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Soil Disturbance Recovery on the Kootenai National Forest, Montana

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Abstract

Determining the extent of soil property changes following forest management activities (e.g., timber harvest, fuels abatement, site preparation) is an ongoing concern for land managers. Monitoring the long-term effects of various harvest operations and fuels treatment methods on soil physical properties and hydrologic function is critical to maintaining forest productivity. We document changes in detrimental soil disturbance (DSD) in harvest units located on the Kootenai National Forest that occurred over two decades. From 1992 through 2006, 251 harvest units on the Kootenai National Forest were monitored by using standard soil monitoring transects. Seventy-three percent of these units were resampled from 2012 to 2013 under the same monitoring protocol. The original sampling included 510 soil transects and 118,956 datapoints; resampling included 394 soil transects and 76,561 datapoints. Both the initial and subsequent sampling efforts evaluated the extent of DSD after forest management activities. Results indicate that about 86 percent of the resampled units had a reduction in DSD when compared to the original soil monitoring data. Processes that contribute to soil recovery include freeze-thaw cycles, wet-dry cycles, vegetative regrowth, and soil organic matter inputs. Soil recovery is logarithmic, with the greatest soil recovery rates occurring in the first 3 to 5 years after harvest activities, particularly on soils influenced by a volcanic ash-cap. Long-term DSD is usually associated with skid trails, temporary roads, and log landings.

Keywords: Soil monitoring, detrimental soil disturbance, volcanic ash-influence, landtype

Cover photo **by John M. Gier.**

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Figure 1—Cutslope displaying surface soil horizons overlying a continental glacial deposit, Kootenai National Forest (photo: J. Gier, Kootenai National Forest).

Introduction

Soils are the foundation of forest ecosystems, providing nutrients, water, oxygen, and mechanical support to vegetation. Forest management activities such as harvest and fuels abatement can alter soil properties (e.g., texture, structure, porosity, chemistry) as well as site productivity, species composition, and site hydrologic function. These changes in soil properties can lead to alterations in soil organic matter decomposition, nutrient cycling and uptake, and element transformations that rely on exchangeable oxygen (Page-Dumroese et al. 2009a). Soil quality is the capacity of a soil to function within ecosystem and land use boundaries such that it sustains biological productivity, maintains environmental quality, and promotes plant and animal health (Doran and Parkin 1994). Maintenance of soil properties (quality) is dependent on the safeguarding of surface layers from erosion, displacement, and compaction, as well as maintenance of nutrient cycling and protection of the surface organic horizons. One easy way to evaluate soil horizons, roots, and rocks within the soil profile is to use cutslopes from road-building activities (fig. 1).

Soils can be physically damaged during harvest operations by compaction, displacement, and puddling by logging equipment or log movement (Han et al. 2006; Page-Dumroese et al. 2000, 2009a,b; USDA FS 1999). Soil physical properties are especially vulnerable to damage during wet weather and moist soil conditions (Adams 1998). Physical soil property changes associated with logging equipment often result in reduced pore space, and the subsequent reduction in the movement of water into and through the soil (Page-Dumroese et al. 2009a). Pore space reduction can also increase overland flow, leading to surface erosion or mass soil movement, or both (Archuleta and Baxter 2008).

To ensure maintenance of long-term soil productivity and site sustainability, soil quality standards and guidelines were developed across the Nation. The current U.S. Department of Agriculture (USDA), Forest Service Northern Region (Region 1) soil quality guidelines limit detrimental soil disturbance (DSD) to no more than 15 percent of an activity area. In areas where more than 15 percent DSD exists from previous activities, the cumulative detrimental effects should not exceed the soil conditions prior to management activities and should move toward a net improvement in soil quality (USDA FS 1994, 1999, 2009, 2011, 2013a,b, 2014). Assessing the soil effects within a harvest activity area is also necessary to meet the intent of the National Environmental Policy Act to describe existing conditions and recovery potential. In addition, the National Forest Management Act of 1976 (USDA FS 1976) and related legislation require that the productive potential of National Forest System (NFS) lands be maintained.

Background

The Forest Service soil resource management goals include maintaining or improving long-term soil productivity and soil hydrologic function. To meet policy direction, levels of soil impacts considered detrimental to land productivity must not exceed 15 percent so that site quality is maintained. Soils are considered to be detrimentally impacted when disturbance thresholds (set by each Forest Service region) at a sample point are exceeded for any or a combination of the following disturbances: compaction, rutting, displacement, loss of surface organic matter, surface erosion, severely burned soil, and soil mass movement. The Kootenai National Forest (KNF) Revised Land Management Plan (USDA FS 2013a) describes the thresholds for these attributes as follows: (1) compaction: a 15-percent increase in natural bulk density; (2) soil ruts: machine-generated soil displacement having smeared the soil (Kootenai National Forest 107 Glossary Term Definition) surface in a rut; wheel ruts at least 2 in [5 cm] deep in wet soils; (3) displacement: removal of 1 in or more [≥2.5 cm] of surface soil, often consisting of the O and A soil horizons, across a continuous area greater than 100 ft^2 [9 m^2]; (4) surface erosion: indicated by rills, gullies, pedestals, and localized soil deposition; (5) severely burned soils: physical and biological changes to the soil resulting from high-intensity burns of long duration as described in the Burned Area Emergency Rehabilitation Handbook (USDA FS 1995); and (6) soil mass movement: any soil mass movement caused by management activity.

Indicators of Detrimental Soil Disturbance

Each indicator of DSD is used to describe changes that can alter both soil and hydrologic function. Although DSD encompasses all of the attributes listed, soil compaction accounts for 95 percent of the soil disturbance on the KNF. Furthermore, soil mass movement is not a typical characteristic of KNF soils and was not used to evaluate DSD in this study (Kuennen and Neilsen-Gerhardt 1995).

Compaction

Compaction is often the most noticeable soil change after harvest activities (Cambi et al. 2015). Soil compaction occurs as a result of vibration and pressure from equipment during harvesting and site preparation activities and results in loss of surface aggregates and decreased macroporosity (Adams and Froehlich 1984; Gomez et al. 2002; Pritchett and Fisher 1987; USDA FS 1994). Maximum soil compaction due to harvest activities normally occurs within the first 10 passes (Gent and Ballard 1984) of harvesting equipment, with the greatest compaction occurring in the first few passes (Froehlich 1978; Froehlich et al. 1980; Han et al. 2006; Lenhard 1986; Wallbrink et al. 2002; Wang 1997). Froehlich et al. (1980) found that the changes in soil density were accompanied by a 43-percent reduction in macroporosity and an 80-percent reduction in saturated hydraulic conductivity.

Loss of macropores impedes root penetration, water infiltration, and gas and nutrient exchange (Han et al. 2009), which may result in changes to tree regeneration and growth rates (Powers et al. 2005). Water infiltration was reduced by 78 percent when a crawler tractor was used and 67 percent when rubber-tire skidders were used at a study near the Tahoe National Forest in California (Froehlich et al. 1980). Soil textures at these sites were sandy loam, gravelly sandy loam, gravelly clay loam, and a loam. Although total soil water may not be affected (Cambi et al. 2015; Froehlich and McNabb 1984), compaction alters pore-size distribution and porosity (altering available water), primarily because soil volume decreases during the compression of pore space (Startsev and McNabb 2001). Changes in pore-size distribution are highly dependent on soil texture and soil water regime, and the use of soil porosity as a monitoring tool for managers requires site-specific data (Gomez et al. 2002). Further, Han et al. (2009) found that soils with an initial high soil bulk density were less compacted after the first few passes of machinery compared to soils with existing low bulk density or undisturbed sites; their results were similar to the work of Page-Dumroese et al. (2006). The number of passes and number of previous entries dictate the additional levels of compaction that may be expected at intermediate harvests.

Compaction of both volcanic ash-cap and mineral soil is typically associated with ground-based equipment operations such as skidding, temporary road construction, blading, firelines, and landings during harvest procedures. Cullen et al. (1991) reported significant increases in volcanic ash-cap bulk density of moderately and severely trafficked areas as compared to areas that were not harvested. Severe soil compaction has been found to cause a slight increase in average soil temperature at a depth of 20 cm (8 in) throughout the growing season (Froehlich and McNabb 1984).

On the KNF, higher DSD values attributed to soil compaction were found in the 1980s to early 1990s when compared to the units that were monitored in the late 1990s and 2000s. This difference can be attributed to several factors. In the early 1990s there could be up to 90 percent soil disturbance in a harvest unit when a bulldozer was used during harvest and fuels operations (e.g., timber removal, site preparation, slash disposal, fireline construction). Bulldozers travel over the entire harvest area using dispersed skidding (slopes of ≤45 percent), resulting in DSD in excess of the 15-percent threshold.

Before the mid-1980s, fuels treatments implemented with a bulldozer could result in additional DSD when large burn piles were constructed and later burned at high temperatures. Starting in the mid- to late 1980s, adoption of new best management practices (BMPs) led to changes in logging operations on the KNF. Montana State BMPs (USDA FS 1988), when applied during implementation of a project, ensure that soil productivity is maintained, soil loss and water quality impacts are minimized, and water-related beneficial uses are protected. Today, bulldozer slash piling is rare; instead, an excavator with a clipper cutter is routinely used to both harvest trees and pile slash. Such activities may take place concurrently or several months or years apart. Soil surface scarification by large equipment may also occur because some species prefer a disturbed soil surface for regeneration. Cut-to-length harvest operations, rather than whole-tree yarding, can also significantly reduce DSD; Han et al. (2006) found that cut-to-length harvest activities effectively minimized soil damage by forwarder operations on ground-based slash mats compared to rubber-tire skidder operations using whole-tree yarding.

