
SOUTHERN
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An Introduction to Fire and Soil Carbon

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IMPORTANCE OF SOIL CARBON

Historically, the interest in fire effects on soil carbon was focused on soil organic matter because of its importance to nutrient retention and overall soil health. Soil organic matter contains organic compounds that can be mineralized and released through decomposition into nutrients for plants. It also provides substrates that hold nutrients and slow down their leaching and loss from the plant root zone. Additionally, it influences soil hydrology, serving to retain moisture when wet and, in some cases, repel moisture when dry.

In recent years, the interest in soil carbon has shifted to the potential for sequestration and storage of carbon to mitigate the effects of climate change driven by emissions from fossil fuels. About 55% of the extra carbon dioxide (CO_2) produced by humans has been re-absorbed by the ocean, plants, and the soil, which serve as sinks (repositories) of carbon fixed through photosynthesis by plants and green algae. Soil carbon originates from many sources, including death of root tissue, root exudates (chemicals exuded for defense against pathogens), soil microorganisms, and introduction of dead plant and animal material to the soil surface. In the southeastern U.S., soils contain at least three times more organic carbon than the atmosphere or terrestrial plants (Schmidt et al. 2011), making it an important sink for global carbon. Soil carbon is important because it is a more stable sink than carbon in vegetation, which is subject to sudden losses to wildfire, harvest for food or short-lived wood products, land clearing, slash or stubble burning, and herbivory, which release CO_2 back into the atmosphere (Stainback and Alavalapati 2008). Even so, some carbon is continually re-emitted into the atmosphere through respiration by fungi and bacteria as they decompose organic matter as well as through combustion during fires.

Combustion by fire converts organic matter and living biomass primarily into carbon dioxide as well as other carbon-based compounds and minerals (Figure 1). However, between periodic fires, carbon dioxide is re-sequestered into the re-growing vegetation through photosynthesis, typically resulting in no net change in atmospheric CO_2 if the ecosystem is not greatly altered by fire exclusion, unnaturally severe fire, or other land use changes. In the case of mineral soils in the South, individual fires are rarely severe enough to have a strong direct effect on soil carbon. Rather, it is the effect of fire regime, which influences ecosystem structure and function over time, that has the most important long-term effects on soil carbon sequestration or loss.

DURATION OF SOIL CARBON STORAGE

Different components of soil carbon move through the carbon cycle at different rates. These carbon components have been classified as transient, temporary, and persistent. Transient carbon, including starches and cellulose, decomposes quickly, resulting in turnover of organic carbon into CO_2 on the time scale of around 2-8 weeks, depending on the chemistry of the organic matter and decomposers present in the soil. Temporary carbon, such as dead roots and fungal hyphae, remains in soils between 2-12 months.

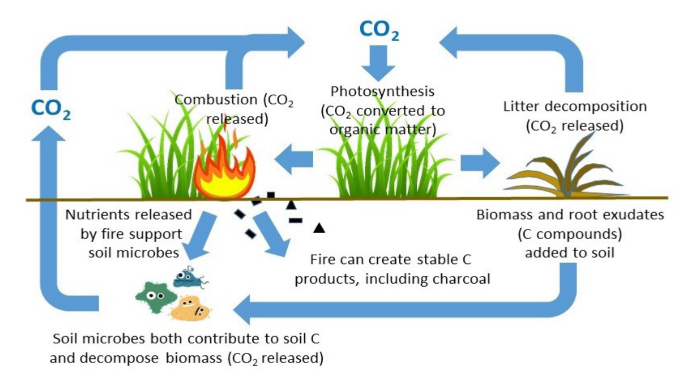

Figure 1. Carbon cycle-Carbon dioxide (CO_2) is released through fire (combustion) and decomposition and then absorbed again by growing vegetation. Fire also influences soil carbon in many direct and indirect ways.

Persistent carbon produced by heating, including pyrogenic carbon or black carbon, can remain for a year to thousands of years. This black carbon has been seen to enhance cation exchange capacity in some southeastern forest soils (Liang et al. 2008). The amount of black carbon found in the soil varies greatly among soils studied but is typically less than a third of the total carbon (Masiello 2004, Hsieh and Bugna 2008).

DIRECT EFFECTS OF FIRE ON SOIL CARBON

Fire can directly influence soil carbon in several ways. First, soil organic matter and living biomass (e.g. duff, roots, soil organisms) can be consumed through combustion (Dixon and Robertson 2018). Heat from smoldering combustion of organic soil may combust some of the organic matter in the underlying mineral soil. The destruction of organic matter and microbial communities can indirectly affect soil carbon by slowing down decomposition rates of remaining organic material, reducing nutrient availability, and reducing plant productivity through damage to mycorrhizal networks (Cerligione et al. 1988).

