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Soil Respiration and their Influencing Factors: A Review

Sonali Tiwari and Archana Meena
Department of Botany, University of Rajasthan, Jaipur-302004, India
*Correspondence for materials should be addressed to Sonali Tiwari (email: sona435768@gmail.com)

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Abstract
Soil is the accommodation for many microorganisms that play various functions in soil ecosystems, including organic matter decomposition, respiration, nutrient cycling, energy generation, growth and development and many more. Development and functioning of microbial communities are governed by the consumption of key nutrients that are available due to the result of nutrient cycles. These cycles play a crucial role in plant-soil metabolism via photosynthesis, enzyme production, energy conversion, soil respiration (SR), community growth and functioning. SR releases energy in terms of carbon efflux that is consumed at different levels in ecosystem functioning through various organisms and directly involved in the global carbon cycle. Seasonal shifts in different environmental factors such as soil temperature, soil moisture, physicochemical properties, enzyme activity and land use conversion create alterations in soil microbial activity and SR that consequently affect soil fertility and health. Therefore, the evaluation of SR provides useful insight into the soil status and productivity.

Keywords: Soil respiration; Microbial activity; Seasonal shift; Soil fertility; Global carbon cycle

Introduction

Soil is a basic component of the natural ecosystem, constituted by different layers where the top layer governs different metabolic activities of flora and fauna, residents of a variety of microbes, and their activity is involved in the degradation of soil organic matter (SOM) and the generation of energy by converting nutrients and trace elements that are required to effectively drive the biogeochemical cycles (Chen et al., 2018). Soil ecosystems have the highest carbon (C) flux due to the respiration of microbial activity that is responsible for the 98 Pg C emission per year in atmospheric environments (Yazdanpanah et al., 2016), creating crucial input of C in the terrestrial C cycle globally (Zhao et al., 2017). Soil CO_2 efflux is greatly influenced by a number of biotic and abiotic factors, such as soil temperature (ST), soil moisture (SM) (Jiang et al., 2020), availability of C substrate, soil microbial activity (SMA) (Bargali et al., 2018), global climate change, precipitation patterns, and human activity (land use conversion, farming, and deforestation), particularly in arid and semi-arid regions (Ahlstrom et al., 2015; Arredondo et al., 2017; Meena et al., 2020). The understanding of the mechanics of SR offers important insights for improving soil management techniques, encouraging sustainable agriculture, and guaranteeing the long-term health of ecosystems. This study's goal is to offer practical knowledge on SR and the many elements that affect its rate in order to achieve the highest possible level of soil fertility and quality.

Components of soil respiration

Soil respiration (SR) is a crucial phenomenon that involves two primary ingredients: the autotrophic respiration (RA), generated by below-ground components that have plant roots, and the rhizospheric portion, whereas the heterotrophic respiration (RH) is generated by soil microorganisms involved in the decomposition of SOM is account for the major portion (54%) in total respiration in forest ecosystems (Ryan and Law, 2005; Vargas et al., 2011). RA is greatly affected by ST and nitrogen content in plant tissues. Conversely, the ST, SM, respiratory enzyme activity, and substrate availability affect the RH rate. This establishes the interconnectedness of soil health, microbial activity, and nutrient cycling. SR is closely associated with byproducts of plant activity, litter decomposition and rhizosphere root activity (Fig. 1).

The production of CO_2 from these substrates is categorized into two vital types: basal respiration (BR) and substrate-induced respiration (SIR). SBR, which reflects the rate of respiration resulting from the mineralization of organic matter (OM), is commonly considered a crucial indication of soil quality (Creamer et al., 2013). This makes it an essential metric for evaluating soil health and productivity. Moreover, the availability of substrates not only elevates the respiration rate (SIR) but also reveals insights about population diversity and their function that are essential to the dynamics of ecosystems.

