Chapter 9.

# Cumulative Effects of Fuel Treatments on Soil Productivity

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## Introduction

Soil quality, function, and productivity potential are interrelated concepts that cover the range of soil properties and their associated ecological processes. Since the passage of the National Forest Management Act in 1976 (NFMA) and related legislation, management of National Forest lands must be done is such a way as to maintain their productive potential as demonstrated through implementation, effectiveness, and validation (research) monitoring. However, the concept of site productivity is not well defined, and the impacts of timber removal or fire on soil productive potential are not well understood or easily measured (Powers 2006). Two main factors make it difficult to define: (1) the variability in soil and climatic conditions across forest sites and (2) the length of time it takes for trees to reach a predictive age. If tree (or vegetative) growth is used as an indicator of productivity, it may take more than 20 years before the consequences of various management practices in many North American ecosystems can be evaluated (Morris and Miller 1994).

In response to this problem, a number of soil-based indices have been proposed as indirect measures of forest site productive potential. For example, Burger and Kelting (1998) suggest that soil monitoring should vary by soil, site, and management practice. Powers and others (1998) recommend establishing a baseline from a soil survey, then use one physical (soil strength), one chemical (anaerobically mineralized nitrogen N), and one biological (soil fauna activity) index to monitor changes in soil properties. Other soil measures of site productivity have been proposed (Burger 1996; Curran and others 2005a; Herrick 2000; Powers and others 1990), but the link between soil indices and site productivity are not conclusive (Curran and others 2005b; Powers and others 1990, 2004). The data from these studies show that soil compaction and organic matter (OM) removal are important drivers in many ecosystem processes, and the maintenance of adequate soil porosity and OM content is important for continued site productivity and ecological function (Jurgensen and others 1997; Powers and others 2004).

Active fire suppression in the western United States during the 20th century has led to OM accumulation in many forest stands that historically supported a regular fire return interval (Oliver and others 1994; Page-Dumroese and others 2003). Forest stands high in OM levels are usually undesirable because of the increased risk from high intensity wildfires and slower OM decomposition rates (Covington and Sackett 1984). These accumulations of woody residue and surface OM from fire suppression activities are likely above the range of natural variability for these ecosystems and would be susceptible to a correspondingly higher loss during a wildfire (Mutch 1995; Page-Dumroese and others 2003). However, previous human disturbances make it difficult to determine baseline, stand level OM values. Fire suppression has also altered tree density, growth, vigor, and susceptibility to diseases and pests (Kilgore 1981), but the effects of this practice on soil properties are unclear (Monleon and others 1997). For instance, fire suppression can result in stagnant nutrient cycles and, therefore, decreased nutrient availability and tree growth (Biswell 1973; Covington and Sackett 1990). Conversely, current growth of ponderosa pine trees on some sites is higher than growth predicted from yield tables developed shortly after fire exclusion (Cochran and Hopkins 1991), which is attributed to a negative impact of fire on soil productivity.

Since the enactment of the Healthy Forest Restoration Act in 2003, forest management decisions to reduce wildfire risk have increasingly relied on partial cuts and prescribed fire to remove small diameter trees and surface OM from forest stands. Low intensity prescribed underburning, thinning, and combined thinning and burning practices are major components of the restoration effort underway in many forests to reduce fuel loads and fire hazards (Stephens and Finney 2002). Such repeated burns and multiple stand entries by mechanical equipment may have cumulative impacts on ecosystem productivity and sustainability at different scales, such as within a cutting unit or an entire watershed (Curran and others 2005a). In this paper, we discuss the effects of mechanical thinning and prescribed fire on soil compaction and OM pools and the impact this could have on residual fuel loads, soil erosion potential, and long-term site productivity (Elliot 2003; Harden and others 2000; Neary and others 2000).

