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Charcoal and carbon storage in forest soils of the Rocky Mountain West

Thomas H DeLuca^{1*} and Gregory H Aplet²

Charcoal represents a super-passive form of carbon (C) that is generated during fire events and is one of the few legacies of fire recorded in the soil profile; however, the importance of this material as a form of C storage has received only limited scientific attention. Here, we review the formation of charcoal in temperate and boreal forest ecosystems, discuss some of its desirable properties, and estimate the potential contribution of charcoal to long-term C sequestration in forest ecosystems. Charcoal deposition over the course of several millennia probably accounts for a substantial proportion of the total soil C pool in fire-maintained forest ecosystems. Forest management processes that interfere with natural fire processes eliminate the formation of this passive form of C. We recommend that charcoal be considered in C storage budgets and modeling of forest ecosystems, especially in light of climate change and increasing occurrence of wildfire.

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All grassland and forest ecosystems have the potential to burn as a result of wildfire or human-induced fires. Charcoal formed from the burning of herbaceous and woody materials during grassland and forest fires results in the deposition of charcoal particles (Forbes *et al.* 2006; Preston and Schmidt 2006), much of which remains on site or immediately nearby (Lynch *et al.* 2004). It is well understood that forest disturbance events such as fire directly influence carbon (C) accumulation rates in soil ecosystems; however, in spite of the fact that charcoal is formed in all fire events, it has rarely been analyzed as a meaningful component of terrestrial C storage (Houghton *et al.* 2000; Kasischke and Stocks 2000; Seely *et al.* 2002; Hicke *et al.* 2004; Kashian *et al.* 2006). Furthermore, charcoal is not considered in most ecosystem models (Parton *et al.* 1994; Law *et al.* 2001; Seely *et al.* 2002), which may limit the ability of these models to predict long-term storage of C in fire-prone ecosystems. This is perplexing, given that charcoal has been found to make up a substantial portion (up to 60%) of total C in grassland (Skjemstad *et al.* 1996; Dai *et al.* 2005) and forest soils (Schultze *et al.*

1999; Carcaillet and Talon 2001; Kurth *et al.* 2006), and considering that soils represent the largest body of terrestrial C storage (Schlesinger 1997).

Recently, there has been growing interest in charcoal as a component of natural ecosystems and driver of processes in both natural and agricultural ecosystems. This is reflected in the publication of several excellent review articles synthesizing the scientific knowledge regarding formation and longevity of black C across various terrestrial ecosystems (Forbes *et al.* 2006; Lehmann *et al.* 2006; Preston and Schmidt 2006). (“Black C” refers to the broad class of high-carbon byproducts of fire, including charcoal, which consists of organic materials that have been subject to partial combustion, and soot, which is produced by the condensation of volatiles created during combustion of organic materials. In this paper, we focus on charcoal created by forest fires.) Furthermore, charcoal generated during biomass pyrolysis (biochar) has been proposed as a soil amendment to create long-term C storage in soil while improving soil physical conditions and reducing environmental pollution (Lehmann 2007). Here, we review recent findings as they pertain to the formation of charcoal in wildfire and prescribed fire events, estimate the potential contribution of charcoal to long-term C sequestration in forest ecosystems of the Rocky Mountain West (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, and Utah), and discuss the impact of management decisions on charcoal formation and function in forest environments of the region.

In a nutshell:

- Charcoal produced during wildfire events represents an important form of long-term C storage in forest ecosystems
- Charcoal has numerous desirable properties that improve soil physical and biochemical conditions
- Charcoal may account for 15–20% of total C in temperate, coniferous forest mineral soils
- Forest management practices, such as salvage logging or thinning without prescribed fire, may reduce soil charcoal content and, thus, long-term C storage in mineral soils

■ Properties of charcoal

Charcoal is a C-enriched, nitrogen (N)-depleted pyrogenic substance with a highly aromatic molecular structure and a number of characteristics that make it an important determinant of terrestrial ecosystem function.

