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Factors Affecting Soil CO_2 Emission in Forest Ecosystems – a Literature Overview

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Abstract

In this paper, our aim is to review the factors contributing to CO_2 emissions from forest soils. Forest ecosystems play a crucial role in the global carbon cycle and they are essential for mitigating the negative impacts of climate change. Soils represent the largest reservoir of carbon in terrestrial ecosystems. Approximately 44% of the carbon within the world's forests is stored in forest soil. Ecosystem respiration encompasses both aboveground and soil respiration. In various forest types, soil respiration (CO_2 emissions from soil) can account for between 55% and 85% of total ecosystem respiration. Globally, soil CO_2 emission is one of the major sources of greenhouse gas emissions, reaching up to 100 Gt C per year. Soil temperature and moisture are the most significant factors influencing soil CO_2 emissions. One of these variables may exert a stronger influence on emissions than the other. Other important factors include soil type, soil properties, land uses (forests, grasslands, croplands, barren areas, and wetlands), land-use change, forest type, stand structure and forest management practices. Understanding how these factors impact soil CO_2 emissions in forest ecosystems is crucial in the context of climate change. Forest management is a key factor influencing emissions and can lead to various outcomes for soil CO_2 emissions in forest ecosystems. By studying the major factors affecting soil CO_2 emissions in forest ecosystems, we can better understand their role in climate change mitigation.

Keywords:
soil temperature, soil moisture, land-use change, forest management

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INTRODUCTION

Forest ecosystems play a crucial role in the global carbon cycle and they are essential for mitigating the negative effects of climate change (Kuznetsova et al. 2019). Forests store enormous amounts of carbon and any disruption in the balance between photosynthesis and ecosystem respiration can result in significant changes in the sequestration or release of CO_2 into the atmosphere (Pregitzer and Euskirchen 2004). Gross primary production (GPP) in forests, which represents the total annual photosynthesis, is estimated to be around 69 Gt of carbon per year globally. The majority of this carbon uptake is released back into the atmosphere through ecosystem respiration (Re) and wildfires (Anderson-Teixeira et al. 2021).

Net ecosystem production (NEP) is a fundamental property of an ecosystem that is defined as the difference between gross primary production and total ecosystem respiration (Lovett et al. 2006). Net primary production (NPP) is defined as the difference between GPP and the autotrophic component of ecosystem respiration (Reich et al. 1999). Ecosystem respiration includes aboveground respiration and soil respiration (Barba et al. 2018). According to Tang et al. (2008), components of ecosystem respiration involve leaf respiration, stem respiration, soil respiration, and surface litter respiration. Soil respiration is a fraction of ecosystem respiration, and it has to be lower than ecosystem respiration at annual or seasonal scales (Barba et al. 2018). Soil respiration is divided into autotrophic and heterotrophic components whose contributions to total Re vary in time and space (Tang et al. 2008).

Soil CO_2 emission can reach from 55% to 85% of total Re in various types of forests (Law et al. 1999, Davidson et al. 2006, Knohl et al. 2008). Bhanja et al. (2022) suggested that soil respiration may even contribute up to 90% of Re. The average annual soil respiration (Rs) within eighteen forest ecosystems in the European Union was 760 ± 340 g C m^{-2}, representing 69% of Re (Janssens et al. 2001). The contribution of soil respiration to total Re (Rs/Re ratio) varied during different seasons in coniferous and deciduous forests (Yuste et al. 2005, Davidson et al. 2006). The highest contribution was recorded during winter and autumn, while the lowest contribution was during the period of leaf growth (Yuste et al. 2005, Davidson et al. 2006).

The total carbon stock in terrestrial ecosystems is approximately estimated to be 3170 Gt. Of this storage, about 2500 Gt (80%) is stored in soil, including organic (1550 Gt) and inorganic carbon (950 Gt) (Ontl et al. 2012). Globally, only oceans have a significantly larger carbon stock (38 400 Gt) compared to soils (Ontl et al. 2012). The global assessment of soil organic carbon content varies from 504 to 3000 Gt with a median of 1461 Gt depending on different databases of soil (Amundson 2001, Köchy et al. 2015, Beillouin et al. 2022). The assessment of soil inorganic carbon accounts for approximately 750 Gt in the top 1 m and over 2300 Gt in the top 2 m, which is nearly equal to organic carbon stock (Zamanian et al. 2021).

