SOIL DISTURBANCE MONITORING OF TIMBER HARVEST OPERATIONS IN THE USDA FOREST SERVICE NORTHERN REGION

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ABSTRACT

Timber harvest may cause changes to soil physical, chemical, and biological properties that reduce site productivity. Determining which physical site factors control soil response to ground disturbing activities is difficult due to the heterogeneity of harvest sites and different soil disturbance monitoring methods used within the USDA Forest Service Northern Region. I used soil disturbance monitoring data from nine Northern Region National Forests to determine: 1) if soil disturbance monitoring data can link disturbance levels to site characteristics using monitoring data collected under disparate protocols, 2) if risk ratings can be developed to identify areas susceptible to high impact harvest techniques using a consistent soil disturbance monitoring protocol, 3) levels of detrimental soil disturbance resulting from helicopter, skyline, and ground-based harvest systems, and 4) how policies pertaining to soil and site sustainability affect management. Results indicate that a common soil monitoring protocol is necessary to determine how site characteristics affect soil resiliency to timber harvest operations. We were able to produce a soil risk rating system based on landtype and harvest season using a consistent soil disturbance monitoring protocol. There are significant differences in soil disturbance resulting from timber harvest systems with helicopter < skyline < ground-based. Policy revision should be considered to give managers the flexibility to meet management objectives while maintaining site productivity. Results suggest that site-specific characteristics control the impacts to soil resulting from timber harvest operations, which should be considered to minimize soil disturbance while meeting management objectives.

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TABLE OF CONTENTS

TITLE PAGE.....i

AUTHORIZATION TO SUBMIT THESIS.....ii

ABSTRACT.....iii

ACKNOWLEDGEMENTS.....iv

TABLE OF CONTENTS.....v

LIST OF TABLES.....x

LIST OF FIGURES.....xi

CHAPTER 1: INTRODUCTION.....1

1.1 Project Justification.....2

1.2 Research Objectives.....3

1.3 References.....4

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW.....5

2.1 Types of Disturbance.....6

2.2 Effects of Disturbance on Nutrients/ Microbes.....13

2.3 Effects of Disturbance on Tree Growth.....18

2.4 Legislation, Soil Quality Standards, and Monitoring Protocols.....21

2.5 References.....26

CHAPTER 3: EVIDENCE SUPPORTING THE NEED FOR A COMMON SOIL MONITORING PROTOCOL.....34

Abstract.....35

3.1 Introduction.....36

3.2 Methods.....40

3.2.1 Data and harvest systems evaluated....................40
3.2.2 Data collection and conversion from disparate databases....................42
3.2.3 Physical site characteristics....................44
3.2.4 Analysis....................45
3.3 Results....................46
3.4 Discussion....................48
3.4.1 National Forest monitoring....................48
3.4.2 Harvest systems....................49
3.4.3 Season of harvest....................50
3.4.4 Slope....................51
3.4.5 Soil texture....................52
3.4.6 Mean soil disturbance....................54
3.5 Management Implications....................54
3.6 Acknowledgements....................55
3.7 References....................56
CHAPTER 4: RISK RATINGS TO PREDICT POTENTIAL DETRIMENTAL SOIL DISTURBANCE FROM GROUND-BASED TIMBER HARVEST ON THE KOOTENAI NATIONAL FOREST....................59
Abstract....................60
4.1 Introduction....................61
4.2 Methods....................64
4.2.1 Data collection....................64
4.2.2 Field collection of soil disturbance monitoring data....................65

4.2.3 Landtypes 66
4.2.4 Statistical analysis 68
4.2.5 Geo-spatial projection 69
4.3 Results 70
4.3.1 Factors controlling disturbance 70
4.3.2 Geo-spatial representation of the statistical model 72
4.4 Discussion 75
4.5 Management Implications 81
4.6 Acknowledgements 81
4.7 References 82
CHAPTER 5: DETRIMENTAL SOIL DISTURBANCE ASSOCIATED WITH TIMBER HARVEST SYSTEMS ON NATIONAL FORESTS IN THE NORTHERN REGION 85
Abstract 86
Research Summary 87
5.1 Introduction 89
5.2 Methods 91
5.2.1 Data collection 91
5.2.2 Detrimental soil impacts definition 93
5.2.3 Monitoring methods 93
5.2.4 Description of harvest systems 94
5.2.5 Statistical analysis 96
5.3 Results 96

5.3.1 Region-wide 96
5.3.2 Individual Forests....99
5.4 Discussion 104
5.4.1 Regional analysis 104
5.4.2 Individual Forest analysis 108
5.5 Conclusion 111
5.6 Acknowledgements....112
5.7 References....113
Appendix A: Mean areal extent of DSD for each harvest system by Forest 116
CHAPTER 6: PRODUCTIVITY MAINTENANCE AS A BARRIER TO ACTIVE MANAGEMENT....117
Abstract....118
6.1 Introduction....119
6.2 Problem Statement....121
6.3 Social Context of the Problem....122
6.4 Decision Context....123
6.5 Analysis of Current Policy....125
6.5.1 Trends 125
6.5.2 Factors affecting current policy 127
6.5.3 Projections....128
6.6 Alternatives to Current Policy 129
6.6.1 Maintain Current Policy....129
6.6.2 Revision of the National Forest Management Act....130

6.6.3 Revision of Forest Service Manual 2500 130
6.6.4 Revision of the Northern Region Soil Quality Standards 131
6.7 Recommendations 132
6.8 References 135
CHAPTER 7: CONCLUSIONS 137
7.1 Summary of Results 138
7.2 Management Implications 141
7.3 References 148

LIST OF TABLES

3.1. Total number of units surveyed by harvest system and season of harvest 41

3.2. Number of harvest units for each forest, data points associated with total number of units and percentage of total monitoring points each forest contributed 42

3.3. The 4 Forest Soil Disturbance Monitoring Protocol disturbance classes and the corresponding Howes (2000) (or other) disturbance classes 43

3.4. Groupings of soil textural classes used in the analysis 44

3.5. Model variables and their associated probability values 46

4.1. Detrimental disturbance thresholds from the Northern Region used by the KNF for monitoring determinations 66

4.2. Selected physical characteristics and acreage for the nine landtypes in this study 67

4.3. Selected geological and ecological characteristics for nine landtypes in this study........68

4.4. Significant model variables and associated probability variables 71

4.5. Parameter estimates used to produce geo-spatial representation of statistical model 75

5.1. Number of timber harvest units associated with individual National forests by harvest system...92

5.2. ANOVA table listing model variables and probability values for a Regional analysis of DSD 96

5.3. ANOVA table listing model variables and probability values for Regional analysis of DSD due to ground-based timber harvest...98

5.4. Mean areal extent of DSD for each harvest system by National Forest.........................116

LIST OF FIGURES

3.1. National Forests located in the Northern region of the USDA Forest Service represented in this study..41

3.2. Mean soil disturbance associated with evaluated timber harvest systems.......................47

3.3. Mean soil disturbance values reported by the individual forests for ground-based harvest systems..47

4.1. Mean areal extent of DSD for each landtype and harvest season evaluated for this study 71

4.2. Mean areal extent of DSD by aspect...72

4.3. Geo-spatial representation of statistical model predicting areal extent of DSD resulting from winter ground-based timber harvest 73

4.4. Geo-spatial representation of statistical model predicting areal extent of DSD resulting from non-winter ground-based timber harvest..74

5.1. National Forests of the Northern Region included in the study......................................92

5.2. Detrimental soil disturbance values by harvest system for all National Forests surveyed in the Northern Region..97

5.3. Areal extent of DSD resulting from ground-based harvest in the Northern Region by season..98

5.4. Areal extent of DSD for ground-based harvest on National Forests in the Northern Region during the summer and winter seasons 99

6.1. National Forests included in the Northern Region 117

CHAPTER 1: INTRODUCTION

1.1 Project Justification

Timber harvest activities cause some degree of soil disturbance (Grigal 2000). Soil physical, chemical, and biological properties altered by soil disturbance resulting from timber harvest may have implications for sustained site productivity (Binkley 1991). Maintenance of site productivity falls under the regulatory umbrella of several statutory and administrative laws, especially the National Forest Management Act (NFMA 1976) and its implementing regulations (USDA-FS 1982). Current directives developed in response to regulatory requirements state that no more than 15% of the areal extent of a timber harvest unit can be detrimentally disturbed (USDA-FS 1999).

This project was initiated by the USDA Forest Service to identify timber harvest operations that routinely result in less than 15% detrimental soil disturbance on timber harvest units. Correlating detrimental soil disturbance with timber harvest systems and site characteristics provides a method to estimate site susceptibility to harvest operations. The results of this study should provide scientific justification for prioritizing resource allocation for monitoring soil disturbance resulting from management activities. In addition, results of this study may indicate if adoption of a universal soil disturbance monitoring protocol is warranted, and could suggest refinements of best management practices seeking to minimize soil disturbance during harvest operations.

1.2 Research Objectives

This thesis regarding soil disturbance has several objectives; with a separate chapter for each discussing methods and results, as follows:

1. Determine if soil disturbance monitoring data collected under disparate monitoring protocols can be used to correlate disturbance levels to harvest systems and site physical characteristics (Chapter 3).
2. Utilize soil disturbance monitoring data to produce a model predicting the areal extent of detrimental soil disturbance based on landscape characteristics and season of harvest (Chapter 4).
3. Evaluate the areal extent of detrimental soil disturbance resulting from timber harvest operations on National Forests in the Northern region of the USDA Forest Service (Chapter 5).
4. Provide an analysis of policy related to soil disturbance in the Northern Region of the USDA Forest Service (Chapter 6).

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CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1 Types of Disturbance

Forest soil maintenance is a key factor for sustaining productive forests (Curran et al. 2005). Timber harvest activities cause forest soil disturbance that have implications for site productivity that range from beneficial to detrimental (Bockheim et al. 1975, Grigal 2000, Curran et al. 2007). Physical, chemical, and biological soil properties are affected by these types of disturbances, which in turn affect forest productivity (Binkley 1991). Maintenance of site productivity is a common objective on federal lands in the United States (Page-Dumroese et al. 2000). Increased demands of a growing population from a shrinking forestry land base will require maintaining or improving site productivity (Thorud 1983). Many chemical, physical and biological factors interact with forest management impacts on site productivity. Results of these activities will also change over time, depending on the current level of impact, and will likely be cumulative (Carter et al. 2006, Page-Dumroese et al. 2010). Short term reductions in site productivity may be reduced over time through natural mitigation processes, or may become permanent with cumulative soil degradation as a result of multiple entries (Page-Dumroese et al. 2010). Maintaining soil productive capacity on USDA Forest Service lands is governed under several laws and directives. Included in these are requirements for monitoring soil disturbance to assess the level of compliance timber harvest activities reach in meeting mandates and directives related to soil disturbance. Soil disturbance resulting from timber harvest operations is recognizable as compaction, rutting, displacement, and erosion. In order to understand the impacts of forest operations on soil productivity it is necessary to consider each of these controlling factors. This discussion will evaluate the range of factors affecting the extent and severity of disturbance resulting from timber harvest and site preparation operations and discuss the mandates and directives governing maintenance of soil productive capacity.

Compaction is the most commonly cited form of soil disturbance resulting from harvest activities because of its potential to negatively impact vegetation growth. (Cochran and Brock 1985, Geist et al. 1989, Williamson and Neilsen 2000, Gomez et al. 2002, Parker et al. 2007, Wang et al. 2007). Compacted soil exhibits a decrease in total porosity and a corresponding increase in bulk density, volumetric water content and soil strength (Greacen and Sands 1980; Gomez et al. 2002). While these relationships are consistent for all soil types, they differ in magnitude. Gomez et al. (2002) reported increases in bulk density due to compaction of 27% in clay soil, 30% in loam soil, and 23% in sandy loam soil corresponding to decreases in total porosity of 27%, 14%, and 18%, respectively. Other properties affected by compaction include reduced hydraulic conductivity, infiltration, and aeration (Parker et al. 2007). Williamson and Neilsen (2000) report reductions in saturated hydraulic conductivity of >90% resulting from increases in bulk density due to compaction. Meek et al. (1992) reported a reduction in infiltration rates of 54% when soil was compacted from 1.6 Mg m^{-3} to 1.8 Mg m^{-3}. Aeration is reduced when precipitation exceeds infiltration and soil becomes saturated. Soil saturation can reduce oxygen supply necessary for root respiration (Russell 1973). Root growth is restricted to soil horizons that have sufficient moisture, nutrient supply, and gaseous exchange (Schaffer et al. 2009). Harvest activities that compact soils limit the effective rooting depth of plants by restricting access to water and nutrients and reducing gaseous exchange (Gomez et al. 2002). Harvest activities that compact soils and increase soil strength can also impede root growth by reducing pore size

(Greacen and Sands 1980). Nugent et al. (2003) reported increases in soil strength of 30%-50% following ground-based harvest operations.

Factors controlling compaction levels in soil include site conditions (*e.g.,* initial bulk density, soil texture or moisture), general harvest operations (Wang et al. 2007), tire size (Han et al. 2009), the number of machine passes, the volume and axle weight of timber hauled, post-harvest site preparation, and characteristics of the harvest equipment (Williamson and Neilson 2000). Sites with a high initial bulk density (~1.4 Mg m^{-3} or greater) show the least increases in bulk density (Powers et al. 2005, Page-Dumroese et al. 2006a). Fine textured soil is more susceptible to compaction than coarse textured soil. The highest bulk densities and lowest porosities following harvest activities are found on clay soils (Gomez et al. (2002). Dry soils are least susceptible to compaction. Saturated soils are resistant to compaction because water is uncompressible and prevents reorientation of soil particles (Miller et al. 2004, Johnson et al. 2007). Soils are most susceptible to compaction when moisture levels are near field capacity. Soil moisture at field capacity lubricates soil particles and facilitates close packing of soil particles (Miller et al. 2004). Williamson and Neilsen (2000) found that a single pass by a rubber-tired skidder increased bulk density by 22% in the upper 10 cm. of a silt loam soil. Three passes by ground-based harvest machinery resulted in 80%-95% of the total increase in bulk density at the end of harvest operations, leading Williamson and Neilsen (2000) to suggest that compaction levels will not significantly increase from levels reached during the initial three passes. Harvest impacts to soils can be minimized by restricting harvest equipment to designated trails spaced as far apart as operationally possible (Johnson et al. 2007).