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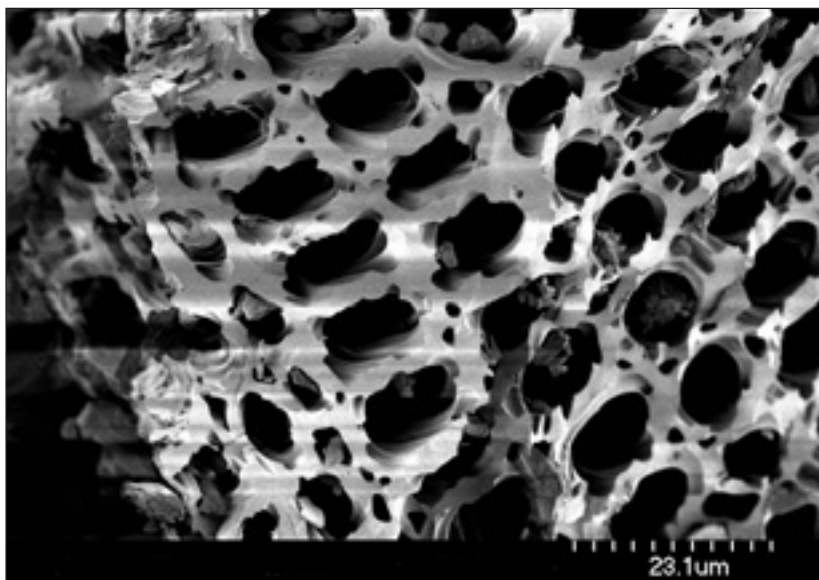


Figure 1. An electron micrograph of charcoal collected from a ponderosa pine forest in northern Idaho that was exposed to fire 79 years prior to collection (Brimmer 2006).

Coniferous wood is generally about 50% C and 0.3% N, while coniferous wood charcoal is about 80% C (Forbes *et al.* 2006) and less than 0.1% N (Tyron 1948). The porous nature of charcoal (Figure 1) lends numerous potentially beneficial physical properties in soil, including increased soil-water holding capacity and reduced soil bulk density (Tyron 1948; Gundale and DeLuca 2006; Lehmann *et al.* 2006). Charcoal can act as a reservoir for alkaline metals and phosphate, provide a source of cation exchange sites, and gives soil its dark color, which influences warming (Bélanger *et al.* 2004; Gundale and DeLuca 2006; Lehmann *et al.* 2006; Liang *et al.* 2006). Given this broad range of beneficial properties, charcoal has the potential to function as a surrogate for humus in temperate, boreal, and tropical forest soils that otherwise have limited soil organic matter content (Glaser *et al.* 2001; DeLuca *et al.* 2006; Lehmann *et al.* 2006). For example, revelations from studies of *terra preta* soils, ancient agricultural soils amended with charcoal and manure, demonstrate that charcoal can greatly influence soil productivity and ecosystem diversity (Glaser *et al.* 2001).

In addition to its porous structure, charcoal generally exhibits hydrophobic properties (Sander and Pignatello 2005) that make it well suited to the sorption of organic compounds. Charcoal has the capacity to adsorb a host of compounds, including plant root exudates, litter decomposition products, and microbial byproducts. Recently formed charcoal adsorbs organic compounds that might otherwise be inhibitory to plants or microorganisms (Keeley and Pizzorno 1986; Zackrisson *et al.* 1996; Wardle *et al.* 1998; Pietikainen *et al.* 2000); this may be important in phenolic-rich ecosystems such as boreal forests, or in the presence of allelopathic invasive species. This capacity to adsorb plant-root exudates and litter decomposition products may be related to the stimulatory effect of char-

coal on nitrification in acidic coniferous forest soils (DeLuca *et al.* 2006). Charcoal's hydrophobic properties may also make it an important factor in soil humus formation (Piccolo *et al.* 2004).