Soil monitoring efforts that use quantitative measurements of soil properties such as bulk density, porosity, or soil resistance are time consuming and expensive. An added complexity to the assessment of soil compaction is the presence of other types of soil damage such as soil displacement or rutting (Cambi et al. 2015), which makes monitoring, sampling, and reporting these parameters difficult.

Soil recovery rates depend on many factors including the number of stand entries, soil moisture conditions at the time of harvest, soil texture, rock-fragment content, and landtype (Liechty et al. 2002). Many studies show that once compacted, forest soils are often slow to recover and may require decades to return to predisturbance levels (Froehlich et al. 1985; Sands et al. 1979; Tiarks and Haywood 1996). Other factors that may influence soil recovery rates are landtype and volcanic ash-cap presence (Froehlich et al. 1985; Johnson et al. 2007). The extent and duration of compaction also determine the effect of timber harvesting on soil recovery rate.

Rutting

Soil ruts are formed when the forest floor or mineral topsoil is deformed by equipment during suboptimal moisture conditions (too wet) or on soils with low bearing strength (Napper et al. 2009). Compacted ruts can channel water downslope, causing erosion and loss of surface organic matter. This DSD typically occurs in units where heavy machinery was operated on moist soils or during winter operations on unfrozen ground, when snow acts as an insulator to keep soils from freezing. On the KNF, harvest activities cease once soil moisture exceeds 18 percent. It should be noted that in areas where the surface soil is rocky, harvest operations during moist conditions cause less soil damage than similar harvest operations on less rocky or finer-textured soil.

Displacement

Topsoil displacement includes removal of the surface organic O- and A-horizons. The resulting exposure of less nutrient-rich subsoil horizons is especially critical in volcanic ash-cap soils, where most of the nutrients needed for conifer tree growth are retained in the surface horizons. Soil displacement involves the removal of soil material from one place to another and is often associated with blading, turning of wheel tracks, dragging logs or whole trees, and blading with bulldozers (Napper et al. 2009). Surface soils on much of the KNF have high infiltration rates, whereas subsoil material typically has lower rates because of parent material type. Soil displacement often leads to increased surface erosion.

Previously, firelines created with a bulldozer were typically 3 to 4 m (10–13 ft) wide, causing very high DSD levels. Currently, firelines are constructed by using an excavator equipped with a bucket. These firelines are less than 3 m wide and only 1 cm (0.4 in) deep. Alternatively, a hand line is made with shovels. In some areas firelines are not constructed after harvest activities.

Bladed skid trails are another form of displacement. These trails are typically located on steeper ground and are installed perpendicular to the slope. Field observations indicate that coniferous vegetation has become established on many of these bladed skid trails, but it is growing at a slower rate than adjacent timber stands.

Erosion

Soils formed in volcanic ash are typically described as having the ability to resist erosion because of numerous stable aggregates and high infiltration rates (Dahlgren et al. 2004; Nanzyo et al. 1993). Because volcanic ash-cap soils have a low bulk density, they are very susceptible to both wind and water erosion when vegetative cover is removed (Arnalds et al. 2001; Kimble et al. 2000). On the KNF, maintenance of forest cover, including both canopy and litter layers, has been an important factor in retention of the volcanic ash-cap (McDaniel et al. 2005). Soil cover on volcanic ash-cap soils is related to the degree of disturbance, and high levels of DSD are likely to lead to erosion.

Erosion is most often associated with harvest and site preparation activities on steeper slopes (Johnson et al. 2007). Studies by Liu and Nearing (1994) indicate a direct correlation between slope gradient and soil erosion. Field observations throughout the KNF suggest that as slope angles increase, the proportion of soil disturbance related to machinery operations increases and is directly related to harvest methods, if all other factors are controlled. Decades ago, harvest operations avoided steeper slopes (>35 percent) because of the wide availability of timber elsewhere. Currently, new equipment makes it easier to harvest steep slopes, so soil erosion may contribute more to the overall disturbance values.

Severely Burned Soil

Until the early 1990s, fuels treatments often involved very large burn piles that left severely burned soil. Burn piles of 0.1 ha (0.2 ac) within a 0.8- to 1.2-ha (2–3 ac) burn area were created by using a bulldozer with a dirt or brush blade to push slash into a central location and then burned. This type of slash pile produced very high (>760 °C; 1400 °F) soil temperatures (Glassy and Svalberg 1983). Under these extreme temperatures, ash-rich soils were fused into a consolidated vitreous material referred to as "clinkers." Fused soil is not conducive to hydrologic function, gas exchange, or tree growth.

Besides altered soil structure, fire effects on soil surface characteristics can include localized or widespread loss of organic horizons and nutrient transformations (e.g., volatilization, immobilization) (DeBano et al. 1988; Hartford and Frandsen 1992; Keane et al. 2002), charcoal addition, and altered color (DeBano et al. 1998; Parsons et al. 2010; Ryan and Noste 1985). Fire also can impair hydrologic function by reducing infiltration and increasing hydrophobicity (DeBano 2000; Keane et al. 2002; Parsons et al. 2010). Different fire intensities will cause different alterations to chemical, physical, and biological soil properties, but the degree of change is directly related to the heat pulse into the soil. Chemical changes can include a reduction in soil acidity; the increase in pH is greater with increasing burn severity (Bisset and Parkinson 1980). Light burning stimulates nitrification and increases the amount of acid-soluble phosphorus and exchangeable potassium. Severe burning greatly reduces the nitrogen content of soil and the availability of phosphorus and exchangeable potassium (Harvey et al. 1989; Niehoff 1985; Nielsen-Gerhardt 1986). Physical alterations are manifested by reduced macropore volume and increased micropore volume, which result in decreased water infiltration (Tarrant 1956). The effect of fire on both soil and vegetation can be defined by (1) the degree of scorch, (2) the amount of vegetation burned, and (3) mortality (DeBano et al. 1998; Hartford and Frandsen 1992; Parsons et al. 2010). Burn severity is related to the degree at which the ecosystem may (or may not) be fire resistant. Biologically, fire affects the soil community by immediately killing or injuring organisms. Indirectly, it has longer-term effects on plant succession, soil organic matter transformations, and microclimate through removal of soil nutrient pools and changes in chemical properties and soil pH (Borchers and Perry 1990). Changes throughout the soil profile include altered acidity, changes in nutrient availability, and altered temperature regimes (Graham et al. 1994; Neal et al. 1965; Raisen 1979; Woodmansee and Wallach 1981). Anything that kills or injures living plants also impacts organisms dependent on plants for energy, nutrients, or habitat. This is especially true within the rhizosphere.

Combustion of coarse woody debris, forest floor litter, and organic matter can result in immediate and long-term consequences to soil conditions (Kuennen 2000).

The increase in soil temperatures because of fuel consumption can produce various effects on the soil environment, and soil heating is typically not uniform across the landscape due to the variability of fuels and fuel consumption. Log landings, jackpot-burn piles, or grapple piles that burn for long periods of time at relatively high temperatures can have negative effects on these surface characteristics. Such temperatures not only fuse the soil but increase the overall DSD values within a unit. These changes are recorded in DSD soil transects when a pile is crossed. Extremely hot temperatures (480–650 ºC; 900–1200 ºF) can lead to a 3-unit increase in pH (Glassy and Svalberg 1983). For example, on the KNF we measured soil pH of 8 to 9 in very hot burns when the initial soil pH was 6.5. This sharp decline in soil acidity resulted in a change in vegetative species. High-severity burns remove most nutrients through volatilization, thus restarting the soil and vegetative clock (Glassy and Svalberg 1983). Conifer species do not establish as rapidly on high-pH soils as on locations where soil pH is unaffected.

Methods

Forest Setting

The Kootenai National Forest is located in the northwestern corner of Montana (fig. 2). The region abuts Canada to the north, Idaho to the west, the Flathead National Forest to the east, and the Lolo National Forest to the south. The study area is underlain by metamorphosed pre-Cambrian mudstone sedimentary rocks known as the Piegan Group of the Belt Supergroup. The soils were developed from glacial till, residual bedrock, alluvial deposits, or volcanic ash material (Kuennen and Nielsen-Gerhardt 1995; Nimlos and Zuuring 1982). The KNF encompasses more than 890,000 ha (2.2 million ac) and contains land with water courses that drain into the Kootenai, Clark Fork, and Flathead Rivers (fig. 2).

