Soil Quality Is Fundamental to Ensuring Healthy Forests

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Abstract

Government agencies, industrial landowners, and private landowners often strive to maintain soil quality after site management activities in order to maintain site productivity, hydrologic function, and ecosystem health. Soil disturbance resulting from timber harvesting, prescribed fire, or site preparation activities can cause declines, improvements, or have no effect on site productivity and hydrologic function. In many cases, detailed soil resource data can be used to determine the stress level and ecosystem health of stands and may be one method used to determine the risk of disease or insect outbreak. Currently, organic matter accumulations in many forests exceed historical levels. Fire suppression or fire exclusion has produced numerous overstocked stands. When this condition is combined with increased climatic variation, drought, and type conversion, these stands have a high risk for catastrophic wildfire. The resulting large, high-intensity, and high-severity fires could contribute to changes in soil quality and lead to outbreaks of insects and diseases in many ecosystems. Changes in ecosystem processes can also be associated with changes in overstory properties that alter forest stand resilience. For example, loss of western white pine to blister rust infection in the Northwestern United States has caused a type conversion to forest species that are not tolerant of root diseases, are not fire resistant, and sequester nutrients in the surface mineral soil and tree crown that can later be lost through logging or fire. These relationships, and others, can be used in conjunction with soil resource data bases to assess susceptibility to threats and to help develop management strategies to mitigate disturbances. Development of monitoring strategies that use common methods that can be utilized by a variety of land management agencies and specialists is a key component for relating forest health to soil changes after fire or other land management activities.

Keywords: Fire suppression, forest health, soil indicators, sustainable forestry.

Soil Quality

Soil quality and function are interrelated concepts that represent the range of soil properties and their associated ecological processes. The National Forest Management Act of 1976 and related legislation direct U.S. Department of Agriculture Forest Service managers to maintain the productivity potential of national forest land. The British Columbia Ministry of Forests uses professional assessment to evaluate the impacts of management practices on organic matter (OM) losses (British Columbia Ministry of Forests 1997). Even with these mandates and laws, the concept of soil productivity has not been well defined, and the impact of timber removal or fire on the productive potential of soils is not well understood or easily measured (Powers and others 2005). Soil quality has been defined as the capacity of a soil to function within an ecosystem to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and others 1996). In addition, soil health definitions include maintaining the integrity of nutrient cycling and resilience to disturbance or stress (O'Neill and others 2005). Tree or stand growth has often been used as an indicator of soil productivity changes, but growth reductions attributable to management practices may take >20 years to become manifest in many North American ecosystems (Morris and Miller 1994). The forest floor is likely a key element in maintaining healthy ecosystems, but it is also the one most impacted by fire and forest management (Tiedemann and others 2000). Maintaining site organic matter at or near the ecosystem baseline levels may help reduce nutrient losses (McNabb and Cromack 1990), insect (Fellin 1980a) and disease (McDonald and others 2000) outbreaks, and may ultimately reduce many forest health problems. For example, Page-Dumroese and Jurgensen (2006) described baseline organic matter levels in 13 undisturbed forests around the Northwestern United States. The levels include measurements of downed wood, forest floor and mineral soil organic matter (OM), carbon (C) and nitrogen (N), and they can be used to determine when a site has excess or deficient organic matter stores. Carbon accumulation, as measured by forest floor depth or amounts of downed wood, can be a useful indicator of forest health because forests with OM levels above their historical baseline levels are at risk from increased insect and disease activities or high-intensity fires (Oliver and others 1994).

Wildfire Impacts

Active fire suppression during the 20th century has increased OM volume on the soil surface in forest stands that historically had supported a regular fire-return interval (Oliver and others 1994). It has been suggested that active fire suppression, together with selective harvesting of seral species, has resulted in a shift in dominance to shade-tolerant Douglas-fir (*Pseudotsuga menziesii*) and grand fir (*Abies grandis*) in many western forests (Mutch and others 1993, Swetnam and others 1995), and a build-up of fuels in other forest types such as ponderosa pine (Covington and Sackett 1984, DeBano and others 1998). A consequence of the advance in succession in some western forests and the suppression of fire in others is the increased accumulation of aboveground biomass and nutrients in standing live trees, standing dead trees, downed wood, and forest floor (Keane and others 2002, Major 1974). Particularly in the Western United States, this increase in OM biomass in fire-suppressed or fire-excluded forests has led to forest floor C accumulation far in excess of normal conditions. In the absence of fire, critical nutrients are tied up in this excess plant debris, possibly causing the site to become nutrient limited (Harvey 1994). Accumulations of woody residue and surface OM from fire suppression activities are also undesirable because of the increased risk from high-severity wildfires and slower OM decomposition rates (Covington and Sackett 1984).