Charcoal is highly resistant to decomposition. In sediment cores from oxygen-limited lake, pond, or marine environments, charcoal may be thousands to millions of years old (Masiello and Druffel 1998). Indeed, biomass burning leads to the deposition and storage of approximately 50–270 Tg of C as charcoal in terrestrial and marine environments annually (Kuhlbusch and Crutzen 1995). In aerobic, terrestrial environments, charcoal has been found to have far greater longevity than herbaceous or woody plant materials (see Figure 2). Incubation experiments have shown that charcoal is initially subject to some decomposition (eg Liang *et al.* 2006), but becomes progressively more

recalcitrant with time (Schneour 1966) and is ultimately far less bioavailable than non-charred woody materials (Baldock and Smernik 2002). Litter and deposited twigs have mean residence times on the forest floor (organic surface horizons) or in the mineral soil environment of months to years, and large woody stems normally last for dozens of years. Although decomposition rates of charcoal in soil are difficult to determine (in part because of the longevity of charcoal), estimates place mean residence times at 3000–12 000 years (Gavin *et al.* 2003; Lynch *et al.* 2004; Forbes *et al.* 2006; Preston and Schmidt 2006), making it considerably more stable than non-charred plant tissues.

Of course, when plant tissues decompose in the soil environment, they do not simply disappear. A portion of the decomposing tissue is lost to the atmosphere as CO₂, but a remaining portion will exist as various decomposition products that are classified into “pools”, according to their resistance to breakdown (Parton *et al.* 1994). The “fast” soil C pool is composed of living organisms and “labile” C, with residence times measured in days; the “slow” soil C pool is composed of non-humic materials and protected organic matter, with residence times measured in years to tens of years; finally, the “passive” soil C pool (40–50% of total soil C) is composed of humic material, which has a residence time of hundreds of years. Soil charcoal represents a “super-passive” form of soil C that provides semi-permanent C storage once it is in the mineral soil (see Figure 3).

■ Charcoal formation and deposition during forest fire events

Charcoal is formed by the incomplete oxidation of vegetable matter during fire events. Incomplete oxidation

occurs as a result of heating in the absence of oxygen, a process that is highly variable spatially and is a function of fuel loading, temperature, moisture, and fire intensity (Preston and Schmidt 2006). Coarse charcoal (>0.4 mm) may be formed from dead and downed wood, stumps and dead roots, or the bark and twigs of live plants. Fine charcoal may be formed from fine, live plant material (eg grass), from litter and duff at the soil surface, or from the mechanical breakdown of coarse charcoal. Some charcoal may be lost from the site during a fire due to the convection of burning embers, but the charcoal that remains on site may be deposited directly onto the mineral soil surface or remain suspended above-ground, as in the case of charred bark that may take years to slough from the tree.

In general, charcoal is formed at a rate of about 1–2% of total biomass available or 1–10% of biomass consumed during a fire (Tinker and Knight 2000; Lynch *et al.* 2004; Forbes *et al.* 2006; Preston and Schmidt 2006). Applying these rates to empirically derived estimates of fuel consumption allows an estimation of the total amount of charcoal formed during a fire event (Table 1). Assuming a charcoal formation rate of 1–10% of fuel consumed, prescribed fire in a ponderosa pine/Douglas-fir forest in western Montana might yield less than 1.0 Mg C ha⁻¹ as charcoal, whereas a wildfire in a Wyoming lodgepole pine forest would leave 0.3 to 3.4 Mg C ha⁻¹ as charcoal. Lodgepole pine forests have historically burned on a longer mean fire-return interval than ponderosa pine (Agee 1993) and yield more charcoal per fire, but ponderosa pine forests burn more frequently, resulting in long-term charcoal formation rates that are probably similar to those of lodgepole pine.

■ Mechanisms of charcoal sequestration and loss

If charcoal has such great longevity and fires have occurred frequently throughout the Holocene, then why aren't soils mostly charcoal? If a ponderosa pine forest burned for the past 10 000 years with a fire-return interval of 35 years (~ 285 fires), a charcoal generation rate of 310 kg charcoal ha⁻¹ fire⁻¹ (3% of biomass exposed to fire), and a C content of charcoal of 80%, one would expect today's soils to contain over 70 Mg C as charcoal ha⁻¹, or about 70 to