Approximately 860 Gt of carbon are stored in the world's forests, with 44% in soil, 42% in live biomass (both above and below ground), 8% in deadwood, and 5% in litter (Pan et al. 2011). Forests cover approximately one third of the land in Europe, with total estimated soil carbon between 22 and 25 Gt (De Vos et al. 2015). The carbon content in forest ecosystems per unit area is higher than in other land use types (Robert 2001).

The species composition in a stand significantly affects the total carbon stock in the stand as well as the amount of organic carbon in the soil (Janssens et al. 1999, Walle et al. 2001). According to a study conducted in Austrian forests, the amount of soil organic carbon stock was higher in coniferous forests primarily composed of Norway spruce (*Picea abies* (L.) H.Karst.) than in mixed deciduous forests. The obtained results included both mineral soil (at a depth of 50 cm) and the litter layer (Jandl et al. 2021). However, Hulvey et al. (2013) suggested that carbon stock increases significantly in mixed forests compared to monoculture over a long period. There are differences in soil carbon stock between deciduous and coniferous forests, with greater differences observed within unmanaged locations compared to managed locations. Additionally, these differences depend on the development of the soil (Schulp et al. 2008, Hüblová et al. 2021, Nickels et al. 2021).

Soil respiration represents the emission of CO_2 from soil, which results from the biological activity of organisms in the soil (Phillips and Nickerson 2015). The emission of CO_2 from soil occurs through soil respiration processes involving root, microbial and faunal respiration (Lubbrns et al. 2013). The agents contributing to soil CO_2 emission are autotrophic and heterotrophic organisms. (Kuzyakov 2006). In the global carbon cycle, the total flux of CO_2 from the soil is one of the largest emissions, releasing up to 100 Gt C per year (Wang et al. 2011, Chiang et al. 2021).

Soil respiration is divided into autotrophic and heterotrophic respiration. Plants are the most important autotrophs contributing to soil CO_2 emission through root respiration, while algae and chemolithotrophs have a lower contribution. The most important heterotrophic organisms in the soil can be divided into two groups: microorganisms (fungi, bacteria, actinomycetes and protozoans) and macrofauna. Microorganisms produce significantly higher amounts of CO_2 compared to macrofauna in the soil (Kuzyakov 2006, Teramoto et al. 2019). Generally, plant root respiration and the oxidation of soil organic matter through decomposition by heterotrophic soil organisms are the main sources of CO_2 production from the soil (Zhao and Shi 2017). Other important sources of soil CO_2 emissions include microbial decomposition of dead plant residues and rhizodeposits from living roots (Kuzyakov 2006).

Plant root respiration (autotrophic component of soil respiration) contributes on average up to 50% of the total soil respiration (Hanson et al. 2000). The variations in autotrophic soil respiration, ranging from 10% to 95%, depend on seasons and the type of vegetation (Kelting et al. 1998, Hanson et al. 2000, Tang and Baldocchi 2005, Wang and Yang 2007, Ferréa et al. 2012). In forests with various tree species, autotrophic respiration reaches its peak in early spring, while the heterotrophic component of soil respiration contributes over 80% during the summer (Ferréa et al. 2012). A long-term drought results in a decrease in soil respiration, primarily autotrophic respiration. This decrease is mainly attributed to reduced soil water availability (Huang et al. 2018).

Due to the significant contribution of soil respiration to ecosystem respiration as well as the importance of soil CO_2 emission in the global carbon cycle we present an overview of the literature discussing the influence of key factors on soil CO_2 emission. We will discuss the impact of the following factors on soil CO_2 emission: soil temperature and moisture, land-use and land-use change, forest type and stand structure, and forest management practices.