# Thinning

Many studies have documented the impacts of clearcut harvesting on soil physical properties, especially compaction (Miller and Anderson 2002; Page-Dumroese and others 2006; Powers 2006; Powers and others 2004). Similar harvesting equipment is also used in thinning operations and could result in soil compaction on repeatedly trafficked areas. Single equipment passes under specific soil moisture and equipment loading conditions (for example, moist soil, fully mechanized harvesting as demonstrated in Curran and others 2005a). Compaction increases soil bulk density and 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). Total pore space is also reduced, especially the volume of large pores (macropores), which are usually filled with air (Siegel-Issam and others 2005). Poor aeration due to compaction is often cited as a cause of declining root growth (for example, Ruark and others 1982; Zaerr 1983). The susceptibility of soil to compaction is a function of soil texture and original bulk density (Page-Dumroese and others 2006; Powers and others 2005; Williamson and Neilson 2000), soil moisture content (Froehlich 1978; Moehring and Rawls 1970), soil OM content (Adams 1973; Howard and others 1981), the number of machine passes (Soane 1990), and the type of machine applying the load (Han and others 2006). Compaction alters air filled pores, which restricts $O_2$ movement and creates anaerobic conditions (Linn and Doran 1984), causes the accumulation of $CO_2$ (Conlin and van den Driessche 2000), and reduces the physical habitat of soil macro- and micro-fauna (Hassink and others 1993).

It is assumed that minimizing soil compaction during a timber harvesting operation is critical for maintaining the productive capacity of a site (Powers and others 2004). While soil compaction can cause substantial declines in tree growth and health in some stands (Conlin and van den Driessche 1996; Froehlich and others 1986; Gomez and others 2002; Heninger and others 2002), they can have little or no impact on growth in others (Powers and others 2004). Growth reductions may occur on both coarse- and fine-textured soils (Cochran and Brock 1985; Froehlich and others 1986; Smith and Wass 1980); however, the reduction of macropore space on course-textured soils may increase soil available water holding capacity and thereby increase tree growth (Gomez and others 2002).

Compaction from repeated trafficking on the same plot of land is the most common cumulative soil effect of mechanical site treatments (Geist and others 1989). However, traffic over many portions of a watershed may also lead to dispersed cumulative impacts in the form of lighter compaction affecting a larger area (Curran and others 2005a). Thinning method also has a strong influence on the degree and extent of soil compaction. For example, cut-to-length logging, particularly on slopes less than 35 percent, can result in spatially dispersed traffic patterns if harvesting machine operators can choose their route to a landing. While this type of logging may show fewer surface impacts (displacement and visible machine tracks or ruts) than thinning with designated skid trails, most compaction occurs in the first few passes and soil damage may be more widespread (Curran 1999; Williamson and Neilsen 2000). Log-forwarder impacts occur mostly on main trails without slash mat protection or near landings, locations where the forwarder makes repeated passes. Using skyline logging systems to thin a stand usually results in soil compaction at the landings or is associated with dragging heavy logs. In northeastern Oregon, both skyline logging and harvester/forwarding operations produced less than 10 percent soil compaction on a number of sites (McIver and others 2003). This amount of compaction is much lower than that found in other harvesting studies from the northwest United States (Allen and others 1999; Froehlich and others 1986; Geist and others 1989). These variable results could be due to differences in harvesting techniques, which in turn affects the amount of soil compaction. Leaving slash from thinning or other harvest activities on skid trails has the potential to help buffer machine traffic to lower the impacts on the mineral soil (Han and others 2006), as does thinning a stand when the soil is dry (Han and others 2006), frozen (Bock and van Rees 2002), or has adequate snowpack (Curran 1999). Consequently, managers have a number of options when they need to reduce fuel over large areas.

Another soil disturbance that may occur as a result of compaction and displacement is soil erosion. When surface moisture is impeded from infiltrating it can result in increased overland flow that can cause erosion and effect off-site resources and water quality. Prudent attention to drainage control and access network planning, construction, and maintenance can help minimize risks associated with erosion. An erosion hazard key is discussed later, under planning and monitoring.