Soils recover from compaction at varying rates. Compaction of coarse textured soils may recover in as little as one year (Mace 1971). Alternatively, on fine textured soils, compaction may persist for decades and become exacerbated by repeated harvest entries (Froehlich et al. 1981, Froehlich et al. 1985, Geist et al. 1989). Factors controlling the rate soils may recover from compaction include temperature, [i.e. frozen or not] soil texture, coarse fragment (particles >2.0 mm) content, number of harvest entries, soil moisture conditions during harvest, and the activity of roots and soil fauna (Miller et al. 1996, Williamson and Neilsen 2000, Liecty et al. 2002). Freeze-thaw cycles associated with cold temperature soils may ameliorate compaction by the shrink-swell process. Soil aggregates are compressed and separated in turn during the shrink-swell process as water filled cavities within the soil profile expand when frozen and compress as they thaw effectively loosening soil and increasing pore space (Hillel 1998). Shrink-swell processes are most effective in soils with clay content exceeding 20% (Parker et al. 2007) due to the increased water holding capacity of clay and relatively small pore size. In soils with clay content less than 20%, shrink-swell cycles are restricted and less effective at ameliorating compaction levels (Page-Dumroese 1993, Busse and Reigel 2005). Coarse fragments in the soil buffer the effects of harvest activities by giving soils added strength (Williamson and Neilsen 2000). Compaction from repeated harvest entries may be cumulative if soils are not given time to recover to their native (pre-harvest) state between rotations (Froehlich et al. 1985). Harvest operations limited to periods of reduced soil moisture can reduce soil susceptibility to compaction and reduce the time required for a return to native bulk density levels (Miller et al. 2004). Roots and soil fauna ameliorate compaction by actively moving soil particles and excavating channels and voids which increases pore space (Miller et al. 2004). Bulk density increases resulting from compaction during timber harvest operations typically decrease with depth due to increased soil strength and higher initial bulk density lower in the soil profile (Gent at al. 1983, Gomez et al. 2002, Carter et al. 2006), but can extend to 45 cm in some soils (Gomez et al. 2002). Soils compacted for the North American Long-Term Soil Productivity study (LTSP) were measured after 10 years. Recovery occurred, but it was slight. Sites that had negligible recovery after 10 years were from Idaho (ash soil), two sites from Michigan (outwash sand and lacustrine clay respectively), and Minnesota (loess/ till)-all sites with frigid soil temperature regimes. These findings led to speculation that freeze-thaw cycles are less effective at ameleorating compaction at depths >10cm. in temperate climates and boreal life zones (Powers et al. 2005). Surface compaction may recover after some time, but compaction at depth in the mineral soil may take decades, or longer, to return to pre-harvest conditions.

Rutting, displacement, and erosion resulting from timber harvest activities are other commonly cited forms of soil disturbance (Geist et al. 1989, Miller at al. 2004). Rutting is defined as impressions in the soil caused by heavy equipment (Page-Dumroese et al. 2009). The risk of soil rutting increases with increased soil moisture content and decreased soil strength (Grigal 2000). Rutting can have detrimental impacts on site productivity by creating preferential flow patterns for overland water flow, decreasing infiltration and gaseous exchange (Page-Dumroese et al. 2009). The degree to which rutting impacts soil physical properties depends on soil texture and soil moisture content. Soils are most susceptible to compaction during the creation of ruts when the soil moisture content is at or just below field capacity (Page-Dumroese et al. 2006b). Fine textured soils at a greater risk for compaction will be affected more than coarse textured soils during periods of elevated soil moisture because of decreased soil strength. (Page-Dumroese et al. 2009). Andic soils of the northwest are particularly susceptible to displacement and compaction during ground-based timber harvest and site preparation activities due to their silty texture and inherently low bulk density (Geist et al. 1989, Cullen et al. 1991, Page-Dumroese 1993, Craigg 2000, Geist et al. 2008).

Soil displacement refers to the transfer of soil from one location to another. Displacement is the principal form of disturbance associated with overhead cable yarding, a result of dragging trees or logs along the soil surface within the skidding corridor (Laffan et al. 2001). Soil is typically displaced in ground-based harvest operations by being scraped with equipment blades, during sharp turns by tracked or wheeled machines or during the yarding process by skidding trees or logs along the soil surface (Page-Dumroese et al. 2009). Soil displacement alters the forest surface litter layer and nutrient concentrations on site. Laffan et al. (2001) found phosphorous, nitrogen, and soil organic carbon reduced by 30-40% where the soil surface layer had been displaced during harvest operations relative to undisturbed areas in the harvest area. Similarly, Miller and Sirois (1986) found reductions in water holding capacity, phosphorous, calcium, and potassium in yarding corridors where surface soil had been displaced. Powers et al. (2005) note on several LTSP study sites that a pulse removal of surface organic matter caused a significant decline in organic C concentrations. This was caused by reduced inputs from the forest floor and accelerated microbial decomposition. Surface soil displacement also exposes highly erodible subsoil (Page-Dumroese et al. 2009), decreases infiltration capacity, and promotes the development of preferential flow paths, all of which increase erosion rates relative to an undisturbed system (Grigal 2000).

Erosion and mass flow are natural processes occurring on all landscapes, but the rate and extent of erosion can be increased by forest management activities (Grigal 2000). For example, road building activities and skid trails associated with timber harvest, alter natural drainage patterns and can lead to increased rates of surface and off-site erosion (Rice et al. 1972, Grigal 2000). Factors controlling erosion and mass flow include slope length and steepness, precipitation intensity duration, infiltration rate, soil texture, geomorphology, and soil cover, e.g. forest litter and vegetation (Sidle et al. 1985, Elliott and Hall 1997, Robichaud et al. 2007). Slope length and steepness control water run-off concentration and influence its speed (Brady and Weill 1996). Precipitation intensity influences the timing and volume of moisture inputs during precipitation events. Soil texture interacts with rainfall duration and intensity by controlling the rate and duration of inputs and the infiltration rate. Soil texture, or fine earth fraction of the soil mineral particles that make up the soil texture classification are sand, silt, and clay particles ≤2 mm in diameter (Brady and Weill 2010). In addition, soil texture refers to the physical composition of soil defined in terms of the relative proportions of the fine earth fraction. Soil texture influences the infiltration rate of water through the soil column. Coarse textured soils have more macropore space (pores in the soil profile ≥ 0.08mm (Brady and Weill 1996) than fine textured soils facilitating higher rates of infiltration. Soil compaction resulting from forest management activities can destroy macropores effectively reducing infiltration. When the rate and duration of a precipitation event exceeds the infiltration rate into the soil, erosion is increased as water moves across the soil surface instead of infiltrating into the soil profile (Troeh et al. 1980). Geomorphology influences erosion by directing flow in divergent or convergent patterns across the landscape, which in turn impacts depth of accumulation and velocity of soil particles (Troeh et al. 1980).

Soils covered with dense vegetation and forest litter provide the most resistance to erosion (Troeh et al. 1980). Forest litter also promotes infiltration and protects the soil surface from impact erosion (erosion resulting from rain drop splash) during precipitation events (Megahan 1990). When vegetation and forest litter soil coverage is removed through management activities, the roughness of the soil surface is decreased and thus facilitates increased water flow along the soil surface (Troeh et al. 1980). Off-site erosion affects site productivity by removing topsoil used as the growth medium for vegetation (Megahan 1990). Off-site erosion decreases plant productivity by transporting nutrient rich soils through soil mass movement, therefore, decreasing nutrient availability for vegetation on site (Jurgensen et al. 1997). Erosion that moves soil around on a site, but does not remove it, may not alter overall site productivity due to the re-deposition of nutrient rich soils, compared to the eroded areas that lose soils from the site (Jurgensen et al 1997).

2.2 Effects of Disturbance on Nutrients/ Microbes

The effect of soil disturbance resulting from timber harvest operations on soil nutrient pools and soil organisms ranges from no response to a decline in nutrient pools and microbial populations. Potential declines in soil productivity resulting from decreased soil carbon and nitrogen pools have raised concerns about shorter harvest rotation cycles and biomass removal (Jurgensen et al. 1997). Microbial community response to disturbance (both natural and management induced) is inconsistent even under similar environmental conditions. The variation in response to disturbance and abiotic site factors adds to our lack of understanding of how microbes respond to disturbances.

Whole-tree harvest techniques may increase the movement of nutrients off site relative to sawlog harvest by removing nutrients stored in tops and limbs before they can return meaningful quantities of nutrients to the soil (Dyck and Mees 1990). However, in a study of 11 forest stands throughout the U.S., Mann et al. (1988) found that whole-tree harvesting caused relatively little effect on hydrologic nutrient losses as compared to sawlog harvesting. Nutrient depletion by whole tree harvesting is of concern in some stands (Westman and Webber 1972, Boyle and Ek 1972, Johnson 1983), but in others it has little effect on total ecosystem nutrients (Miller et al. 1980, Hornbeck and Kropelin 1982). Bigger and Cole (1983) reported biomass reductions ranging from 54.9 Mg ha^{-1} to 140.7 Mg ha^{-1} (70% to 75% of total site biomass) on low and high productivity Douglas-fir sites in western WA resulting from whole-tree harvest operations. The reduction in biomass resulted in nitrogen losses of 0.325 Mg ha^{-1} (32% of site total) from low productivity site and 0.728 Mg ha^{-1} (24% of site total) from high productivity Douglas-fir sites (Bigger and Cole 1983). Similarly, Carter et al. (2006) reported biomass reductions ranging from 100.2 Mg ha^{-1} to 237.1 Mg ha^{-1} resulting from whole-tree harvest on the Gulf Coastal Plain of the United States. The reduction in biomass resulted in nitrogen losses ranging from 0.193 Mg ha^{-1} to 0.259 Mg ha^{-1} which represented 38% to 62% of the above ground nitrogen on the study sites. Biomass removal and the subsequent decline in nitrogen on site may not negatively impact future productivity. Powers et al. (2005) reported no general decline in site productivity ten years post-treatment after a complete removal of surface organic matter on 26 LTSP sites across North America.

The effect of various timber harvest operational disturbances on soil carbon and nitrogen pools are variable and conflicting results suggest the effect is site specific and time dependent. Sanchez et al. (2006) found there was no significant effect on soil carbon and nitrogen pools resulting from organic matter removal, compaction, or competition control five years post-treatment as part of the LTSP study. Ten year results from the LTSP suggest that removal of organic matter leads to a significant decline in soil carbon and nitrogen concentration across a wide variety of site types, and to reduced nitrogen availability on drier sites located in California (Powers et al. 2005). Similarly, Nave et al. (2010) found in a meta-analysis of soil carbon response to soil disturbance resulting from harvest activities in temperate forests worldwide, that harvest impacts reduced soil carbon eight percent on average. Nave et al. (2010) further suggest that the reduction in soil carbon resulting from harvest impacts is controlled by vegetation species composition (coniferous/ mixed stands or hardwoods), soil taxonomic order, and time since harvest. On average, carbon stores in the forest litter layer of hardwood stands were reduced more than carbon stores in the litter layer of coniferous/ mixed stands. This may be the result of increased top breakage left on site during harvest activities on coniferous sites. Nave et al. (2010) reported carbon stores were unchanged on Spodosols and Alfisols over the whole mineral soil (defined as upper 100 cm. of mineral soil for this study). In contrast, carbon stores were reduced in Ultisols and Inceptisols by 7% and 13% respectively. Significant effects of time since harvest were limited to Inceptisols. Whole mineral soil carbon stores declined 25% five years post-harvest, but recovered to pre-harvest values in 6-20 years (Nave et al. 2010). Carbon stores in the forest litter layer were reduced 30% on average across all studies in the meta-analysis. In contrast, there was no significant reduction in mineral soil carbon stores; suggesting that carbon stores in the forest litter layer are much more susceptible to disturbance than carbon stores in the mineral portion of the soil (Nave et al. 2010). Although Johnson and Curtis et al.

(2001) found no effect on soil carbon and nitrogen across the spectrum of harvest operations in their meta analysis of 26 papers, they did report differences in soil carbon and nitrogen in the A horizon between harvest methods (whole-tree vs. bole-only), and between species within bole-only harvest operations. Whole-tree harvest resulted in slight declines (-6%) in soil carbon and nitrogen. Bole-only harvest resulted in an 18% increase in soil carbon and nitrogen, with the increase in soil carbon and nitrogen restricted to coniferous sites (Johnson and Curtis 2001). Changes in soil carbon and nitrogen in the B horizon were not significant, but followed the same pattern as the A horizon (Johnson and Curtis 2001). These results suggest there is a greater effect on surface soil carbon stores (e.g. forest litter layer and upper portion of the mineral soil), and the effect on these carbon stores is reduced with depth in the soil profile.