SOIL TEMPERATURE AND SOIL MOISTURE – KEY DRIVERS

Soil temperature and soil moisture represent the most significant factors affecting soil CO_2 emission. One of these factors may have a stronger effect on emission than the other (Fang and Moncrieff 2001, Dilustro et al. 2005, Tang et al. 2006, Li et al. 2008, Chen et al. 2013, Wei et al. 2014a, Sarzhanov et al. 2017, Teramoto et al. 2017, Prasad and Baishya 2019, Yu et al. 2021). Soil temperature is a key factor in emission and depends on radiation, exposure, soil cover, soil color and wildfires. Soil moisture is also a very important driver of emission and depends on water-filled pore space, precipitation and drought (Oertel et al. 2016). Other important factors affecting emissions include soil type, land use (forests, grasslands, croplands, barren lands, wetlands), vegetation (age, type, distribution), nutrients, C/N ratio and pH value. Local climate has a significant impact on soil CO_2 emission, primarily through soil temperature and moisture (Oertel et al. 2016). Land use and vegetation type also strongly influence the main drivers of soil CO_2 emission (Oertel et al. 2016). Many authors suggested that the rise in soil temperature is often followed by an exponential increase in soil respiration (Han et al. 2007, Peng et al. 2009, Shen et al. 2021, Lei et al. 2022).

The temperature sensitivity of soil respiration can be explained by the Q_{10} coefficient which represents an increase in CO_2 release for every 10°C increase in temperature (Davidson and Janssens 2006, Nie et al. 2019). The estimated values of the Q_{10} coefficient for soil respiration ranged from 1.2 to 3.3 within various ecosystems (Raich and Schlesinger 1992, Chen et al. 2010, Meyer et al. 2018).

In most cases, soil CO_2 emission increases with higher soil temperature. Elevated temperatures lead to an increase in the production of soil CO_2 through autotrophic and heterotrophic respiration (Wang et al. 2010). In a forest primarily composed of Norway spruce in the Austrian Alps, a study showed that soil warming caused a rise in soil respiration. Specifically, both autotrophic and heterotrophic respiration had similar response to the increase in soil temperature (Schindlbacher et al. 2009). In a subtropical forest (China), the autotrophic and heterotrophic components had different response to soil warming. Soil warming increased soil respiration and its heterotrophic component without considerable change in soil moisture. Within experimental plots in a forest predominantly composed of red spruce (*Picea rubens* Sarg.), soil warming by 5°C induced a 25–40% increase in soil CO_2 emission compared to the control plot (Rustad and Fernandez 1998).

Drought stress can decrease soil CO_2 emission in mesic and xeric ecosystems, while in hydric ecosystems, drought stress can increase emission through stimulating soil microbial activity (Wang et al. 2014). The autotrophic and heterotrophic components of soil respiration show different responses to climate warming and drought (Zeng et al. 2021). Generally, heterotrophic respiration is more sensitive to drought stress compared to autotrophic respiration (Unger et al. 2010, Zeng et al. 2021). However, in some ecosystems, root respiration can be more sensitive than heterotrophic respiration during long-term drought due to water stress (Wang et al. 2014).

Soil warming and increased precipitation both significantly increase CO_2 emission from soil due to elevated soil temperature and moisture which stimulate microbial activity and accelerate carbon cycling (Wu et al. 2020). After soil warming, the decomposition of organic matter was more intense in warmed soil compared to non-warmed soil. Soil warming also led to increased activity of enzymes (β-Glucosidase, Sulfatase and Chitinase) as well as microbial activity (Hou et al. 2016).

Precipitation notably affected an increase in soil water content in a subtropical forest of China. After precipitation, slight mean annual increase in soil respiration was observed in forests primarily formed of *Pinus massoniana* Lamb. (Deng et al. 2012). In the Gurbantunggut desert, the increase in precipitation could lead to higher carbon release as soil respiration linearly increased with precipitation. The increased abundance of bacteria and fungi after precipitation affects the increased release of carbon in this ecosystem (Huang et al. 2015). Precipitation likely has stronger effect on dry sites than wet sites (Zhou et al. 2009). Within nine sites along the precipitation gradient in Oklahoma (USA), a linear increase in soil CO_2 emission was recorded with an increase in precipitation (Zhou et al. 2009).