# Underburning

Underburning is a low intensity prescribed fire that is used to reduce fuel loads and fire hazards in overstocked stands (Monleon and others 1997). Since fire suppression caused a shift in forest structure, frequent underburnings are one method used to restore stands to pre-European settlement fire regimes (Bork 1985). The impacts of prescribed underburning on fuel loads and surface soil conditions can vary considerably depending on fuel characteristics and loading, soil climatic conditions at the time of burning, and resulting soil burn severity (Gundale and others 2005). Nitrification and N-mineralization showed strong positive correlations with fine fuel consumption after underburning in a Montana ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws) stand (Gundale and others 2005). In contrast, underburning a ponderosa pine stand in central Oregon resulted in a long-term (12 years) decrease in available N, even though short-term increases were found in the surface (0 to 5 cm) mineral soil immediately after the fire (Monleon and others 1997). This lowering of soil N levels and subsequent decrease in tree growth after underburning may support the supposition that fire suppression will increase soil fertility (Cochran and Hopkins 1991).

Underburning alone or in combination with thinning can alter microbial communities in a forest stand by increasing the temperature of the post burn soil surface or changing the availability of organic substrates (Gundale and others 2005). Many studies have shown that soil heating during the burn results in a substantial short-term loss of microbial biomass or a shift in community structure (Choromanska and DeLuca 2002; Korb and others 2003; Pietikainen and Fritze 1995). These changes, and their duration, are the result of the interactions of fuel load, fuel moisture content, weather conditions, landscape position, light-up sequence, and resulting fire behavior and resident time combined with heat transfer variability within the soil profile (Busse and others 2005; Hungerford and others 1991). If a prescribed underburn occurs after a stand is thinned, the increased fine fuel load usually results in a higher intensity fire, more OM loss, and changes in soil C and N (Pietikainen and others 2000). Total C in the surface OM can also be significantly higher after thinning alone as compared to thinning and underburning (Gundale and others 2005), but is dependent on the amount of C in the undisturbed stand (Page-Dumroese and Jurgensen 2006). The lowering of surface C and N pools by underburning is normally short lived, as OM accumulates from the residual trees (Gundale and others 2005).

The intent of underburning is to produce a low intensity, fast moving fire that leaves much of the humus layer intact (McCandliss 2002) to protect the mineral soil from raindrop splash and erosion. However, if large fuel (>7 cm diameter) are dry during the underburning, there can be a significant reduction in the amount of coarse wood on the soil surface (Youngblood and others 2006), which may affect many species of fungi, cryptogams, invertebrates, and vertebrates (Harmon and others 1986). The amount of woody residue remaining in a stand after underburning will vary depending on fuel load, moisture content, fire intensity, residence time, and suppression activity. Compared to other methods of fuel treatment (thinning, thinning and underburning combined), underburning alone usually results in the lowest quantity of residual coarse wood. For example, underburning resulted in less than 30 logs/ha, thinned and burned stands ~50 logs/ha, thinning alone ~150 logs/ha, and the control stand had larger than 200 logs/ha (Youngblood and others 2006). Of these residual logs, decay class 5 logs (Triska and Cromack 1979) comprised 18 percent of the coarse woody residue in the thinned only and control treatments, but were only 7 percent in the underburned and the thinned and burned treatment (Youngblood and others 2006).

# Planning and Monitoring

The development of a hazard assessment process to determine how sensitive a soil may be to mechanical and/or fuel reduction treatments can help minimize risk on forest sites and watersheds. For example, the Forest Practices Code of British Columbia, now replaced by the Forest and Range Practices Act (Province of BC 2004), defines site hazards as a combination of soil texture, coarse fragment content and soil moisture regime. This, in turn, can help guide practitioners in deciding on the appropriate types of equipment to be used, the harvest and maintenance schedule, or type of harvest operation (see Erosion Hazard key as an example in table 1, which is based on science and rationale presented in Carr and others 1991, with updates based on the research of Commandeur 1994). The Weyerhaeuser Company assesses risk to site productivity from all types of management activities to site productivity for each soil mapping unit, largely based on soil physical properties (Heninger and others 1999). The risk ratings are based on modal soil characteristics for each soil series and site factors. Principles behind risk rating with further examples are discussed in Curran and others (2005b, 2007). Compaction, displacement, erosion, and slope stability risks are often interpreted from soil mapping (that needs to be verified onsite) or site specific data collected for harvest planning (for example, as per Curran and others 2000) and prescribed fire assessments. Harvesting,