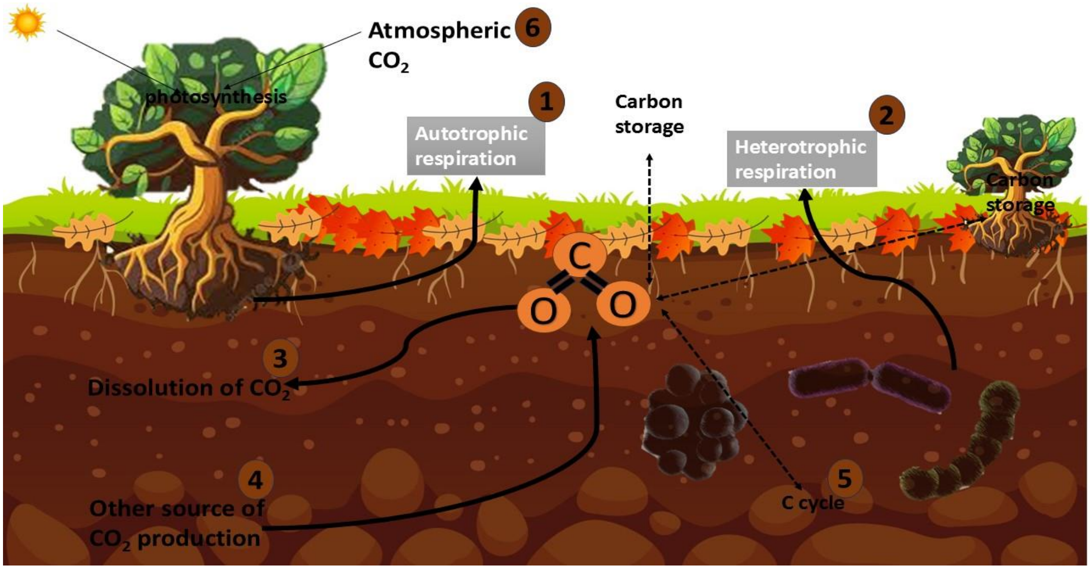

Figure 1. Components of soil respiration and its dynamics ([1]Autotrophic respiration (Yazdanpanah et al., 2016); [2]Heterotrophic respiration (Liu et al., 2016); [3]Dissolution of CO_2 (Lima et al., 2023); [4]Other sources of CO_2 production (Global Carbon Budget, 2023); [5]C cycle (Black et al., 2017); and [6]Atmospheric CO_2 (Global Carbon Budget, 2023).

Variation in soil respiration

The contribution of SR to the release of CO_2 between the atmosphere and the terrestrial environment is substantial. Consequently, changes in SR have a significant impact on the C cycle. Many variables contribute to variations in SR, which may be seen as variations in the rate of CO_2 emissions from soil to the atmosphere. SR fluctuates both spatially and temporally (Kosugi et al., 2007; Tomar and Baishya, 2020; Yu et al., 2021). Seasonal variations in SR have been reported in a number of international studies (Xue and Tang, 2017; Tian et al., 2019; Meena et al., 2020).

Factors affecting soil respiration

The irregular precipitation and extreme weather conditions create stress on soil microbiota, ST and SM, resulting in seasonal variation in SR (Xu et al., 2018; Tomar and Baishya, 2020), whereas land use patterns (Tomar and Baishya, 2020); bulk density (Dore et al., 2014); soil management activities, SC content, root biomass, microbial biomass (Jiang et al., 2020); and cultivation approaches create variation in SR spatially (Meena et al., 2020) (Fig. 2). Some factors that shaped these variations are the following:

Soil temperature: Extreme weather, vegetation, deforestation, landscape placements, and human activity are the causes of ST shifting (Licht and Al-Kaisi, 2005). These changes also affect the composition of the microbial community that determines the responsiveness of SR to temperature changes, also dependent on SM conditions. According to Meyer et al. (2018), agriculture is less responsive to ST than forest soil. Prior research has employed several models, such as logistics (Schlentner and Van Cleve, 1985) and linear and quadratic correlations (Holthausen and Caldwell, 1980), to offer important insights into the link between ST and SR.

Soil moisture: According to Zhang et al. (2013) and Lima et al. (2023), SM is in charge of the diffusion of CO_2 and soluble substrate by creating porous soil and controlling rhizospheric microbial activity, which in turn affects soil CO_2 levels. Due to the inhibition of microbial functioning, low SM levels can impede SR (Yuste et al., 2007), whereas in another study by Lai et al. (2013), reported an increase in SM increased the SR. Although too much SM might cause waterlogging, decrease soil porosity, and limit the amount of CO_2 that is released (Davidson et al., 2000).