Determining the effect disturbance has on soil microbes is challenging due to the range of responses reported by researchers, and the range of environmental conditions occupied (Madsen 1996, Busse et al. 2006). Contradictory results and studies with confounded treatments (i.e. forest floor removal and compaction) lead to a lack of consensus about the effect different types of disturbances resulting from timber harvest have on soil microbial populations. Harvest operations resulting in the removal of the forest litter layer may decrease soil microbial diversity and/or biomass by increasing soil temperature and decreasing soil moisture (Zabowski et al. 1994). Busse et al. (2006) reported that compaction, reduction in surface organic matter and, vegetation control did not result in significant changes to microbial biomass or respiration in general. The lone exception to this trend was a 12% reduction in microbial biomass in compacted soil relative to the uncompacted plots during the spring at a subtropical site in NC. On the CA site, whole-tree harvest plus removal of the forest litter layer resulted in significant reductions in microbial biomass in both the fall and spring relative to microbial biomass on bole-only plots (Busse et al. 2006). Despite the reduction in microbial biomass on the CA site, they concluded that soil microbial communities are largely unaffected by post-harvest soil disturbance in sub-tropical and Mediterranean-type climates. In a separate LTSP study, Tan et al. (2005) investigated the effect of soil compaction and organic matter removal achieved through whole-tree harvest on soil microbial biomass carbon and soil microbial biomass nitrogen in a boreal forest. Results reported by Tan et al. (2005) are similar to the results reported by Busse et al. (2006). In this study, soil microbial biomass carbon and soil microbial biomass nitrogen in the forest floor were not affected by compaction, although the authors noted strong seasonal variations with values for both variables at their lowest in July and peaking in September. Results for microbial biomass carbon and microbial biomass nitrogen in the mineral soil were mixed despite a mean increase in mineral soil bulk density of 24% to ~1.4Mg m^{-3}. Microbial biomass carbon in the mineral soil was unaffected, but microbial biomass nitrogen was reduced in compacted mineral soil.

In contrast with Busse et al. (2006), Li et al. (2004) reported significant ($p= 0.04$, percent decline not reported) declines in microbial biomass nitrogen resulting from surface organic matter removal achieved through whole-tree harvest at a subtropical LTSP study site on a coastal plain in NC. Li et al. (2004) also noted a significant decline of 18% on microbial biomass carbon as a result of vegetation control at the same site. Whalley et al. (1995) suggests disturbance effects soil biological processes by reducing soil microbial activity, which in turn reduces nutrient availability by modifying mineralization rates. This is consistent with other studies that report soil disturbance manifested as compaction can decrease root elongation (Zabowski et al. 1994) and decrease the habitable poor space for micro-organisms.

2.3 Effects of Disturbance on Tree Growth

Soil disturbance resulting from timber harvest operations has consequences that may be favorable or detrimental for soil properties that impact tree growth. Forecasting the magnitude and duration of disturbance on tree growth is difficult due to variation in tree response among sites (Heninger et al. 2002). Growth responses to disturbance depend on a tree species biological traits, site characteristics (Parker et al. 2007), type and severity of disturbance, and climatic conditions (Heninger et al. 2002). Soil disturbance resulting from timber harvest is most commonly found to have no effect on subsequent tree growth (Ares et al. 2005, Miller et al. 2010), although it can reduce juvenile (Geist et al. 2008) and mid-rotation tree growth and economic value (Murphy et al. 2004) or may improve growth (Gomez et al. 2002). Decreased height growth has been observed in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) (Froehlich et al. 1979, Greacan and Sands 1980, Cochran and Brock 1985), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Heninger et al. 2002), and radiata pine (*Pinus radiata* D. Don) (Murphy et al. 2004) due to soil compaction and the associated increase in soil bulk density. Cochran and Brock (1985) reported tree height growth negatively correlated with increasing bulk density resulting from compaction five years post-establishment. In this study, bulk density values increased over 15% (≥1.17 Mg m^{-3}) from a mean of 1.02 Mg m^{-3} over 37% of the study area. Helms and Hipkin (1986) reported declines of 55%-69% in volume per unit area on skid trails and unit landings where bulk density increased 30% to 43% (~1.27 Mg m^{-3}) relative to unaffected soils in a 16 year old ponderosa pine plantation in California. Heninger et al. (2002) reported reductions in mean annual height growth of 24% in Douglas-fir four years post establishment on skid trails relative to logged areas adjacent to skid trails. Mean bulk density values increased from 0.836 Mg m^{-3} to 0.957 Mg m^{-3} (14%) on skid trails relative to adjacent areas in their study (Heninger et al. 2002). Similarly, Froehlich (1979) reported a 2/3 reduction in volume of 17-yr old ponderosa pine grown in heavily used skid trails relative to adjacent areas. Murphy et al. (2004) reported declines of 8% in average tree volume of 21-yr old radiata pine on plots where the litter layer had been removed and the topsoil had been compacted, and declines of up to 42% on plots with litter layer removal and subsoil compaction. Projected loss in per tree economic value of up to 60% was greater than the decline in average tree volume (Murphy et al. 2004). The loss in economic value per tree was attributed to a decrease in pruned export and domestic logs. These products declined on compacted soils where the litter layer had been removed because stands were characterized by small, poorly formed trees that were not selected for pruning and in many cases did not meet minimum top diameter specifications for pruned logs (Murphy et al. 2004).

Assuming that any soil disturbance causes a reduction in tree growth is unwarranted (Heninger et al. 2002, Miller et al. 2004). Initial tree growth can be improved by compaction of coarse textured soils (Powers et al. 1999). In a LTSP study across a broad range of sites total biomass increased >40% in sandy textured soils and decreased 50% on clayey soils (Powers et al. 2005). These results support findings reported by Gomez et al. (2002), who reported an increase in the stem volume of ponderosa pine on compacted sandy loam soils. In the same study, Gomez et al. (2002) noted a reduction in ponderosa pine stem volume growth on compacted clay soils and subsequently concluded that alterations in the physical structure of the sandy loam soil resulting from compaction were ultimately beneficial because of an increase in the water holding capacity.

Complex interactions between time, soil properties (including bulk density), climate, and management practices preclude making a definitive statement about the effect of disturbance on tree growth (Greacen and Sands 1980). Heninger et al. (2002) reported a decline in mean height growth in juvenile Douglas-fir planted in skid trails two years post establishment on coastal Washington sites and seven years post establishment on sites in the Oregon Cascades. However, they found no differences in mean height growth between Douglas-fir planted on skid trails and those planted on logged sites adjacent to the skid trails after seven years on the coastal Washington sites. Similarly, Miller et al. (1996) reported an initial decline in the growth of Douglas-fir, Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) on primary skid trails. However, re-measurements eight year later found no difference in stand growth between trees planted on un-tilled primary skid trails and trees planted on other plots at most sites. This may have resulted from low climatic stress and/or a reduction in competing vegetation on the primary skid trails, or tree roots reaching beyond the influence of skid trails after trees age and occupy more growing space. The primary exception reported by Miller et al. (1996) was a reduction in survival and growth of western hemlock, but not Douglas-fir on one of the study sites, giving credence to the suggestion by Parker et al. (2007) that tree species influence the effect soil disturbance has on productivity. It is worth noting in the Heninger at al. (2002) study that the reduction in mean height growth was not correlated with the percentage of increase in soil bulk density, leading them to conclude that tree growth is not controlled solely by increases in bulk density, but is also influenced by supplementary environmental factors including moisture-nutrient stresses and competing vegetation. Cochran and Brock (1985) reported a decline in initial height growth of ponderosa pine five years after establishment. They attribute this decline in initial height growth to soil compaction, but acknowledge some uncertainty as to the effect other factors may have had on their findings (Cochran and Brock 1985). Carter et al. (2006) reported significant declines of loblolly pine (*Pinus taeda* L.) growth on one site where soil bulk density had increased 0.1 Mg m^{-3} as a result of ground-based harvest and site preparation activities. The same increase in soil bulk density (0.1 Mg m^{-3}) had no effect on loblolly pine growth at another site (Carter et al. 2006). Findings reported by Miller (1996), Heninger et al. (2002), Gomez (2002), and Carter et al. (2006) imply that factors controlling tree growth response to soil disturbance are not limited to a change in soil bulk density values. The variation in tree growth response to multiple variables has made translating our scientific understanding in practical administrative guidelines for maintaining site productivity challenging.

2.4 Legislation, Soil Quality Standards, and Monitoring Protocols

Soil management activities conducted by U.S. Department of Agriculture – Forest Service (USDA-FS) managers on National Forest System lands in the United States are governed by several statutes: Organic Administration Act of 1897, Multiple-Use, Sustained Yield Act of 1960, National Environmental Policy Act of 1969, and Forest and Rangeland Renewable Resources Planning Act of 1974 as amended by the National Forest Management Act of 1976 (USDA-FS 2010). Each statute is summarized below. The Organic Administration Act of 1897 mandates that the forest reserves established in 1891 and subsequent years be improved, protected, and "… furnish a continuous supply of timber for the use and necessities of the United States." Consideration of economic value in resource management activities is directed by the Multiple-Use, Sustained Yield Act of 1960, which states that "… the combination of uses that will give the greatest dollar return or the greatest unit output ... without impairment of the productivity of the land." The National Environmental Policy Act of 1969 mandates that federal agencies consider the environmental consequences of proposed management activities and a set of reasonable alternatives (including no action) to those plans to meet management objectives (Davis et al. 2010). The National Forest Management Act of 1976 (NFMA) provides the most specific statutory direction. Davis et al. (2010) identifies three key passages in NFMA relevant to impacts on soil resulting from management activities:

1. "…insure research on and (based on continuous monitoring and assessment in the field) evaluation of the effects of each management system to the end that it will not produce substantial and permanent impairment of the land." (§6(g)(3)(C)),
2. "…insure that timber will be harvested from National Forest System lands only where soil, slope, or other watershed conditions will not be irreversibly damaged." (§6(g)(3)(E)(i)), and
3. "…insure that clearcutting, seed tree cutting, and other cuts… are carried out in a manner consistent with the protection of soil, watershed, fish, wildlife, recreation and esthetic resources, and the regeneration of the timber resource." (§6(g)(3)(F)(v)) (NFMA 1976, Davis et al. 2010).

The USDA-FS response to these legislative mandates of NFMA resulted in two important administrative developments affecting soil maintenance: the development of soil quality standards and soil monitoring programs.

Soil quality standards are current threshold values delineating detrimental soil disturbance. These were developed for each USDA-FS region in 1983 and revised in 1999 (Page-Dumroese et al. 2000). These soil quality standards describe the process for collecting data to gauge the extent that management activities are meeting mandates related to maintenance of soil productivity (Neary et al. 2010). Examples of threshold values taken from *Forest Service Handbook* (USDA-FS 2010, §2509.18) were adopted as detrimental threshold values used in the development of the soil quality standards despite a footnote in the *Handbook* which clearly states they were not intended for use as soil quality standards (Neary et al. 2010). Consequently, guidance from the *Handbook* was adopted and "detrimental" soil disturbance on greater than 15% of an activity area (areal extent of an activity area) was selected as the soil quality standard for most of the National Forest System lands. In effect, these standards were not based on available science, but instead on an example in the *Forest Service Handbook* (Neary et al. 2010).

Soil monitoring programs involve disturbance monitoring protocols and disturbance classifications. Such things have been used on private timberlands since the late 1970's (Heninger et al. 1998). The monitoring system developed by Weyerhaeuser Corporation in 1977 utilizes a four-class system with a modifier describing soils that stay saturated for 10 days or more as a result of disturbance from harvest operations. These visual classes describe disturbance along a continuum ranging from undisturbed to severe. Operating standards were then developed to place targets on the allowable areal extent of each disturbance class in a harvest unit (Heninger et al. 1998). Thirty years after development, this monitoring system has proven to be easy to use by field operation personnel over a wide range of soil conditions when supported by a rigorous training program (Napper et al. 2009, Miller et al. 2010).

Soil monitoring programs have been used on National Forest System (NFS) lands since the early 1980s (Howes et al. 1983). Preliminary efforts to determine if management activities were meeting Forest Service soil quality standards resulted in a variety of soil disturbance monitoring methods being used. The disparate methodology led to results that were easily and routinely challenged (Howes 2006). In recognition of these challenges, Howes et al. (1983) developed the first statistically sound, defensible quantitative soil disturbance monitoring protocol widely used on NFS lands in the northwest (Howes 2006). This protocol utilized a systematic grid randomly oriented on either aerial photos or a map of the harvest unit. Transects were established on a random azimuth extending from grid point intersections. Compaction was measured at five-foot intervals along the transects by taking core samples or air permeability measurements (Howes et al. 1983). Although this system was legally defensible and statistically sound, it was resource-intensive and eventually replaced by a qualitative methodology in an attempt to increase the intensity of soil disturbance monitoring (Howes 2001). The qualitative assessment was developed using the same systematic grid approach to establish sampling transects. In this system, however, soil disturbance condition classes were assigned into one of seven disturbance classes ranging from undisturbed to altered drainage using visibly recognizable surface features (Howes 2006).

Recent attempts to increase monitoring efficiency for field personnel and provide consistent definitions of disturbance led to the development of the Forest Soil Disturbance Monitoring Protocol (FSDMP)(Page-Dumroese et al. 2009). The FSDMP is a qualitative assessment of soil disturbance defining and delineating four disturbance classes. Aust (1998) suggested that increasing the amount of disturbance classes is unnecessary and may over differentiate changes in soil physical properties, thus rendering some such classes meaningless as indicators of harvesting disturbance. The FSDMP system is designed to provide a rapid assessment and offers several advantages: 1) field personnel are able to monitor more harvest units, increasing economic efficiency, because it is a rapid assessment, 2) pre-planned grid systems are not necessary, reducing the sample planning burden, 3) it provides clear, common definitions that can be applied to any terrain and harvest operation, 4) this protocol is not training intensive and can be utilized by professionals and laymen alike, even though training is a necessary component of any monitoring program, 5) statistically sound and defensible, results can be used to estimate the areal extent of each disturbance class within a pre-selected margin of error, and 6) no special tools or laboratory analysis is required (Page-Dumroese et al. 2009).