The KNF has 50 landtypes, which can be subdivided into 5 groups (Kuennen and Nielsen-Gerhardt 1995):

- Water-deposited landforms: low valley floodplains and terraces (100 series)
- Breakland landforms: slopes greater than 60 percent (200 series)
- Continentally glaciated landforms: those affected by the Cordilleran Ice Sheet moving south from British Columbia, Canada (300 series)
- Alpine landforms: those formed in alpine glaciation such as cirque basins and wall-like cliffs with a slope greater than 60 percent (400 series)
- Erosion landforms: those developed by structurally controlled residual material (500 series)

More than 70 percent of the area was influenced by the Cordilleran Ice Sheet (8,000–12,000 BCE), which was the last major landform-shaping event. Glacially influenced mineral soil results from two types of glaciation, continental and alpine. Continental glaciation covered vast land areas; it scoured ridge tops and filled drainage bottoms, resulting in a more rounded landscape with more subdued relief. Soils influenced by continental glaciation are composed of silts, fine sands, and rounded gravels

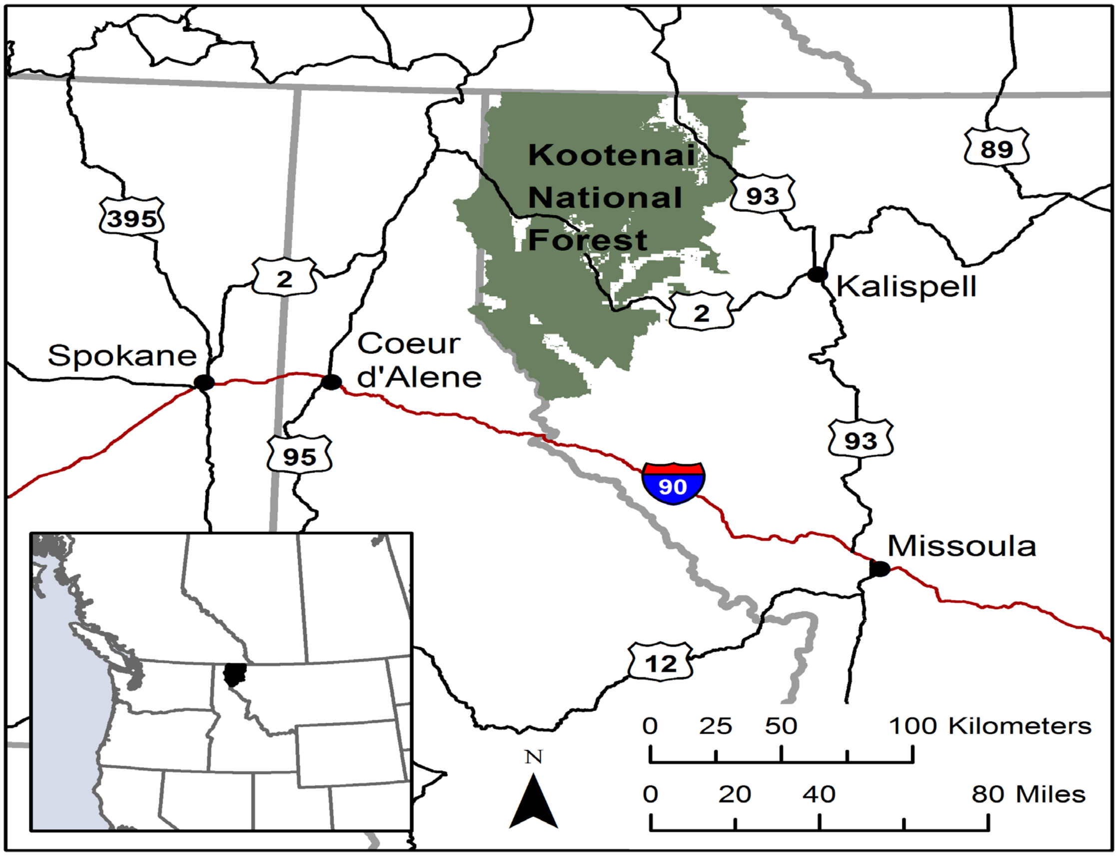


Figure 2—Location of the Kootenai National Forest.

and boulders. Continental glacial debris is very dense and consists mostly of one soil particle size; it contains rounded rock material, and a densely packed till horizon. Alpine glaciation was restricted to localized ice buildup on higher elevations and resulted in landscape features such as arêtes, horns, U-shaped valleys, and alpine lakes. As the ice melted, it revealed other glacial features that had formed under the ice or at the margins. Alpine glaciation-influenced soils have a coarser texture and contain more gravel and rock than continental soils (Kuennen and Nielsen-Gerhardt 1995). The Appendix describes the landtypes and dominant soil taxonomic classifications for the KNF; a notation indicates whether volcanic ash influences the soil.

Objectives

One element of successful management of NFS lands is an understanding of the short- and long-term effects of harvest operations. Timber harvest combined with postharvest site preparation efforts (fuels abatement) to reduce fuel loads within a unit can create a complex mosaic of soil impacts. Ground-based harvest equipment, skidding, temporary road construction, blading of forest soils, and mechanical fireline and landing construction during timber harvest activities can substantially change soil physical properties. Soil recovery is the capability of soils to rebound over time from compression of soil macropores and micropores, which reduces infiltration, porosity, water and nutrient holding capacity, and biological activity. The aim of this study was to provide insight into the following issues on the KNF: (1) Is soil recovery occurring? (2)

If so, is it measurable and to what extent is it occurring? (3) Is soil recovery rate related to soil properties in the study area? (4) Is there a relationship between fuels abatement and recovery rates? (5) Is there a relationship between soil recovery and soil physical properties in ash versus non-ash soils?

Soil Monitoring on the Kootenai National Forest

For three decades (1988–present), the KNF has maintained a soil monitoring database of random sampling points within selected harvest units. Soil monitoring data collection and review were performed after postmanagement (e.g., after site preparation, burning, and temporary road decommissioning) activities were completed for all selected harvest units.

Initial soil monitoring (1988–1991) data were collected by using random "walk through" unit reviews; however, none of the units reviewed in this study was resampled with this method. In 1992, the KNF started collecting soil disturbance monitoring information by using a random stratified quantitative procedure involving soil transects within the harvest unit. Kuennen (2006a,b) developed and implemented monitoring methods adapted from Howes et al. (1983). Kuennen (2006a,b) refined these methods further after a review of Hazard and Geist (1984) to assess forest soil conditions following management activities. The outcome was a methodology that resulted in a 95-percent confidence level on more than 90 percent of the units sampled.

The methodology uses linear transects placed randomly and perpendicular to the direction of the most recent ground-disturbing activities (i.e., skid trails and roads) to ensure uniform representation of the full range of disturbance levels within a particular unit. When global positioning systems became widely available, beginning and ending coordinates were recorded for all transects. Approximate transect location was identified before field review to avoid bias. Types of harvest methods sampled with this transect method were helicopter, skyline cable, forwarder, tractor (rubber-tire skidders and tracked vehicles), and horse logging. Harvests were conducted in both summer and winter. Summer harvesting is defined as operations that follow spring breakup and cease with the fall rainy season. Winter harvesting is defined as operations occurring in December, January, and February, although this category may shift based on seasonal temperature fluctuations.

All 251 timber sale units monitored in this study were sampled during the summer and each unit was independently monitored for soil disturbance ratings. Monitored disturbances were compaction, rutting, displacement, surface erosion, and severely burned soil. Depending on the size of timber harvest unit, monitoring points were sampled about 0.9 to 2.1 m (3–7 ft) apart. Once a monitoring point distance was selected for a unit, it was held constant throughout the entire unit. At each monitoring point, a soil spade was used to determine resistance to soil penetration (Page-Dumroese et al. 2009a). In areas with highest levels of compaction, a shovel blade is capable of penetrating only a short distance into the soil with great effort. Sampling adjacent undisturbed soils outside the unit provided comparison to the harvest unit and helped the surveyor with calibration to local soil conditions.

Because transects are placed perpendicular to the most recent skidding or skyline direction, more recent machinery tracks may be superimposed on previous harvest activities, thereby adding to the complexity of soil disturbance effects. This was more common on intermediate harvest units, where the initial entry was a selective harvest prescription.

The current database on the KNF contains soil monitoring data representing a subsample of the total annual harvest units completed in a given year. The data are limited to harvest and slash disposal methods that were previously monitored for soil disturbance. However, resulting DSD values for a given harvest unit on the KNF are the culmination of all soil disturbance and do not separate specific attributes of disturbance (i.e., compaction, erosion, rutting, or fire damage) or harvest and fuels activities. For example, detrimental disturbance for a summer tractor harvest unit takes into account skid trails, temporary roads, mechanized piling, and firelines within the unit. These soil monitoring data were used to determine subsequent sampling efforts and appropriate harvest units to be remeasured to evaluate soil recovery.

Seventy-three percent (183 units) of the 251 harvest units that were monitored between 1992 and 2006 were resurveyed during the 2012 and 2013 field seasons. Of the five groups of landtypes, only four were resampled (100, 300, 400, and 500 series) (Appendix). Landtypes containing extremely steep slopes (200 series) or low soil productivity (107, 109, 111, 114, 201, 303, 401, 403, and 503) are not part of this study. Fewer soil units in the 200, 400, and 500 series were available for resampling due to the smaller subset of units that were originally sampled from 1992 through 2006. To ensure a minimum of 5 years of recovery for all monitored units, sampling was limited to those units monitored between 1992 and 2006.

Both walk-through (qualitative) and soil transect data (quantitative) were collected during this time, but only those units originally monitored by using soil transects were included in the resampling process. In this way, consistency could be maintained in the ongoing collection of soil monitoring data. The original monitoring dataset included data from 108 timber sales, which covered 7,725 ac (3,128 ha) (510 soil transects and 118,956 datapoints). This study remonitored 183 of the 251 original timber units and covered 5,253 ac (2,128 ha), or 68 percent of the original area monitored. The remonitored dataset includes 394 soil transects (76,561 monitoring points). Resampling was conducted by using monitoring procedures identical to the ones used during original data collection. Fewer units were resampled partly because of changes in land ownership and forest management requirements.

Field Data Collection

At each soil monitoring point along each transect within a harvest unit soil disturbance was categorized as (1) undisturbed, (2) light or moderate disturbance, or (3) heavy disturbance. Soil assigned to the undisturbed category showed no indication of soil disturbance (fig. 3a). Litterfall and understory vegetative growth made it difficult to distinguish between light and moderate disturbance after long periods of time, so these two categories were combined. Soils in the light or moderate disturbance category had some combination of the following features: faint wheel tracks with intact forest-floor layers, low burn severity, and shallow soil compaction depths (0–10 cm); or moderately deep wheel tracks or depressions, missing forest floor layers, surface soil removed through gouging or piling, surface soil displacement, high burn severity, or potential

Figure 3—Examples of soil from the same harvest unit in the Kootenai National Forest: (a) an undisturbed soil (note deep roots, thick understory vegetation, and lack of impacts from surrounding harvest activities); and (b) detrimental soil disturbance (platy structure) caused by an excavator-made skid trail (photo: J. Gier, Kootenai National Forest).

soil compaction up to 30 cm (1 ft) deep (Kuennen et al. 1979; Page-Dumroese et al. 2009a,b). Heavy disturbance is DSD as defined in USDA FS (2014) and FSM 2500 (USDA FS 1999, 2009) and indicates that long-term site productivity and soil quality are likely to have been impacted (fig. 3b). Attributes of DSD were compaction, rutting, displacement, erosion, or severe burning.

