisture between years, and simple linear regression to examine relationships between soil respiration and environmental factors. All analyses were conducted in SPSS 16.0.

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3. Results and Analysis

3.1 Soil Temperature and Moisture

Soil temperature during the 2014 growing season followed a parabolic distribution, peaking in mid-season (August). Mean growing season soil temperature was 24.7°C in 2014, 0.3°C higher than in 2015 (24.4°C). Before the pest outbreak (June), there was no significant difference in soil temperature between years ($P > 0.05$). However, during July, August, September, and October 2014, soil temperatures were 0.26°C, 0.51°C, 0.83°C, and 0.07°C higher, respectively, than in the corresponding months of 2015 ($P < 0.05$).

Soil moisture showed different temporal patterns between years. In 2014, soil moisture gradually declined through the growing season, whereas in 2015 it remained relatively stable. Before the outbreak (June), 2014 soil moisture was 3.7% higher than in 2015 ($P < 0.05$). After the outbreak, soil moisture in July, August, and September 2014 was 8.6%, 7.2%, and 6.1% lower than in 2015, respectively, with differences reaching significance in August and September ($P < 0.05$) [Figure 1: see original paper].

3.2 Interannual Differences in Soil Respiration

Soil respiration exhibited similar seasonal dynamics in both years, peaking in August (6.53 and 2.84 mol m ^{2} s ^{1} in 2014 and 2015, respectively). Before the outbreak (June), there was no difference in soil respiration between years. However, when the outbreak occurred in July, soil respiration increased dramatically and remained elevated through subsequent months, though the magnitude of flux declined over time (from 6.53 to 2.27 mol m ^{2} s ^{1}). The pest outbreak significantly increased soil respiration in July, August, September, and October by 129.9%, 77.1%, 61.6%, and 58.9%, respectively ($P < 0.05$). Mean growing season soil respiration in the outbreak year was 3.55 mol m ^{2} s ^{1}, 36.2% higher than the normal year (2.77 mol m ^{2} s ^{1}).

Heterotrophic respiration is an important component of total soil respiration. During the growing season, heterotrophic respiration averaged 29.7% higher in the outbreak year compared to the normal year. However, the relative increase in total soil respiration caused by the pest outbreak was greater than that of heterotrophic respiration, and this difference decreased over time (15.4% in July vs. 24.2% in October) [FIGURE:2, FIGURE:3].

3.3 Relationships Between Soil Respiration and Environmental Factors

Exponential regression models revealed that soil respiration was significantly positively correlated with soil temperature in both years ($P < 0.05$), but showed no significant relationship with soil moisture. Using the temperature-respiration relationship, we calculated temperature sensitivity (Q) values of 1.189 for the outbreak year and 1.074 for the normal year, indicating higher temperature sensitivity during the pest outbreak [Figure 4: see original paper].

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4. Discussion

Changes in soil carbon emissions following defoliating pest outbreaks result from combined responses of autotrophic and heterotrophic respiration. When leaves are heavily consumed, plant respiration declines substantially or ceases entirely [20]. Reduced photosynthate production decreases the allocation of labile carbon belowground, potentially weakening root and rhizosphere respiration [16, 20]. In this study, the greater increase in total respiration compared to heterotrophic respiration suggests that the pest outbreak stimulated autotrophic respiration, possibly due to mobilization of stored reserves for refoliation. This aligns with findings from a red oak forest study where *Lymantria dispar* outbreak significantly increased soil respiration, attributed to combined effects of rhizodeposition and labile soil organic carbon rather than frass quantity [21].

Pest outbreaks also strongly stimulate heterotrophic respiration. Post-outbreak increases in canopy transmittance raise surface temperatures and improve soil moisture conditions, enhancing microbial activity. Pest frass and plant debris contain abundant labile carbon and nitrogen that, when deposited on the soil surface, increase microbial activity and accelerate nitrogen cycling, promoting organic carbon decomposition [18-19]. The easily decomposable organic carbon in frass improves microbial nitrogen use efficiency [18], while deposited nitrogen partially remains in soil, sustaining higher decomposition rates over time.

The seasonal pattern of soil respiration persisted despite the outbreak, with stimulation effects diminishing as temperatures declined—consistent with regional climate constraints [22]. Madritch et al. found that canopy herbivory by forest tent caterpillars significantly increased soil respiration in northern hardwood forests [22]. However, the effects of frass deposition versus litter addition differ temporally: over longer periods, litter addition stimulates respiration more than frass, while in the short term (especially immediately post-outbreak), frass causes more significant increases, particularly when plant species diversity is high [22]. For easily digestible leaf types, frass effects on microbial activity exceed those of less digestible litter [22].

Our study has methodological limitations. Soil temperature and moisture, the most direct factors influencing respiration, showed interannual differences related to climate variation. However, meteorological data indicate minimal differences in temperature and precipitation between 2014 and 2015, suggesting limited climate influence on our results. The fertilization effects of frass deposition and its impacts on trees may have persistent or lagged effects influencing subsequent years [23], potentially causing underestimation of outbreak impacts. Additionally, pest outbreaks may alter litterfall timing without changing total quantity, as observed in Pennsylvania oak forests where gypsy moth outbreaks shifted seasonal allocation but not total litter mass [24], suggesting potential positive effects on soil carbon inputs.

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5. Conclusion

Forest pest outbreaks are important disturbances affecting forest ecosystem services and carbon budgets. This study demonstrates that defoliating pest outbreaks can significantly increase soil carbon emission fluxes, with stimulation effects diminishing over time. In the short term, pest outbreaks enhance carbon efflux from ecosystem soil carbon pools, thereby affecting forest net carbon balance and global terrestrial carbon cycling. The impacts of forest pests on carbon cycling warrant greater consideration in global carbon cycle estimation and evaluation.

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