Deep accumulations of organic material (those in excess of decomposition) are generally lost through fires (Oliver and others 1994). If the fires are frequent and of low severity, few organic matter (or nutrient) losses occur (Neary and others 1999, Page-Dumroese and Jurgensen 2006), but infrequent, high-severity fires can be catastrophic to soil productivity and forest health if significant amounts of biomass have accumulated (Habeck and Mutch 1973). Neary and others (1999) outlined the threshold temperatures for biological disruptions in soils. The cumulative impact of a catastrophic fire may directly affect belowground processes because it can alter nutrient inputs (soil macro- and microfauna), increase soil temperatures, increase erosion, alter evapotranspiration rates, and decrease moisture availability (Neary and others 1999). These detrimental impacts may also exacerbate insect and disease outbreaks (Harvey and others 1989, Jurgensen and others 1990).

Management Impacts

The Healthy Forest Restoration Act of 2003 was designed to help alleviate the accumulation of OM by using partial cuts and prescribed fires to remove small-diameter trees and surface OM from many forest stands. Prescribed fire and harvesting operations are important variables in determining soil OM losses because they both influence the removal of organic matter, C, and N on the soil surface and influence the amount of OM within the mineral soil profile. However, frequent repeated burns and multiple entries by mechanical equipment to reduce wildfire risk may impact ecosystem processes, soil quality and productivity, and site sustainability at a variety of scales (e.g., a cutting unit or an entire watershed).

Prescribed Fire

Prescribed fire, as a site preparation method or for underburning intact stands, is a major component of the restoration effort to reduce fuel levels in many forested ecosystems (McIver and Starr 2001). Prescribed fires produce a wide range of fire intensities, depending on fuel loads, fuel moisture content, slope position, and slope aspect (Brown and others 1991, Huffman and others 2001, Little and Ohmann

1988, Oswald and others 1999, Vose and others 1999). Fire severity is a term used to describe the impact of fire on both above- and belowground stand components (DeBano and others 1998, Keane and others 2002). Various burn indices have been developed to evaluate fire effects on ecosystem processes and soil productivity (Neary and others 1999), but three classes are commonly used: **low severity**—a non-lethal, low-intensity surface fire in which patches of surface OM are lost, **moderate severity**—a patchy fire that creates a mixed mosaic of fire intensities and all small-diameter (<7.6 cm) OM is consumed, and **high severity**—a stand-replacement fire that kills more than 90 percent of the trees, consumes most surface OM, and some OM in the mineral soil has been lost (mineral soil changes color) (Keane and others 2002). Information is needed on the impact of prescribed fire on soil OM content and distribution to evaluate the effects of fire management practices on residual fuel loads, soil erosion potential, and long-term site productivity (Elliot 2003, Neary and others 2000).

Because of the range of fire conditions possible in any given stand, the range of soil conditions will also be variable (Landsberg 1994). Often, reduced productivity or health of the remaining stand is influenced by the amount of injury to remaining trees, crowns, and roots, reductions in microorganisms in the surface mineral soil, and changes in C and other nutrient pools (Klemmedson and Tiedemann 1995, Page-Dumroese and others 2003). In addition, the impacts of prescribed fire are dependent on forest type and past management (Schoennagel and others 2004). Historically, dry forests of the Western United States (e.g., *Pinus ponderosa*, dry *Pseudotsuga menziesii*, etc.), which had a relatively short fire return interval and low fire intensity (Agee 1998), did not usually develop disease problems (like *Armillaria* spp.) when the fire return interval remained short (McDonald and others 2000). However, because these dry stands are water limited and have relatively shallow forest floors (Page-Dumroese and Jurgensen 2006), as fire exclusion and suppression increase, so does the stress and competition between trees for limited water and nutrient resources (McDonald and others 2000).

The combined effects of harvest operations and prescribed burning on the remaining forest slash may severely impact mesofauna living in the forest floor by either directly killing them or removing their desired food source (Fellin 1980b). This includes both pests and beneficial insects. For instance, predators and parasites of spruce budworm that live in the forest floor may help to regulate budworm numbers at low levels so that existing populations do not reach epidemic proportions (Fellin 1980b). Stands affected by low-severity fires, which can leave many unburned areas of the forest floor, may provide a favorable location for maintaining important insects in the forest floor and ensuring that decomposition and nutrient cycling processes continue (Fellin 1980b).