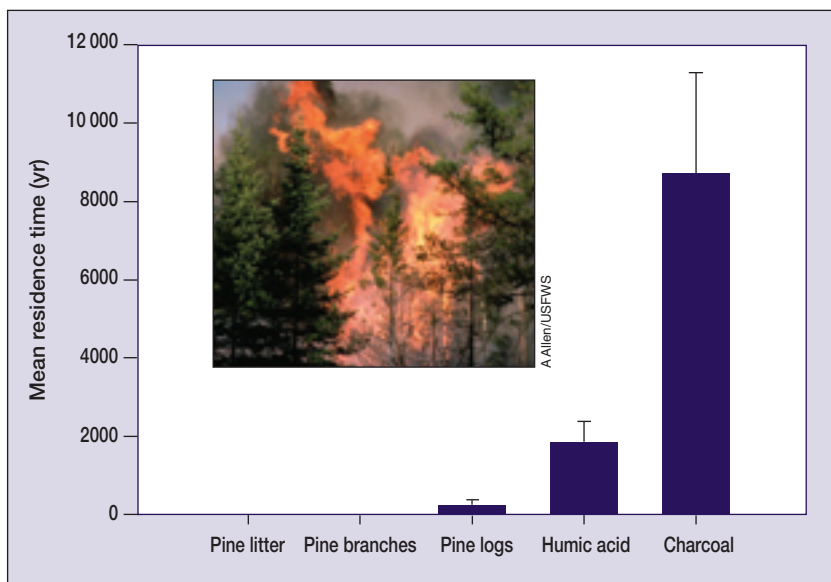


Figure 2. Mean residence times for woody materials, humic acid, and charcoal. Error bars represent one standard error; n = 3 (Parton *et al.* 1994; Law *et al.* 2001; Preston and Schmidt 2006). Pine litter = 7.5 years; pine branches = 80 years.

> 100% of total mineral soil C rather than the reported 0 to 60% (Forbes *et al.* 2006; Preston and Schmidt 2006). The reason for this discrepancy is that not all charcoal produced ends up sequestered; depending on post-fire events, charcoal may be lost to erosion or subsequent burning. Unfortunately, to date, we are not aware of any research that quantifies the proportion of charcoal that actually makes it into long-term soil storage and thus must constrain our analysis to a qualitative description of mechanisms of charcoal sequestration.

The charcoal produced during fire events is generally

Table 1. Fuel consumption and charcoal formation estimates for a prescribed-fire study and the average wildfire fuel consumption estimates for mixed ponderosa pine and Douglas-fir forests in Western Montana

	Litter consumption (Mg ha ⁻¹)	Woody fuel consumption (Mg ha ⁻¹)	Charcoal formation ¹ (Mg C ha ⁻¹)
<i>Ponderosa pine</i>			
Prescribed fire + thin and burn	4.0 ²	17.3 ²	0.17–1.70
Prescribed fire + burn alone	3.0 ²	6.0 ²	0.07–0.72
Wildfire	5.0 ³	18.0 ⁴	0.18–1.84
<i>Lodgepole pine</i>			
Harvest and broadcast burn	10.0 ³	14.0 ³	0.19–1.92
Wildfire	10.0 ⁵	32.0 ⁵	0.34–3.36

Notes: ¹Charcoal formation estimate of 1–10% of fuel consumed, charcoal is assumed to be 80% C (Tinker and Knight 2000; Lynch *et al.* 2004; Preston and Schmidt 2006); ²Fuel consumption data from ponderosa pine restoration study (Gundale *et al.* 2005); ³Estimated fuel consumption data for surface wildfire (Tinker and Knight 2000); ⁴Estimated woody fuel consumption after Agee (1993); ⁵Estimated fuel consumption data for stand-replacing crown fire (Lynch *et al.* 2004)