Precipitation: Precipitation affects the SR rate in addition to ST and SM (Bolat et al., 2015). According to statistics, precipitation has decreased in frequency and increased in intensity in recent decades. Rainfall events have an impact on soil when it is already at its ideal moisture level, and plant microbial activity influences SC emissions. Understanding the mechanism of rainfall events on soil C efflux aids in the prediction of SC dynamics, as the influence of precipitation on SR estimates in terrestrial ecosystems is ambiguous (Guan et al., 2023; Han et al., 2024).

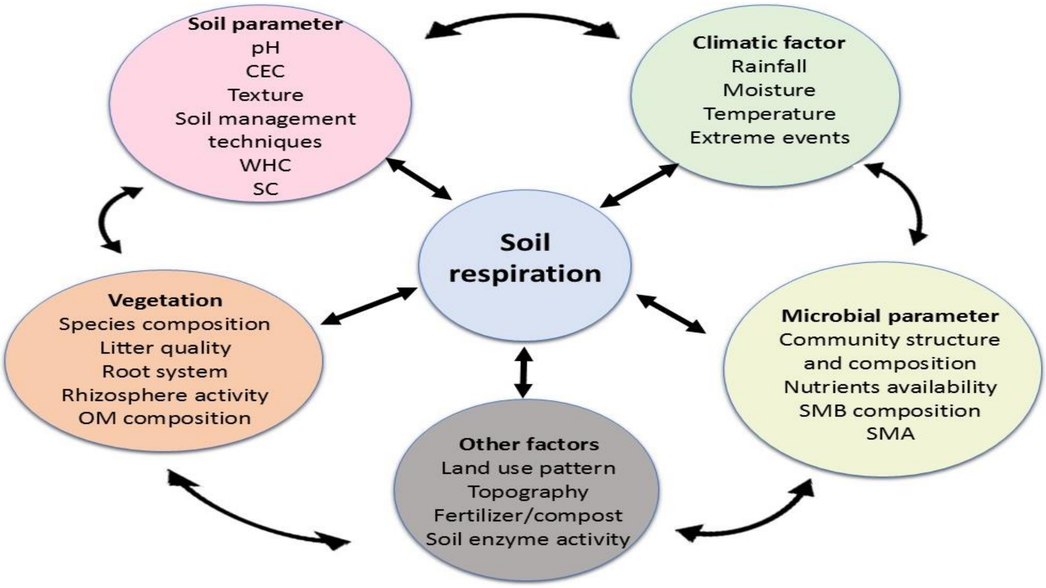

Figure 2. Factors responsible for variation in soil respiration

Soil physicochemical activity: SR has been identified as one of the major soil health indicators. Soil pH and cation exchange capacity (CEC), bulk density, and C:N ratio affect the SR (Pinto et al., 2018; Bao et al., 2019). However, Jong et al. (1974) reported decreased respiration due to mineral nitrogen addition, whereas it increased with MWD, EC, pH, K and P but decreased with silt content.

SOM composition: The microbial composition (Vargas et al., 2011), photosynthetic metabolism (Zhang et al., 2013), and the use of organic amendments like manure and compost (Guan et al., 2023) all have an impact on soil productivity, which influence SR rates. According to Matyas et al. (2018), applying additional OM to the field under an organic farming method increased SR in both organic and conventional soils.

Climate variation: Climate change significantly impacts SR, a critical process in the C cycle, by altering temperature and precipitation patterns. These modifications impact microbial activity and SOM dynamics, which in turn impact the rate at which CO_2 is emitted from soils. Factors including ST, SM, and plant traits affected seasonal changes in SR, underscoring the intricate relationship between climate change and SR in semi-arid areas (Wang et al., 2023; Li et al., 2023).

Vegetation: Vegetation influences SR by changing the microclimate of the soil, the amount and quality of litter, and the respiration rates of the roots. According to Raich and Tufekcioglu (2000), coniferous forests have lower respiration rates than broad-leaved forests, but grasslands might have greater respiration rates than forests. The significance of vegetation in soil health and respiration dynamics is highlighted by another study that found that grasslands had higher rates than non-native pine plantations (Joshi et al., 2024). This suggests that vegetation type can have a significant impact on SR under certain conditions (Vargas et al., 2008).

Litter input: The amount and community structure of soil microorganisms are impacted by litter input, which in turn impacts the SR (Wu et al., 2017). On the other hand, the process by which litter inputs affect SR is quite intricate. Most research has indicated that litter inputs considerably enhanced SR (Zimmermann et al., 2009; Pinto et al., 2018), whereas a small number have observed a decrease in SR (Fekete et al., 2014).