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CHAPTER 3: EVIDENCE SUPPORTING THE NEED FOR A COMMON SOIL MONITORING PROTOCOL

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Abstract

Many public land management agencies monitor forest soils for levels of disturbance due to management activities. Although several soil disturbance monitoring protocols based on visual observation have been developed to assess the amount and types of disturbance caused by forest management, no common method is currently used on National Forest lands in the U.S. We present data on relative soil disturbance based on harvest system from National Forests throughout Montana and Idaho, USA. Each National Forest used its' own method for data collection, therefore we developed a common, well-defined visual class system for analyses based on the existing soil monitoring data that accurately normalized disparate classifications. Using this common system, we detected differences in soil disturbance between the ground-based and overhead harvest systems, however no site attributes (slope, aspect, soil texture etc.) affected soil disturbance levels. Individual National Forest was the most important factor explaining differences among harvest units. The effect of National Forest may be explained by different forest types, soils, harvest practices or administrative procedures, but the most likely explanation is differences among the various qualitative classification approaches to soil disturbance monitoring. Although this analysis used a large dataset, our inability to correlate disturbance with site characteristics and the differences between monitoring methods points to the need for common terms and comparable guidelines for soil disturbance monitoring.

KEYWORDS: *soil disturbance, timber harvest, disturbance monitoring*

3.1 Introduction

Forest management activities result in rates of soil disturbance that range from minimal to extreme (Grigal 2000). Soil disturbance associated with harvest activities can reduce, increase, or not effect growth rates in future stands, contribute to sediment loading in streams and give the appearance of poor stewardship (Heninger et al. 2002, Miller et al. 2004, Powers et al. 2005). The amount and type of soil disturbance associated with timber harvest activities is of increasing concern to managers and stakeholders alike. On lands managed by the United States Department of Agriculture (USDA) Forest Service, many proposed management projects have been appealed or litigated on the grounds that projects will result in soil degradation (Craigg and Howes 2007), even though there are no clear links between soil degradation, productivity and sustainability (Curran 2005).

The first soil disturbance monitoring protocols in the world were developed by the USDA Forest Service in response to legislation requiring the maintenance of site productivity. Soil productive capacity on National Forest lands in the U.S. is governed under numerous laws and acts, including the Multiple Use and Sustained Yield Act of 1960, the National Environmental Policy Act of 1969, the Forest and Rangeland Renewable Resources Planning Act of 1974, and the National Forest Management Act of 1976 (Page-Dumroese et al. 2000). Specifically, the National Forest Management Act requires that "management systems will not produce substantial and permanent impairment of the productivity of the land" (NFMA 1976). Policies developed for many of the National Forests of the USDA Forest Service require that 85% of a timber harvest unit must be in "satisfactory condition" when timber harvest and site preparation activities are completed. The areal extent of detrimental soil disturbance (soil disturbance that results in a loss of productivity or change in hydrologic function) existing on the harvest unit must be <15% to meet the satisfactory condition requirement.

Current detrimental soil disturbance thresholds, or soil quality standards, for each USDA Forest Service Region were developed in 1983 and refined in 1999 (Page-Dumroese et al. 2000). The USDA Forest Service soil quality standards spell out a systematic process in which data is collected to determine if soil management objectives to maintain long-term productivity are achieved (Neary et al. 2010). When the soil quality standards were developed, the USDA Forest Service Handbook (2509.18) gave several examples of what could be used. For instance, an increase in bulk density of >15%, a reduction in porosity of >10%, or forest floor removal along with 25 mm of mineral soil were given. The Handbook also indicated that things such as threshold values, areal extent, sample size and variability, and data collection should be addressed. Subsequently, the guidance from the Handbook went forward and “detrimental” soil disturbance on greater than 15% of an activity area was selected as the soil quality standard for most of the USDA Forest Service. Additionally, when the Handbook came out, detrimental soil disturbance was defined as a combination of compaction, rutting, soil displacement, severely burned areas, surface erosion, and soil mass movement on >15% of the harvest unit. In essence, an “example” became the “standard” for most of the US (Neary et al. 2010).

The debate as to where the threshold for “detrimental” disturbance exists is complicated by site conditions and vegetation species present. Different soils range in their ability to withstand and recover from disturbance (Craigg and Howes 2007); consequently, Burger (1997) and Craigg and Howes (2007) suggest that assessments of soil quality indicators should be site specific. Assuming that any soil disturbance causes a reduction in tree growth is unwarranted (Miller et al. 2004). For example, it is generally recognized that compaction can negatively impact tree growth in some settings; however, Gomez et al. (2002) suggests that the correlation between soil disturbance and tree growth is dependent on soil texture and soil water regime, thereby furthering the argument for site specific assessments relative to soil disturbance and the possible impacts on forest sustainability.

Detrimental soil disturbance thresholds are currently applied uniformly across each USDA Forest Service Region. This approach, while administratively convenient, applies an inflexible framework to variable site conditions (DeLuca and Archer 2009) and the correlation between soil monitoring variables and potential productivity is mostly anecdotal or regionally restricted (Powers et al. 2005). However, the lack of long-term studies tied to quantifiable measures of forest productivity has been lacking. Despite the debate of disturbance levels that degrade productive capacity, maintenance of the soil resource is increasingly recognized as a key to sustainable forest productivity and the basis for the North American Long-Term Soil Productivity (LTSP) study (Powers et al. 2005). The LTSP study was founded to shed light on the productive capacity of forest soils and how that is altered by compaction and organic matter removal; two factors readily altered by land management.

Howes et al. (1983) provides initial guidelines for quantitative forest soil monitoring, but an effort to reduce the monitoring burden discouraged quantitative assessment in favor of a qualitative approach to allow more data collection and assessment (Howes 2001). Qualitative, ocular assessments have been used since the 1970’s on privately held timber lands in the United States and since the late 1980’s on federal lands (Howes 2001). Qualitative classification systems offer advantages relative to quantitative assessment. Less labor intensive qualitative assessments are important in an era of dwindling resources

(Curran et al. 2005); however, they are inherently subjective and need to be validated by quantifiable, ecologically relevant variables (Curran et al. 2005, DeLuca and Archer 2009).

Existing evidence demonstrates that timber harvest and subsequent slash disposal operations cause some degree of soil disturbance in forest soils (Xu et al. 2002). Soil compaction, displacement and erosion are commonly cited as concerns among foresters (Geist et al. 1989), however other concerns include rutting, topsoil mixing, burning, and erosion. Ongoing debate involves how much disturbance causes a substantial and permanent decline in forest productivity, and what are the indicators of detrimental disturbance (Howes 2006; Page-Dumroese et al. 2006; DeLuca and Archer 2009).

Since the first soil quality standards were developed in 1983, there has been considerable data collected using methods that employ both quantitative and qualitative measures. Determining a useful way to use this legacy data and convert it to a common database is one key in helping to define site specific responses to forest management activities. Therefore, we accessed all soil monitoring data collected from 11 National Forests within the Northern Region of the USDA Forest Service from 1999 to present and addressed the following hypotheses: (1) soil disturbance amounts are correlated with timber harvest systems (*e.g.*, helicopter, skyline, ground based), (2) soil monitoring protocols employed by various National Forests will not influence the level of soil disturbance observed when similar harvest systems are used during the same harvest season in areas with similar site characteristics and (3) soil disturbance indicators can be linked to site-specific characteristics (*e.g.*, soil texture, slope, coarse-fragment content).

3.2 Methods

3.2.1 Data and harvest systems evaluated

Post-harvest soil monitoring and site characteristic data was collected from within the USDA Forest Service Northern Region (Figure 3.1) and consisted of data from 157 harvest units representing 13,870 individual monitoring points. These units had been harvested between 1993 and 2009. A variety of ground-based, skyline, and helicopter harvest systems used during four annual seasons are accounted for in the data (Table 3.1). Harvest season was assigned by the completion date. Spring consists of March, April, and May; summer of June, July, and August; fall of September, October, and November; winter of December, January, and February.

Tractor units (listed as tractor in Table 3.1), are a combined category for ground-skidded and hand fell harvest units, as well as the ubiquitous units labeled as "ground-based" in the data provided in the monitoring data received. The number of units included in the data from each forest and the number of corresponding monitoring points are listed in Table 3.2.

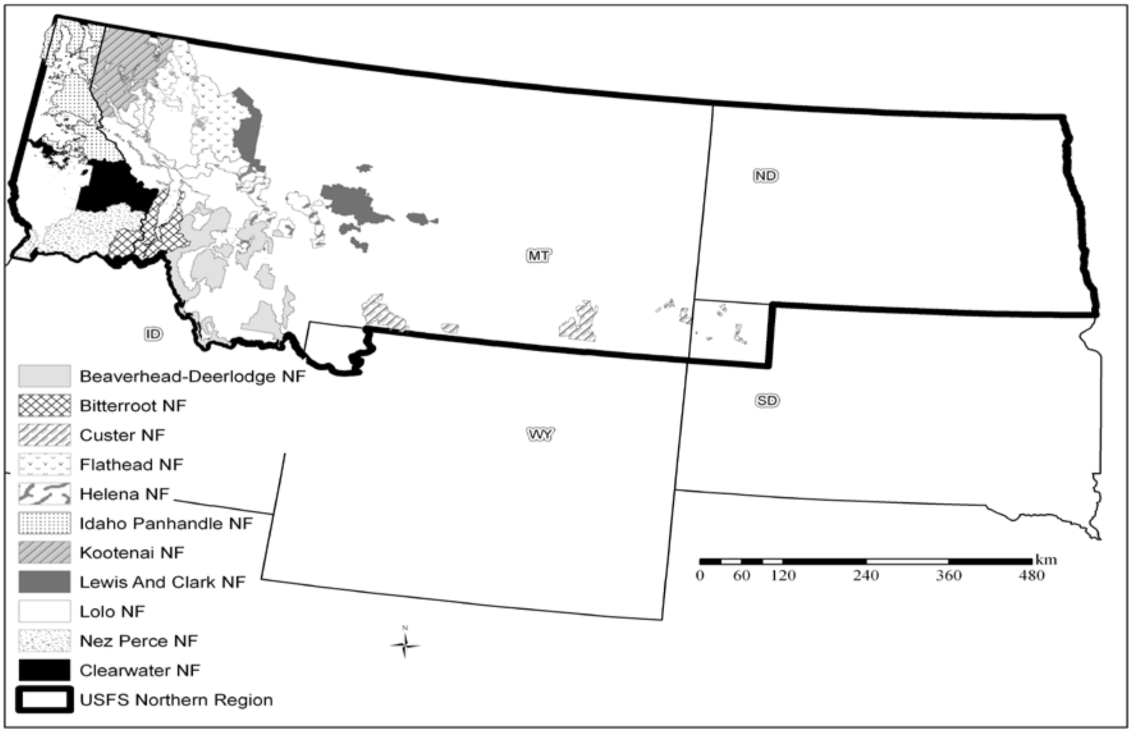

FIGURE 3.1. National Forests located in the Northern Region of the USDA Forest Service that are represented in this study.

TABLE 3.1. Total number of units surveyed by harvest system and season of harvest.

Harvest system	Total units	Spring	Summer	Fall	Winter
Cut to length	29	0	16	5	8
Ground/ machine fell	46	6	16	0	24
Helicopter	13	2	5	2	4
Helicopter/ machine piled	7	0	4	3	0
Skyline	21	0	14	4	3
Skyline/ machine fell	4	0	3	0	1
Tractor	37	3	16	2	16

TABLE 3.2. The number of harvest units for each forest, data points associated with the total number of units and the percentage of total monitoring points each forest contributed.

Forest	**# of harvest units**	**# of monitoring points**	**% of total monitoring points**
Beaverhead-Deerlodge	2	200	1.4%
Bitterroot	10	890	6.4%
Clearwater	23	1552	11.2%
Custer	1	200	1.4%
Flathead	15	1558	11.2%
Helena	12	2249	16.2%
Idaho Panhandle	23	1743	12.6%
Kootenai	25	1808	13.0%
Lewis and Clark	7	810	5.8%
Lolo	33	2590	18.7%
Nez Perce	6	270	1.9%

3.2.2 Data collection and conversion from disparate databases

Data was compiled from existing soil monitoring data bases, soil monitoring reports produced by individual National Forests, and by post-harvest monitoring data we collected using the Forest Soil Disturbance Monitoring Protocol (FSDMP; Page-Dumroese et al. 2009). Existing data from the Northern Region was collected by using several different visual class methods, including the FSDMP. To develop a consistent database, make relative comparisons of each harvest system, and normalize results among Forests, we transformed existing data from the class system it was originally recorded in to the 4 class system defined by the FSDMP. The majority of the transformed data was collected using the 6 visual class protocol developed by Howes (Howes 2001), some data was collected using other methods, but resulted in the same 6-disturbance class soil monitoring structure as Howes (2001). To merge this data with the FSDMP, we used the conversion system outlined in Table 3.3. The transformation system we used keyed on the condition of the forest floor, rutting depth, and evidence of compaction. These keys allowed us to consistently merge disturbance classifications into the FSDMP disturbance class best reflecting the original observations.

The primary exception to the soil monitoring efforts that used 6 visual classes (Howes 2001) was the data collected on the Kootenai National Forest. This Forest used a 3 class system to evaluate soil disturbance at each step across a transect that spanned the entire length or width of the harvest unit. Soil monitoring data was entered into the Kootenai National Forest database as class 1, 2, or 3 (undisturbed, slight disturbance, heavily disturbed). For this analysis, data from the Kootenai National Forest was transcribed using the original written observations recorded on field data sheets provided by the Forest and data points assigned a FSDMP disturbance class (Page-Dumroese et al. 2009).

In addition, the Idaho Panhandle National Forest also used a 3 class system. Harvest units are monitored according to the FSDMP, with the exception that disturbance classes 2 and 3 are combined into a single class. As with the Kootenai National Forest, field data sheets provided the necessary information to re-distribute the lumped classes into FSDMP visual class 2 or class 3.

TABLE 3.3. The 4 Forest Soil Disturbance Monitoring Protocol (FSDMP) disturbance classes and the corresponding Howes (2000) (or other) disturbance classes.

FSDMP class	**Former Howes disturbance class**	**Former KNF/ IPNF disturbance class**[a]	**Key component**
0	0	1	undisturbed
1	1,2	1, 2	forest floor disturbed/ remains intact
2	3	2	forest floor is not intact, ruts go to 10 cm. deep
3	≥4	3	forest floor is missing, compaction is evident

[a] Soil disturbance monitoring data was merged from the Kootenai National Forest (KNF) and Idaho Panhandle National Forest (IPNF) into the 4 class system defined by the FSDMP using written observations recorded on the original soil disturbance monitoring data sheets provided by the forests.

