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Soil Respiration and Climate Change

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Introduction

Soil respiration is the release of carbon dioxide (CO_2) gas from oxygen-consuming soil microorganisms and plant roots. The soil respiration rate is often measured and quantified as the rate (i.e., amount per unit area per unit time) of CO_2 that leaves the soil surface to the atmosphere (i.e., efflux, or simply CO_2 flux). The soil respiration rate depends on several environmental factors, such as soil temperature, soil water content and the amount of readily available, C-containing organic material.

The soil surface CO_2 flux is affected by both soil respiration processes and the CO_2 transport within the soil profile to the soil surface. Carbon dioxide transport in the soil profile is highly correlated to soil texture (i.e., mixture of sand, silt and clay present), bulk density and porosity. Disturbances such as rainfall, irrigation events or in-field management practices (particularly tillage) can increase soil respiration for a period before reverting to a lower, more constant respiration rate.

While CO_2 can be produced from the dissolution of inorganic carbonate (CO_3^{2-})-containing rocks during weathering processes, CO_2 release from carbonate weathering is not considered part of the soil respiration process. Due to the generally humid and moist conditions of Arkansas soils, nearly all inorganic C within the soil profile has been leached out of the soil profile and does not typically contribute to the soil surface CO_2 flux or soil respiration.

Soil respiration is a key process in the terrestrial C cycle and provides a mechanism that contributes to soil C storage and climate-change mitigation. Soil respiration also plays a significant role in nutrient cycling and management, and thus is also a key component of soil health. Consequently, it is important to quantify and understand the spatial and temporal trends, variations and controlling factors of soil surface CO_2 fluxes across various ecosystems and scales (Figure 1; Crookston et al., 2023; Brye et al., 2016). Ongoing studies in the Lower Mississippi River Valley aim to evaluate respiration processes in various crop systems under different management practices.

The Carbon Cycle

The carbon cycle begins with the fixation of atmospheric CO_2 by plants to convert the gas into organic C as plant biomass.

Figure 1. Quantifying soil respiration using absorption spectroscopy equipment in a soybean field near Dumas, AR. Picture taken in 2024.

Some of the fixed organic C is used to grow plant tissues, while a portion is used for metabolic reactions that release energy and CO_2 back into the atmosphere, a process known as plant respiration. Similar metabolic processes occur in the soil microbial biomass that release CO_2 during aerobic respiration. Divided into aboveground (i.e., stems and leaves) and belowground (i.e., roots) respiration, plant respiration is classified as autotrophic, or having the ability to make one's own food, while microbial respiration is defined as heterotrophic, or only being able to use organic materials as a food source. Soil respiration is the sum of the autotrophic belowground and the heterotrophic microbial respiration. Soil respiration and aboveground respiration combined represent ecosystem respiration.

In agricultural settings, the contribution of soil respiration to ecosystem respiration varies during the year, fluctuating from almost 100 percent during winter months when the crop is not planted or slowly growing to ~ 60 percent during the growing season (Curtis et al., 2005). Therefore, soil respiration plays a fundamental role in an ecosystem's total primary production, which is defined as the annual total amount of C removed from the atmosphere via photosynthesis. Subtracting soil respiration from total primary production will estimate net ecosystem production. Released C from dead microbial and plant biomass can get assimilated into the soil as soil organic matter (SOM).

Environmental Factors Affecting Soil Respiration

Soil OM is generally composed of ~ 50 percent organic C, along with other elements such as nitrogen (N), sulfur (S), and phosphorus (P). Therefore, SOM is a natural source of soil fertility, suppling nutrients for plants, contributing to the soil's cation exchange capacity and promoting soil structure formation (Coleman et al., 2004). Decomposition of SOM by microbes releases nutrients via mineralization, which are subsequently consumed or immobilized by microbes that release CO_2 as a byproduct.

Climatic conditions, specifically air temperature and precipitation, regulate the rate of SOM accumulation or decomposition and the inputs and outputs to the soil organic C (SOC) pool (Six et al., 2000). At local or regional scales, factors like soil temperature, moisture, oxygen concentration, soil texture, pH and substrate supply influence soil respiration. The relationship between temperature and biochemical processes follows an exponential relationship, where a steady increase occurs in low- to mid-range temperatures and reaches a plateau around 45ºC or 113 ºF (Laidler, 1972).

In agricultural settings, soil respiration rates are determined by the aboveground demand for carbohydrates. This demand is dictated by crop type and by carbohydrate supply, which is regulated by environmental conditions, particularly soil moisture. Typically, soil respiration increases up to approximately 60 percent water-filled pore space, after which soil respiration declines as soil moisture content continues to increase towards saturation.