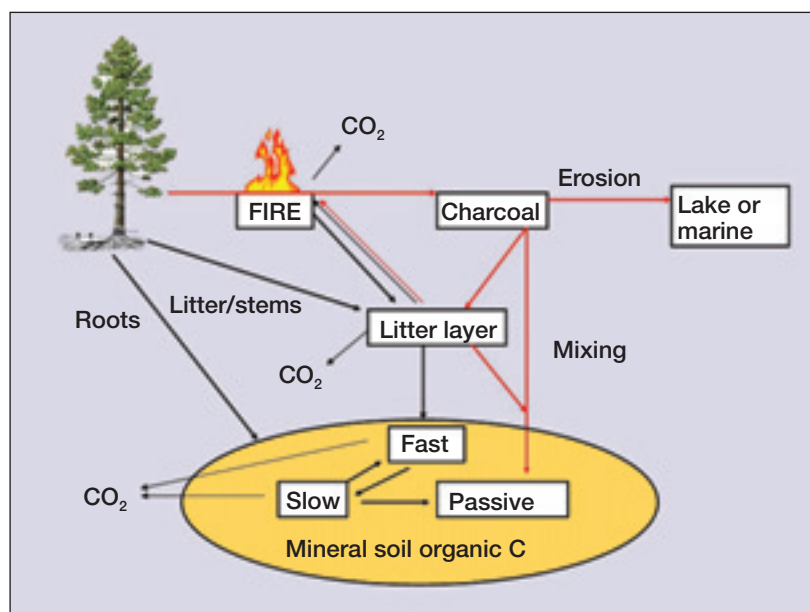


Figure 3. A simplified C model that demonstrates the flow of C from forest litter and residues into various soil C pools and the direct flow of charcoal C into the passive soil C pool in the presence of fire.

deposited on the forest floor (Lynch *et al.* 2004) until it is mixed into the soil or lost from the site. A variety of processes, including freeze–thaw events, tree tipping, and soil disturbance by animals, mix surface organic matter, including charcoal, into the mineral soil (Gavin 2003). Charcoal may be mixed to depths of up to 1 m (Carcaillet 2001), but the vast majority remains above 30 cm in depth, with approximately 70% or more remaining above 10 cm in depth (Carcaillet 2001; Gavin 2003). The greater the prevalence of windthrow events (trees uprooted by wind), the greater the potential for charcoal to be mixed into mineral soil (Gavin 2003). Conversely, charcoal tends to be concentrated in the forest floor or in the surface mineral soil in ponderosa pine or Scots-pine forests (Zackrisson *et al.* 1996; Brimmer 2006; Kurth *et al.* 2006; Preston and Schmidt 2006).

Charcoal that is not mixed into the mineral soil remains vulnerable to loss through erosion or to combustion in the next fire (Zackrisson *et al.* 1996). Eroded charcoal may eventually be deposited in lake or marine sediments and remain sequestered indefinitely (Masiello and Druffel 1998), but charcoal that is consumed by fire obviously cannot be considered sequestered. Therefore, processes of soil mixing are critical to the sequestration of charcoal C in terrestrial ecosystems.

Direct measurements of the proportion of aboveground charcoal that is eventually mixed into the mineral soil are lacking, but the large range of charcoal's contribution to surface mineral soil C suggests that the proportion is highly variable, depending on the rate of generation and the degree of soil mixing. In general, the charcoal content of coniferous forest mineral soils ranges from 1% to 43% of mineral soil C (Table 2). Soils of low-elevation, fire-maintained, coniferous forests of the Rocky Mountain

West contain approximately 50–100 Mg total C ha⁻¹ in the surface 100 cm of soil (Law *et al.* 2001; Page-Dumroese and Jurgensen 2006). Soil C in this region may be 15–20% charcoal (Kurth *et al.* 2006) in the surface 10 cm of soil. If we assume that the remaining 25–50 Mg C ha⁻¹ in the mineral soil exists between 10 and 100 cm depth, and 15–20% of this is charcoal, then soils of this region would contain approximately 7–20 Mg C ha⁻¹ as a non-cycling form of C, indicating that a considerable amount of charcoal undergoes more or less permanent storage.

Recent fire history appears to be less important to the charcoal content of mineral soil than it is to the amount of charcoal accumulated on the surface. Forest floor charcoal mass is often less than that in the mineral soil (Table 2), consisting only of that charcoal deposited in the most recent fire event(s) (Schiffman and Johnson 1988). Forest floors of unmanaged ponderosa pine/Douglas-fir forests of the inland northwest exposed to multiple fires contained about three times more charcoal than forests that had not experienced fire in the past 79–130 years (Brimmer 2006). In contrast, the surface 10 cm of mineral soil, which contained 10–30 times more charcoal than the forest floor, exhibited no significant difference between sites exposed to multiple recent fires and those that experienced no recent fires (Kurth *et al.* 2006). Although recent fires probably contributed some charcoal to mineral soils, these results indicate that the vast majority of charcoal in the mineral soil predates that formed in recent fires.