FIRE EFFECTS ON SOIL CARBON IN SOUTHERN U.S. COMMUNITIES

In southeastern U.S. pine communities, the effects of frequent burning (1-3 year fire return intervals mimicking historical conditions) are typically slight and often positive with regard to total soil carbon (Heyward and Barnette 1934, Greene 1935, Wells 1971, McKee 1982, Godwin et al. 2017) (see Figure 2). Current evidence suggests stable or increased levels of soil carbon under frequent burning are a result of decreased rates of turnover (decomposition) of soil organic matter in the soil, which tips the balance toward soil carbon accumulation instead of loss. Slower turnover rates in burned versus unburned old-field pinelands has been indicated by isotope analysis (Hsieh et al. unpublished data) and suggested by lower CO$_2$ emissions from soils of burned areas (Godwin et al. 2017). Higher levels of soil C in burned versus unburned areas also have been found in pine communities outside of the region, including southwestern U.S. ponderosa pine woodland (Neary 2003), New Jersey pitch pine barrens (Burns 1952), and maritime pine (*P. pinaster*) woodlands of the Iberian peninsula (Mayor et al. 2016). The mechanisms by which periodic fire reduces decomposition rates are not yet known, but they could include one or more of the following: direct effects on microbes, effects on plant species composition, and increased stability of organic matter introduced into the soil.

FIRE EFFECTS ON MICROBES

Fire can have differential impacts on soil microbial activity which can influence the decomposition of soil organic matter. Fire can negatively impact soil microbial activity through heating and it can also positively impact soil microbial activity through the release of previously unavailable minerals and favorable changes to the microbe environment such as increased temperature or moisture. In the case of mineral soils, microbe death is usually associated with combustion of coarse fuels releasing heat over a long period of time, which can heat and even sterilize the soil. In the case of organic soils, microbes can be killed directly through soil consumption in addition to heating. In either case, decomposition can be reduced during the recovery period (Godwin et al. 2017). Fire also changes soil chemistry, including nutrients, which can alter the activity of soil microbes. Soil bulk density often increases with the occurrence of fire, attributed to char and ash filling the micro-pore space, which decreases oxygen availability and microbial activity (Neary et al. 1999).

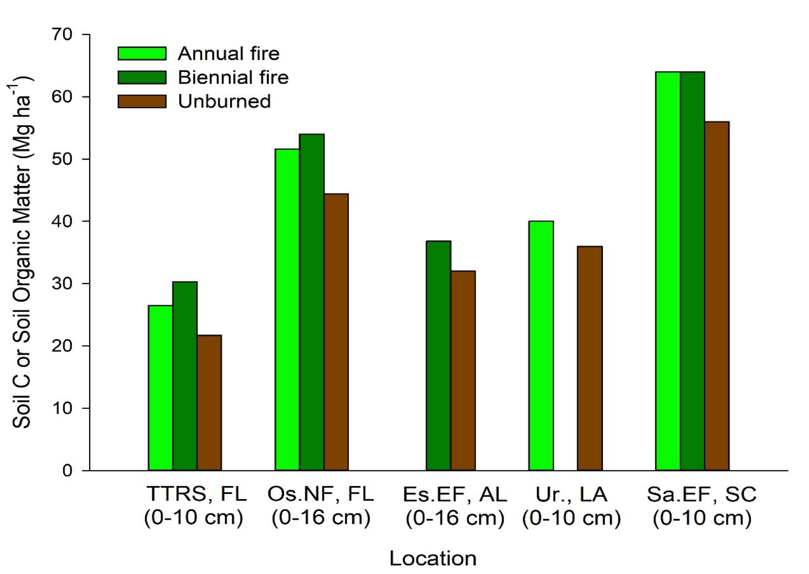

Figure 2. Total soil C (TTRS, FL) or soil organic matter (other locations) per unit area recorded after 12 or more years of annual or biennial burning or fire exclusion (unburned), with depth of soil sampling indicated. Sites and soil orders were Tall Timbers Research Station near Tallahassee, FL (TTRS), Ultisols; Osceola National Forest, FL (Os.NF), Spodosols; Escambia Experimental Forest, Brewton, AL (Es.EF), Ultisols; Urania, LA (Ur.), Ultisols; Santee Experimental Forest, Charleston, SC (Sa.EF), moist Ultisols. Results are from Godwin et al. (2017) and McKee et al. (1982).