**Table 1.** Example of a hazard rating system for surface soil erosion within a cutting unit (adapted from the British Columbia Ministry of Forests from the Forest Practices Code soil disturbance hazard guidebook, currently available in Curran and others 2000).

| | Degree of contribution of factors | | | |
|---|---|---|---|---|
| **Site factors** | **Low** | **Moderate** | **High** | **Very High** |
| Climate precipitation factor | Low | Moderate | High | Very high |
| **(points)** | **2** | **4** | **6** | **8** |
| Topography | | | | |
| slope gradient (%) | 0-10 | 11-20 | 21-50 | >50 |
| **(points)** | **1** | **3** | **6** | **9** |
| length/uniformity | Short broken | Short uniform | Long broken | Long uniform |
| **(points)** | **1** | **2** | **3** | **4** |
| Depth to water-restricting layer (cm) | >90 | 61-90 | 30-60 | <30 |
| **(points)** | **1** | **2** | **3** | **4** |
| Surface soil detachablity (0-15 cm) | SC, C, SiC | SiCl, Cl, SCL | SL, L | Si, SiL, fSL, LS, S |
| **(points)** | **1** | **2** | **4** | **8** |
| Surface coarse fragments (0-15 cm) | >60 | 31-60 | 16-30 | <16 |
| **(points)** | **1** | **2** | **3** | **4** |
| Subsoil permeability (16-60cm) | S, LS, SL, fSL | L, SiL, Si | Cl, SCl, SiCl | SC, SiC |
| **(points)** | **1** | **2** | **3** | **4** |
| Erosion hazard rating | **Low** | **Moderate** | **High** | **Very High** |
| **(point total)** | **<16** | **16-22** | **23-31** | **>31** |

thinning, and underburning strategies have been described for meeting soil disturbance standards under site conditions in western Washington and Oregon by Heninger and others (1997) and for Interior BC by Curran (1999). The objective is to match site treatment to site disturbance sensitivity. Ground based equipment may be restricted to designated trails or allowed to travel overland depending on the soil and climatic conditions (in other words, dry soil, frozen soil, or snowpack).

Assessing soil changes associated with management is a critical step toward understanding which sites are amenable to trafficking or burning treatments. Generally, monitoring after underburning or thinning activities is collected through transect sampling of continuous line or point data (for example, Howes and others 1983; BC Ministry of Forests 2001, respectively). However, soil quality evaluations must also assess cumulative management impacts at a landscape scale, which is much harder to accomplish than a simple point sampling methodology. When working in larger areas, sampling schemes can be stratified (for example, by soil texture, parent material, vegetation type, harvest methods, etc.) to improve sampling efficiency and reduce costs (Herrick 2000).

Visual disturbance class indicators (Curran and others 2005b) have been used to assess soil displacement or compaction severity after mechanical operations. Such visual class systems are also amenable to the collection of burn severity categories (fire caused changes to soil hydrologic function as evidenced by soil characteristics) and to visually evaluate the extent of burning into the mineral soil and loss of forest floor and surface fuel (Ice and others 2004). The visual assessment of surface OM changes after thinning or underburning is often used as a surrogate or proxy for changes in soil properties. These properties are associated with loss of soil aggregates and increased erosion, which could indicate a loss of site productivity. Placing management impacts in the broader context of the range of natural variability observed before harvesting is another appropriate method for evaluating the consequences of thinning and underburning (Bock and Van Rees 2002; Grigal and Vance 2000; Landres and others 1999; Pennock and van Kessel 1997). Using baseline data from non-harvested stands will help quantify the magnitude of variability so that change in a soil property can be gauged against this variability and help define the processes that thinning or underburning operations influence (Grigal and Vance 2000; Page-Dumroese and others 2000).

Changes in soil OM can also be used as an indicator of soil biological activity and, indirectly, the effect of thinning and underburning on soil quality and site sustainability (Weil and others 2003). Weil and others (2003) developed a simple method to measure active soil C and they note that a change in the labile OM fraction can give an early indication of soil degradation.

All of the methods listed above need to be applied in an adaptive management framework that will allow for changes in methods and procedures as new information or techniques become available (Curran and others 2005c). This adaptive process will ensure that the monitoring of thinning and underburning treatments is using best management practices, coordinating development of training materials and tools, and reporting post treatment evaluations.

