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CHAPTER 13

Fire and Fire-Suppression Impacts on Forest-Soil Carbon

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INTRODUCTION

The potential of forest soils to sequester carbon (C) depends on many biotic and abiotic variables, such as: forest type, stand age and structure, root activity and turnover, temperature and moisture conditions, and soil physical, chemical, and biological properties (Birdsey and Lewis, Chapter 2; Johnson and Kern, Chapter 4; Pregitzer, Chapter 6; Morris and Paul, Chapter 7). Of increasing interest to U.S. and global soil C sequestration scenarios is the impact various forest management practices, such as harvesting, site preparation, reforestation, drainage, and fertilization, have on soil C pools and cycling (Post, Chapter 12; Hoover, Chapter 14). A subject of many recent studies is the possible effect of higher atmospheric CO_2 levels on forest-soil C accumulations caused by increased tree growth, changing internal C allocations, and alteration of climate temperature and precipitation patterns (e.g., Caspersen et al., 2000). Projected climate change may also increase the incidence and severity of wildfires in some forest regions, which could have a major impact on soil C pools (Flannigan et al., 2000; Stocks et al., 2000).

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Confounding the possible impact of climate change on soil C pools is the widespread interest in using fire to restore perceived and real changes in forest productivity caused by fire-suppression activities (Kimmins, 1977; Ballard and Gessel, 1983; Vose and Swank, 1993; Monleon et al., 1997). Much of the concern is focused on the relationships of fire, fire suppression, and nutrient losses and gains (Freedman, 1981). In particular, active fire suppression in forest stands that historically supported a regular fire-return interval has led to C accumulation in many forest stands, especially in the western United States (Oliver et al., 1994). These accumulations are likely undesirable because of slower decomposition rates and the risk of increased fire severity (Covington and Sackett, 1984). Consequently, in this chapter we will discuss the impact of fire on soil C pools, recovery after fire, the effects of a fire-suppression policy on soil C, methods to estimate C losses from fire, and the implications of fire management on soil C cycling and sequestration.

SOIL CARBON LOSSES FROM FIRE

Any fire alters the amount and distribution of C pools in forest soil (Wells et al., 1979). The amount of soil C lost due to fire depends on: (1) temperature of the burn, (2) amount and distribution of surface soil organic matter (OM), and (3) decomposition rates of residual OM after fire.

Fire Temperature

Fire temperature, expressed as maximum ground temperature, is an important variable in soil C loss. Fire severity is usually described in three classes: light, with surface temperatures around 250°C; moderate, with surface temperatures up to 400°C; and high, with surface temperatures in excess of 675°C (Neary et al., 1999). Surface OM and C are consumed when fire temperatures reach 450°C. Fires occurring in areas with heavy slash buildups may produce ground temperatures of 500 to 700°C but can reach 1500°C (DeBano et al., 1998). At these temperatures, surface and subsurface organic matter (to a depth of 5 cm) can range from partially scorched (light) to totally consumed (high).

Most soil C losses occur when fires burn in one area (e.g., around downed logs) for a long period of time and transfer heat into the mineral soil (Neary et al., 2000). However, heating the forest floor at temperatures ranging from 175 to 205°C for ≈20 min or longer can result in the formation of volatiles, which diffuse downward into the surface mineral soil. These organic compounds cool, condense on soil particles, and form water-repellent soil layers when mineral soil moisture content is less than 12 to 25% (Robichaud and Hungerford, 2000). Although extremely variable, measurements of hydrophobicity persistence in soil have shown that this layer weakens after the first year but can persist for at least two years (Huffman et al., 2001; Pierson et al. 2001). It is unclear how much forest floor C moves into the mineral soil by this process, but it could be appreciable in heavily burned areas.

Amounts and Distribution of Soil OM

Fuel amounts and distribution vary greatly by forest type and stand age (Johnson and Kern, Chapter 4). Many variables contribute to the range of C estimates, such as vegetation type, stand age and structure, organic-matter decomposition rate, and whether forest floor and surface woody residues are included with the mineral soil pool (Oliver and Larson, 1990). Total-profile C pools are generally the highest in late seral/climax stages, when tree mortality becomes an important part of the soil C cycle (Harvey et al., 1999a). For old-growth stands in the northwestern United States, mineral soil C ranges from 35 to 131 Mg C ha^{-1}, and surface organic horizons range from 48 to 246 Mg C ha^{-1} (Table 13.1). In many of these stands, the proportion of C in the surface organic horizons is greater than 50% of the total pool.

