Monitoring Changes in Soil Quality from Post-fire Logging in the Inland Northwest

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Abstract—*The wildland fires of 2000, 2002, and 2003 created many opportunities to conduct post-fire logging operations in the Inland Northwest. Relatively little information is available on the impact of post-fire logging on long-term soil productivity or on the best method for monitoring these changes. We present a USDA Forest Service Northern Region study of post-fire logged sites using a variety of methods to assess changes in soil productivity and site sustainability after timber harvesting activities. The disparate soil and climatic conditions throughout the Northern Region made it an ideal area to study post-fire logging operations. Our results indicate that post-fire logging during the summer creates more detrimental disturbance (50% of the stands) than winter harvesting (0% of the stands). In addition, on the sites we sampled, equipment type (tractor > forwarder > rubber-tired skidder) also influenced the amount of detrimental disturbance. Number of sample points is a critical factor when determining the extent of detrimental disturbance across a burned and harvested unit. We recommend between 80 and 200 visual classification sample points, depending on confidence level. We also provide a summary of methods that will lead to a consistent approach to provide reliable measures of detrimental soil disturbance.*

Introduction

During the last century, wildfires in the western USA have been viewed by many land managers and the public as catastrophic events (Kuuluvainen 2002). Until recently, fire suppression has been used to control the extent of these fires, but now stand-replacing fires are occurring on many Federal lands in the western USA. Consequently, the standard policy on many National Forests has been to harvest fire-killed trees for economic value before they decay (Lowell and Cahill 1996; McIver and Starr 2001). Proponents and opponents of post-fire logging are abundant (Beschta and others 2004; Sessions and others 2004; Donato and others 2006), but one critical issue of concern to each group is the impact of this practice on the soil resource.

Wildland fires can impact more than 10,000 ha of forest land at one time and, combined with post-fire logging, significant soil impacts can occur. Loss of surface organic matter and nutrients from the fire, increased decomposition from increased insolation, decreased soil porosity, increased erosion, and compaction may all combine to alter site productivity after wildfire and post-fire logging activities (Poff 1996). There are no specific methods that directly assess the impact of post-fire logging on soil productivity, but many methods for measuring proxies exist (see Burger and Kelting 1999; Schoenholtz and other 2000). Measures of wood production, net primary productivity, or changes in some specific soil properties (e.g. bulk density, forest floor depth,

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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cover type, etc.) can all be readily determined, but the link between forest management, soil properties, and site sustainability is not easily obtained.

Historically, maintenance of soil productivity on public lands in the USA has been governed by the Multiple Use Sustained Yield Act of 1960, the Forest and Rangeland Renewable Resources Planning Act of 1974, and the National Forest Management Act of 1976. As an outgrowth of these policies, each USDA Forest Service Region developed soil quality standards and guidelines, which were designed to act as a first warning of reduced site productivity after harvest and site preparation operations. The general concepts and the basis for the various guidelines are described in Griffith and others (1992). Lacking better methods, these standards and guidelines have also been used to evaluate soil productivity changes after wildfire and post-fire logging.

Concern about an accurate assessment of soil properties has expanded because of the growing public interest in the consequences of forest management practices on soil quality and its productive capacity (Burger and Kelting 1999; Schoenholtz and others 2000). Worldwide initiatives including the Helsinki Process (1994) and the Montreal Process (1995) have resulted in the development of criteria and indicators for monitoring sustainable forestry practices at broad levels (Burger and Kelting 1999). Recently, progress has been made on developing a common approach to soil monitoring in northwestern North America (Curran and others 2005). The key questions are: What do we measure and what does it mean? The literature is rife with examples of how a soil chemical, physical or biological property may contribute to changes in biomass production, hydrologic function, or ecosystem sustainability (see Schoenholtz and others 2000 for a summary). However, as budgets and personnel dwindle, land managers need a visual assessment of disturbance that can be completed quickly, efficiently, and easily by either field soil scientists or others trained in the assessment process (Curran and others 2005).

Wildfires and post-fire logging generate unique soil surface conditions. Visual disturbance criteria estimate the amount of detrimental disturbance and may need to be specifically designed to encompass the impacts of both fire and logging. Therefore, the objectives of our study were to: (1) determine the magnitude and areal extent (as defined by current soil quality standards) of detrimental disturbance from wildfire and post-fire logging across the Northern Region of the USDA Forest Service, (2) determine the most appropriate spatial sampling design methods for assessing the magnitude of soil impacts, and (3) develop visual criteria that can be used following post-fire salvage harvests to assess disturbance across disparate soil and climatic regimes.