■ Implications for forest management

Fire management

Thus far, we have been concerned with the partially burned residual C produced by forest fires, but forest fires also release considerable C into the air, potentially exacerbating rising levels of global atmospheric CO₂. The potential contribution of forest fires to climate change requires a better understanding of the relationship between forest fires, C release, and C sequestration. In 1988, extensive fires burned across Yellowstone National Park, creating a world-class laboratory for the study of C dynamics following fire. Kashian *et al.* (2006) recently evaluated C storage and loss across this landscape and estimated that stand-replacing fires in lodgepole pine forests led to substantial C loss from both combustion and post-fire decomposition, but that forest regrowth over a period of about 250 years would overcome the C deficit, resulting in no net loss of C over a natural fire cycle. This work represents an important advance in our understanding of post-fire C dynamics; however,

their analysis took no account of charcoal and soil organic matter fluctuations. Tinker and Knight (2000) generated estimates for C loss during fire in the same landscape and concluded that 8% of coarse woody debris is lost to the atmosphere and another 8% is converted to charcoal in a lodgepole pine crown fire. Applying a charcoal conversion rate of 2% (Lynch *et al.* 2004) of the 87 Mg C ha⁻¹ of live, standing biomass in a mature lodgepole pine forest in Yellowstone Park (Litton *et al.* 2004), combined with Tinker and Knight's charcoal formation rate of 8% of the 19 Mg C ha⁻¹ of coarse woody debris, suggests a yield of approximately 3.25 Mg C ha⁻¹ as charcoal in a single fire event. In addition, approximately 3% of the decomposing wood (assuming ~ 20 Mg C ha⁻¹ is available for decomposition after fire, which includes the remaining coarse woody debris, decaying roots, and decaying windthrown trees) should be converted to humus, representing an additional 1.0 Mg C ha⁻¹ stored as humic matter. Thus, wildland fire need not be viewed only as a cause of C loss to the atmosphere, demanding suppression, but rather, as a driver of long-term C sequestration.

Forest restoration

Forest management strategies may directly or indirectly influence the accumulation of charcoal in the soil environment. Activities that exclude fire from the forest stand, including wildfire suppression, road building, and land development, eliminate the contribution of this stable, yet biochemically important form of C to the soil ecosystem. The long-term implications of such activities could result in shifts in ecosystem processes that cannot currently be easily predicted.

Thinning for fuel reduction or forest restoration is widely applied in dry ponderosa pine (Covington 2000) and mixed ponderosa pine/Douglas-fir and western larch forests (Fiedler 2000). Fuel reduction treatments in ponderosa pine forests would lead to the removal of anywhere between 20 and 40 Mg C ha⁻¹ as biomass, depending on the nature of the harvest prescription. This removal of biomass from the forest ecosystem represents a *long-term* loss of C that would otherwise contribute to soil development; however, the reduced stand density potentially allows for the reintroduction of fire and a re-establishment of natural fire intervals.

To illustrate this potential, we provide a hypothetical comparison of C storage in two forests over 200 years of future development (Figure 4). Both forests begin as the typical ponderosa pine stand of the inland northwest: a dense, unthinned forest that developed following logging

Table 2. Charcoal accumulated in the forest floor and surface mineral soil (0–10cm) of coniferous forest ecosystems

Stand type	Forest floor		Mineral soil	
	Charcoal (kg C ha ⁻¹)	Charcoal (% total C)	Charcoal (kg C ha ⁻¹)	Charcoal (% total C)
<i>Pinus ponderosa</i> / <i>Pseudotsuga menziesii</i>	10–336 ¹	0.1–1.11	4365–13 755 ²	13.6–26.4
<i>Pinus sylvestris</i>	140–1622 ^{3,4}	3.5–24	1398–4000 ⁵	12.9–43.2
<i>Pinus cembra</i> , <i>P. sylvestris</i> , <i>Picea abies</i>	na	na	10–30 000 ⁶	0.1–20
<i>Pinus virginiana</i>	4500	30 ⁷	na	na