Precipitation significantly caused an increase in soil water content and soil CO_2 emission, while it decreased soil temperature within *Robinia pseudoacacia* L. plantation and *Quercus liaotungensis* Koidz. forest on the Loess Plateau in the Shaanxi province, China (Shi et al. 2011). Rewetting of dry soils usually causes a pulse in soil C and N mineralization known as the "Birch effect" (Lado-Monserrat et al. 2014). A significant variation in soil respiration was observed among ten different tree species in India. The study revealed that soil respiration was higher during the rainy season attributed to increased microbial activity during the monsoon (Rawat et al. 2021). However, a four-year study showed that soil respiration had a significantly negative correlation with precipitation in a coastal wetland in the Yellow River Delta. In this ecosystem, an increase in precipitation led to an increase in soil moisture, resulting in the reduction of soil CO_2 emissions. Additionally, anoxic conditions caused a decrease in soil CO_2 emission due to limited oxygen availability and reduced biological activities of plant roots and microorganisms (Han et al. 2018). According to Zhu et al. (2020), soil respiration showed varying responses to soil temperature and moisture during various seasons in *Populus* × *canadensis* Moench (*P.* × *euramericana* (Dode) Guinier) plantation. The study found that soil respiration increased in spring due to precipitation, but that precipitation caused reduction in soil CO_2 emission during summer and autumn, unlike during spring.

Results of an experiment conducted in northeast China (Jilin Province) showed that soil carbon stock, soil temperature, soil moisture and soil respiration variation depended on slope positions. Additionally, this study revealed that soil CO_2 emission was controlled by soil moisture during the initial 27 days of the study, while soil temperature affected emission during last 20 days (Wei et al. 2014a). The study found a strong correlation between soil temperature, soil moisture and soil respiration in forests of different successional stages in southern China. Soil CO_2 emission was considerably higher in hot humid seasons compared to cool dry seasons under the seasonal influence of soil temperature and precipitation (Tang et al. 2006). However, Tang et al. (2003) suggested that soil temperature had strong effects on soil CO_2 flux during the summer dry season in an oak-grass savanna in California (USA).

Seasonal variation in soil respiration can be explained by the interaction of soil temperature and moisture (Cui et al. 2020). Warmer and wetter soil conditions lead to increased CO_2 emission due to higher activity of plant roots and soil microorganisms (Cui et al. 2020). Additionally, seasonal variation in soil respiration in Ethiopia depended on soil temperature and moisture as well as their combined effect (Fekadu et al. 2023). In mixed pine forests, soil temperature had a strong impact on soil CO_2 emission, while soil moisture was also correlated with soil CO_2 emission during periods of water stress (Dilustro et al. 2005). Combined models including both soil temperature and moisture are better for predicting soil respiration compared to models using only soil temperature as the independent variable (Reichstein et al. 2003, Zhao et al. 2013).

THE IMPACT OF LAND-USE AND LAND-USE CHANGE ON SOIL CO_2 EMISSION

Soil carbon accumulation significantly depends on vegetation type. Land-use changes can impact the storage of soil carbon, potentially leading to either the sequestration or emission of carbon-dioxide (Poeplau and Don 2013) Deforestation and afforestation have a significant impact on soil carbon storage and climate change (Fujisaki et al. 2015).

The conversion of forests and grasslands into croplands leads to the disturbance of soil structure and induces mineralization of soil organic matter, resulting in the loss of carbon storage and an increase in soil CO_2 emission (Poeplau et al. 2011, Wei et al. 2013, Wei et al. 2014b, Fujisaki et al. 2015). Conversely, the conversion of cropland to grassland and forest leads to an increase in soil carbon stock (Poeplau et al. 2011). In general, it is observed that soil carbon stock is higher in grassland and forest compared to cropland (Wiesmeier et al. 2012, Morais et al. 2019, Ostrogović Sever et al. 2021). However, after 20 years since the conversion from grassland to forest, there was a decrease in the organic carbon stock in the soil. Additionally, after 100 years since the conversion, the soil along with the forest floor accumulated larger amounts of carbon compared to the initial period. (Poeplau et al. 2011).

The values of soil CO_2 emissions varied significantly during the assessment of greenhouse gas emissions (N_2O, NO, CO_2 and CH_4) within thirteen European sites under different land-use and climate (Schaufler et al. 2010). This study revealed that the highest CO_2 emissions were observed in grassland and wetland compared to cropland and forest. The highest soil CO_2 emission was recorded from grassland in the United Kingdom and wetland in Finland, while the lowest emission was found in the forest in Germany (Schaufler et al. 2010). Management practices within grassland in northeast China pronouncedly affected soil CO_2 emission. Within all tree management practices (mowing, grazing exclusion, and grazing), soil CO_2 emission showed a strong positive correlation with soil moisture. During a dry year, the highest values of soil CO_2 emission were observed for grazing, while in a wet year, the highest values were recorded for mowing (Gong et al. 2014). A study carried out in north-western and northern Iran across various land-uses revealed that a higher value of soil respiration was recorded in agricultural land compared to naturally covered land (Ebrahimi et al. 2019).