Fire typically releases a pulse of mineral nutrients (e.g., Ca, P, Mg, K) which might be expected to increase microbial activity, but N is less predictable (Christensen 1977) and may decrease following fires. Preliminary research in longleaf pine communities also suggests that fire and time since fire influences the composition of soil fungi and bacteria (Sikes et al. unpublished data). Fungal composition and environmental conditions can influence microbial carbon use efficiency, which describes how much biomass digested by microbes is converted to microbial biomass and exudates as opposed to being released as CO_2 (Manzoni et al. 2012).

CHANGES IN PLANT SPECIES COMPOSITION

Fire regime has strong effects on species composition and associated soil carbon dynamics. Frequent fire typically promotes dominance by C4 grasses, forbs, and fire-tolerant trees (often conifers) and prevents dominance by broad-leaved woody plants and vines (Bond and Keeley 2005). While grasslands average 20% higher soil respiration than forest stands on similar soils (Raich and Tufekcioglu 2000), C4 grasses typically decompose more slowly than C3 plants (Martin et al. 1990), which may contribute to carbon accumulation. Additionally, conifer forests have 10% lower soil respiration rates than broad-leaved forests of the same soil type (Raich and Tufekcioglu 2000; Yuste et al. 2005). Grasses have abundant fine roots and higher rates of root turnover, a major contributor to soil carbon. Fine roots (2 mm or less in diameter), which account for more than 30% of global total net primary production (Jackson et al 1997), are short-lived, replacing themselves up to three times per year (West et al. 2004), so they contribute a great deal of organic matter to the soil.

Fine roots also influence soil carbon through their bacterial and fungal symbionts. While microbial activity generally promotes decomposition (Schmidt et al 2011), ectomycorrhizal fungi may slow the decomposition of roots (Langley et al 2006) and lengthen the period of organic matter retention. Mineralized soil carbon was found to be significantly higher under C4 bunchgrasses than adjacent locations in southeastern pine savannas, suggesting both additions from root turnover and increased microbial activity (West and Donavan 2004). It follows that in southern pinelands, soil carbon sequestration likely depends on management that promotes grasses and other herbs, specifically frequent fire and timber management that maintains an open canopy. Some research has found replacement of grasslands with dense pine forest results in decreased soil carbon. In longleaf pine dominated communities, known for the dominance of bunch grasses in surface layer vegetation, fine roots likely play an important role in mediating carbon fluxes (Guo et al. 2004).

CHANGES TO CARBON STABILITY

Fire typically changes some biomass into chemically more stable forms. One explanation for the accumulation of soil carbon in frequently burned southern pine communities is that the most flammable fuels are also the most susceptible to decomposition, such that inputs to the soil from fuel not consumed by fire are less palatable to microbes (Wells 1971). Also, fire converts part of the fuel into char, also known as black carbon or elemental carbon, formed from the heating and gasification of volatile chemicals leaving behind almost pure carbon. Molecular composition and stability of black carbon resulting from fire can vary widely depending on the fuel source, fire intensity, and specific fire conditions (Lehmann et al. 2006, Nguyen et al. 2010, Coates et al. 2017), but in general they are quite stable and tend to accumulate in soils. In southeastern U.S. pine communities, char is formed from fallen trees and stumps, branches and twigs, pine cones, and pine needles. However, comparison of frequently burned (1-2 year interval) and a 50-year unburned site that was previously frequently burned showed no measurable differences in amounts of char, suggesting that char accumulation is very slow (Hsieh and Robertson, unpublished data).

RELEVANCE TO MANAGEMENT

Although a certain amount of “gray literature” in the past few decades has suggested that fire reduces soil carbon in southeastern U.S. pinelands, scientific evidence suggests that application of frequent prescribed fire regimes will not significantly decrease soil carbon and may increase it. Although the mechanisms of soil carbon retention and accumulation in frequently burned pinelands are not precisely known, it seems advisable to burn frequently enough to prevent conversion from grass-dominated to woody-dominated communities and to manage timber to allow sufficient light penetration to maintain a continuous herbaceous community. Soil disturbance should also be minimized as soil aeration by disking greatly increases rates of soil organic matter decomposition (Wood and Edwards 1992) and was found to decrease soil C by 50% in a longleaf pine savanna (Robertson unpublished data). Burn piles of heavy slash, which likely volatize most of the near-surface soil carbon, should be located in previously disturbed sites, such as past burn pile locations or disked fields, that have initially low soil carbon. Soil carbon sequestration is likely to become an increasingly important goal of land management as markets for carbon credits expand (Dwivedi et al. 2009, McKinley et al. 2011).

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