Table 13.1 Carbon Pools and Distribution in Select Soil Components in Undisturbed Stands and Potential Loss due to Prescribed or Wildland Fire

Species and Location	Stand Age (years)	Carbon			
		Pool (Mg ha^{-1})	Distribution (%)	Range of Potential C Loss (%)[a]	Range of Potential C Loss (Mg ha^{-1})
Hemlock, Idaho	120				
Surface organic matter[b]		75	56	11–100	4–75
Mineral soil (0–30 cm)		59	44	1–9	<1
Hemlock, Montana	100				
Surface organic matter		70	40	10–100	1–70
Mineral soil (0–30 cm)		102	60	2–9	2–9
Grand fir, Idaho	150				
Surface organic matter		75	67	5–31	3–25
Mineral soil (0–30 cm)		35	33	—[c]	—
Ponderosa pine, Idaho	87				
Surface organic matter		50	57	2–25	1–8
Mineral soil (0–30 cm)		38	43	—	—
Ponderosa pine, California	300				
Surface organic matter		48	44	2–23[d]	1–7
Mineral soil (0–30 cm)		62	56	—	—
Subalpine fir, Montana	100				
Surface organic matter		61	62	9–100	2–61
Mineral soil (0–30 cm)		37	38	1–3	<1
Douglas-fir, Oregon	200				
Surface organic matter		152	66	19–100	24–152
Mineral soil (0–30 cm)		81	34	<1–2	<1
Sitka spruce, Oregon	150				
Surface organic matter		246	66	29–100	56–246
Mineral soil (0–30 cm)		131	34	<1–3	<1

[a] Range of C lost if 15% and 100% of the land area experiences detrimental burning.
[b] Surface organic matter includes the forest floor and highly decayed coarse wood, not intact coarse woody debris.
[c] No predicted C loss from the mineral horizon.
[d] No detrimental burning standard for USDA Forest Service Region 5; we assumed similar standards as USDA Forest Service Region 4.

Source: From Page-Dumroese, unpublished data.

Generally, surface fuels are high right after a stand has been harvested or after experiencing severe blowdowns or ice damage, after which the level of fuel slowly decreases as these residues decompose with little additional organic-matter input (20–70 years). In contrast, surface fuel accumulation after a severe wildfire is usually the opposite, with little surface organic material remaining after the fire. However, fuel levels increase 10 to 30 years later as snags of trees killed by the fire finally fall and litter inputs from the reestablished understory communities greatly increase (Covington and Sackett, 1992; Baird et al., 1999). Surface accumulations of dead and partially decayed coarse woody debris greatly increase the risk of another severe fire, which would deplete soil C pools even further (Oliver et al., 1994).

Organic-Matter Decomposition

While most soil C is lost as a direct result of the combustion process, changes in the decomposition rate of soil organic matter can also play a key role in C storage. A number of studies have shown that decomposition rates of fresh litter placed on burned soil can range from nearly the same to 50% less compared with unburned soil (Monleon and Cromack, 1996). However, organic matter remaining in the forest floor after a fire has been shown to decompose very rapidly, even though needles and leaves from both residual dead and live trees added considerable mass (Covington and

Sackett, 1984). Krankina and Harmon (1994) estimate that each 10% loss of the forest floor from burning is equivalent to 0.5 to 1 year of decay.

The increase in decomposition of residual soil organic matter is likely from increased microbial activity caused by warmer temperatures and higher soil moisture in the newly opened stand (Harvey, 1994). There is also an increase in surface soil pH following fire as a result of basic cations released through the combustion process. Jurgensen et al. (1981) found soil acidity of the organic horizons had decreased over two pH units immediately following a fire in Montana and had not returned to prefire levels after four years. The pH change varies depending on vegetation type, soil organic-matter content, and precipitation (Grier, 1975), but the more severe the burn, the greater the soil pH increase. Both soil bacteria and fungi populations change in response to lower soil acidity levels and are likely responsible for much of the increased organic-matter decomposition (Pietikäinen and Fritze, 1995; Visser and Parkinson, 1999). Greater available N after a fire would also contribute to greater decay rates (Raison, 1979).