Methods and Materials

Site Descriptions

In the summer of 2004 and 2005, post-fire logging sites were located on the Custer, Helena, Bitterroot, Kootenai, Lewis and Clark, Flathead, and Lolo National Forests (Table 1). Thirty-six stands were sampled over 2 field seasons; 20 had been post-fire winter logged and 16 were post-fire summer logged. Sites were selected by local soil scientists in areas that had recently burned in a wildfire (2000, 2002, or 2003) and had subsequently been logged. If available, we selected three replicate units on each forest, which had similar slope, aspect, soil type, and logging practices.

Table 1—Post-fire logging study site characteristics.

Season of harvest	Logging method	National Forest	Year burned	Year of harvest	Elevation (m)	Parent material	Surface soil texture
Summer	Tractor	Custer	2002	2003	1200	Sandstone	Loamy sand
	Tractor	Helena	2000	2003	1700	Metasediments	Sandy loam
	Tractor	Helena	2000	2002	1700	Metasediments	Loamy sand
	Forwarder	Lolo	2000	2005	1400	Metasediments	Loamy sand
	Forwarder	Flathead	2000	2002	1900	Quartzite	Sandy loam
Winter	Tractor	Bitterroot	2000	2002	1750	Granitic	Loamy sand
	Tractor/RTS[1]	Flathead	2000	2002	1150	Limestone	Silt loam
	Tractor	Helena	2000	2002/03	2500	Metasediments	Sandy loam
	Tractor	Helena	2000	2002	1700	Metasediments	Loamy sand
	Tractor	Lewis & Clark	2001	2003	2200	Limestone	Silt loam
	Forwarder	Kootenai	2000	2003	1600	Glacial till	Silt loam
	Forwarder	Lolo	2000	2005	1500	Metasediments	Loamy sand

[1] RTS= Rubber tired skidder.

Soil Indicator Assessment

In each post-fire logging unit, a 100 point systematic grid and a 100 point random transect were established from a fixed corner point. At each grid and transect point, we described the soil surface cover (e.g. rill erosion, forest floor, bare mineral soil, rocks, etc.) and the presence or absence of platy structure in the underlying mineral soil in 1 m^2 plots. Once the soil surface had been described, we assigned a soil disturbance category to each plot (Table 2), based on the classification systems of Howes (2001) and Heninger and others (2002). In addition to a visual classification, soil strength was determined at each sampling point using a RIMIK CP40 recording penetrometer (Agridry, Toowoomba, Australia).

Statistical Analysis

Chi-square tests for homogeneity were used to evaluate the relationships between disturbance class and soil texture, parent material, season of harvest, and harvest method. Chi-square tests for homogeneity were also used to evaluate relationships between detrimental soil disturbance, soil texture, parent material, season of harvest, and harvest method. Analysis of variance was used to examine relationships between soil strength and soil texture, parent material, season of harvest, and harvest method. All analyses were performed using SAS 9.1.

Results

In this study, there were no significant differences between the grid and random transect methods when visually assessing soil disturbance after fire and post-fire logging ($p < 0.001$). Therefore, data from both the grid and random transect were pooled for subsequent analyses.

Table 2—Description of soil condition classes used.

Condition class	Identifying features
0	Undisturbed forest floor
1	No evidence of past equipment operation, but records of harvesting No wheel ruts Forest floor intact No mineral soil displacement
2	Trail used by harvester (ghost trails) Faint wheel tracks and ruts Forest floor intact No mineral soil displacement and minimal mixing with forest floor
3	Trail used by harvester and forwarder Two track trails created by one or more passes Wheel tracks are >10 cm deep Forest floor is missing/partially intact
4	Skid trails existed prior to reentry and reused Old skid trails from 20th century selective harvest Recent operation had little impact on old skid trail Trails have a high level of soil compaction Evidence of mineral soil displacement from trails
5	Old and new skid trails present Mineral soil displacement from area between skid trails Forest floor is missing

In the USDA Forest Service Northern Region, a stand is considered detrimentally disturbed if greater than 15% of the area is in disturbance class 3, 4, or 5 (Table 2). Of the stands we sampled, 50% of the summer-logged sites and no winter-logged sites had more than 15% of the sampling points in the detrimental disturbance categories (Table 3). The relationship of logging season and detrimental disturbance is significant ($p < 0.0001$) and is primarily characterized by platy structure on skid trails or cow trails.

Table 3—Average soil disturbance after summer and winter post-fire logging.