3.2.3 Site physical characteristics

Physical characteristics recorded for each unit include location (lat., long.), slope, aspect, and soil texture. Minimum and maximum slope values (%) were recorded for each unit. Where slope values were not given, or recorded by the soil disturbance monitors, they were extracted from a 30 m DEM using GIS software. Harvest unit aspect was similarly extracted from a DEM when observed values were unavailable. At sites we visited, soil texture was recorded in the field using the “feel method” (Brady and Weill 2004, p.101) from the uppermost B horizon. When the soil texture was unavailable in the monitoring reports, the texture was recorded in the data set using the appropriate soil survey manual. To limit the number of soil texture classes, they were grouped according to the USDA Natural Resource Conservation Service soil survey manual (NRCS 1993) and described in Table 3.4.

TABLE 3.4. Groupings of soil textural classes used in the analysis.

NRCS soil texture groups	Pooled analysis groups
Coarse sand, sand, fine sand, very fine sand, Loamy coarse sand, loamy sand, loamy fine	Very coarse
Sand, loamy very fine sand	
coarse sandy loam, sandy loam, fine sandy loam	Coarse
Very fine sandy loam, loam, silt loam, silt	Medium
Clay loam, sandy clay loam, silty clay loam	Fine
All soils containing a coarse modifier (skeletal, gravelly, etc.), regardless of texture	Skeletal

3.2.4 Analysis

Because of the number of units monitored, the diversity of sites, and different logging systems, we used the FSDMP classes to develop a mean soil disturbance (MSD) variable for each harvest unit using the equation:

where:

MSD is the mean soil disturbance value

i is the disturbance class

M_c is the number of points in the respective disturbance class

M_t is the total number of data points for the unit

Ci is the value of the disturbance class

n is total number of disturbance classes (i.e., 4 in this study)

The advantage of this method is that it gives one overall soil disturbance value for each harvest unit and is linked to site attributes (climate, texture, etc.), harvest season, and logging system. It also allows for cross-forest comparison of similar harvest methods, season, etc. A MSD allows greater flexibility for assessing how logging equipment influences overall soil disturbance within any given harvest unit.

We first analyzed the complete data set and then analyzed a subset of the data including just the ground-based harvest systems. To evaluate the complete data set, slope values were grouped at 10% intervals beginning with 0-9% (slope class 0); slopes in excess of 50% were grouped together as slope class 5. All analyses were conducted using SAS (SAS Institute 2008). A general linear model was used to generate least-squares means and was used to test for significant effects (alpha=.05) on MSD due to differences in the forest, harvest system, slope class, aspect, soil texture, and season of harvest. All interaction terms were insignificant and subsequently removed from the model.

3.3 Results

In the analysis, harvest system and forest were the only variables affecting MSD (*P*<0.0001) (Table 3.5). The analysis considered the effects of the three harvest systems (ground-based, skyline, and helicopter), physical site characteristics, season of harvest, and forest. Ground-based harvesting with a feller buncher, cut-to-length system, and tractor logging all caused greater soil disturbance than did the other harvest methods (Figure 3.2). However, soil disturbance was not large for any harvest system. MSD for harvest types other than helicopter was usually the equivalent of class 1 disturbance from the FSDMP. There were no differences in MSD between ground-based harvest systems (Figure 3.2). However, calculated MSD resulting from ground-based harvest differed among forests (*P*<0.0001) (Figure 3.3). As with harvest system, most forests had a MSD class on ground-based units of class 1 or less, with the exception of the NP forest with a MSD of 1.7.

TABLE 3.5. Model variables and their associated probability values. Variables with significant effect (alpha = .05) are listed in **bold.**

Variable	p-Value
Forest	**<.0001**
Slope class	0.6407
Aspect	0.1214
Season	0.5733
Soil texture	0.6388
Harvest system	**<0.0001**

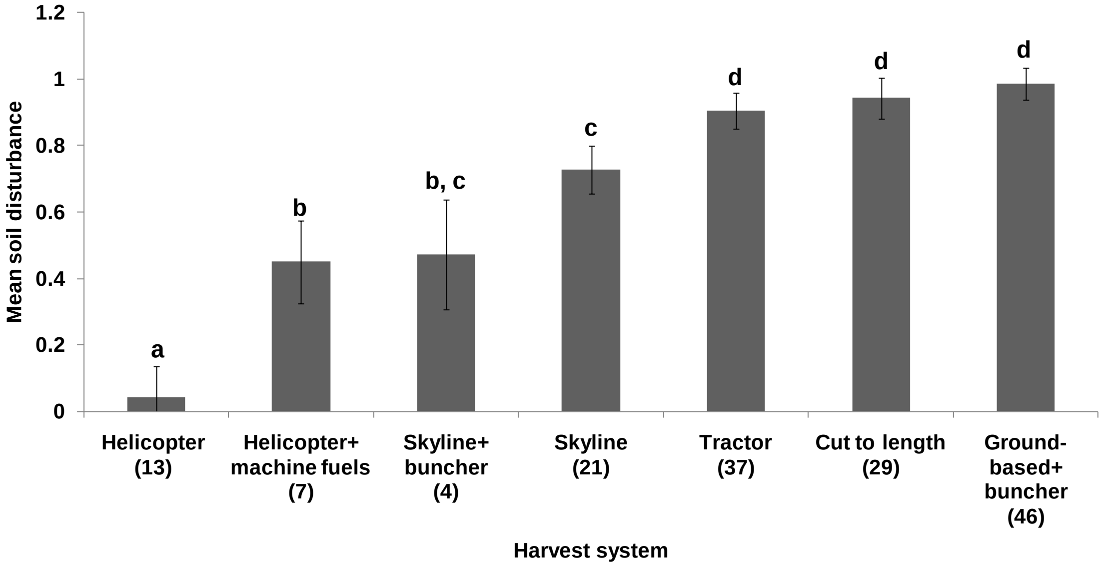

FIGURE 3.2. Mean soil disturbance associated with the evaluated timber harvest systems. The number of units associated with each harvest system is indicated in parentheses. Bars with the same letter above are not significantly different (alpha = .05).

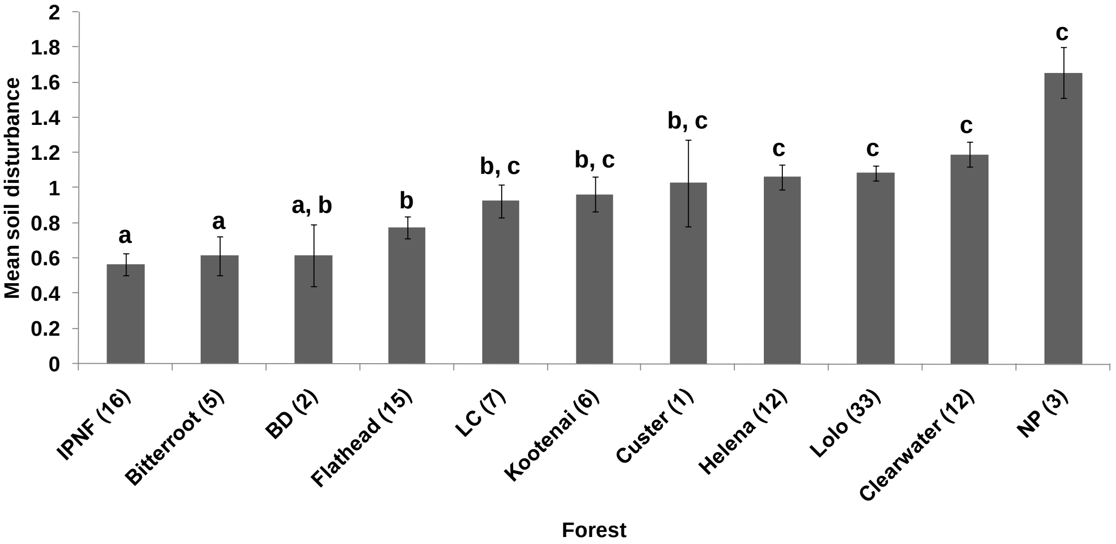

FIGURE 3.3. Mean soil disturbance values reported by the individual forests for ground-based harvest systems. The number of units represented for each forest is listed following the forest name (BD is the Beaverhead-Deerlodge National Forest, LC is the Lewis and Clark National Forest and NP is the Nez Perce National Forest) The number of units associated with each harvest system is indicated in parentheses. Bars with the same letter above are not significantly different (alpha = .05).

3.4 Discussion

3.4.1 National Forest monitoring

We rejected our hypothesis that the influence of National Forest was not expected to have a significant effect when similar harvest systems were used during similar harvest season on sites with similar physical characteristics. This may have resulted from different monitoring protocols, influence of differing landscape, impact of operator skill and experience, or sale administrator experience and knowledge of local conditions and operator tendencies.

An objective of this project was to find a system that would allow the use of legacy soil monitoring data collected with disparate soil monitoring methods and subsequently define common soil disturbance classes to correlate soil disturbance to harvest systems and physical site characteristics across a wide geographic range. Combining monitoring data taken by dissimilar methods may have added to the variation we reported among National Forests. Disparate sampling techniques (Curran et al. 2005, Craigg and Howes 2007) and differences in monitor training and experience (Miller et al. 2010) have been linked to results that are incomparable and unreliable in some cases. Significant National Forest differences suggest that the diversity of monitoring methods and/or protocols employed by the different forests produces results that are too variable to lend themselves to the degree of precision necessary to tie disturbance values to site characteristics across an entire geographic region. Differences among forests that encompass the area from which we obtained samples are not surprising given the amount of variability in site characteristics inherent in the region. What is surprising is that no site physical variables (texture, slope, aspect, etc.) proved to have an effect. Some of this might be explained by the logging harvest machine operators. Logging operator skill has been noted to effect disturbance levels among similar harvest systems (Pinard et al. 2000, Stone 2002). Sale administrator knowledge of local conditions and operator tendencies also play an important role in keeping soil disturbance to acceptable levels (Reeves et al. 2011*)*. Although these factors may have added to the variation in MSD among National Forests, it is reasonable to assume operator skill and sale administrator knowledge and competency varies among National Forests as well. The variation in operator skill and sale administrator knowledge and competency should not have produced the differences found between National Forests if that assumption is true. Differences in MSD between Forests are likely explained by the lack of a common disturbance monitoring protocol.

Visual observations of soil disturbance are inherently subjective. Monitoring results may vary with the individual soil disturbance monitors experience, preconceptions, and individual bias (Miller et al. 2010). Our results reflect and highlight this reality. Making the most effective and efficient use of soil monitoring resources should be a paramount objective of public land management agencies. Adopting universal soil disturbance class definitions concurrent with a statistically reliable soil disturbance monitoring protocol is a key process in meeting this objective (Curran et al. 2005).

3.4.2 Harvest systems

We confirmed our hypothesis that harvest systems and forest will have an impact on MSD when all harvest systems were evaluated. Not surprisingly, ground-based logging had the greatest effect on MSD compared to skyline or helicopter operations. These results suggest that forests relying more heavily on low impact harvest systems can reduce MSD associated with timber harvest operations. An increase in the use of low- impact harvest systems on some forests may have influenced our conclusions regarding the significance of those forests on MSD when all harvest systems are considered. These results agree with others finding skyline and helicopter based harvest systems produce less soil disturbance than ground-based harvest systems (Bockheim et al. 1975, Miller and Sirois 1986, Laffan et al. 2000, Miller et al. 2004, Page-Dumroese et al. 2006).

We were unable to show differences in MSD between ground-based harvest systems. The term "tractor" is sometimes used as a default category when soil monitoring is conducted 1-2 yrs after an area is harvested, because the harvest system is often not detailed in forest records. This renders conclusions about relative levels of soil disturbance between ground-based harvest systems as highly suspect. MSD is a useful tool for describing the relative trends among helicopter, cable-yarding, and ground-based harvesting for the National Forests we obtained data for. We were able to show differences between helicopter, line, and ground-based harvest systems consistent with published trends despite the variation in the data and the use of MSD.

3.4.3 Season of harvest

We rejected the hypothesis that season of harvest affects MSD (Table 3.5). Often, ground-based harvests conducted in winter conditions produce less soil disturbance than during other seasons and winter logging is used to mitigate soil disturbance impacts associated with ground-based harvest (Miller et al. 2004, Page-Dumroese et al. 2006, Johnson et al. 2007). Johnson et al. (2007) maintain that low disturbance levels on ash-cap soils common in the inland Northwest associated with winter harvest occur when the soil is frozen to depths of 10-15 cm or has a minimum of 15 cm. snow cover. Stone (2002) states that the depth of frost in the mineral soil that is necessary to reduce compaction is dependent on the harvest equipment used. Stone (2002) and Kuennen (2007) maintain that soil must be frozen to reduce the susceptibility to disturbance, and make the critical point that snow cover does not achieve the same objective as frozen soils. Moist soils insulated by snow cover will not freeze to levels that reduce soils resistance to compaction by ground-based harvest equipment (Kuennen 2007). After consolidating the data, season of harvest was placed into the category that reflected the month in which harvest operations were completed. Two possible explanations for the inconsistency between our findings and others could be: (1) the variation in local weather patterns produced conditions during the period classified as winter where snow pack was reduced or eliminated and saturated soils thawed to a point conducive to rutting. This highlights the necessity of removing snow cover from skid trails and allowing them to freeze before operating on them and monitoring local soil conditions closely during harvest operations prior to halting operations when preferential conditions do not exist or (2) a bias exists toward concentrating monitoring resources in areas where there is a concern about site conditions. If the second factor is true, then winter harvest units more susceptible to disturbance may be monitored preferentially as opposed to a random selection of winter harvest units to monitor for soil disturbance.