The sampling procedures used in this study meet Forest Service Region 1 protocol. We did not use the methodology outlined in Page-Dumroese et al. (2009a,b, 2012) so that we could maintain statistical consistency with previous surveys.

Historically, the KNF and other national forests in Region 1 did not include temporary roads and log landings located outside the harvest unit when crews sampled for DSD. Consequently, soil compaction values associated with temporary road segments or landings were sampled only when the linear soil transects crossed them within the harvest units. For statistical consistency with previous monitoring, harvest units that were remonitored considered only temporary roads and landings that existed within unit boundaries. Figure 4 shows an example of an original sample transect location with the resample transect location. Both transects were perpendicular to the historical bulldozer skid trails.

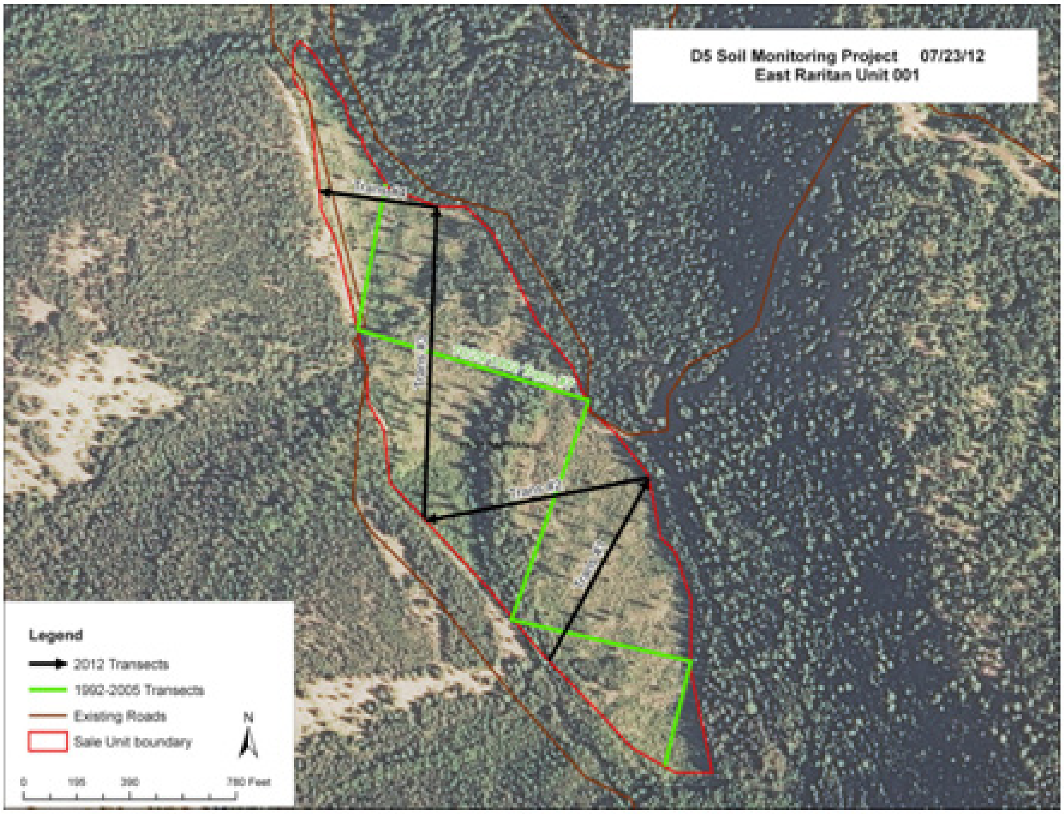


Figure 4—Comparison of transects collected on the East Raritan timber sale unit on the Kootenai National Forest. Green transect represents the initial transect locations (1992); black transect represents the location of randomly selected 2012 transects. Brown color indicates the existing Forest Service road from the geographic information systems layer. Red is the timber sale unit boundary.

Statistical Analyses

All analyses were done with SAS® PROC GLM (SAS Institute Inc., Cary, North Carolina). A linear multiple regression analysis was used to test for significant effects ($\alpha = 0.05$) for a change in DSD related to recovery period, fuels treatment, harvest methods, harvest season, skidding method, type of sale, aspect, slope, vegetative complex, and soil characteristics. Number of years since harvest, landtype, harvest methods, fuels treatment, soil texture, and volcanic ash presence were treated as class variables. All other variables were found to be insignificant. Regressions were conducted by using Excel® to determine the effect of time since sampling on changes in DSD and ash versus non-ash relationships.

Harvest Methods

Tracked bulldozers were the primary type of harvest equipment used on the KNF until the late 1980s. Changes in environmental laws and the gradual move to mechanization prompted the development and adoption of other machinery, which now includes the rubber-tire skidder, excavator, forwarder, feller-buncher, and clipper cut. Today, stand regeneration and intermediate harvests are the principal harvest methods used on the KNF. Harvesting for stand regeneration includes seed tree, shelterwood, and

Figure 5—Examples of harvest methods showing (a) regeneration winter harvest, which used clipper cut, excavator piling, and rubber-tire skidder yarding; and (b) intermediate harvest using hand falling, leaving tops and limbs on the soil surface with summer rubber-tire skidder yarding (photo: J. Gier, Kootenai National Forest).

clearcut harvest methods. Intermediate harvesting uses selective thinning, which usually involves removal of certain tree species or sizes, or a combination thereof.

In this study, about 70 percent of the units resampled during the 2012–2013 field seasons were harvested by using stand regeneration methods and 30 percent were harvested by using intermediate methods. These proportions reflect the prevalence of stand regeneration harvest methods in the early 1990s; later harvest operations shifted to intermediate harvesting (fig. 5).

Harvest methods were grouped into three cutting types: hand-cut only, hand/clipper cut, and clipper cut. In general, hand-cut only units dwindled as the practice of clipper cut became more established. This shift was closely tied to meeting objectives for increased harvest volumes in shorter timeframes. Hand-cut only units were 20 percent of the study units. Hand falling combined with mechanical clipping (18 percent of the study group) was used in portions of the units with steep slopes; the bulk of the units were harvested only by a clipper. In general, clipper cut (62 percent of the study group) was the primary method of harvest used in both intermediate and regeneration harvest units.

Fuels Treatments

Until the early 1990s, fuels abatement activities, as for harvest operations, on the KNF primarily involved bulldozers. The wide variety of current disposal methods for harvest slash ranges from large-area broadcast burning to no treatment. Soil monitoring in 1992 indicated a high level of DSD immediately following harvest and fuels treatment; 49 percent of the 510 soil transects surveyed exceeded the 15-percent threshold for DSD specified in the forest plan. This is partly the result of intensive fuels abatement activities, which resulted in large piles that burned very hot (fig. 6). After 1992, loggers switched to the use of rubber-tire skidders and grapple pile machinery.

In areas where timber harvest activities took place before 1988, the following was assumed: (1) tracked vehicles (bulldozers) were used on slopes of 45 percent or less, (2) cable systems were used on slopes steeper than 45 percent, and (3) various

Figure 6—Example of a grapple pile being burned too hot. This area is expected to contain detrimental soil disturbance because 100 percent of the woody material and forest floor will be removed, rocks are easily fractured, and soil color is altered to orange (photo: J. Gier, Kootenai National Forest).

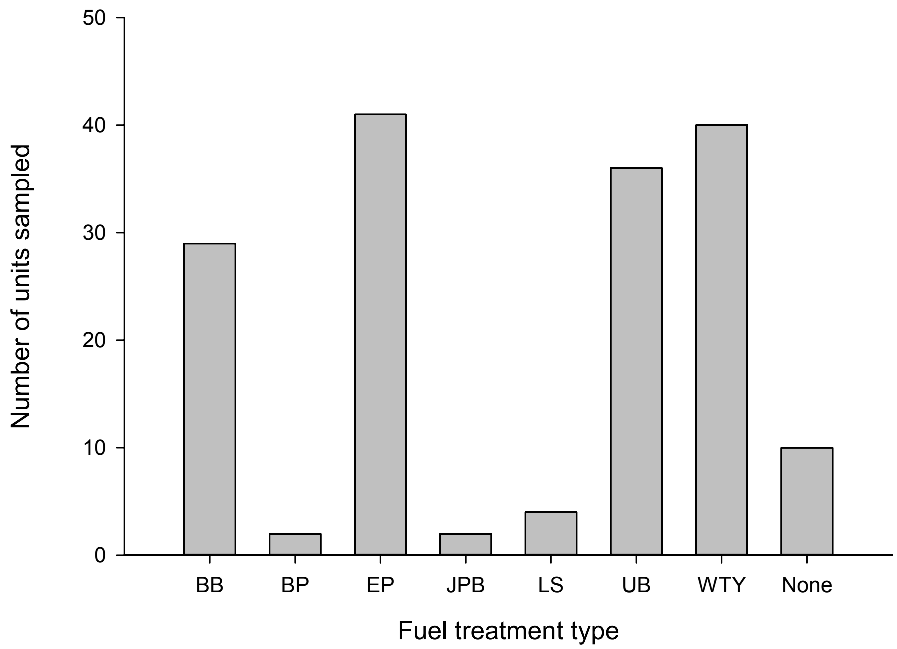


Figure 7—Fuels treatments and the frequency of use on the Kootenai National Forest. BB = broadcast burn; BP = bulldozer pile; EP = excavator pile; JPB = jackpot burn; LS = lop and scatter; UB = underburn; WTY = whole-tree yard; and None = no postharvest fuels abatement.