Results of studies of repeated prescribed fires on soil quality and forest health are mixed. Annual or biannual prescribed fires have been shown to reduce pools of C, N, and sulfur (S) in the forest floor after 30 years (Binkley and others 1992). Burning on a 2-year interval for 20 years reduced N from both the forest floor and mineral soil (Wright and Hart 1997). However, a study of prescribed fire at intervals of 1, 2, 4, 6, 8, and 10 years in ponderosa pine resulted in an increase of soil C and N (Neary and others 2002). These long-term changes in nutrient status may or may not affect long-term site productivity (Jurgensen and others 1997), but on some sites they could affect insect and disease outbreaks (Harvey and others 1989). For example, the introduction of white pine blister rust (*Cronartium ribicola*) in the Western United States has reduced the number of 5-needled pines (e.g., *Pinus monticola* or *P. lambertiana*) in many ecosystems (Monnig and Byler 1992). These pines, along with ponderosa pine (*P. ponderosa*) and western larch (*Larix occidentalis*) tend to be broadly adapted species (Rehfeldt 1990) and are relatively tolerant to many native pests. However, in the absence of fire, they are strongly reduced and are more susceptible to nonnative pest outbreaks (Harvey 1994). This shift from more tolerant species has also reduced nutrient cycling within the surface organic matter and mineral soil (Harvey 1994). Typically, more carbon is held in aboveground biomass when there is a compositional shift toward less tolerant species, and this can result in more plant stress when available moisture is low (McDonald 1990).

Mechanical Soil Disturbance—

Soil displacement (removal of surface organic and mineral soil) is most often measured by the amount of forest floor removed. Loss of surface OM either by equipment or through accelerated erosion may produce detrimental changes if it is moved off site, is unavailable to tree roots, or if mineral soil removal results in exposing subsoil horizons. However, careful placement of harvesting and yarding layout in ground-based units could mitigate some detrimental displacement. For instance, McIver and others (2003) noted that when displacement along the edge of trails is included (i.e., displacement caused by the harvester moving close to trails to cut logs) in the inventory, displacement can be extremely variable (5 to 43 percent). However, if soil displacement along trail edges was excluded from the site inventory, displacement was no greater than USDA Forest Service guidelines of 15 percent. The report by McIver and others (2003) and the information in Curran and others (2005) both stress that it is imperative to have uniform terms for describing soil disturbance to improve our techniques for tracking the consequences of forest practices on soil productivity and forest health.

Often soil erosion is not a significant problem on slopes that have some soil cover. Using information about slope, amount of the hillside with some soil cover, and local precipitation values, Page-Dumroese and others (2000) noted that in many cases, soils with at least 50-percent soil cover did not produce more than 2 to 4 mg ha^{-1} of soil erosion. In some cases, removal of soil from the upper slope to somewhere downslope may reduce upslope productivity, but increase downslope productivity. However, if soil is moved off site, productivity is reduced permanently (Elliot and others 1998). Both onsite and offsite soil movement results in lower soil productivity for part of the slope because of loss of nutrients, water-holding capacity, and rooting depth, and it may also impair forest health on that portion of the landscape. Combining soil-cover loss with compaction can accelerate erosion rates above the natural soil formation rates (Elliot and others 1998). Soil loss is only one problem associated with accelerated erosion. Often N, C, and cation exchange capacity are also moved offsite with the moving soil (Page-Dumroese and others 2000). Erosion rates are usually highest immediately after soil is disturbed mechanically or as a result of fire (Robichaud and Brown 1999).

Minimizing soil compaction during harvesting and mechanical site preparation operations on forested lands is critical for maintaining the productive capacity of a site (Powers and others 2005). Compaction increases soil bulk density and soil strength, decreases water infiltration and aeration porosity, restricts root growth, increases surface runoff and erosion, and alters heat flux (Greacen and Sands 1980, Williamson and Neilsen 2000). These changes can lead to substantial declines in tree growth and forest health (Froehlich and others 1986, Gomez and others 2002) or, conversely, have little impact (Powers and others 2005). Significant changes in soil physical properties occur more often on fine-textured soils than on coarse-textured soils (Page-Dumroese and others 2006), and knowing basic site conditions like texture and soil moisture content along with designating skid trails or providing operator training may help reduce undesirable soil conditions and maintain long-term productivity (Quesnel and Curran 2000).

Most forests are dependent on a variety of biological processes to regulate nutrients and cycle organic matter. For instance, forest diseases such as *Armillaria* and *Annosus* root diseases are a key ecosystem process to recycle carbon (Harvey 1994), but they can also expand to epidemic proportions if conditions are favorable. Trees not adapted to a site, wounded during thinning operations, growing on compacted soils, or in areas of disturbed hydraulic function, are at risk from both disease infection (Goheen and Otrosina 1998, Wiensczyk and others 1997) and insect outbreaks (Larsson and others 1983). In a study in loblolly pine (*Pinus taeda*) plantations, *Annosum* was positively correlated with areas of higher bulk density that had stressed numerous trees (Alexander and others 1975). Low vigor, stressed forest stands are also susceptible to insect attacks (Larsson and others 1983). The recent outbreak of mountain pine beetle (*Dendroctonus ponderosae*) in British Columbia, Canada, and the Pacific Northwest of the United States have caused significant changes in water flow, soil moisture, and groundwater levels in many forest stands (Uunila and others 2006). These changes in water abundance and timing can affect the health of subsequent stands by changing annual water yields, times of low flow and peak flows (Uunila and others 2006).