A study in India showed that soil respiration had higher values in cultivated land compared to forest. This study indicates that activities such as tillage and fertilization reduce soil carbon stock, as aeration enhances microbial activity and the decomposition of organic matter in croplands (Meena et al. 2020). Similar results were obtained in Mexico where decreased soil CO_2 emissions were recorded in an eucalyptus (*Eucalyptus camaldulensis* Dehnh. and *E. microtheca* F.Muell.) plantation compared to other land uses (Díaz et al. 2007).

In the Hubei province (China), soil CO_2 emission reached its maximum in summer, while minimum values were observed in winter across various land use types within Acrisol and Ferralsols. The significantly higher values were recorded in paddy soil compared to orchard and forest soil (Iqubal et al. 2008). According to Anokye et al. (2021), soil organic carbon content and soil CO_2 emission varied across different land uses in Ghana. The study found that the soil carbon content was 62% lower in arable land and 23% lower in a palm plantation compared to the forest. Additionally, arable land emitted 30–46% more CO_2 than forest and palm plantation.

Land-cover change can have significant impact on soil respiration, as it alters plant species composition, vegetation structure, soil properties and microclimate (Huang et al. 2020). The most significant changes in soil CO_2 emissions occur when natural ecosystems are converted to croplands. Deforestation and the conversion of forests to croplands results in the biggest losses of carbon, as forests store enormous amounts of carbon compared to croplands. Approximately 25–30% of carbon is lost at a depth of 1 m due to soil cultivation (Houghton and Goodale 2004).

During the 2.5-year study period, it was determined that the conversion of pasture to forest reduced soil respiration by 41% (Kellman et al. 2007). In southeastern China, the conversion of secondary forest of Chinese cork oak (*Quercus variabilis* Blume) to loblolly pine (*Pinus taeda* L.) plantation can notably increase soil CO_2 emission and reduce temperature sensitivity of soil respiration (Shi et al. 2009). However, study comparing a 200-year-old natural forest of *Castanopsis carlesii* (Hemsl.) Hayata with two 36-year-old plantations of

Cunninghamia lanceolata (Lamb.) Hook. and *Pinus massoniana* showed that plantations had significantly lower values of soil CO_2 emission compared to natural forests (Guo et al. 2016). The age of stand and the tree species can significantly affect soil respiration. Therefore, higher values of soil respiration in a natural forest can be explained by factors such as forest floor depth, increased root biomass and abundance of soil microbial community (Guo et al. 2016).

THE IMPACT OF FOREST TYPE AND STAND STRUCTURE ON SOIL CO_2 EMISSION

Many studies suggest that forests composed of various tree species can have different responses to soil CO_2 emissions (Wang et al. 2006, Bréchet et al. 2009, Vesterdal et al. 2012, Akburak and Makineci 2013, Li et al. 2017, Rawat et al. 2021). Soil carbon stock is controlled by the balance between carbon input from litterfall and carbon loss through decomposition, which is related to the heterotrophic component of soil respiration. Tree species can affect both of these fluxes (Vesterdal et al. 2012).

In the tropical forest, there were significant differences in soil CO_2 emissions between stands of the same age composed of different tree species (Bréchet et al. 2009). This study showed that the variation in soil respiration was related to the quantity and quality of litterfall as well as the basal area. There was no significant relationship between soil respiration and root biomass (Bréchet et al. 2009). Soil respiration pronouncedly depends on vegetation type, soil carbon stock, soil temperature and soil moisture in six different stands composed of different tree species in northeastern China. This study showed that annual soil respiration was 72% higher in a deciduous forest than in a coniferous forest (Wang et al. 2006). However, the values of soil respiration were higher below the canopy of pine compared to oak and ash in a 300-year-old mixed stand of *Pinus koraiensis* Siebold et Zucc., *Quercus mongolica* Fisch. ex Ledeb. and *Fraxinus mandshurica* Rupr. Lower nitrogen concentration and a higher C/N ratio result in slower decomposition and decreased heterotrophic component of soil respiration under pine unlike ash and oak. The autotrophic component of soil respiration was dominant under pine, while the heterotrophic component was dominant under ash and oak (Li et al. 2017).