Season of harvest	National Forest	Number of stands	Amount of Disturbance	
			Not detrimental	Detrimental
			- - - - - - - - - -*percent* - - - - - - - - - -	
Summer	Custer	4	72	28
	Flathead	3	77	23
	Helena	3	96	4
	Lolo	4	91	9
Average			**84**	**16**
Winter	Bitterroot	3	97	3
	Flathead	3	90	10
	Kootenai	3	97	3
	Lewis & Clark	3	92	8
	Lolo	2	99	1
	Helena 1	3	92	8
	Helena 2	3	87	13
Average			**93**	**7**

There is a significant relationship ($p<0.0001$) between site parent material and the areal extent of detrimental disturbance. Metasediments, limestone, and granitic parent materials were the least detrimentally disturbed with 75% of the visual classification points being in class 0 or 1.

Surface soil strength was generally not related to disturbance class; however, some exceptions occurred at the 2.5 cm depth. The exceptions were two stands on the Helena National Forest ($p = 0.0312$; $p = 0.0236$) and two stands on the Flathead National Forest ($p = 0.0235$; $p = 0.0033$). These four stands are unique as there was no relationship between surface soil strength, harvest season, type of equipment, or total areal extent of disturbance. However, all four of these sites were burned in 2000 and post-fire logged in 2002. The time between post-fire logging and sampling could have been enough for some soil recovery before soil monitoring occurred.

For all sites, there is a significant relationship ($p < 0.0001$) between visual disturbance class, areal extent of detrimental disturbance, and harvest method. In 66% of the forwarder harvested units, 85% of the rubber-tired skidder units, and 45% of the tractor units, we detected less than 15% areal extent of detrimental disturbance. Many of the sampling sites classified as not detrimentally disturbed had less exposed bare mineral soil than detrimentally disturbed units ($p < 0.0001$). On sites with a significant portion of soil cover, many had live plants, forest floor, moss and lichens present, which may likely indicate soil surface recovery after post-fire harvesting.

Discussion

Severe wildfires greatly impact below-ground ecosystems, including development of water-repellent soils (DeBano 2000) and decreased evapotranspiration (Walsh and others 1992), which can lead to overland flow of water and significant soil erosion. Additionally, the loss of forest floor material reduces water storage in the surface mineral soil (McIver and Starr 2001). The subsequent cumulative effects of fire followed by logging in such a landscape have been difficult to measure (McIver and Starr 2001). Soil surface conditions after post-fire logging is highly influenced by management decisions, which determine equipment type and harvest season. Regardless of disturbance origin (fire or logging), soil productivity in a given area may be influenced by site characteristics (topography, parent material, revegetation, and climate), logging method, and construction of additional roads or skid trails. Our visual disturbance classes (0-5) along with a quick presence or absence survey of key factors (platy or massive structure, forest floor displacement, rut, sheet, rill, or gully erosion, mass movement, live plant, forest floor, wood debris <3″ or >3″, or bare soil) can determine if a harvest unit will meet soil quality guidelines. However, our disturbance classes need to be modified to include soil burn impacts associated with severe wildfires. Removal of surface organic matter may not be detrimental to site productivity unless it is coupled with a change in color in the mineral soil (Neary and others 1999).

Detrimental disturbance was least with rubber-tired skidders, greater when using forwarders, and the most with tractors. In addition, the number of stands with detrimental disturbance was significantly decreased when logging operations occurred during the winter. This is similar to work by Klock (1975) in which he found that tractor skidding over exposed mineral soil caused the greatest amount of detrimental disturbance (36%), followed by cable skidding (32%), and tractor skidding over snow (10%).

Eighty-two percent of our stands were categorized as not having a detrimental soil disturbance after post-fire logging. The remaining stands that approached or exceeded the 15% areal extent of detrimental soil disturbance may require amelioration before other management activities are considered. Detrimental soil disturbance ratings are generally higher after wildfire and post-fire logging when compared to green timber sales, since both wildfire and post-fire logging sites generally lack understory vegetation and forest floor (Klock 1975). Ground-based logging can mitigate some detrimental impacts by leaving logging residue on site or by delaying harvesting until after killed trees drop their needles after a wildfire to establish some forest floor. Both measures provide additional protection from erosion (Megahan and Molitor 1975).

Compaction of the surface soil is also a common concern after ground-based logging operations (Froehlich 1978; Adams and Froehlich 1981; Clayton and others 1987; Page-Dumroese 1993; Miller and others 1996), and surface soil disturbance is more evident immediately post-harvest. Using visual classification categories, we were able to distinguish impacts of summer and winter logging, the influence of parent material, and harvest methods. In some cases, our visual assessments were a direct indication of changes in soil physical properties (e.g. platy or structure) or in surface properties (e.g. displacement of surface organic matter, churned mineral soil, or ruts), and could be used as a surrogate for more intensive sampling. However, the time elapsed between the wildfire and logging activities, and the time between post-fire logging and soil monitoring can be important factors in the degree of detrimental disturbance measured. For instance, on sites with several years between the fire and logging and then another time period between logging and monitoring, some revegetation would likely occur and deposit plant litter on the soil surface. Plant establishment could improve some soil physical properties and influence whether a sample point is categorized as detrimental (class 3) or not detrimental (class 2). The short times between fire, logging and monitoring (1 year between each) may be a reason the Custer National Forest had 28% detrimental disturbance, compared to the Helena National Forest (3 years between fire and logging, and 1 year between logging and monitoring) with only 4% detrimental soil disturbance.