Notes: ¹Forest floor, visual separation, gravimetric analysis (Brimmer 2006); ²Mineral soil 0–10 cm, chemical digestion, C analysis (Kurth *et al.* 2006); ³Forest floor, digestion, gravimetric analysis (Zackrisson *et al.* 1996); ⁴Forest floor, digestion, chemical analysis (Czimczik *et al.* 2005); ⁵Mineral soil 0–25 cm, digestion, chemical analysis (Schulze *et al.* 1999); ⁶Mineral soil whole profile, visual separation (Carcailet and Talon 2001); ⁷Forest floor, induction furnace, visual observation (Schiffman and Johnson 1988)

near the turn of the 20th century. In this scenario, both stands are thinned initially, but one treatment is followed by prescribed fire and the other is left unburned. The unburned stand is assumed to grow back to pre-treatment conditions and burn in two catastrophic crown fires, whereas the “restored stand” is maintained in an open condition through repeated prescribed surface fires on a 20-year average return interval. Under this scenario, both stands add aboveground biomass at a rate of 0.5 Mg C ha⁻¹ yr⁻¹ (Law *et al.* 2001) and the dead trees decay at a similar rate. After 200 years, the “restored” forest has accumulated 1.5 times as much aboveground biomass through the growth of large trees, while the other forest consists of a 60–70-year-old forest of small, albeit dense trees. The restored forest is underburned and then burned ten times in low-intensity fires, depositing 1.2 Mg C ha⁻¹ each time (with 50% lost each time to the subsequent fire), yielding 7.2 Mg charcoal C ha⁻¹ (over a 200-year period), increasing soil C storage and maintaining “restored” levels of surface fuels, litter, and duff. In contrast, crown fires in the other stand produce charcoal at a rate of 2% of standing biomass exposed to fire (as described above), yielding little increase in soil charcoal; however, the longer interval between fires allowed for build-up of surface fuels and high litter and duff levels. Figure 4 is not meant to accurately characterize shifts in ecosystem C allocation through management, but to illustrate how restoration may yield increases in total C storage through charcoal sequestration and reduced fire severity. As a corollary to this hypothetical scenario, Schiffman and Johnson (1988) demonstrated that the forest floor in a 50-year-old plantation of loblolly pine contained more C than the unburned “natural” forest and attributed this difference to the deposition of recalcitrant charcoal C during site preparation, which involved burning of forest residues distributed throughout the forest stand. In our scenario, there is less C accumulated in the