In forest ecosystems, the impact of stand age on soil respiration varies among different studies (Wiseman and Seiler 2004). There are studies that indicate soil CO_2 emission increase with stand age, while other studies suggest that emission decrease with stand age. The authors provided various explanations for each scenario (Klopatek 2002, Wiseman and Seiler 2004, Saiz et al. 2006, Tedeschi et al. 2006, Zhao et al. 2016, Gao et al. 2019, Yu et al. 2019, Karaklić et al. 2024).

A study conducted in four differently aged stands (10-, 15-, 31-, and 47-year-old stands) of Sitka spruce (*Picea sitchensis* (Bong.) Carrière) found that the highest soil respiration was observed in the younger stands. More precisely, soil respiration decreased with stand age due to a decrease in fine root biomass. Soil respiration in older stands was relatively uniform (Saiz et al. 2006). Root respiration decreases with stand age, but this decline is compensated by increased decomposition of accumulated organic matter. The decrease in the autotrophic component of total soil respiration in older stands can be attributed to higher root activity in younger stands (Saiz et al. 2006). Similar results were obtained in 20- and 40-year-old Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) stands (Klopatek 2002), 5- and 15- year-old poplar plantations (Gong et al. 2012) and 45- and 25-year-old ponderosa pine (*Pinus ponderosa* Douglas ex P.Lawson et C.Lawson) stand (Law et al. 1999). In *Pinus banksiana* Lamb. stands, soil respiration was highest in an 8-year-old stand and decreased with stand age (Striegl and Wickland 2001). Furthermore, a decrease in soil respiration was also observed with increasing stand age in *Pinus tabuliformis* Carrière, *Populus davidiana* Dode and coppiced *Quercus cerris* L. stands (Tedeschi et al. 2006, Zhao et al. 2016). In the coppiced *Quercus cerris* forest, the decrease in soil respiration was estimated at 24% for a 20-year-rotation period (Tedeschi et al. 2006). Additionally, these authors suggested that sensitivity of soil respiration to soil temperature decreased with stand age, or, more precisely, that soil temperature had stronger effect in young stands (Tedeschi et al. 2006). The study conducted in Serbia showed that a 4-year-old pedunculate oak (*Quercus robur* L.) stand had significantly higher soil CO_2 emission compared to a 70-year-old stand (Karaklić et al. 2024). The increased soil CO_2 emissions in younger stands can be attributed to a higher bacteria/fungi ratio, the active physiological processes of fine roots, and elevated soil temperatures. These factors lead to loss of soil carbon and increased CO_2 emission from the soil (Zhao et al. 2016).

However, Wiseman and Seiler (2004) noted that soil CO_2 emission increased with stand age in *Pinus taeda* plantations primarily due to the greater root biomass in older stands that respire. A study conducted in stands of four different age stands (8-, 17-, 27-, and 36-year-old stands) showed that soil respiration increased from younger to older stands. Furthermore, the increase in soil temperature was followed by an exponential increase in soil respiration (Yu et al. 2019). According to Gao et al. (2019), the highest values of soil respiration were recorded in a 49-year-old *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg. plantation, while the lowest values were recorded in a 12-year-old plantation. In *Pinus massoniana* plantations, the increase in soil CO_2 emission with stand age is explained by quality of soil carbon stock and volume of root biomass (Yu et al. 2019). The increased CO_2 emissions from the soil in mature forest stands can be attributed to the greater biomass of roots, higher amount of litterfall, and larger abundance of microorganisms compared to younger stands (Guo et al. 2016).

Unlike previous studies, stand age did not have a notable impact on soil respiration in *Larix gmelinii* var. *principis-rupprechtii* (Mayr) Pilg. (*L. principis-rupprechtii* Mayr) plantations (Ma et al. 2014).