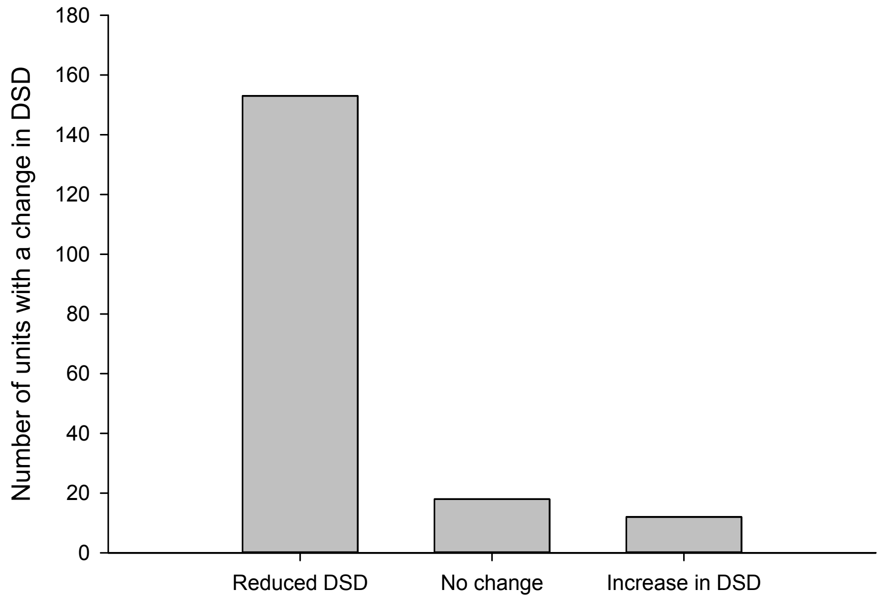
fuels abatement activities would follow in areas where clearcuts and seed tree harvests occurred (fig. 7). In addition, the dispersed skidding associated with these harvest activities was assumed to result in 15 percent DSD, and an additional 15 percent or more DSD could be attributed to the related fuels abatement activities.

Results and Discussion

Detrimental Soil Disturbance Recovery

Overall, 86 percent of units resampled in 2012–2013 displayed reduced DSD when compared to the initial soil disturbance data collected between 1992 and 2006

Figure 8—Percentage change in the number of units with detrimental soil disturbance (DSD) from the initial monitoring (1992–1999) to the remonitoring (2012–2013) on the Kootenai National Forest (n = 183 units).



(fig. 8). Nine percent of the resampled units had no change in DSD. A reduction in soil disturbance can occur from freezing and thawing, or wetting and drying, or through vegetative growth and organic matter inputs (Cambi et al. 2015). Harvest units with either increased soil disturbance or no change were typically found in areas with very low original soil disturbance, in highly impacted lacustrine rich soils, or in more recently disturbed areas (e.g., postharvest fuels treatments, cattle grazing). An overall increase in DSD values may reflect variability of disturbance within units and differences in the placement of random soil monitoring transects (e.g., transects crossed machinery tracks or skid trails at an angle different from the original transect angles). The increase could also be attributed to additional soil disturbance caused by skid trails used to reach adjacent timber sale units or public recreation. In general, the amount of disturbance and its longevity are related to harvest methods, landtype, and the presence of an ash-cap.

Average recovery values tended to be greater for samples first collected in more recent sampling periods as compared to older samples of similar soil types (fig. 9). Soil DSD recovery within 15 years was lowest in older units and was not related to landtype. This result makes sense because soil disturbance that was clearly visible in newly harvested units becomes obscured as forest floor, macrofauna and microfauna, and climatic factors affect soil disturbance severity. One monitoring concern for soil scientists is that individual harvest units may have more than one landtype and units may not be divided into specific landtypes before monitoring. For example, a harvest unit may extend from low-gradient valley bottoms (100-series landtypes) up to steeper slopes (300-series landtypes). Landtypes in the 100 and 300 series (continentally glaciated landforms) had greater overall recovery than the 500-series landtypes (erosion landforms) (fig. 10). It is unclear why this difference occurred, but it could have resulted from the larger sample size in the 100 and 300 series.

Generally, soils with lower bulk density are more prone to compaction (Powers et al. 2005). Volcanic ash-cap soils have very low bulk density and are found on much of the KNF (Kimsey et al. 2007; Vaughan 2016). The prevalence of these soils increases the likelihood that a given sample point will be susceptible to soil compaction

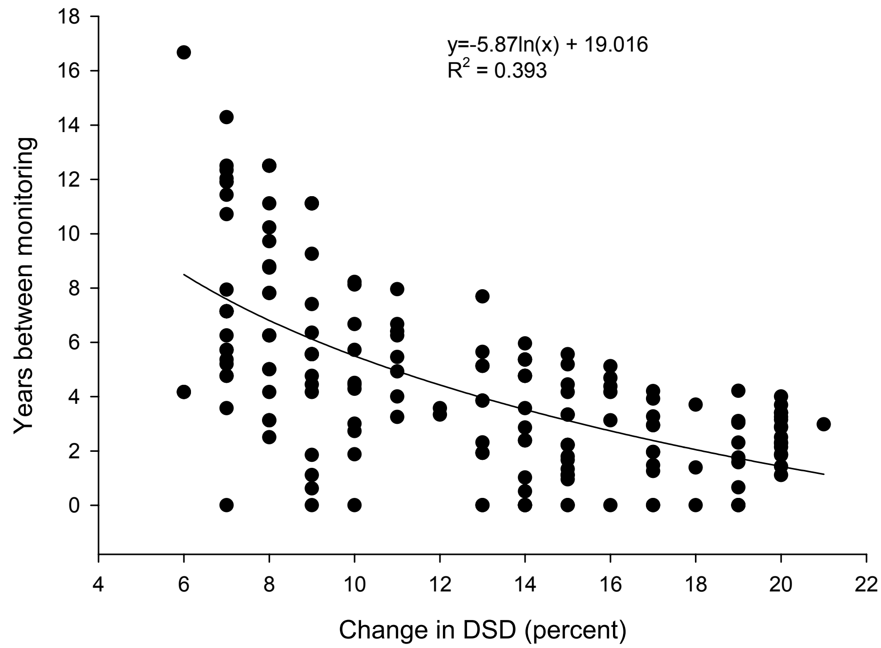


Figure 9—Relative change in detrimental soil disturbance (DSD) values per year from the initial monitoring (1992–1999) to the remonitoring (2012–2013) on the Kootenai National Forest for combined ash and non-ash soils.

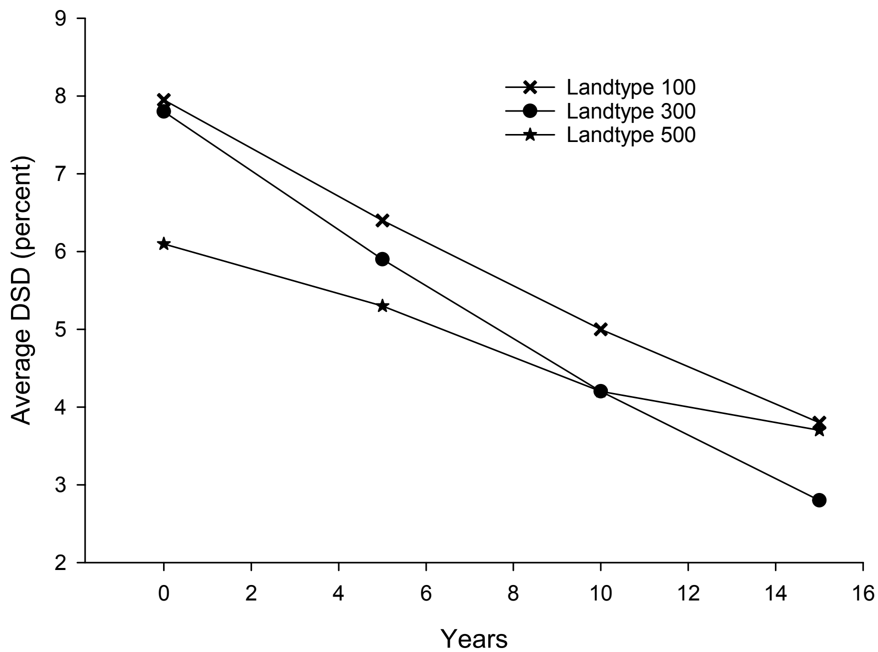


Figure 10—Average recovery time from detrimental soil disturbance (DSD) on landtypes in the 100 series (n = 19), 300 series (n = 154), and 500 series (n = 8) on the Kootenai National Forest.

(Allbrook 1986; Page-Dumroese 1983; Page-Dumroese et al. 2006). Once compacted, soils become relatively resistant to further compaction due to an increased proportion of micropores and a reduction of macropores (Ampoorter et al. 2012). Above a critical moisture content, all soil textural classes are susceptible to machine-induced soil deformations such as topsoil puddling and eventually deep rut formation (Hillel 1998; Williamson and Neilsen 2000).