SOIL CARBON CHANGES

Pools after Fire

Many wildfires burn hotter than most prescribed fires and are associated with greater losses of soil C (Johnson, 1992; Table 13.1). Wildfires, which burn hundreds to thousands of hectares, have a larger potential for seriously affecting soil productivity than prescribed burns because soil and fuel moisture is usually lower and the weather is drier (McNabb and Cromack, 1990). However, frequent low-intensity prescribed burns can also cause significant surface and mineral soil C losses (McKee and Lewis, 1983; Monleon and Cromack, 1996). Fire burning over a landscape often creates variable C losses depending on vegetation types (Table 13.2), but these estimates often do not include C losses in downed, intact logs.

In undisturbed forests, coarse woody debris can contribute another 5 to 30% to the C pool (Laiho and Prescott, 1999). Covington and Sackett (1984) noted that woody material was reduced by 63% after a prescribed burn in Arizona. On the eastern slopes of the Cascade Mountains in Washington, coarse woody debris mass declined 33% in a ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) forest after burning (Baird et al. 1999). Similarly, after a burn in a high-elevation lodgepole pine (*Pinus contorta*) forest, coarse woody debris was reduced 80% (Lopushinsky et al., 1992). Variation in the amount of wood, decay stage, and intensity of fire will influence C storage in this forest component (Baird et al., 1999). Additionally, formation of charcoal in the surface soil will also enhance long-term C storage and affect soil microbial populations (McKee, 1982; Pietikäinen et al., 2000).

FIRE SUPPRESSION

Frequent, low-intensity fires that occur in fire-dependent ecosystems, especially in the western United States, limit the amount of OM accumulation in the forest floor and have little impact on overall soil productivity (Neary et al., 1999). However, large amounts of fine and coarse fuels accumulate on the soil surface of fire-suppressed stands. These stands are at risk for substantial C losses and decreased site productivity when an infrequent, high-intensity fire occurs (Harvey et al., 1994; Oliver et al., 1994; Harvey et al., 1999b). For example, a ponderosa pine stand in Idaho with no fire for 87 years had 57% of the total-profile C pool in the forest floor as compared with 20% in a stand where fires are frequent (10–15 years) (Table 13.2; Figure 13.1; Neary et al., 2000). In the Pacific Northwest, many forested stands have a majority of the total-profile C pool associated with these organic horizons because of fire-suppression activities dating back to the early 1900s

Table 13.2 Examples of Fire Impacts on Soil C Levels for Various Types of Vegetation

Location	Species	Carbon Changes	Reference
		Wildfire	
Washington	Mixed conifer	40% loss of forest floor	Grier, 1975
Alaska	Spruce, birch and aspen	Increased loss of forest floor with increasing fire intensity	Dyrness et al., 1989
Maine	Mixed hardwoods	Large loss of forest floor, mineral soil recovery after 1 year	Fernandez et al., 1989
Washington	Ponderosa pine/Douglas-fir Lodgepole pine/Englemann spruce	C was 30% less after 1 year C was 10% less than control after 1 year	Baird et al., 1999
		Prescribed Fire	
Washington	Mixed conifer	26% increase in OM in northern Cascades; 2% decrease in southern Cascades	Kraemer and Hermann, 1979
Alabama	Longleaf pine burned every 2 years in winter	No difference from control	McKee, 1982
Florida	Slash pine periodic winter burn and annual winter burn	After 20 years, periodic burn plots had 17% more C than control; annual burn plots were not different than control	McKee, 1982
Australia	Radiata pine	40–50% loss to 60 cm in mineral soil	Sands, 1983
Minnesota	Oak savanna	38–70% less C in forest floor	Tilman et al., 2000

(Oliver et al., 1994). Grigal and Ohmann (1992) found an increase in both forest-floor and mineral-soil C pools on fire-suppressed upland sites in the upper Great Lakes region. However, Tilman et al. (2000) reported no soil C gains in a Minnesota oak-savanna ecosystem, even though fire suppression caused nearly twice as much C to accumulate in aboveground biomass than in stands that had a moderate-to-high fire frequency.