Soil microbes: Semi-natural environments such as forests and grasslands have higher populations of soil microbes. Important factors influencing microbial diversity include crop management techniques (Romdhane et al., 2022), soil depth (Piotrowska-Długosz et al., 2022), and land-use conversion. They have a seasonal effect on microbial diversity, Soil Microbial Biomass Carbon (SMBC), enzyme activities, and SR, with increases in the monsoon season and lows in the winter in semi-arid countries like India, where variations in precipitation subsequently lead to changes in ST and SM (Bolat et al., 2015; Tomar and Baishya, 2020) that also impact SMA and SR.

Enzyme activity: Enzymes are involved in the breakdown of OM, may be utilized as a gauge of microbial activity (Boerner et al., 2005). Its effects vary depending on the substrate's availability, microbial diversity, and temperature. Enzymes have been shown to correlate with SR in earlier research. These include β-glucosidase (Daunoras et al., 2024), alkaline phosphatase activity (Zhao et al., 2018), catalase, saccharase, urease, dehydrogenase, and phenol oxidase (Tomar and Baishya, 2020).

Table 1. Soil respiration and major influencing factors in different land use in various Indian literature

S. No	Major influencing factor	Land use pattern	Duration of study	Results	Seasonal pattern	Study area	References
1.	SC, SM, MBC	Moist sandy flat (MSF), uncultivated sandy land (USL) and cultivated sandy land (CSL) along the river Ganga across the Varanasi stretch.	December–January (peak of winter) 2014–15	CSL > USL > MSF	The dry season has the greatest CO_2 efflux.	Varanasi, Uttar Pradesh	Singh et al., 2017
2.	ST	Pichavaram mangrove forest	February 2016 to October 2016	Surface soil CO_2 concentration ranged from 375 to 532 ppm.	CO_2 efflux was highest during the pre-monsoon, whereas it was low during the monsoon.	Southeast coast of India	Gnanamoorthy et al., 2019
3.	ST, SM and evaporation of soil	Natural evergreen forest of Kempt watershed, Mussoorie with 3 different elevation points (1700, 1800 and 1900m)		Maximum 1800 m altitude.	SR is maximum in the rainy season and lowest in winter.	Himalayan moist temperate forests	Kumar et al., 2020
4.	ST and SM	Different ridges of Delhi	Pre-monsoon, post-monsoon and winter		SR was highest in monsoon and lowest in winter.	NCT of Delhi	Tomar and Baishya (2020)
5.	SM	MFC (mixed forest cover), AF (agriculture field), VF (vegetable field), PFC (*Prosopis juliflora* (Sw.) DC-dominated forest cover)	Monthly	MFC > PFC > AF > VF	SR was highest in the monsoon and lowest in summer (PFC, MFC, and AF); in VF, it was high in summer and low in winter.	Semi-arid area of Delhi	Meena et al., 2020
6.	ST, SM, biotic and abiotic factors	Chajing Lakpa, Chaning Lairembi, Kalika Lairembi, Ibudhou Loiyalakpa, Panam Ningthou and Nongpok Ningthou.	Monthly for 2 (April 2012-March 2014)	The maximum SR in Panam Ningthou is 950.97±41.15; ST is the most influencing factor for SR.	SR was maximum in different months of the rainy season in most of the study areas and decreased in winter.	Manipur	Sanjita et al., 2022
7.	Kinds of forest, season	Chir pine (CP), Banj oak (BO), and banj oak regenerated (BOR) forest		The SR was higher in BO and BOR than that of the CP forest in the rainy season.	CO_2 efflux was significantly higher during the precipitation than in winter and summer.	Kumaun hill region, central Himalayan Forest	Kumar et al., 2023
8.	ST, AT and altitude.	Temperate Forests of the Western Himalayan region		SR varied under different subtypes and species types of the Himalayan temperate forests.	The SR was the maximum among the major tree species of the Western Mixed Coniferous Forest.	Uttarakhand and Himachal Pradesh	Pandey et al., 2023
9.	ST and SM	Dry deciduous teak forest (DDTF), dry deciduous mixed forest (DDMF) and Boswellia forest		July has the highest SR among all the forest sites. January minimum DDMF has the highest SR.	SR was high in the monsoon and summer and lowest in winter.	Sagar, Madhya Pradesh, Vindhyan range	Dar et al., 2023

SM- soil moisture, MBC- microbial biomass carbon, ST- soil temperature, SR- soil respiration, AT- air temperature, SC- soil carbon

Soil carbon: SC has a significant impact on SR, an essential process in the global C cycle. SC serves as a substrate for microorganisms and plant roots, which metabolize them and exhale CO_2. As SC increases, respiration rates rise, which can affect atmospheric CO_2 levels and the global C cycle. Root and rhizospheric activity, SOM composition, and SMBC all affect the SR rate and SC content (Kotroczo et al., 2023; Ghorbani et al., 2023).