3.4.4 Slope

We reject the hypothesis that slope influences MSD. The slope class associated with each harvest unit was based on the maximum slope recorded for the unit. We were not surprised that there were no significant differences in MSD between adjacent slope classes.

However, we did expect slope to have a significant effect on MSD (Table 3.5). According to Miller et al. (2004), the risk of soil disturbance increases from “low” at slopes ranging from 0-5%, to “very high” at slopes exceeding 30%. Agherkakli et al. (2010) reported increases in compaction and rutting on slopes exceeding 20%. This is due in part to the necessity for building skid trails using cut and fill construction techniques on steeper slopes. These skid trail construction techniques contribute to increased levels of class 3 disturbance. Possible explanations for the discrepancy between our data and published trends (Miller et al. 2004; Agherkakli et al.2010) are: (1) the degree of error associated with data collected under separate and disparate sampling techniques, (2) monitoring points representing cut and fill skid trail construction were under represented in our data set, which seems unlikely given the relative distribution of harvest units in each slope class, or (3) although unlikely, it is possible that slope does not have the effect on MSD previously described within these National Forests.

3.4.5 Soil texture

We expected to see some differences in MSD between soil textures. A soil operability risk classification system developed by Weyerhauser Corporation (Heninger et al. 2002) rates sandy textured soils as “low risk” and clayey textured soils as “very high” risk (Curran et al. 2005). Water holding capacity is related to soil texture. Soil moisture content has been related directly to the severity of rutting and compaction during ground-based harvest operations (Williamson and Neilsen 2000). Recognition of the role soil moisture content plays in compaction levels has led to recommendations that ground-based harvesting be limited to periods of reduced soil moisture content. Soils with moisture contents less than

15% usually have a greater capacity to support increased ground pressure, which helps limit soil compaction to the surface mineral soil (Johnson et al. 2007). Undisturbed coarse textured soils will have lower moisture contents than fine textured soils under similar moisture regimes because of the difference in pore-size distribution among soil textural classes.

Weyerhauser Corporation's soil operability risk rating for 5 mapped soils in Oregon rates the very gravelly loam as the only soil with a "low" risk rating (Heninger et al. 2002, Curran et al. 2005). In addition, the presence of coarse fragments in a soil can act as a buffer to compaction by ground skidding machines and resist reductions in hydraulic conductivity values as compared to fine textured soils (Williamson and Neilsen 2000).

Surprisingly, our data across 11 National Forests showed no differences in MSD between soil textural classes. The soil textural groups we used (Table 3.4) proportionally underrepresented some soil textures. For instance, there were 28 harvest units that had a coarse texture modifier (equivalent to ≥15% coarse fragments) and 65 units in the medium-textured group. This underscores several possibilities: (1) our textural groupings, combined with the MSD groupings did not capture the heterogeneity of soil texture across the harvest units, (2) the degree of error and variability associated with qualitative data collected using separate and disparate sampling techniques, and (3) possible errors in the description of the soils associated with the harvest units. These factors combined likely resulted in soil texture being non-significant.

3.4.6 Mean soil disturbance

MSD is a method that can describe overall impacts on individual harvest units and then can be used to compare numerous sites that encompass a wide variety of geographic areas. We recognize that MSD levels do not lend themselves to illustrating the range of conditions in any given harvest unit. MSD is likely heavily weighted to describing a unit with little or no disturbance in the higher disturbance classes (Fig 3.2.) because most harvest units, even those using ground-based logging systems, have an overwhelming amount of class 0 and 1 points and relatively few disturbance areas in classes 2 or 3 (often limited to skid trails and landings). However, even with this flaw, MSD provides a measure of relative soil disturbance levels that can be used to evaluate disturbance levels resulting from timber harvest operations across a broad range of site conditions and harvest methods.

3.5 Management Implications

To attain the precision necessary to correlate soil disturbance to site characteristics over landscape scales will require adopting a standardized monitoring protocol. Our approach to converting legacy data into a common dataset is one method for using disparate data, but the errors associated with this may overshadow the ‘true’ disturbance levels. In addition, using MSD as the metric, we were able to demonstrate that there are significant differences in soil disturbance associated with different timber harvest systems despite the variation in the data. This is consistent with current literature on the subject. Reliable monitoring methods and the ability to compare results from one harvest unit, National Forest, or other areas of interest are dependent on a common language for terminology, a consistent protocol, and an effort to ensure that sampling is unbiased and statistically valid. Concomitant with these criteria should be an effort to ensure training and quality control for those individuals who are monitoring.

The ability to correlate disturbance with site characteristics would be an important tool for managers to utilize in project planning. An analysis of a large soil disturbance monitoring database where soil disturbance data has been collected using consistent methods should be done to determine if soil disturbance due to management activities can be correlated with harvest season and landscape characteristics (Chapter 4). A standardized approach will also ease communication barriers and raise awareness among resource managers, operators, and the public regarding soil issues.

3.6 Acknowledgements

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CHAPTER 4: RISK RATINGS TO PREDICT POTENTIAL DETRIMENTAL SOIL DISTURBANCE FROM GROUND-BASED TIMBER HARVEST ON THE KOOTENAI NATIONAL FOREST

As appears in: Reeves, D., M. Reeves, A. Abbott, D.S. Page-Dumroese, and M. Coleman. *in submission.* Risk ratings to predict potential detrimental soil disturbance from ground-based timber harvest on the Kootenai National Forest. Canadian Journal of Forest Research.

Abstract

A decision support tool identifying risks associated with ground-based timber harvesting in northwest Montana, USA was developed. Equations to predict the areal extent of detrimental soil disturbance resulted in a geo-spatial map encompassing nine landtypes on the Kootenai National Forest. Timber harvest activities result in varying levels of soil disturbance and high-impact harvest techniques, such as ground-based harvest systems, can result in changes in soil physical, chemical, and biological properties that may adversely impact soil processes and subsequent stand growth. Soil susceptibility to increased harvest disturbance is controlled by soil physical properties, site specific physical characteristics, climatic regime, and the season of harvest. In this paper we present a predictive model to determine areal extent of detrimental (potentially plant growth limiting) soil disturbance resulting from ground-based timber harvest based on site characteristics and season of harvest. Data was collected primarily by one observer using a consistent soil monitoring protocol. Landtype, slope, aspect, and harvest season were the key variables controlling the areal extent of detrimental soil disturbance. This tool can be modified to be used on other National Forests and models built on this framework can provide managers with a decision support tool useful in project planning.

KEYWORDS: *soil disturbance modeling, timber harvest, risk rating, long-term soil productivity*

4.1 Introduction

Maintenance of site productivity on National Forests in the United States is federally mandated under the National Forest Management Act (NFMA) of 1976. Monitoring the effects of timber harvest on soils and site productivity is required by this mandate and is a key component of adaptive management strategies (Curran et al. 2005a, Miller et al. 2010). Therefore, soil quality standards (SQS) were developed for each region of the USDA Forest Service in response to legislative mandates and defined thresholds for soil disturbance (USDA-FS 1999). Thresholds for impaired soil productivity or hydrologic function (detrimental disturbance) were defined for rutting, compaction, displacement, severe burning, surface erosion, loss of surface organic matter, and soil mass movement. Soil disturbance cannot exceed these thresholds for soils to be considered in satisfactory condition. On most USDA Forest Service land, units must have 85% of the harvested area in satisfactory condition when harvest activities, including site preparation, are completed, in order to fully meet policy directives. In addition, the Forest Service Manual (FSM) 2500 (USDA-FS 2010) directs that soil quality monitoring be used to validate the disturbance thresholds and refine management decisions.

Currently, there is no common soil monitoring protocol consistently applied in the United States to determine the level of soil disturbance resulting from management activities. Drawing conclusions about the effect of site variables (slope, aspect, soil texture, weather, etc.) on soil disturbance is difficult across large areas when disparate monitoring protocols are used to collect monitoring data (Chapter 3). Disparate soil disturbance monitoring techniques (Curran et al. 2005b, Craigg and Howes 2007) and differences in monitor training and experience (Miller et al. 2010) have been linked to results that are incomparable and unreliable.

Forest soils can be detrimentally impacted by timber harvest operations using rubber-tired and tracked vehicles (Bockheim et al. 1975, Miller et al. 2004, Curran et al. 2005a). Detrimental soil disturbance associated with ground-based harvesting often includes rutting, lateral soil displacement, horizon mixing, and compaction (Clayton et al. 1987). However, soils do not respond uniformly to disturbance associated with ground-based harvest (Powers et al. 2005). Soil response to disturbance is inherently variable, changes over time depending on the level of impact and may be cumulative within a watershed (Carter et al. 2006, Page-Dumroese et al. 2010a). Assuming that any soil disturbance causes a reduction in tree growth is unwarranted (Miller et al. 2004). Soil disturbance resulting from ground-based timber harvest may enhance (Gomez et al. 2002), or have no effect on subsequent tree growth (Miller et al. 2010). Conversely, soil disturbance can reduce juvenile (Geist et al. 2008) and mid-rotation tree growth and economic value (Murphy et al. 2004). However, Gomez et al. (2002) suggests that the correlation between soil disturbance and tree growth is dependent on soil texture and soil water regime. These differences underscore the importance of a site specific approach to soil disturbance monitoring and the ability to correlate disturbance levels to long-term site productivity.

Soil changes linked to harvest activities depend primarily on soil moisture during harvest operations, soil organic matter content and soil textural class. Other factors include the axle weight of the load applied, tire size and the number of machine passes (Williamson and Neilsen 2000, Han et al 2009). Site characteristics (inherent soil bulk density, forest type, soil parent material, and slope) also play a major role in how soils react to ground-based harvest activities (Williamson and Neilsen 2000, Curran et al. 2005a and b, Agherkakli et al. 2010).

Soil disturbance monitoring can be labor intensive and cost prohibitive in an era of shrinking budgets. This necessitates that monitoring resources should be focused on high risk sites and/ or inherently sensitive soils (Curran et al. 2005b, Miller et al. 2010). Effectively predicting the susceptibility of specific soils to disturbance is a core component of an adaptive management process outlined by Curran et al. (2005b). Since current and future resource conditions drive management decisions (Peng 2000), the ability to predict soil disturbance levels due to ground-based timber harvest based on site characteristics and harvest season would provide land managers a valuable decision support tool and is fundamental to responsible use of forest lands (Miller et al. 2010). The decision support tool should be capable of identifying areas more susceptible to high disturbance levels resulting from ground-based timber harvest.

Reeves et al. (Chapter 3) attempted to correlate soil disturbance with site characteristics, equipment type, and harvest season by combining soil disturbance monitoring data that had been collected using disparate methods. In that study we developed a system for placing visual class information into the standardized Forest Soil Disturbance Monitoring Protocol visual classes (Page-Dumroese et al. 2009). Soil disturbance levels defined through that study were dependent on the harvest system employed and the personnel conducting the field work or the monitoring protocol (Chapter 3). Consequently, to develop a decision support tool based on systematically collected soil monitoring data, in this study we accessed a large soil disturbance monitoring dataset collected using a consistently applied monitoring protocol to achieve two objectives: (1) determine the factors affecting soil disturbance and

(2) create a geo-spatial model to predict the areal extent of detrimental soil disturbance resulting from ground-based timber harvest on the Kootenai National Forest (KNF) in northwest Montana based on landscape characteristics and season of harvest. On this forest, detrimental soil disturbance (DSD) is defined as: disturbance in excess of the soil quality standard thresholds for compaction, rutting, displacement, severe burning, erosion, and soil mass movement as defined in Table 4.1.

4.2 Methods

4.2.1 Data collection

The Kootenai National Forest has monitored harvest disturbances using a consistent monitoring protocol based on SQS developed for the Northern Region of the USDA Forest Service since 1988. We compiled post-harvest soil monitoring records from 167 ground-based timber harvest units that were provided by the KNF. Soil disturbance classifications were assigned and recorded for 87,744 monitoring points on these units. No soil monitoring data were used that were completed prior to the last revision of the Northern Region SQS (USDA-FS 1999). Data collected included dominant site parameters (e.g. slope, aspect, soil texture, and landtype), harvest season, harvest type (intermediate or regeneration), and the machine(s) used during ground-based harvest operations. Harvest season was delineated by the month harvest operations were completed. Ground-based harvest units were those units where timber had been harvested by rubber-tired skidders, harvester/forwarder (cut-to-length), and tractors. Both hand-felled and machine-felled harvest units were included. Harvest units that were machine-felled and yarded by helicopter or skyline systems were not included because these harvest systems usually result in relatively low levels of DSD on the KNF and throughout the Northern Region (Chapter 5).

4.2.2 Field collection of soil disturbance monitoring data

Post-harvest soil disturbance monitoring data had been collected on the KNF using a three class (undisturbed, disturbance present but not detrimental, disturbance present and detrimental) system to determine the areal extent of DSD across the harvest unit. Line transects were walked across each harvest unit from harvest boundary to harvest boundary perpendicular to the direction of ground disturbing activities such as skid trails and skyline corridors (Kuennen 2006). Transects perpendicular to the skid trail pattern were found to be the most efficient sampling method that represented disturbance due to harvest activities (Kuennen 2006). Soil disturbance classification was recorded at each step across the transect using a spade and/or knife along with ocular observations to determine both quantitative and qualitative disturbance values present. A monitoring point was considered detrimentally disturbed if the disturbance present was in excess of the Northern Region SQS for compaction, rutting, displacement, severely burned soil, erosion or mass movement (Table 4.1).

TABLE 4.1. Detrimental disturbance thresholds from the Northern Region Supplement No. 2500-99-1 (USDA 1999) and used by the KNF for soil monitoring determinations.