Fire-suppression policies have also allowed many forest types in the Intermountain western United States to gradually shift from more-open stands of fire-dependent ponderosa pine to closed stands comprising a mixture of fire-intolerant climax species, such as Douglas-fir and grand fir (Harvey et al., 1999a and 1999b). Pine stands generally have a greater proportion of soil C in the

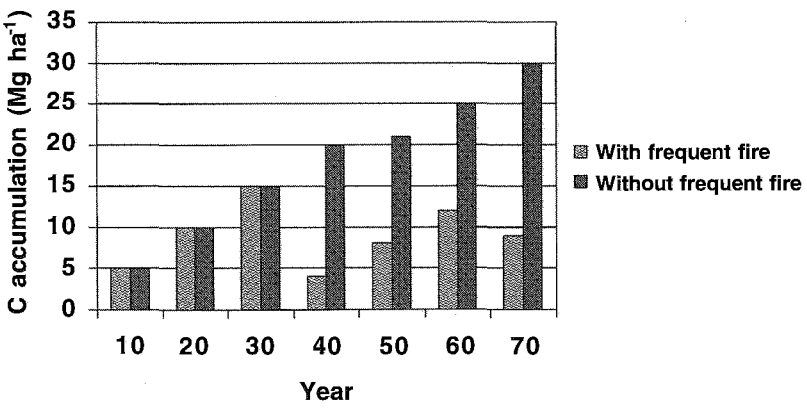

Figure 13.1 Schematic representation of C accumulation in forest ecosystems with and without frequent fire. (From Oliver, C.D. et al., *J. Sustainable For.*, 2: 113–133, 1994. With permission.)

surface mineral soil, while mixed pine/fir stands have more C in the forest floor and in coarse woody debris (Table 13.1). Fire suppression leads to higher C contents in surface organic materials, which increase the potential for greater C losses when a fire finally does occur. The development of a fir understory ladder-fuel complex in pine stands also increases the possibility of a stand-replacing fire and consequently greater C losses (Harvey et al., 1994). Site productivity and recovery is often dependent on the amount of surface organic matter remaining after stand disturbance (Jurgensen et al., 1997).

PREDICTING SOIL C LOSS

As seen in Table 13.2, there are many reports on soil C losses from site-specific fires. However, in order to incorporate C losses from fire into soil-C-sequestration predictions and models, estimates are needed of soil C losses from many forest types, age classes, etc. for which no fire-loss information is available. Without such estimates, it is difficult to formulate predictions of which stands are at greatest risk from catastrophic fires, changes in soil C pools over larger scales, and forest ecosystem responses to fires of various intensities. One method would be to use published soil-survey information and fire criteria formulated in the USDA Forest Service Regional Soil Quality Standards and Guidelines. These standards and guides were designed to measure the possible impact of management on soil productivity, site resiliency, and long-term productivity (Jurgensen et al., 1997; Johnson and Todd, 1998). Although specific thresholds were written for each USDA Forest Service Region and for several different disturbance regimes, these fire standards can be used to estimate the range of possible soil C losses from fires of different severities (Page-Dumroese et al., 2000).

Several examples of this type of calculation are shown for representative forest stands in the Pacific Northwest (Table 13.1). The amounts and distribution of soil C in western old-growth stands shows the wide variability in soil C pools among different forest ecosystems and can be used as an upper limit of C losses after a severe, stand-replacing fire. We followed the methods outlined in Page-Dumroese et al. (2000) and used two possible burning scenarios: (1) 15% of the area was burned severely enough to reach the USDA Forest Service detrimental fire threshold, and (2) 100% of the soil surface was burned severely enough to reach the USDA Forest Service detrimental fire threshold for that forest.

As shown in Table 13.1, most of the C in the forest floor would be destroyed in the event of a severe, stand-replacing fire, while mineral soil losses likely would be relatively small. Even though Sitka spruce stands on the Oregon coast have large accumulations of soil C, their fire frequency is very low (>900 years), and hot, stand-replacing fires rarely occur (Agee, 1993). Consequently, the probability of losing large amounts of soil C to fire in this ecosystem is small. However, other forests with higher fire-return intervals, such as ponderosa pine, have much smaller C pools but would sustain much greater short-term ecosystem losses of C. Stands with more C in the mineral soil (hemlock in Montana, with 60% C in mineral soil) are at a much lower risk for catastrophic C losses than those with a larger proportion in the surface organic matter (grand fir in Idaho, with 33% C in mineral soil).