Long term research projects are one of the best methods for quantifying the consequences of fuel reduction treatments and evaluation of monitoring strategies. Development of effective and practical methods for assessing changes in soil productivity has been the major focus of the North American Long Term Soil Productivity (LTSP) study (Powers and others 2004). Although designed to measure the long-term impacts of compaction and OM removal after clear-cut timber harvest, this study will also help to validate soil quality standards and monitoring changes in soil productivity after fuel reduction operations. While the LTSP study did not have a fire component, the Fire and Fire Surrogate study was established nationwide to evaluate the ecological impacts of thinning and burning treatments on vegetation, fuel, soils, and other ecosystem functions (Weatherspoon 2000).

# Conclusions and Management Implications

Restoration treatments used to restore or enhance ecological processes and/or structure to a forest stand usually involve some variations of thinning and burning. Numerous soil impacts can occur from these treatments, but the impacts can be quite variable, depending on both manageable factors and inherent site sensitivity factors, which together dictate the severity and extent of compaction and burn severity. Manageable factors include equipment configuration and use, decisions on fuel arrangement and moisture levels, light-up sequence, and resulting fire behavior, all timed to take advantage of seasonal soil conditions to minimize impacts. Inherent site sensitivity depends on soil texture and mineralogy, coarse fragment content and arrangement, and organic matter levels and rooting, among other factors. The impacts of commercial or pre-commercial thinning operations (with or without burning) on residual tree growth will have to be measured to calibrate (validate) soil disturbance proxies and feed results into practice improvements to ensure sustainable productivity. When pre-treatment data is available, post-treatment monitoring can use soil disturbance proxies to provide an indirect measure of the impact that a fuel reduction treatment will have on soil properties that are currently considered to control productivity and hydrologic function. The results from these monitoring studies need to be validated against subsequent tree or stand growth. In contrast to clear-cut harvesting, the impacts of thinning operations on changes in soil quality can be difficult to quantify. Although the impacts of thinning operations on soil properties can be assessed relatively easily, the associated changes in site productivity are not documented. Thinning reduces total stand biomass, but can increase the growth of individual trees (Karlsson 2006; Liechty and others 1986). If the response of stand productivity to thinning is only measured on the residual trees, the negative impacts of soil compaction could be masked by the increased growth of the remaining trees.

Increasingly, managers must balance biomass removal to reduce wildfire risk with maintaining soil productivity. Thinning and underburning treatments require accurate monitoring of soil impacts using proxies that are calibrated against longer term effects over time. In the interim, these proxies need to be based on best available science and disturbance limits conservatively set to ensure that productivity and hydrologic function will be maintained. The wide variability in forest soil properties makes this a challenging task. However, by using risk rating systems, various soil factors affecting site sensitivity (response) can be organized and managed during planning and operations. The objective is to identify the inherent site sensitivities and/or seasonal soil conditions that create vulnerability to negative impacts of the selected fuel reduction treatments.

These include factors such as specific soil texture, rock content, low soil fertility, a high proportion of OM pools on the soil surface, or topographic features. Successful fuel reduction monitoring protocols must use proxies that integrate the correct combination of chemical, physical, and biological properties and are calibrated to demonstrate the maintenance of long-term productivity. Use of best management practices (for example, site characterization, Curran and others 2000), detailed soil inventory, use of models to predict erosion (for instance, WEPP), thinning and underburning strategies to minimize disturbance, climatic considerations, soil disturbance monitoring, and prudent use of rehabilitation, all in an adaptive management approach (Curran and others 2005a and b), will help limit localized soil damage and reduce the potential of cumulative fuel reduction effects within a watershed. Ultimately, net primary productivity is the measure to determine the positive or negative impacts of thinning and underburning treatments and will have to be measured in controlled experiments that also calibrate the operational disturbance proxies. Consequently, the results from the North American LTSP network, the Fire and Fire Surrogate study, and other long-term studies must be an integral part of the effort to evaluate both short and long-term impacts of fuel reduction treatments on soil productivity and the validation of monitoring protocols and standards.

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