Disturbance type	**Detrimental threshold value**
Compaction	15% increase in natural bulk density
Rutting	Wheel (or track) ruts ≥ 2 in. (5 cm.) deep in wet soils
Displacement	Removal of ≥ 1 in. (2.5 cm) of any surface horizon from a contiguous area greater than 100^2 ft. (9.3^2 m).
Severely burned soil	Physical and biological changes to the soil resulting from high-intensity burns of long duration as described in the Burned-Area Emergency Rehabilitation Handbook (FSH 2509.13).
Surface erosion	Rills, gullies pedestals, and soil deposition
Soil mass movement	Any soil mass movement caused by management activity

4.2.3 Landtypes

There are 50 landtypes in the KNF as described by Kuennen and Nielsen-Gerhardt (1995). Of the 50 landtypes present on the KNF, nine were selected for this study based on the availability of post-harvest DSD data for each landtype. These nine landtypes cover over 1.4 million acres and represent ~47.5% of the landbase within the administrative boundaries of the KNF. Landtype boundaries were plotted on the basis of physiography (Table 4.2), geology and vegetation (Table 4.3) (Kuennen and Nielsen-Gerhardt 1995).

TABLE 4.2. Selected physical characteristics and acreage for the nine landtypes used in this study.

Landtype	**Slope**	**Aspect**	**Elevation**	**Area**	**Number of harvest units**	
	%		m	ha	Winter	Non-winter
302	30-60	southerly	914-1280	17912	0	3
321	10-40	variable	762-1158	13050	5	1
322	15-35	variable	762-1524	32225	1	5
323	15-35	variable	762-1524	35754	7	23
324	15-35	variable	762-1219	37306	3	19
328	15-35	northerly	914-1646	20877	3	7
329	15-35	variable	914-1676	27414	7	10
352	20-60	northerly	671-1707	201000	15	28
355	20-50	northerly	914-1676	187336	23	7

Modified from Kuennen and Nielsen-Gerhardt 1995.

TABLE 4.3. Selected geological and ecological characteristics for the nine landtypes used in this study.

Landtype	**Soil parent material**	**Dominant landform**	**Habitat type**
302	compact glacial till	glaciated mountain slopes	Douglas fir/ snowberry
321	calcareous glacial till	drumlins/ moraines	Douglas fir/ pine grass
322	loess and volcanic ash over compact glacial till	moraines	western hemlock/ queencup beadlilly
323	loess and volcanic ash over calcareous glacial till	moraines	Douglas fir/ pine grass
324	calcareous glacial till	moraines	Douglas fir/ pine grass
328	loess and volcanic ash over calcareous glacial till	glaciated mountain slopes	subalpine fir/ twinflower
329	loess and volcanic ash over calcareous glacial till	moraines	subalpine fir/ twinflower
352	loess and volcanic ash over compact glacial till	glaciated linear mountain slopes	western red cedar/ queencup beadlilly
355	loess and volcanic ash over compact glacial till	glaciated rounded mountain slopes	western red cedar/ queencup beadlilly

Modified from Kuennen and Nielsen-Gerhardt 1995.

4.2.4 Statistical analysis

All analyses were done using SAS PROC GLM (SAS Institute 2008). A linear multiple regression analysis was used to test for significant effects (alpha=.10) of harvest season, aspect, slope, landtype, soil texture, ground-based equipment used, harvest type, unit acres, and coarse fragment content in the soil on the areal extent of DSD. Aspect, landtype, soil texture, ground-based equipment, and harvest type were treated as class variables. Variables and interactions that did not have a significant effect on the areal extent of detrimental soil disturbance were removed from the final model. Pre-harvest DSD was subtracted from post-harvest DSD values where it was available for a harvest unit. When pre-harvest DSD was not available for a harvest unit, it was assumed to be zero. For the purposes of this study, harvest units listed as winter were completed in December, January, or February. Harvest units completed during other months were treated as non-winter. Aspect was treated as a class variable consisting of the eight cardinal directions and harvest units that were flat (no definable aspect). Slope values were based on the maximum slope recorded for each harvest unit. Least-squared means were generated and used to test for significant differences between levels of predictor variables.

4.2.5 Geo-spatial projection

Statistical parameters generated in the GLM analysis were used to develop equations for a predictive model of the areal extent of DSD resulting from ground-based timber harvest based on landtype and harvest season. The statistical model used to generate parameters for the geo-spatial representation evaluated the effect on the areal extent of DSD of aspect, maximum slope of the harvest unit, harvest season (winter or non-winter), landtype, and the interaction between harvest season and landtype. The geo-spatial representation was created using parameter estimates generated from the statistical model in the equation: DSD= $B_0+B_1\ldots.B_5$

Where: DSD is the predicted areal extent of DSD in the harvest unit

B_0 is the y-intercept

B_1 is the slope

B_2 is the aspect

B_3 is the season of harvest

B_4 is the landtype

B_5 is the interaction between season of harvest and landtype

Equations developed through this process were programmed in Arc Macro in the Grid environment (ESRI 2007) enabling predictions of the areal extent of DSD resulting from ground-based timber harvest for eight landtypes during winter harvest and nine landtypes during non-winter harvest.

4.3 Results

4.3.1 Factors controlling disturbance

Detrimental soil disturbance was affected by ground-based timber harvest between landtypes, and between harvest seasons on the same landtype (Figure 4.1). Non-winter ground-based harvest resulted in higher ($P \leq 0.0356$) DSD on landtypes 322 and 329 than non-winter harvest on landtypes 328 or 352. Winter ground-based harvest operations resulted in higher ($P \leq 0.0399$) DSD on landtypes 323, 324, and 328 than winter harvest on other landtypes. DSD resulting from non-winter harvest was higher ($P \leq 0.0433$) than DSD resulting from winter harvest on landtypes 322, 329, 352, and 355. DSD resulting from winter harvest was higher than non-winter harvest only on landtype 328 ($P=0.0007$). There were also differences in the areal extent of DSD resulting from ground-based timber harvest between aspects (Figure 4.2). Harvest units with south and east influenced aspects had higher levels of DSD ($P \leq 0.0816$) than harvest units with a northwest aspect (Figure 4.2). Detrimental soil disturbance levels increased slightly (.05% per 1% increase in slope) with an increase in the maximum slope value for the harvest unit. Aspect, slope, landtype, and the interaction between harvest season and landtype (harvest season* landtype) were significant variables in the model (Table 4.4).

TABLE 4.4. Significant model variables and associated probability values.

Variable	**p-Value**
Aspect	0.0217
Slope	0.0738
Harvest season	0.1637
Landtype	0.0002
Harvest season* landtype	0.0002

Parameter estimates generated from the GLM used for the geo-spatial projection equations are listed in Table 4.5.

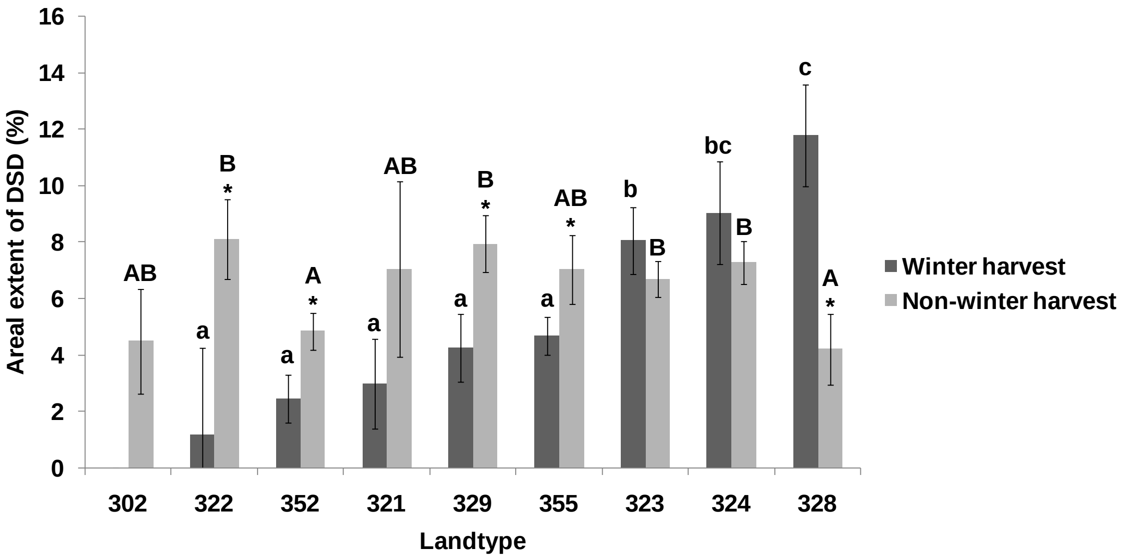

FIGURE 4.1. Mean areal extent of DSD for each landtype and harvest season evaluated for this study. Bars represent the standard error about the mean. Bars with the same letter above are not significantly different (alpha = .10). Lowercase letters compare winter harvest operations; uppercase letters compare non-winter. Uppercase letters are not comparable with lowercase letters. Bars with an asterisk (*) above indicate significant differences (alpha=.10) in DSD between harvest seasons on the same landtype. We had no data for winter harvest on landtype 302.

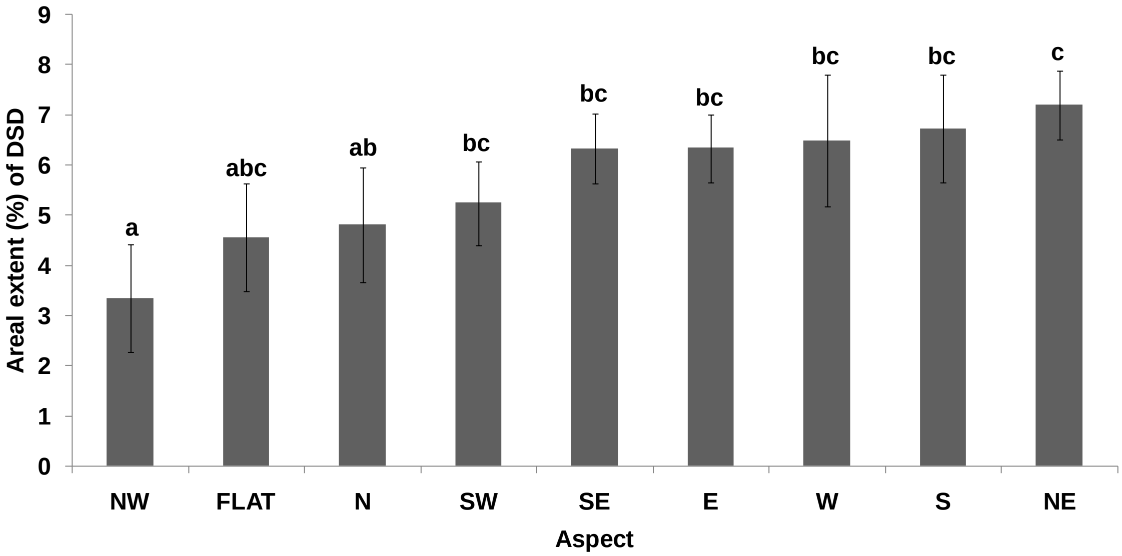

FIGURE 4.2. Mean areal extent of DSD by aspect. Bars represent the standard error about the mean. Bars with the same letter above are not significantly different (alpha = .10).

4.3.2 Geo-spatial representation of the statistical model

We produced a geo-spatial representation of the statistical model for winter harvest (Fig. 4.3) and non-winter harvest (Fig. 4.4) using parameter estimates generated from the GLM (Table 4.5). Modeled values for the areal extent of DSD resulting from winter ground-based harvest ranged from 0% to 14%. Modeled values for the areal extent of DSD resulting from non-winter ground-based harvest ranged from 0% to 16%. While the overall areal extent of DSD was similar for winter and non-winter harvest, there was some variation in the distribution of predicted DSD between winter and non-winter harvest among landtypes. Detrimental soil disturbance values associated with the geo-spatial representation were tightly correlated with the statistical model (r^2 values for winter and non-winter were 0.998 and 0.984 respectively).

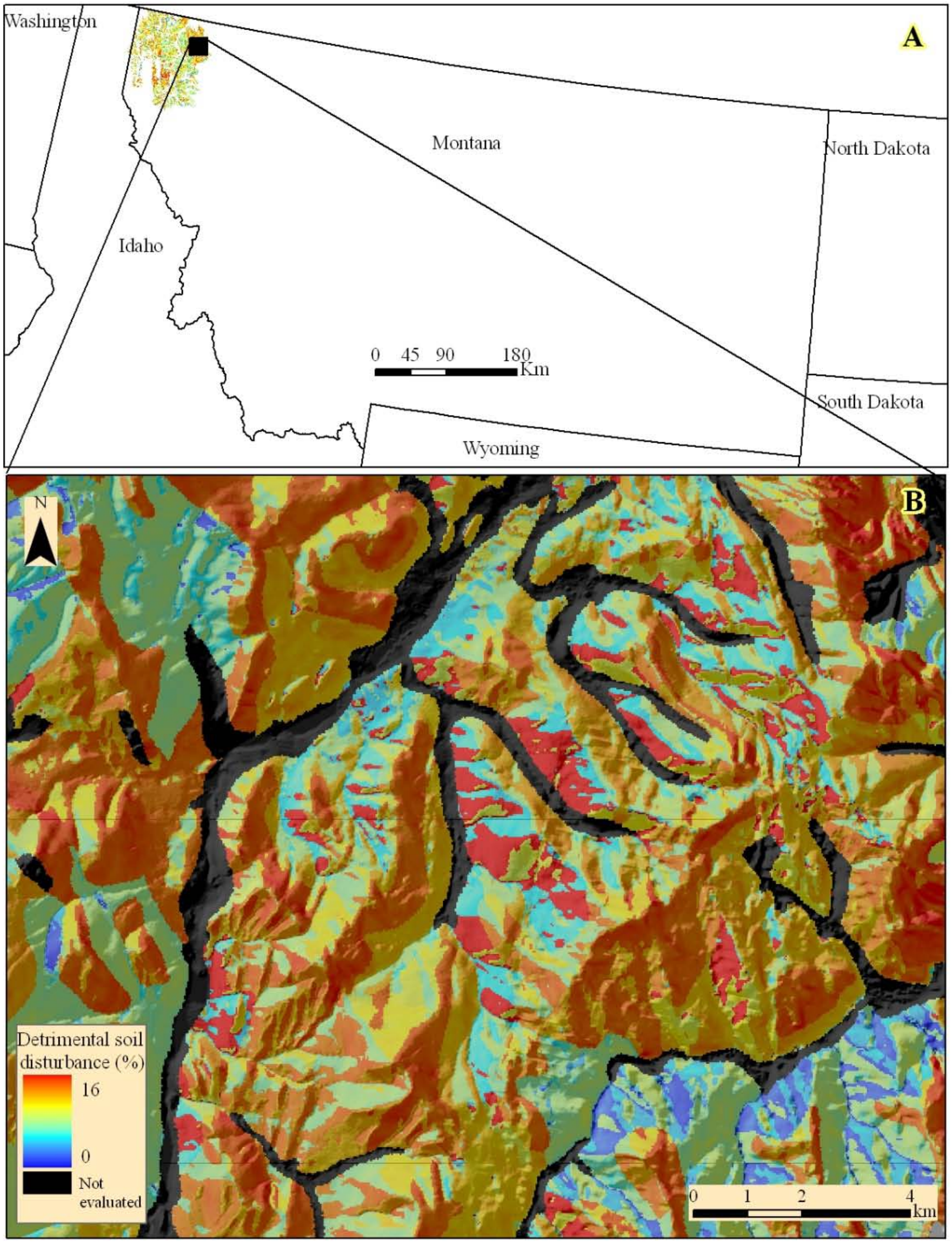

FIGURE 4.3. Geo-spatial representation of the statistical model predicting areal extent of DSD resulting from winter ground-based timber harvest. Panel A is landscape projection showing study area. Panel B shows small scale projection of a segment of study area. Areas in black represent landtypes not evaluated in this study.