Thus, the greatest aerobic decomposition rate, hence soil respiration rate, is often around field-moisture capacity or ~ 30 percent volumetric water content (Figure 2). Soil texture affects porosity and soil water-holding capacity, thus soil texture also affects gas diffusion in the soil. Fine-textured soils (i.e., clayey soils) tend to slowly release soil moisture, buffering the effect of soil moisture on soil respiration. Coarse-textured soils (i.e., sandy soils) tend to have lower fertility, unsaturated hydraulic conductivity, and water-holing capacity than fine-textured soils often resulting in reduced capacity for CO_2

Figure 2. Example of visible difference between a saturated soil (left) and the same soil at field capacity (right). Images are depicting the same Dewitt silt-loam soil (Typic Albaqualf) under different water management regimes.

production and release. Soil respiration reaches a maximum rate when pH is around 7 and tends to decrease when soil pH deviates lower or higher from neutral conditions.

Soil respiration in different regions showed a constant decomposition rate decrease with increased latitude, consequently a decrease in air temperature. Organic matter decomposition rates and soil respiration commonly increase by a factor of 1.6 to 2 for every 10oC or 50ºF increase in soil temperature from a base temperature (IPCC, 2018). The numerous abiotic factors that affect CO_2 production and release are not independent, but rather simultaneously interact to influence soil surface CO_2 fluxes from specific environmental conditions (Motschenbacher et al., 2015). The influence that plants and microbes have on the factors regulating soil respiration creates a complex set of direct and indirect effects that result in widely ranging soil respiration rates, even within an ecosystem type.

Agricultural soils are considered a substantial source of CO_2 to the atmosphere, contributing ~ 1 percent to global net CO_2 emissions (OECD, 2000). However, soils are also potential sinks for atmospheric CO_2, highlighting the importance of management practices as possible controlling factors that can alter CO_2 emissions, the C cycle in general, and source/sink balance (Li et al., 2010; Jensen et al., 1996). Agricultural practices can increase or decrease the amount of organic substrate in the soil and influence SOM decomposition, thus affecting CO_2 production and soil respiration (IPCC, 2018).

Management Practices Affecting Soil Respiration

Tillage, cover crops, plant cultivar, water regime, and fertilizer application have been shown to affect SOM decomposition and soil respiration. Consequently, a wide range of soil surface CO_2 fluxes have been reported because of the various field management practices that affect soil respiration (Motschenbacher et al., 2015). Soil disturbance related to tillage activities commonly increases surface roughness, reducing soil structure and creating more large voids that can intensify soil surface CO_2 fluxes (Wang et al., 2020; Ball et al., 1999). Loose, porous, recently tilled soil allows full infiltration of air into the plow layer, facilitating SOC mineralization and soil respiration.

The input of organic matter from crop residues, litter, roots and organism secretions can directly and indirectly affect soil respiration. The presence of residues on the soil surface reduces evaporation and contributes to maintaining greater soil moisture contents, which tend to enhance soil respiration and CO_2 emissions. Water-saving practices in rice, such as mid-season drainage, alternate wetting and dry and furrow irrigation (Figure 3), create more aerobic conditions in the soil than other irrigation

Figure 3. Furrow-irrigated rice at the Rice Research Extension Center near Stuttgart, AR. Pictures taken in 2018.

practices in rice, promoting SOM decomposition and soil respiration, consequently affecting the soil's net ecosystem exchange.

Nitrogen fertilization enhances plant biomass as well as microbial and soil processes. Commonly, soil respiration increases with increased fertilizer-N rate; however, a plateau is often reached when crop demand is exceeded. The positive effect of fertilizer-N additions on soil respiration is likely to continue until there is abundant availability of C substrates. If external C inputs cannot compensate for C losses due to the enhanced soil respiration following fertilizer-N additions, the C-limited status of the soil becomes a controlling factor that will inhibit CO_2 production even when further N is added.

Soil Respiration and Climate Change

Carbon dioxide emissions from soil to the atmosphere can be considered an indicator of the soil ecosystem's productivity status because CO_2 fluxes are correlated to the organic material microbes and plants have access to (Paustian et al., 2000). In stable environmental conditions, soil respiration follows plant growth stage, with lower respiration rates during earlier growth stages and greater rates with the progress of vegetative growth.

Due to the predominant roles of soil temperature and moisture in regulating ranges and trends of soil respiration, changes in rainfall patterns and the rise of diurnal and nocturnal temperatures related to climate change and the greenhouse effect will likely disrupt soil respiration processes, creating variable environmental conditions and soil responses. Extreme rainfall events and prolonged drought periods will force soil respiration to deviate from stable conditions, creating scenarios in which soil-C loss can be accentuated in short periods.