Soil recovery from DSD is logarithmic and greatest during the first 3 to 5 years following timber harvest and fuels abatement activities; recovery decreased over time (fig. 9). Some units had 100-percent soil recovery relative to the original soil monitoring data and more than 77 percent of the resampled units had a reduction in DSD of at least

2 percent. Portions of units still containing DSD had high levels of soil compaction and are likely to have long-term impacts from which the soil may take decades to recover (Froehlich et al. 1985; Page-Dumroese et al. 2010). Examples of residual DSD include deeply rutted equipment tracks, skid trails, and log landings within a harvest unit. Initial sampling showed that 6 percent of the units had DSD values exceeding 15 percent. After resampling, none of the 183 units exceeded 15 percent DSD. Of the units that initially had less than 15 percent DSD, the resampling effort showed that 28 percent of the units still had 1 to 2 percent DSD. Units with DSD greater than 15 percent during the initial sampling were found to now average around 8 percent DSD. These results indicate that recovery rates may not be uniform across all disturbance types and that the greater the initial disturbance value, the more time is necessary for DSD levels to reach 1 to 2 percent. On the North American Long-Term Soil Productivity sites, compaction (as measured by bulk density) recovery within 5 years was related to initial bulk density (Page-Dumroese et al. 2006). Sites with a low initial bulk density (ash-cap soils) compacted easily and were the slowest to recover, even with an active freeze-thaw cycle. Coarse-textured soils, which have a higher initial bulk density, were not easily compacted to a root-limiting bulk density and recovered faster. After 15 years on skid trails with a clayey-skeletal soil, no recovery of soil compaction was detected and the soil continued to exhibit platy structure, which altered water movement into the soil (Rawinski and Page-Dumroese 2008).

Another factor contributing to DSD in the late 1980s to early 1990s was large-scale fuels abatement, usually by broadcast burning, excavator piles, underburning, or whole-tree yarding. The fuels treatment was selected according to the desired long-term goals for stand structure or wildlife. For example, if winter habitat or browse were required for big game animals, the KNF would often prescribe postharvest underburning within that unit.

Harvest methods, type of equipment, number of stand entries, season, and operator skill affect the amount of soil disturbance in any harvest unit. When studying soil monitoring transect data on the KNF, Reeves et al. (2012) generally found that the amount of DSD in a harvest unit depended on landtype and season of harvest. Harvest unit topography (slope and aspect) was also a significant factor in the amount of DSD resulting from ground-based harvest.

Other Harvest Design Characteristics

In addition to harvest methods, other characteristics of harvest design influence initial soil disturbance. For example, the number of passes is related to soil disturbance level (Froehlich 1978; Froehlich et al. 1980; Gent and Ballard 1984; Han et al. 2006, 2009). On the KNF, average DSD values monitored between 1991 and 1995 and later were lower than those after similar harvest operations in the late 1980s and early 1990s, as bulldozer piling fell out of practice and excavators became the machinery of choice. Additionally, comparison of data from 1995 through 2000 with data from 2000 through 2005 showed the effect of seasonality on average DSD values. In the earlier timeframe, average DSD values were lower because of winter harvest activity and logging operations on frozen soils, in contrast with summertime operations in the latter time period. Finally, the DSD values tended to increase when compared to the previous decade as harvest operations on monitored units went from intermediate harvest operations to full regeneration harvest prescriptions, and fuels treatment methods changed from under-burning to more frequent excavator piling operations.

Equipment Type

Results of previous monitoring display a strong relationship between equipment type and original level (percentage) of DSD. Early- to mid-1990 data suggest much greater disturbance from the use of bulldozers and very large (≥0.1 ha) burn piles used during harvest and fuels abatement activities, in contrast with recent harvest activities. More common practices recently are forwarder and excavator use combined with smaller fuels treatment activities (e.g., jackpot burn piles or grapple pile operations on areas 0.03 to 0.05 ha [0.07–0.1 ac]).

Different types of machinery exert different amounts of pressure from tire tracks on soils (table 1). For example, data from 1992 soil monitoring indicated that 49 percent of the area sampled exceeded 15 percent DSD whereas monitoring from 1993 through 2006 showed only 1 percent of the area exceeding 15 percent DSD. Shifting from bulldozers that create large burn piles to rubber-tire skidder yarding and excavator piling is probably responsible for the decrease in DSD values. Results also suggest that hi-drive machinery (bulldozer) causes less detrimental disturbance than rear-drive bulldozers.

During resampling field work, we noted that soil recovery was actively occurring in timber sale units during the first 3 to 5 years following harvest. Recovery was evident primarily in the areas of a timber harvest unit that did not contain main skid trails, temporary roads, landing sites, and areas of higher temperature burns. This result is similar to those reported by Froehlich (1979), who found soil densities in skid trails at depths of 7 to 15 cm (3–6 in) and 22 to 30 cm (9–12 in) were 18 and 9 percent greater, respectively, than in adjacent undisturbed soils. During the original sampling on the KNF, DSD on 90 percent of the units was attributed to soil compaction increases.

Soil Texture

Lack of soil recovery or minimal soil recovery in harvest units was roughly correlated to soil physical properties. For example, an intact, healthy, volcanic ash-cap-influenced soil promotes faster regrowth of the remaining trees or of the second-growth stand. This regrowth helps to reduce soil compaction as roots fracture the compacted

Table 1—Ground pressure applied to soils based on mechanical harvest equipment (Froehlich 1978; Froehlich and McNabb 1984).

	Pressure on soil	
Machinery type	**kilopascals**	**pounds per square inch**
D6 bulldozer static	48–55	7–8
D6 bulldozer moving	172–206	25–30
Rubber-tire skidder static	65	9.5
Rubber-tire skidder moving	117	17 (17 percent slope)
Forwarder static	20–34	3–5
Forwarder moving	48–64	7–9

layer. However, if the initial compaction level exceeds root-limiting bulk densities (Daddow and Warrington 1983), root growth into the compacted layers may be limited. Furthermore, past glacial activities removed the surface horizons, resulting in a very thick clay-rich subsoil that is still at the soil surface and that impedes recovery. Field observations on the KNF show that residual soils (which have angular structure, contain 70 percent rock, are not affected by glaciation, and have weathered in situ), are less susceptible to equipment impacts than soils containing glaciated rounded rock (35–50 percent rock). These differences indicate that soil textural class and rock-fragment content should be taken into account when considering harvest and site preparation methods.

Landtype

The resampling effort evaluated soil disturbance changes on soils from different soil mapping groups associated with the 100-, 300-, 400-, and 500-series landtypes. The greatest amount of recovery from DSD was found on the 100- and 300-series landtypes, whereas soils in the 500 series had less overall recovery (fig. 10, table 2). Other factors such as root growth and soil freeze-thaw cycles as well as initial soil bulk density may play a more critical role in soil recovery than landtype.

Volcanic Ash-Cap Recovery

Volcanic ash-cap deposits on the KNF originated from the Mount Mazama eruption about 6,850 years BP and the 1980 eruption of Mount St. Helens (Daley-Laursen 2007; Zdanowicz et al. 1999). Soils influenced by either an ash-cap or mixed ash and mineral soil are located across the western half of the KNF (Nimlos and Zuuring 1982). Locations without volcanic ash today probably received ash deposits from the Mount Mazama volcanic eruption, but over time, wind and water removed these materials. Of the 183 units that were resampled, 58 percent had volcanic ash either on top of or mixed into the surface mineral; the remaining units (42 percent) lacked these deposits.

We compared soil recovery rates for volcanic ash-derived soil (fig. 11) and soil not influenced by volcanic ash (fig. 12). Of 171 units showing a decrease or no change in DSD, we identified 117 units with ash-derived soils and 54 units with non-ash-derived soils.

Results indicate a higher soil recovery rate for units with an ash-cap ($R2 = 0.48$; fig. 11) than for the non-ash soils ($R2 = 0.26$; fig. 12). On ash-cap soils, recovery after 5 years averaged 9 percent and after 10 years, 6 percent. On non-ash-influenced soils, recovery after 5 years was 7 percent and after 10 years was less than 6 percent. The two soil recovery curves suggest the inability of highly compacted glacial till soils to recover as quickly from mechanical activities as ash-rich soils. These differences in recovery rate may also reflect differences in tree-growth rates on the two types of soil (data not shown). Conifer species growing in ash-rich soils often grow at faster rates and develop a thicker understory than they do on mineral soils. This additional root growth could aid in recovery. Similarly, visual observations of older soil compaction (1960s or earlier) on glacial till soils without an ash-cap still indicate slower tree growth. These observations are consistent with reports of reduced tree growth rates with increased soil compaction

Table 2—Average soil recovery from detrimental soil disturbance (DSD) on the Kootenai National Forest after 15 years based on landtype. Harvest units with an increase in DSD are not shown.

Landtype	Number of units sampled	Range of DSD recovery	Average DSD recovery
		---------- *Percent* -----------	
102	3	0–5.4	2.7
103	1	2.4	2.4
104	2	1.5–7.4	4.4
106	7	0–12.5	4.9
108	3	5–5.6	4.4
112	3	0–4.2	3.6
100 Series	**19**	**0–12.5**	**3.9**
301	1	3.4	3.4
302	2	0.5–3.1	1.9
321	6	0–6.3	5.3
322	11	3.7–11.1	6.6
323	22	0–12.5	5.6
324	10	3–7.9	5.4
328	5	6.3–11.9	9.4
329	12	1.1–12.5	7.1
351	2	2.9–4.2	3.5
352	53	0–8.2	3.1
353	2	0–7.7	3.9
355	22	0–16.5	5.0
357	4	0–3.1	1.4
360	1	4.0	4.0
300 Series	**153**	**0–12.5**	**4.7**
406	2	0–4.2	2.1
400 Series	**2**	**0–4.2**	**2.1**
502	3	0–3.3	2.4
555	5	1–4.8	3.3
500 Series	**8**	**0–4.8**	**2.9**

in other studies, such as Froehlich and McNabb (1984), Sands et al. (1979), and Powers et al. (1990).