Soil management activities: Soil management significantly influences SR by altering microbial activity and C pools. Effective management practices can enhance respiration rates, while poor practices may block them, ultimately affecting the SC cycle and its response to climatic changes. When compared to forest soils, agricultural methods including tillage, varying plant density, and row spacing raise CO_2 emissions, underscoring the effect of land use on SR rates and C dynamics (Vasquez et al., 2013; Lewczuk et al., 2023).

Fertilizer application: Generally, fertilization would affect SR and its components via altering the soil physicochemical and biological factors, while the effects of fertilization on SR components largely depended on the fertilizer type and dose, plant species, soil quality, and local environmental conditions (Yang et al., 2017; Zhang et al., 2021). Long-term fertilization in semi-arid areas has changed the structure of bacterial communities and the amounts of SC and SN, which has led to an increase in CO_2 emissions (Wang et al., 2022).

Land use conversion: SR varies significantly with changes in land use (Xue and Tang, 2017). Several factors are responsible for this variation, including soil microclimate condition (Liu et al., 2016), land use conversion duration (Wang et al., 2015), and biotic and abiotic factors (Zhang et al., 2015). Changes in land use also affect soil C flow, which is thought to be the second-largest contributor of CO_2 emissions caused by human activity and accounts for almost 25% of worldwide CO_2 emissions. For example, between 1850 and 1990, changes in land usage resulted in an emission of around 123 Pg C into the ambient air (IPCC, 1990). These land-use changes impact positively as well as negatively on SR, as some studies reported increases in SR (Zhang et al., 2015), while others disclose a drop-in SR rate (Liu et al., 2016; Xue and Tang, 2017). However, changes from one land use to another, such as cropland to orchards, grasslands, and woodlands, lead to vegetation restoration, enhance SC and root biomass, and also affect the SR (Zhang et al., 2015). Higher SR ratios are seen in forest land use because of microbial biomass and certain soil characteristics high in natural ecosystems (Kumar et al., 2023). Forests in India's semi-arid regions promote more soil nutrient cycling and microbial activity than cultivated areas, which suffer from lower SC, N, and BR as a result of intensive land-use management techniques (Meena and Rao, 2021). Accordingly, topography and landscape have an impact on any land use modifications, and these elements also affect the spatial distribution of SR (Tian et al., 2019). Table 1 represents the soil respiration and major influencing factors in different land uses in the Indian context.

Conclusion

Continuing to investigate the complex relationships between soil respiration (SR) and the factors that influence it is essential for enhancing our understanding and management of soil health and ecosystem sustainability. This is particularly vital in semi-arid ecosystems, where unpredictable precipitation patterns significantly impact carbon (C) flux. Thus, conducting annual SR measurements in these regions is not just beneficial; it is crucial. Soil SR serves as a powerful indicator of soil health and productivity within terrestrial ecosystems. Its direct influence on atmospheric CO_2 levels highlights its pivotal role in the global carbon cycle and storage. The variability of SR is profound, fluctuating significantly throughout the seasons and across diverse landscapes. This fluctuation is shaped by several critical factors, including soil temperature, soil moisture, vegetation composition, climate variability, topographical features, and land use changes. Furthermore, key environmental and soil characteristics—such as precipitation patterns, water availability, soil organic matter, soil pH, and cation exchange capacity play influential roles in determining SR. This comprehensive literature review provides a deep understanding of SR and the factors that influence it. It emphasizes the strong connections between the metabolic and microbial activities of both soil and plants, which vary seasonally and spatially, resulting in changes to soil fertility and productivity. Such studies are essential for developing effective strategies for sustainable land and soil management practices, promoting healthier and more productive soils, and balancing carbon efflux between the atmosphere and terrestrial ecosystems.

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