Acidic Deposition and Forest Health

The risks posed by atmospheric deposition to forest health are complex because of distinct regional patterns of deposition and temporal variations in air quality (McLaughlin and Percy 1999). However, air pollution stresses in North American forests and their impact on insect and disease incidence are a major consideration in both the United States and Canada (McLaughlin and Percy 1999), particularly in the eastern part of North America. One potential threat from changes in air quality on many forested lands is the altered nutrient balance and soil acidity (Adams and others 2000), which then affect insect and disease outbreaks. Soil impacts and threats to forest health can be caused by nitrogen (N) saturation (Aber and others 1989), depletion of basic cations due to increased leaching (Federer and others 1989), and altering nutrient availability (Robarge and Johnson 1992). Combined, all these nutrient stresses may cause long-term declines in site productivity (Likens and others 1996) and may increase the number and severity of disease or insect outbreaks (McLaughlin and Percy 1999). Soil processes altered by deposition of air pollutants also alter the way forests grow and respond to biotic and abiotic stresses within their regional environments. The potential for large-scale forest health changes becomes greater over time (McLaughlin and Percy 1999).

Monitoring

Current soil monitoring efforts primarily address changes in soil quality through measures of compaction, pH, water infiltration, hydrologic function, water availability, and plant-available nutrients, but do not address ecological function of a site (van Bruggen and Semenov 2000). Ecological function may be difficult to assess because of season, management, or climate variables. Potential approaches to assess ecological function can include techniques that extract DNA to determine microbial species composition (Zhou and others 1996), determine substrate utilization (i.e., Biolog) to trace microbial communities (Bossio and Scow 1995), or decomposition of a wood substrate (Jurgensen and others 2006). In addition, levels of root pathogens or disease suppression organisms could also be considered as potential bioindicators of soil health (Hoeper and Alabouvette 1996, Visser and Parkinson 1992).

In North America, several forest monitoring programs, [i.e., Forest Health Monitoring (FHM, U.S.A.), Acid Rain National Early Warning System (ARNEWS, Canada), North American Maple Project (NAMP, joint United States and Canada), Forest Inventory and Analysis (FIA, U.S.A.)] have been developed as a result of studies that indicated widespread changes in forest health (McLaughlin and Percy 1999). Many of these “tree” monitoring programs also include soil indicators in their protocols (O’Neill and others 2005). In addition, the Montréal Process (an international effort to develop criteria and indicators of forest sustainability) is working to provide a common framework for describing soil changes by using two important soil characteristics: significantly diminished organic matter and significant compaction (Montréal Process Working Group 1997). The USDA Forest Service is mandated to monitor management impacts on soil productivity, site resiliency, and long-term productivity (Johnson and Todd 1998, Jurgensen and others 1997, Page-Dumroese and others 2000) and is part of an international, multiagency effort to pursue correlation and common definitions of practical standards for soil disturbance and maintenance of forest productivity capacity (Curran and others 2005).

There are numerous tools available to monitor a forest site or soil for changes over time or after wildfire, prescribed fire, or mechanical disturbances. Together, forest and soil monitoring data can provide a backdrop for current conditions and trends in forest health. Successful forest and soil monitoring programs must:

- Be simple to use.
- Have repeatable methods that are useable by nonspecialists.
- Provide meaningful results.
- Comprise collaborative efforts between both scientists and various government agencies.
- Provide a compelling link between soil properties and forest growth or health.

Summary and Management Implications

Solutions to the current forest health problems are neither clearcut nor easily managed (Tiedeman and others 2000). However, maintenance of the forest floor during prescribed fire or mechanical forest treatments will help to maintain soil quality, soil health, and ultimately forest health (Fellin, 1980a, Page-Dumroese and Jurgensen 2006). The indirect influence of changing microclimatic conditions of the forest floor will depend on the kinds of site treatment and the condition of the previous stand. Overcrowded and fire-suppressed stands will likely differ in their response to treatment than more open-grown stands. Similarly, stands with seral species will respond differently to nutrient, water, insect, and disease stressors than those stands occupied by less tolerant, narrowly adapted species (Harvey 1994). Forest health can be successfully managed if we shift the focus from just "tree health" to entire ecosystem health. Current levels of pest problems are not due only to a single organism, but to the complex of environmental conditions and stand histories that determine stand resilience to pest outbreaks. Healthy and resilient forest soils can also help limit the extent of forest pest problems.

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