Data on soil recovery rates on the KNF are not consistent with research elsewhere because non-ash soils are generally expected to have higher recovery rates than ash-rich soils (Page-Dumroese et al. 2006). There are several hypotheses about why ash-cap soils may not recover as readily from compaction. One hypothesis is that compaction actively breaks down soil particles and realigns them in a platy structure. A second hypothesis is that glass particles in the volcanic ash-cap become physically locked in place (Johnson et al. 2007). A third hypothesis postulates that the lack of a freeze-thaw cycle in many of the drier regions of the Intermountain United States prevents recovery within a stand

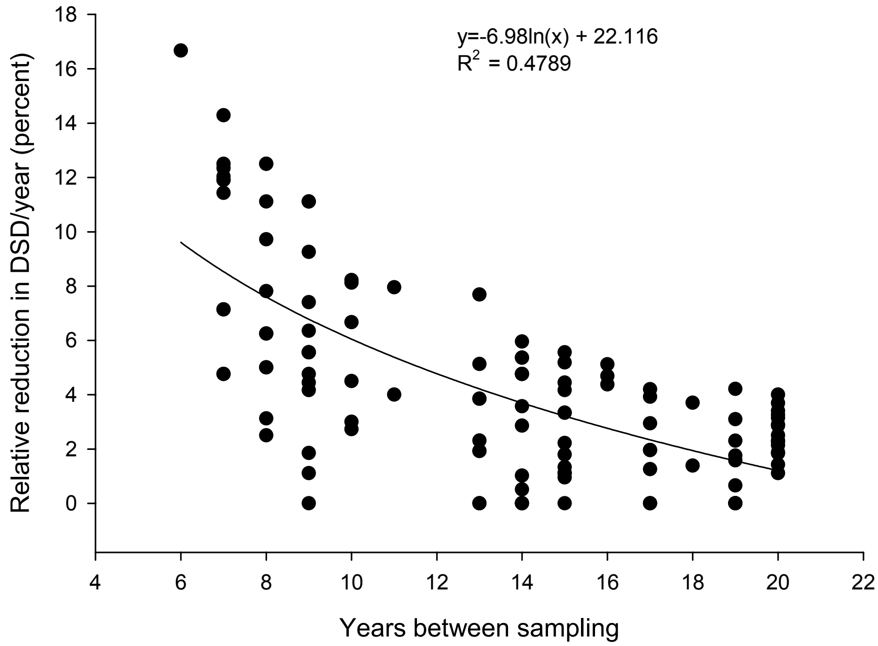


Figure 11—Relative rate of recovery from detrimental soil disturbance (DSD) on volcanic ash-cap soils on the Kootenai National Forest.

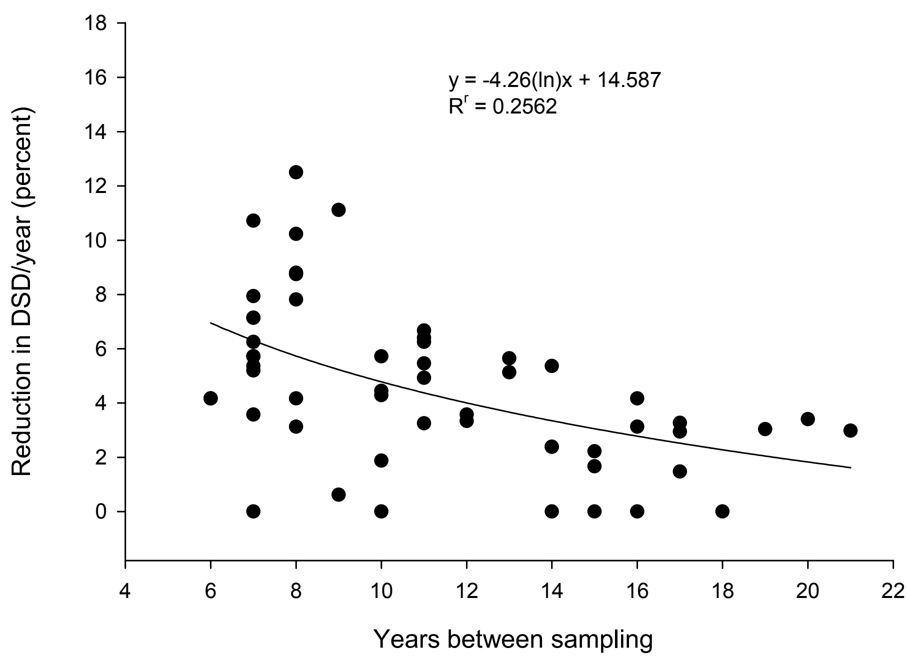


Figure 12—Relative rate of recovery from detrimental soil disturbance (DSD) on non-ash soils on the Kootenai National Forest.

rotation (Johnson et al. 2007). Froehlich et al. (1985) observed that compaction in ash-cap soil had 26 percent higher soil bulk density at a depth of 15 cm (6 in) in trails than off trails 20 to 25 years after harvest.

Our results may be partly explained by the higher growth rates in both understory and overstory vegetative species on ash-rich soils. The location of the monitoring transects may also help to explain the discrepancy. Resampled units located in the western portion of the KNF had deeper ash-layers, whereas units in the eastern half of the forest, in general, had much more shallow ash deposits. But connecting recovery rate to category of soil disturbance is complicated by differences in soil moisture in the two halves of the forest. The western half of the KNF is the moister area, so vegetative growth rates (and thus soil recovery) are expected to be higher than in the eastern portion. Other research indicates that the effects of compaction are highly variable (Busse et al. 2006; Page-Dumroese et al. 2006; Powers 2006) and largely dependent on site conditions and microclimatic regimes in the rooting zone (Gomez et al. 2002). In contrast, Froehlich et al. (1985) found that ash-cap soils take longer to recover than non-ash-cap soils. Differences in results emphasize that site-specific data are critical to determining long-term impacts.

Soil recovery curves are directly related to postharvest fuels treatments. Statistical analysis of 2012 data from 55 timber sales (118 timber units) involving 3,335 ac (1,350 ha) revealed that 20 percent of the difference in soil recovery was related to fuels treatments and 14 percent was related to harvest methods. The DSD is likely the result of both harvest and fuels abatement operations that resulted in large piles of burned woody material, which would be expected to have a greater impact on the forest floor and A-horizons as compared to an underburn. As mentioned already, piling woody residues and burning them can produce very high soil temperatures that destroy the underlying forest floor, alter mineral soil properties, and affect vegetative growth (Glassy and Svalberg 1983). The average rate of recovery from DSD after bulldozer piling is lower than for other fuels reduction methods (fig. 13). Detrimental soil disturbance may be further exacerbated in areas of large lacustrine deposits formed under the Cordilleran Ice Sheet. These areas have dense soils and lack permeability; they were substantially affected by past management activities. Similar conditions exist where there are large areas of soil displacement and compaction that removed the O- and A-horizons. Across all landtypes we note that soil recovery over time was significantly greater in the recent harvest operations as compared to those occurring earlier. These results probably reflect changes in harvest operations and fuels abatement techniques.

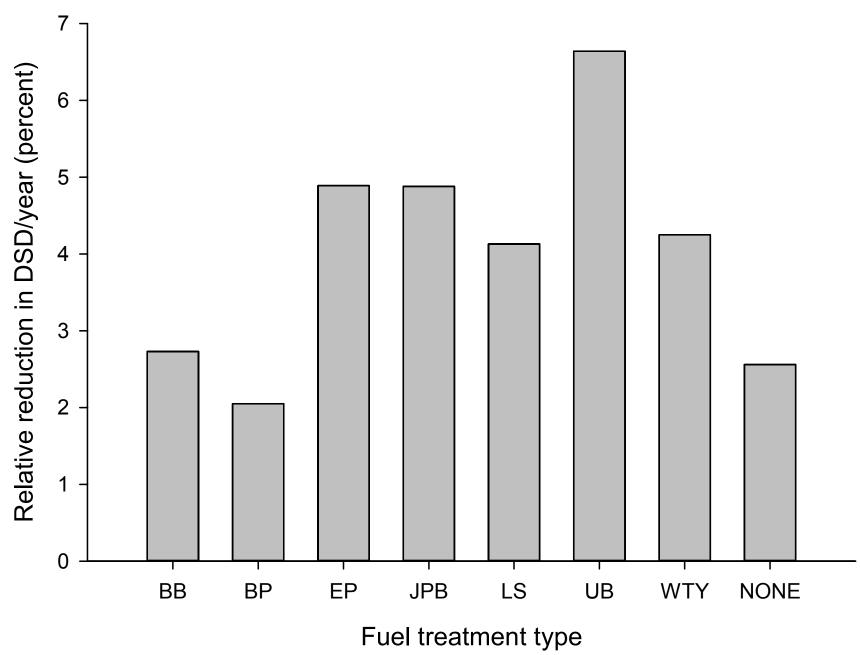


Figure 13—Change in detrimental soil disturbance (DSD) between initial sampling and resampling for each type of equipment used for fuels abatement activities on the Kootenai National Forest over the past 30 years. BB = broadcast burn; BP = bulldozer pile; EP = excavator pile; JPB = jackpot burn; LS = lop and scatter; UB = underburn; WTY = whole-tree yard; and None = no postharvest fuels abatement.