SOIL C RECOVERY AFTER FIRE

We have shown that fire can reduce soil C pools, depending on fire severity. Equally important to forest ecosystem health and productivity is how quickly soil C pools recover after fire. Severe fires often result in long-lasting C declines, while low-intensity fires may result in little C change and sometimes even an increase in site productivity (Baird et al., 1999). For example, 24 years after an intense burn in a radiata pine stand in Australia, mineral soil C was still 40 to 50% lower than unburned controls (Sands, 1983). However, surface organic matter can recover much more

Table 13.3 Average Forest-Floor Carbon and Organic-Matter Pools in a Western Montana Subalpine Fir Forest (Two Habitat-Type Phases) 30 Years after Treatment

Habitat Phase and Treatment	(Mg ha^{-1}) Carbon	OM
Dry Phase		
Uncut old growth	36	67
Thinned (not burned)	28	54
Prescribed burn	7	14
Prescribed and wildfire	13	26
Wildfire, uncut	15	30
Wildfire, after clear-cut	5	9
Moist Phase		
Uncut old growth	61	108
Thinned (not burned)	28	53
Prescribed burn	26	48

rapidly. Visser and Parkinson (1999) reported forest-floor recovery 41 years after wildfire in Alberta jack pine stands.

A study established in western Montana in the late 1960s to investigate the impacts of fire on soil and vegetation dynamics has given an insight on how a subalpine fir, Douglas-fir, and Engelmann spruce ecosystem can respond to both prescribed fire and a wildfire. Study plots on different slope aspects (north, east, south, and west) were clear-cut in 1966 and then subjected to prescribed burning during 1967 and 1968. In August 1967 a wildfire burned (or reburned) several of the plots (DeByle, 1981; Shearer, 1989). In 1996 we resampled representative plots along with adjacent undisturbed stands to evaluate C recovery over this 29-year period (Table 13.3).

Thirty years after site treatment (prescribed fire, wildfire, or clear-cut and not burned), all disturbed stands have lower levels of both C and organic-matter content in the forest floor. Particularly outstanding are the low levels of C and organic matter in the dry-phase stand that had a wildfire after clear-cut (5 Mg ha^{-1} C and 9 Mg ha^{-1} organic matter compared with 36 Mg ha^{-1} C and 67 Mg ha^{-1} organic matter in the old-growth stand). In the moist phase of the forest type (north and east slopes), the thinned and prescribed-burn stand were similar in both forest floor C and organic matter after 30 years. However, the old-growth stand had more than twice as much forest-floor C and organic matter.

Five years after logging and fire, surface mineral soil organic-matter content had recovered to 5.2% and was similar to the undisturbed old-growth stand levels (DeByle, 1981). At the time of our resampling, mineral soil OM averaged 7.4% for all plots and was similar to the undisturbed areas, indicating that mineral soil organic matter (and likely C) continues to accumulate (Page-Dumroese, unpublished data). The striking differences among these forest-floor and mineral-soil data illustrate the importance of evaluating both mineral soil and surface organic-matter pools before and after fire.

MANAGEMENT PERSPECTIVE

Many ecosystems, particularly in the western United States, are now overloaded with surface fuels that have accumulated from fire suppression. This type of stand condition, with large amounts of surface fuel, is conducive to wildfire and can trigger catastrophic changes in soil productivity if fire severity is high (Sands, 1983; Harvey et al., 1999a). Much of a forest stand's C storage likely occurs above ground or in the deeper mineral soil horizons (Grigal and Ohmann, 1992; Tilman

et al., 2000). Therefore, changes in mineral soil C (or lack of change) may not be an indicator of total-site C losses, since most C losses from fire occur in the forest floor material. Maintaining total-soil-profile C levels and soil productivity while reducing wildfire incidence in fire-suppressed stands will likely be achieved through a variety of strategies aimed at developing stands consisting of multiple species and multiple ages rather than managing for one species or age (Tiedemann et al., 2000). This change in structure and age will also affect biological decomposition. Increased biological decomposition, along with prescribed fire, thinning, and salvage logging, can all be used to reduce fuel loads to help protect the soil resource.

While it seems desirable to accelerate burning frequency in fire-dependent ecosystems that have not experienced recent fires, this could lead to changes in the cycling of soil nutrients (e.g., N, P, S), loss of soil water-holding capacity, increased soil hydrophobicity, alteration of microbial communities, and impaired long-term soil productivity through loss of organic matter on some sites. A lowering of soil productivity after fire would also reduce future soil C sequestration, since biomass production in the subsequent stands would be less (Tiedemann et al., 2000). However, the extent and impact of such soil changes under controlled burning conditions are largely unknown, but need to be researched as part of any large-scale ecosystem fire management plan.

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