Understanding the role of climatic and environmental parameters on soil respiration and C cycling can facilitate the development of appropriate and specific management practices targeted to minimize soil-C losses. In turn, this will avoid the reduction of agricultural or biomass production to prevent disruption of ecosystem services in natural environments and maintain agricultural sustainability in managed lands.

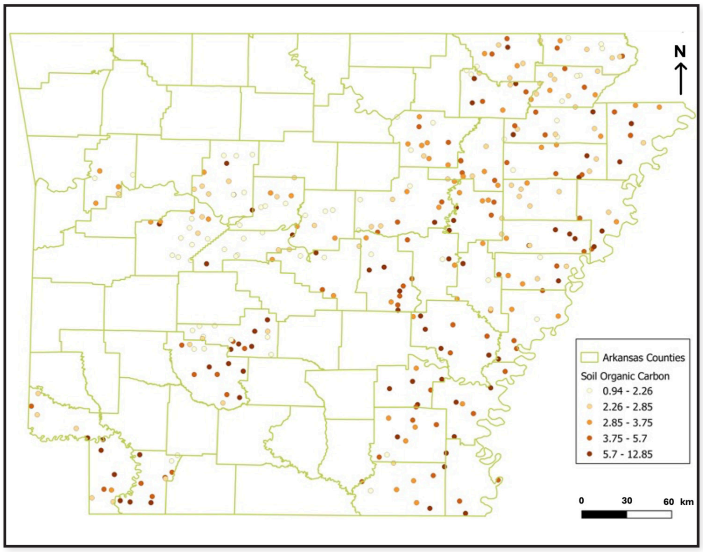
Soil Respiration and Climate-change Mitigation

Agricultural practices can reduce or increase the amount of organic substrate present in the soil and influence the capacity of the soil to accumulate or reduce SOM, consequently affecting soil respiration and therefore CO_2 production and emissions. Soil OM is a useful soil metric to predict soil respiration (Brye and Riley, 2009). In agricultural settings, it is difficult to isolate single process and components of soil respiration, consequently creating a challenge in developing management practices that can effectively reduce CO_2 emissions. However, soil respiration is still a crucial environmental indicator to understand and assess.

Practices that reduce or limit wide and sudden fluctuations in environmental parameters, such as soil temperature and soil moisture, can help maintain stable soil respiration rates. A stable, regular and uniform respiration rate is an indicator of a healthy and productive ecosystem. Reduced tillage and cover crops help control O_2 diffusion and temperature fluctuations, respectively, at the soil surface, keeping soil respiration rates stable to limit soil-C losses (Della Lunga et al., 2023; Brye et al., 2023). Addition of organic amendments, such as biochar or poultry litter, can provide C inputs to replenish the amount of substrate lost through soil erosion and soil respiration, helping to maintain a fertile and resilient soil (Smith et al., 2010).

Without mitigation practices aimed to control CO_2 fluxes in agricultural settings, global soil respiration rates have been projected to increase to 11 x 107 Mg C per year, which will continue to contribute to the greenhouse effect and air temperature rise. Mitigation strategies that control soil respiration rates and direct C back into the soil (i.e., soil C sequestration) will not only enhance soil fertility, but also alleviate the pressure of climate change on agricultural activities. Many soils throughout Arkansas, paired with the appropriate management, likely have a larger soil C sequestration potential compared to soils in the upper Midwest due to lower initial soil C concentrations (Figure 4; Aragon et al., 2024).

Figure 4. Soil organic carbon data in the top 10 cm (4 inches) across Arkansas in 2023. Data were obtained from Web Soil Survey (www.websoilsurvey.sc.egov.usda.gov). Units of the legends are in percentage (%).



Summary

All ecosystems show some degree of seasonal variation in soil respiration, with greater soil respiration during summer and lower rates during winter. Interannual climatic variability and disturbances from agricultural practices affect plant physiological and microbial response to the factors regulating soil respiration. Recommended management practices, such as reduced tillage, crop rotation, cover crops and inorganic and organic soil amendments can reduce CO_2 emissions in the long-term and increase soil C sequestration in agricultural soils.

Management practices that lead to a healthy pedosphere, such as climate-smart practices, can result in a temporary increase in CO_2 production mostly due to the enhanced microbial activity and a greater degree of nutrient cycling compared to more traditional management practices. When the total C lost through soil respiration and the C accumulated through plant and microbial fixation/immobilization equilibrate over the course of several years, climate-smart/conservation practices can achieve net C sequestration in the soil profile and improved soil health.

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