Conclusions: Ecosystem Responses to Detrimental Soil Disturbance

The Long-Term Soil Productivity (LTSP) studies were initiated in 1989 to evaluate how differing levels of soil compaction and organic matter removal may alter soil function and subsequent stand productivity (Powers et al. 2004). After 5 years, soil bulk density at a depth of 20 to 30 cm (8–12 in) in 3 of the 12 LTSP study sites showed an increase in compaction (Page-Dumroese et al. 2006), probably due to high site variability or organic matter removal. The LTSP results also revealed that fine-textured soils were more easily compacted and, therefore, soil recovery was much slower (Page-Dumroese et al. 2006). Furthermore, there was a link between DSD and depth of surface organic matter. On sites containing thicker surface organic horizons, DSD tended to be much lower than on those sites with thin or missing surface organic matter. Therefore, it is critical to leave the forest floor intact during harvest and site preparation.

This study of soil recovery after DSD is critical to understanding the relationships between soil physical properties at the time of timber management activities and direct effects on DSD recovery speed. Other variables that we did not include in our resampling effort were slope, aspect, elevation, harvest type, cutting method, and operational period, but they were shown to be important in a separate study on the KNF (Reeves et al. 2011). A key finding is that the DSD recovery rate is not constant; most recovery occurs during the first 3 to 5 years after operations cease. This is based on continual soil monitoring data collected on the KNF. Understanding when to monitor harvest sites is critical to interpreting the results. Soil monitoring is often conducted 1 to 3 years following harvest after site preparation is complete. This lagtime allows for some short-term recovery to take place (e.g., formation of a litter layer and establishment of groundcover on the forest floor), but displacement, erosion, rutting, and compaction are still detectable. Assessing these same sites at a later date will help to determine whether the soil is recovering function.

Unlike in other studies, we did not find a difference in recovery based on soil texture although texture is believed to have a strong relationship with soil disturbance. Powers et al. (2004) indicate that increases in harvest-related bulk density correspond to lower recovery rates. This is similar to findings on the KNF, particularly where glaciated lacustrine soils lack a well-developed forest floor and A-horizons. Higher bulk density due to harvest may be one reason that harvest units with higher initial DSD after bulldozer activity or under less favorable conditions still exhibited high DSD at the resampling.

Results of this study indicate that legacy soil compaction can be detected even decades after harvesting. In general, more than 90 percent of the long-term DSD found in this study was directly related to the main skid trails, temporary roads, and landings while activities such as firelines or fuels abatement activities had a much smaller impact on overall DSD. When revisiting older harvest units, we noted that linear skid trails had few conifers, perhaps because of compaction and the lack of organic horizons. Conversely, soils without heavy equipment passes are readily moving toward soil recovery; 86 percent of the stands showed a reduction from the initial DSD. In many resampled units, the 1980 Mount St. Helens eruption produced ash that covered some soil disturbance and provided a good matrix for seedling establishment and understory vegetative growth. Such natural disturbances further hide the effects of historical machinery activities and mask what may have at one time been a more disturbed soil. Resampling locations lacking deep volcanic ash-caps or where historical glaciation removed surface organic layers indicated that legacy compaction was easily identified on bladed skid trails. In areas where harvest operations used similar equipment except for blading trails, there is still a deep forest floor and A-horizon.

Understanding DSD requires knowledge of other factors such as: (1) harvest equipment; (2) season of operation; (3) timber sale oversight by contracting officer or purchasers, or both; and (4) amount of the harvest operation completed during less desirable conditions (e.g., wet soil, nonfrozen ground). Early work on the KNF found: (1) granular soil, sands, and gravels show little change as a result of compaction; (2) soil structure changes associated with compaction take a long time to recover; and (3) compaction occurring on saturated soil causes compaction deep within the soil profile (Napper et al. 2009; Page-Dumroese et al. 2006; Reeves et al. 2011). The degree of equipment-caused DSD, if any, often depends on soil texture and moisture. Davis (1992) found that a sandy-loam soil with a volcanic ash-cap was not affected by changing soil moisture. However, Han et al. (2006) found that fine loamy soils appear to be very sensitive to soil moisture content and are more likely to form ruts. We also note a strong relationship between fuels abatement activities and soil recovery times. In units where piles are burned extremely hot, soil properties are altered; changes in soil pH and nutrient content make these areas unsuitable for conifer regeneration and promote understory species that may delay conifer establishment.

Management Implications

Our results show that DSD recovery is not constant and that most soil recovery occurs in the first 3 to 5 years following operations. This information can help managers determine whether the harvest unit is on track to recover before the next planned stand entry or whether ameliorative treatments to reduce DSD are necessary. Equipment changes, such as using waste woody biomass for bioenergy instead of pile burning, and reusing skid trails can reduce the impact of harvest operations on soil and hydrologic functions, thereby supporting sustainable forest operations.

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Appendix—Landtype and soil classifications for the Kootenai National Forest. Asterisk (*) indicates landtypes in harvest units that were monitored between 1992 and 2006 and resampled in 2012 or 2013.

Landtype[a]	Soil taxonomic classification[a]	Volcanic ash-cap	Not influenced by volcanic ash-cap
101	Fluvents		X
102*	Andic Dystric Eutrochrepts, fine silty mixed frigid	X	
103*	Andic Dystrochrepts, loamy-skeletal, mixed, frigid	X	
104*	Andic Dystrochrepts, loamy-skeletal, mixed, frigid; Umbric Vitrandepts, medial over loamy, mixed frigid	X	
105	Aquic Udifluvents, coarse-loamy, mixed, frigid		X
106*	Andic Dystrochrepts, loamy-skeletal, mixed frigid	X	
107	Typic Xerochrepts, loamy-skeletal, mixed, frigid		X
108*	Andic Distric Eutrochrepts, fine-silty, mixed, frigid; Andic Dystrochrepts, loamy-skeletal, mixed, frigid	X	
109	Typic Xerochrepts, loamy-skeletal, mixed, frigid		X
110	Eutrochrepts, coarse-loamy, mixed, frigid		X
111	Calcixerollic, Xerochrepts, coarse-loamy, mixed, frigid		X
112*	Eutric Glossoboralfs, fine illitic		X
114	Typic Eutrochrepts, fine-silty, mixed, frigid		X
201	Lithic Ustochrepts, loamy-skeletal, mixed, frigid; Typic Ustochrepts, loamy-skeletal, mixed, frigid		X
251	Andic Dystrochrepts, loamy-skeletal, mixed, frigid; rock outcrop 25–50%; north and east aspects	X	
252	Andic Dystrochrepts, loamy-skeletal, mixed, frigid; rock outcrop 5–15%; north aspect	X	
301*	Dystic Eutrochrepts, loamy-skeletal, mixed, frigid	X	
302*	Typic Ustochrepts, loamy-skeletal, mixed, frigid		X
303	Lithic Estrochrepts, loamy-skeletal, mixed, frigid		X

321*	Typic Eutroboralfs, loamy-skeletal, mixed		X
322*	Eutric Glossoboralf, fine, sandy		X
323*	Typic Eutroboralfs, fine-loamy, mixed		X
324*	Typic Eutrochrepts, loamy-skeletal, mixed, frigid		X
325	Aeric Calciaquolls, fine-silty, frigid		X
328*	Andic Cryochrepts, loamy-skeletal, mixed; rock outcrop <5%	X	
329*	Andic Cryochrepts, loamy-skeletal, mixed; rock outcrop 5–15%	X	
351*	Andic Dystrochrepts, loamy-skeletal, mixed, frigid; rock outcrop 10%; 30–60% slope	X	
352*	Andic Dystrochrepts, loamy-skeletal, mixed, frigid; rock outcrop <5%; 20–60% slope	X	
353*	Andic Cryochrepts, loamy-skeletal, mixed; Lithic Cryochrepts, loamy-skeletal, mixed	X	
355*	Andic Dystrochrepts, loamy-skeletal, mixed, frigid	X	
357*	Andic Cryochrepts, loamy-skeletal, mixed; Lithic Cryochrepts, loamy-skeletal, mixed	X	
360*	Lithic Cryochrepts, loamy-skeletal, mixed	X	
365	Andic Dystrochrepts, loamy-skeletal, mixed, frigid	X	
370	Andic Dystrochrepts, loamy-skeletal, mixed, frigid	X	
381	Typic Ustochrepts, loamy-skeletal, mixed, frigid; Lithic Ustochrepts, loamy-skeletal, mixed, frigid	X	
401	Andic Cryochrepts, loamy-skeletal, mixed; Lithic Cryochrepts, loamy-skeletal, mixed	X	
403	Lithic Cryochrepts, loamy-skeletal, mixed; Andic Cryochrepts, loamy-skeletal, mixed	X	
404	Andic Cryochrepts, loamy-skeletal, mixed	X	
405	Lithic Cryochrepts, loamy-skeletal, mixed; Andic Cryochrepts, loamy-skeletal, mixed	X	
406*	Andic Cryochrepts, loamy-skeletal, mixed	X	
407	Andic Cryochrepts, loamy-skeletal, mixed	X	
408	Andic Cryochrepts, loamy-skeletal, mixed	X	
502*	Typic Ustochrepts, loamy-skeletal, mixed, frigid		X
503	Lithic Ustochrepts, loamy-skeletal, mixed, frigid		X
510	Typic Calcixerolls, loamy-skeletal, mixed, frigid		X
520	Andic Dystric Eutrochrepts, loamy-skeletal, mixed, frigid	X	

522	Andic Dystrochrepts, loamy-skeletal, mixed, frigid	X
552	Andic Dystrochrepts, loamy-skeletal, mixed, frigid	X
555*	Andic Cryochrepts, loamy-skeletal, mixed	X
570	Andic Dystrochrepts, loamy-skeletal, mixed, frigid; Typic Ustochrepts, loamy-skeletal, mixed, frigid	X

[a] Source: Kuennen and Gerhardt (1984).

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