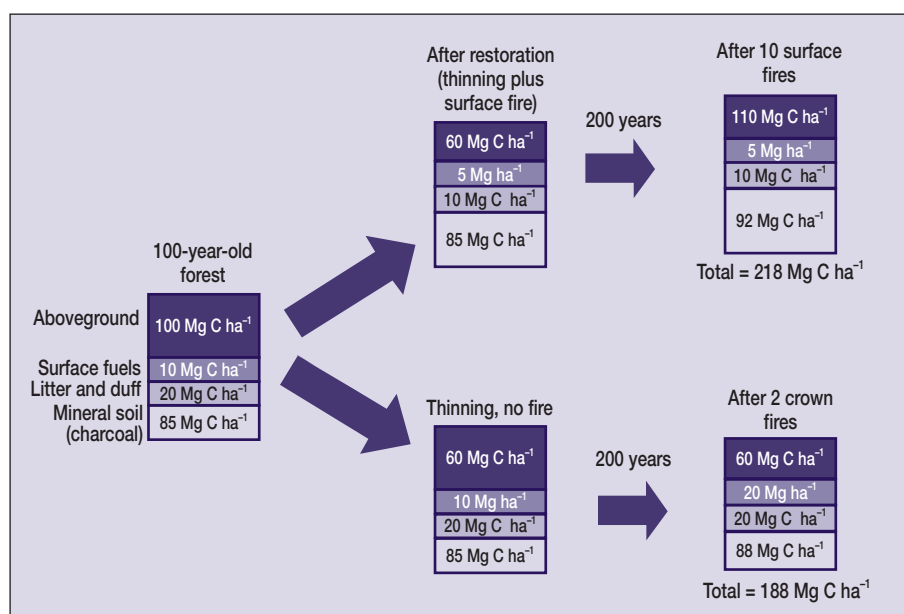


Figure 4. A hypothetical forest C sequence for a 100-year-old ponderosa pine forest that is subject to thinning, then subject to either: (1) prescribed fire followed by ten surface fires over a 200-year period, or (2) no prescribed fire and two stand-replacing crown fires over a 200-year period. Forests are assumed to be thinned to 60 Mg C ha^{-1} , following which stands accumulate C at a rate of $0.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ (Houghton et al. 2000; Law et al. 2001; Hicke et al. 2004). Two stand-replacing crown fires consume 30% of the stand, and generate charcoal at 2% of biomass exposed to fire twice during the 200-year period, with half of the charcoal being consumed in the second fire, yielding $1.8 \text{ Mg charcoal C ha}^{-1}$. The fire-maintained system is underburned, consuming 15 Mg of forest floor and woody debris (generating about $1.2 \text{ Mg charcoal C ha}^{-1}$) and then burns ten times during the 200-year period, generating $1.2 \text{ Mg charcoal C ha}^{-1}$ with each fire event, but losing half ($0.6 \text{ Mg charcoal C ha}^{-1}$) to consumption in the subsequent fire, yielding 7.2 Mg C ha^{-1} . Humus is formed at a rate of 3% of decaying wood, assumed to be 20 and 10 Mg C ha^{-1} as decaying wood for the crown fire and fire maintained systems, respectively.

duff and litter layer in the site regularly exposed to fire, but a greater proportion of what remains would be passive, highly recalcitrant C.

Salvage logging

Trees scorched during fire events represent charcoal accumulation at the base of snags and live trees that, along with wood, will ultimately be deposited onto the forest floor or into the soil environment. Salvage logging has few, if any, ecological benefits and numerous detrimental impacts, including poor stand regeneration, reduced biodiversity, degraded wildlife habitat, and degraded riparian condition (Noss et al. 2006). Not previously considered is the long-term impact of salvage logging on charcoal input to soil after fire. Clear-cut salvage of a lodgepole pine stand could result in the removal of about $0.8\text{--}1.2 \text{ Mg C ha}^{-1}$ as charcoal in a forest with trees scorched to a height of 3 m (Agee 1993), an average tree height of 16.9 m, total bark biomass of 10.8 Mg ha^{-1} , and a stem-to-total-aboveground-biomass ratio of 0.75:1 (Monserud et al. 2006). Cutting of trees in salvage logging operations also reduces the potential for tree-tip mixing of charcoal into the min-

eral soil, thus increasing the potential for loss during the next fire of charcoal left in the litter layer.

Conclusions

Charcoal represents an important component of the soil organic matter pool in temperate grasslands and forests. It contributes to the total water-holding capacity, ion exchange complex, and surface area of the soil environment. Once deposited in soil, charcoal is highly stable, having mean residence times 30–100 times longer than that of woody materials and 5–12 times greater than humic materials. Contributions to this pool are dependent upon the occurrence of fire events in which biomass is partially consumed. The amounts of charcoal formed during a given forest-fire event is highly variable and dependent upon fire severity and fuel composition; however, a safe estimate would be 1 to 4 Mg charcoal as C ha^{-1} . This stable form of C may be ultimately mixed into the mineral soil or it may be lost, either to biomass burning in a subsequent fire event or an erosion event. Erosion represents a loss only from the immediate ecosystem, as it will

ultimately be deposited in a lake or marine environment, where it may remain for millions of years.

The role of charcoal in the forest ecosystem is just now being explored. The long-term implications of fire exclusion and the elimination of charcoal deposition in forests are not well understood. Timber harvest without prescribed fire may be applied as a forest restoration tool; however, under these conditions, charcoal, as a passive C contribution to the soil system, will be eliminated and will lead to a modest, but long-term loss of C from the forest ecosystem. Conversely, restoration harvests that incorporate prescribed fire will more effectively emulate natural fire events and deposit charcoal across the activity unit. The importance of charcoal in soils and its contribution to long-term C storage requires greater consideration during ecological assessment, C modeling, and in forest management.

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