THE IMPACT OF FOREST MANAGEMENT PRACTICES AND NUTRIENT ADDITION ON SOIL CO_2 EMISSION

Forest harvesting can significantly affect carbon storage, and this influence is related to soil type, species composition and time since harvest. Compared to mineral soil, carbon stored in forest floors is more susceptible to loss due to harvest (Nave et al. 2010). Unmanaged forests generally contain a larger amount of soil carbon, while the degradation of forests and their conversion to cropland lead to significant losses in carbon storage in the topsoil (Mayer et al. 2020). Site preparation for afforestation and reforestation can cause soil disturbance, particularly in the organic topsoil, leading to a decrease in soil carbon stock (Mayer et al. 2020). Burning and fire can cause significant losses of soil carbon stock, especially in the forest floor (Jonson et al. 1992).

Regeneration cutting and thinning in forests lead to notable changes in aboveground carbon stock, while their effects on soil CO_2 emissions vary (Peng et al. 2008). Some studies suggest that harvesting increases soil respiration (Lytle and Cronan 1998, He et al. 2018), while others indicate that harvesting causes a reduction in soil respiration (Striegl and Wickland 1998, Bautista et al. 2021). Additionally, there are studies where forest harvesting did not have an effect on soil CO_2 emission (Johnson and Curtis 2001, Pang et al. 2013). The authors provided different explanations for each scenario. The factors affecting variation in soil respiration include stand age, species composition and the length of time after harvest (Peng et al. 2008).

Fertilisation and thinning were carried out in a poplar (*Populus trichocarpa* Torr. et Gray ex Hook.) plantation. The study showed that fertilisation increased soil respiration, while soil respiration decreased with increasing thinning intensity (Jonsson et al. 2010). Although, all thinned trees were left on site following thinning, it was expected that heterotrophic respiration would increase. However, the decrease in autotrophic respiration had a greater effect than the anticipated increase in the heterotrophic component of soil respiration (Jonsson et al. 2010). The thinning generally leads to a decline in soil respiration. This was shown in a study conducted in two different plantations of *Quercus rotundifolia* Lam. (*Q. ilex* subsp. *ballota* (Desf.) Samp.) and *Pinus halepensis* Mill. in eastern Spain (Bautista et al. 2021). Similar results were obtained in *Pinus ponderosa* plantations (Tang et al. 2005). Soil respiration was measured before and after thinning, when 30% of the biomass was removed. Thinning significantly affected the decrease in soil respiration by 13%. This is likely related to root density affecting the autotrophic component of soil respiration (Tang et al. 2005). The influence of thinning on soil CO_2 emission directly depends on the effects of thinning, such as reduced plant biomass and decreased root respiration. Additionally, thinning results in an increase in plant residues, leading to an increase in the heterotrophic components of soil respiration (Bautista et al. 2021). The impact of thinning on soil respiration is complex, affecting changes in soil temperature, soil moisture, root respiration, microbial respiration and decomposition of dead plant residues. Changes in canopy coverage lead to changes in temperature and precipitation (Tang et al. 2005). Thinning indirectly affects microclimate conditions which can accelerate the decomposition of organic matter (Bautista et al. 2021).

Light thinning (20%), medium thinning (30%) and high thinning (40%) are conducted in pine (*Pinus tabuliformis*) plantations. Soil respiration increased with thinning intensity in these plantations. Soil respiration increased by 8–21% in thinned plantations compared to unthinned plantations (Cheng et al. 2014). After 6–8 years, high thinning (60%) reduced soil respiration, on average, by 24.56% in plantations of the same species (Yang et al. 2022). Fifteen years after thinning, soil respiration significantly increased with increasing thinning intensity, while soil carbon stock decreased in *Picea crassifolia* Kom. plantations (He et al. 2018). The negative effects of thinning in these plantations include reduced soil carbon storage and accelerated organic matter decomposition due to higher temperatures. Additionally, thinning led to a significant increase in bulk density and soil pH, while thinning decreased nitrogen and C/N ratio (He et al. 2018).

Soil respiration was measured in 50-year-old *Larix kaempferi* (Lam.) Carrière stands. After six months, the results showed that there were no differences in soil respiration between thinned and unthinned stands, while soil temperature was significantly higher in thinned stand (Masyagina et al. 2010). Similar results were obtained in thinned and unthinned plots within pine plantations (*Pinus tabuliformis* and *P. armandii* Franch.) (Pang et al. 2013).