Soil resistance, as measured using a penetrometer, could be easily evaluated on many sites, but the influence of rocks, roots, and low soil moisture, later in the growing season limited its usefulness as tool to make compaction comparisons among sites. However, the use of the penetrometer within one area of similar soil characteristics during a time when soil moisture is fairly high (near field capacity) is feasible for monitoring changes in soil penetration resistance (Utset and Cid 2001).

Management Implications

For our study, we used 6 visual disturbance categories (classes 0-5) to describe areas that had been burned by wildfire and subsequently logged. These visual disturbance classes described combinations of soil disturbance that recur across each harvest unit and can be a relatively quick and easy method for quantifying soil disturbance (Howes et al. 1983). However, season of logging, equipment used, and time between disturbance activities and monitoring were important variables that determine the extent of detrimental disturbance. The visual classification measurements do seem to be an easy, inexpensive method for timely monitoring, and with more data collection, can likely be correlated with long-term vegetation growth. Visual classifications that encompass burn conditions of the soils (charcoal, mineral soil discoloration and ash deposition) are also needed to refine the disturbance assessments, which would make them more useful to forest managers and soil scientists.

Our data indicate that at the 95% confidence level, a sample size of approximately 200 sample points in a 10 ha unit would detect 15% (±5%) detrimental disturbance (Table 4 and unpublished data). A site with 5% detrimental disturbance would only need 75 sample points; whereas a site with a high proportion (>30% of the unit) of detrimental disturbance would need 340 sample points at this confidence level. A confidence level of 80% would significantly lower the number of samples needed. For instance, a site with little disturbance (<5% of the unit) would need only 32 sample points, but a site with a large amount (30% of the unit) of disturbance would need 139 sample points. Using either random transects or grid points are appropriate strategies for laying out monitoring points for similar wildfire burned and post-fire harvested sites when using our visual classification method.

In the USDA Forest Service, soil assessment of management impacts is typically linked to site productivity through soil quality standards (Page-Dumroese and others 2000). However, these standards are not site-specific, do not specify collection of baseline data, are not always linked to changes in biomass production or carbon accumulation, and, in many cases, the monitoring techniques are cumbersome, lengthy, costly and require some laboratory analysis. Reliable assessment of soil disturbance and the link to site productivity is critical. Visual classifications have been used throughout the Pacific Northwest by the B.C. Ministry of Forests (Forest Practices Code Act 1995) and Weyerhaeuser Company (Scott 2000), but have not been linked to tree growth. To date, visual classification systems only describe surface soil conditions, and have not been validated to response variables that are ecologically important (e.g. tree growth, survival). A necessary step in the acceptance of any visual soil disturbance criteria is to develop direct evidence that there is a change in site function, productivity, or sustainability (Curran and others 2005). Our test of visual criteria for assessing soil disturbance after wildfire and logging operations could be used to determine areal extent of detrimental impacts within a harvest unit.

Although visual classifications are not directly linked to ecosystem functions at this time, it is generally recognized in the northwestern USA that surface organic matter can help maintain site productivity (Page-Dumroese and others 2000; Jurgensen and others 1997; Harvey and others 1981).

Table 4—Sample points needed to detect 15% areal extent of detrimental disturbance in a 10 ha unit at different confidence levels (±5%).

Confidence level	Sample points needed
95%	196
90%	139
80%	84

Existing studies such as the North American Long-Term Soil Productivity (LTSP) study, established in the USA and Canada, are investigating the effects of OM removal and compaction on soil productivity (Powers and others 2004), but fire was not included as a disturbance variable. However, the physical removal of surface OM on LTSP study sites generally resulted in lower mineral soil C pools and reduced N availability 10 years after treatment, and tree growth was reduced on low productivity sites (Powers and others 2005). Additionally, tree growth declined on compacted clay soils and increased on sandy soils, but was strongly related to control of the understory vegetation. Recently, the Fire and Fire Surrogate study was started by the USDA/USDI to evaluate the effects of mechanical fuel reduction treatments and prescribed fire-severity on above- and below-ground productivity in a variety of forest ecosystems across the USA (Weatherspoon 2000). Both of these sources of information are needed to complement monitoring data to help develop post-fire harvesting methods that maintain adequate amounts of OM and limit soil compaction to maintain soil productivity.

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