The application of pesticides is necessary for the successful regeneration of pedunculate oak stands. During the regeneration of pedunculate oak, the experimental plots treated with pesticides showed a more pronounced increase in soil CO_2 emissions with rising soil moisture in the summer period compared to the control plot (Karaklić et al. 2023). The application of pesticides likely stimulated microbial activity, leading to an increase in soil CO_2 emissions (Araújo et al. 2003, Karaklić et al. 2023). Additionally, Karaklić et al. (2024) pointed out that an artificially regenerated stand of pedunculate oak had significantly higher values of soil CO_2 emissions compared to a natural middle-aged stand. Also, environmental variables such as soil moisture and temperature had different influence on soil respiration through various seasons within managed and unmanaged parts of the pedunculate oak forest (Galić et al. 2024).

Nitrogen addition significantly decreased soil respiration in 21-year-old *Larix gmelinii* var. *principis-rupprechtii* plantations (Sun et al. 2014). Soil respiration was reduced by 12.5% under a nitrogen treatment of 5 g N ha^{-1} (Sun et al. 2014), while a nitrogen treatment of 15 g N m^{-2} caused a 14% reduction in soil respiration within a mature tropical forest (Mo et al. 2008).

A low level of nitrogen addition can stimulate soil respiration, while high level can decrease it (Zhu et al. 2016, Zhou et al. 2019). Additionally, nitrogen addition in a subtropical secondary forest in China caused a reduction of both components of soil respiration (Zhang et al. 2021). Autotrophic and heterotrophic components of soil respiration exhibited different responses to nitrogen addition, with the autotrophic component decreasing more than the heterotrophic component in an alpine meadow on Gelic Cambisol (Wang et al. 2019). Three-year field experiment showed that soil respiration was stimulated by nitrogen fertilization during normal rainfall years. However, the results of this experiment also showed that nitrogen fertilisation did not have significant effect on soil respiration during a wet year, because extreme rainfall inhibited both components of soil respiration (Chen et al. 2017).

Phosphorus addition in a eucalyptus forest (*Eucalyptus pauciflora* Sieber ex Spreng.) caused an 8% reduction in soil respiration (Keith et al. 1997). The effect of phosphorus and nitrogen on soil respiration varies when added separately compared to when added in combination (Ren et al. 2016). Phosphorus addition had various effects on soil respiration in a subtropical secondary forest in China. However, the combined effect of nitrogen and phosphorus caused an increase in soil respiration (Zhang et al. 2021).

CONCLUSION

Soil CO_2 emission is crucial in the global carbon cycle, as it can reach up to two thirds of total ecosystem respiration in forest ecosystems. Soil temperature and moisture are the key factors driving soil CO_2 emissions, and their effects vary depending on factors such as soil cover, precipitation, radiation, season and climate zones. Models that combine both soil temperature and moisture are more effective in predicting soil CO_2 emission than models that use only soil temperature or moisture as independent variables. Drought usually increases soil CO_2 emission in hydric ecosystems, whereas in xeric and mesic ecosystems, drought can reduce emission. The effect of drought on the autotrophic and heterotrophic components of soil respiration can vary in different forest ecosystems.

Land-use change modifies the composition of plant species, vegetation structure, soil properties and microclimate. It can have a substantial effect on soil CO_2 emission. The conversion of forests to croplands leads to the disturbance of soil structure and induces mineralization of soil organic matter, resulting in the loss of carbon storage and an increase in soil CO_2 emission. The varying responses of soil CO_2 emissions under different tree species can be attributed to the varying contributions of autotrophic and heterotrophic components of soil respiration.

Studies indicate that soil CO_2 emission increases with stand age. The increased CO_2 emissions from the soil in older forest stands can be attributed to the greater biomass of roots that respire as well as a higher amount of litterfall and a larger abundance of microorganisms compared to younger stands. However, in some studies, a decrease in soil CO_2 emission with stand age is explained by a higher bacteria/fungi ratio, the active physiological processes of fine roots, and elevated soil temperatures.

Forest management practices can alter microclimatic conditions within a stand, leading to shifts in soil temperature and moisture that directly and significantly impact soil CO_2 emissions. Thinning can lead to a decline in soil CO_2 emission due to a decrease in the autotrophic component of soil respiration. However, some studies suggest that thinning may actually cause an increase in soil CO_2 emission, potentially due to accelerated organic matter decomposition resulting from higher temperatures.

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