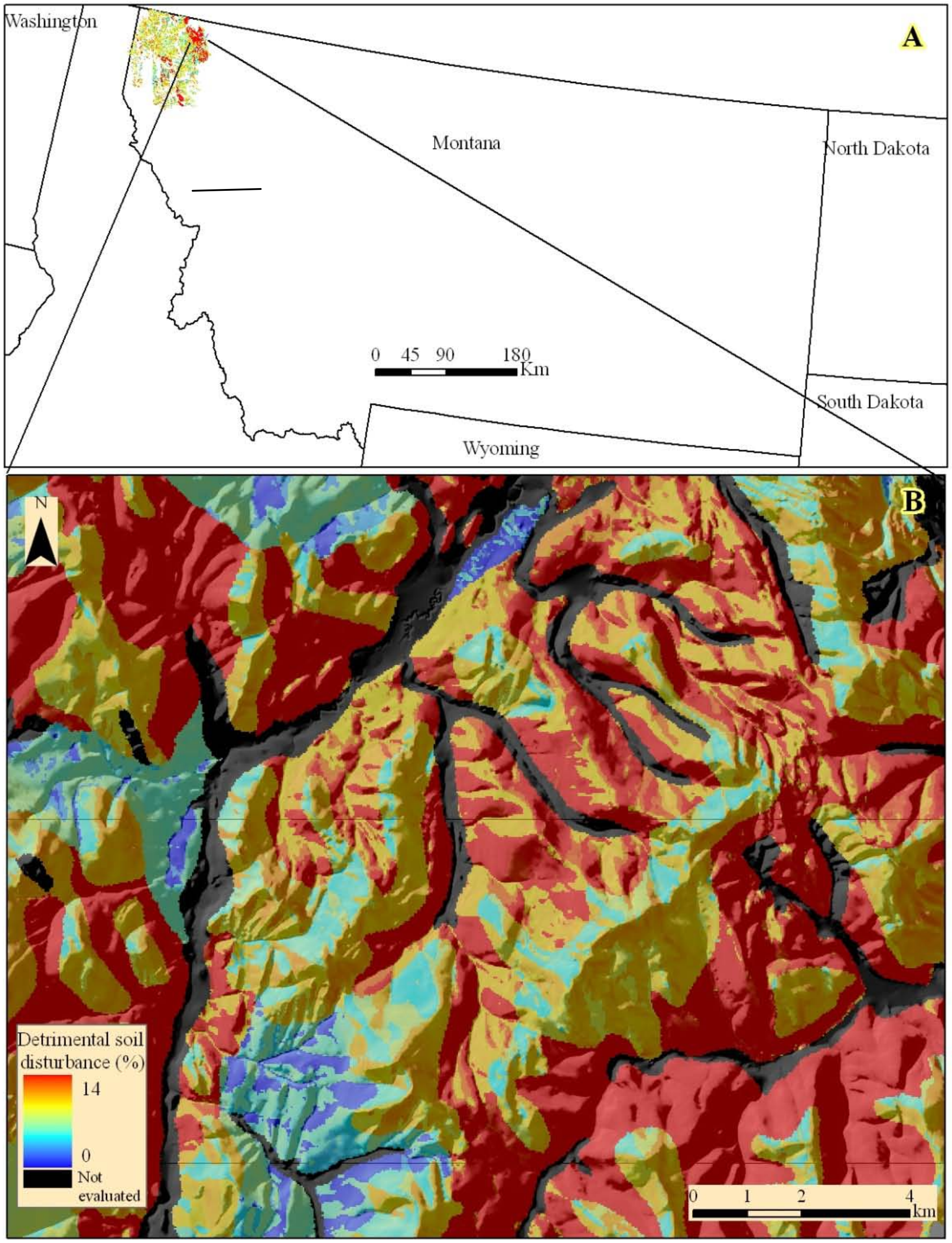

FIGURE 4.4. Geo-spatial representation of the statistical model predicting areal extent of DSD resulting from non-winter ground-based timber harvest. Panel A is landscape projection showing study area. Panel B shows small scale projection of a segment of study area. Areas in black represent landtypes not evaluated in this study.

TABLE 4.5. Parameter estimates used to produce geo-spatial representation of the statistical model predicting areal extent of DSD for harvest unit.

	CLASS	**Estimate**		**CLASS**	**Estimate**
Mean		4.22	Season of harvest*landtype		
Slope (%)		0.06	Non-winter	302	0.00
				321	1.69
Aspect	E	0.24		322	4.57
	N	-1.92		323	-3.72
	NE	0.51		324	-4.11
	NW	-3.67		328	-9.94
	S	0.42		329	1.32
	SE	0.26		352	0.04
	SW	-1.02		355	0.00
	W	0.00			
	Level	-1.63			
Season of harvest	Winter	0.00	Season of harvest*landtype		
	Non-winter	2.36	Winter	302	0.00
				321	0.00
Landtype	302	-2.54		322	0.00
	321	-1.68		323	0.00
	322	-3.49		324	0.00
	323	3.39		328	0.00
	324	4.36		329	0.00
	328	7.11		352	0.00
	329	-0.41		355	0.00
	352	-2.22			
	355	0.00			

4.4 Discussion

The amount of DSD reported on harvest units in this study depended primarily on the landtype and season of harvest. The physiography (slope and aspect) of the harvest unit played a lesser, but still significant role in the amount of DSD resulting from ground-based harvest. Soil disturbance after non-winter harvests was significantly higher on moraines (landtypes 322 and 329) than on glaciated mountain slopes (landtypes 328 and 352). Aside from the dominant landforms delineating these landtypes, other physical characteristics are similar. The rolling topography associated with moraines make them conducive to ground-based harvest because of the relative ease with which harvest equipment can travel across the ground. The increase in DSD on the moraines may have been due to a lack of designated skid trails or the ability to turn freely across these sites. This disperses harvest activity across the harvest unit and does not confine DSD to designated areas, increasing the areal extent of DSD. The glaciated mountain slopes on landtypes 328 and 352 likely restricted machine travel across the harvest unit to designated skid trails.

Winter harvest was effective at decreasing DSD across most of the study area. This is consistent with regionally published trends (Chapter 5). Winter harvest conducted during optimal conditions over frozen soil is effective at reducing DSD resulting from ground-based harvest (Miller et al. 2004, Johnson et al. 2007) and it is often prescribed as a best management practice because it has been shown to minimize soil damage (Miller et al. 2004, Page-Dumroese et al. 2006, Johnson et al. 2007, Page-Dumroese et al. 2010b).

Mean winter DSD levels exceeded mean non-winter DSD levels on three landtypes (323, 324, and 328), and was significantly higher on landtype 328. This was particularly surprising on landtype 328 given the landtypes dominant northerly aspect (Table 4.2) and relatively low disturbance levels for non-winter harvest (Figure 4.1). Kootenai National Forest personnel believe that the predicted values are inconsistent with actual post harvest DSD levels resulting from winter harvest on landtype 328 (personal correspondence with John Gier, Forest Soil Scientist, KNF, October 5, 2010). There are a number of factors that may have influenced the high levels of DSD predicted by the model on landtype 328 for winter harvest. Kuennen (2007) notes that timber sale contract language on the KNF can state that harvest activities are restricted to ground that is frozen or covered by a minimum of

46-61 cm of snow; however, these parameters do not achieve the same objective. Ground that receives insulating snow pack prior to freeze up will not freeze to the point necessary to produce optimal winter harvest conditions. Snow should be removed from skid trails and skid trails left to "freeze-up" before harvest activities commence to achieve ideal conditions (Kuennen 2007).

There were five harvest units on landtypes 323, 324, and 328 where winter harvest DSD levels ranged from 11%-18%. These five harvest units represent 38.5% of the data for winter harvest on these landtypes. Harvest took place on these five units during the winters of 1999-2000, 2000-2001, 2003-2004, and 2004-2005. Temperature and precipitation data from the Libby 1 NE Ranger STN, MT weather station (High Plains Regional Climate Center 2010) indicates that temperatures at the weather station for December, January, and February were above the 98 year average for each of the winters with high DSD levels on those landtypes. Additionally, precipitation levels over the same three month period were below the 98 year average for each of the winters with high DSD levels on those landtypes except for the winter of 1999-2000 (High Plains Regional Climate Center 2010). While site conditions at the time of harvest are unknown, these data suggest that winter harvest conditions on these five units may have been sub-optimal due to higher than average temperatures and decreased snow pack leading to an increase in winter harvest DSD due to saturated soils during harvest activities.

The variation in DSD during winter harvest may be attributable to other factors. For example, categorizing December, January, and February as "winter" may have influenced our results. In our experience, these three months are the most likely to exhibit the necessary temperatures and snow pack to produce optimal winter harvest conditions. However, the categorization technique we used was based on the month in which management activity was completed. It is possible that DSD levels were high because of harvest operations that took place in late fall while soils were more susceptible to rutting and compaction after fall rains and before harvest operations were completed in the period we designated as winter.

Operator and sale administrator skill and the harvest equipment may also play a role in the variation of DSD levels. Operator skill and experience has been documented to affect disturbance levels in similar harvest operations (Pinard et al. 2000, Stone 2002). Sale administrator knowledge of local conditions and operators on site can also have an impact on the amount of DSD resulting from timber harvest operations (Chapter 3, Chapter 5). Although we found no significant DSD differences among ground-based harvest equipment, other research points out that different equipment can produce disparate results (Stone 2002, Page-Dumroese et al. 2006). Our findings may be due to a lack of precision in noting the type of harvest equipment used in each harvest unit. Ultimately, allocation of monitoring resources likely impacts our conclusions because post-harvest monitoring resources can be directed toward areas deemed more susceptible to high levels of disturbance. Consequently, monitoring activities for winter harvest in landtype 328 could have been restricted to harvest units that were known to be at risk due to sub-optimal conditions. Similarly, it is possible that the values predicted by the statistical model are an anomaly due to a small sample size (Table 4.2).

Developing a decision support tool that uses risk ratings based on landscape characteristics and the associated geo-spatial representation is a theoretically straight forward task. Data collection on landscape scales and stratification based on factors that control site-specific responses to management activities is labor intensive and less straight forward. The risk rating system we developed was based on data collected over an 11 year span using a consistent protocol. Careful documentation of the results from post-harvest soil disturbance sampling and the development of the landtype characteristics were key to the success of the project. Use of a consistent method, such as the one documented by Page-Dumroese et al. (2009) will also allow development of a decision support tool that is useful across broad landscapes. Previous reports indicate that variation attributed to combining data collected with different protocols masks expected site factor effects observed is this study (Chapter 3).

Management objectives typically seek to minimize DSD and its cumulative effects (Curran et al. 2007). Site specific differences in soil physical properties and landscape characteristics along with pre-harvest site condition are key parameters in how soils react to management activities (Curran et al. 2005b). Assessing how these features affect disturbance levels requires accurate documentation of site specific characteristics combined with a common, consistently applied soil disturbance monitoring protocol. Landtype surveys capture much of the variation associated with physical site characteristics and climatic regimes on a landscape scale. Predicting disturbance levels based on these site specific characteristics helps land managers identify and develop mitigation plans for those sites most susceptible to high levels of disturbance (Curran et al. 2005b).

Predictive models can be improved by increased sample points within a unit to assure that a greater proportion of variability is captured during the monitoring process. Predicted values for the areal extent of detrimental soil disturbance for the area modeled are produced from 167 harvest units and extrapolated over millions of pixels encompassing many variations of physical composition. This is best illustrated by examining the predicted values for the areal extent of DSD for ground-based winter harvest. The model predicts post-harvest disturbance levels ranging from 0% to 15%. While modeled values appear to be reasonable over a broad range of conditions, values on the extreme ends of the spectrum may be influenced by extrapolations of poorly fitted or unfitted data.

During our analysis we lacked sufficient data to withhold a portion of the data set to validate the model. Model validation is a key component in promoting user confidence and establishing the range of error associated with predicted values. This model can be revised, validated, and improved by consolidating post-harvest soil monitoring data collected on the KNF over the coming monitoring seasons. In addition, we also lacked pre-harvest soil disturbance data on some harvest units that might indicate a level of disturbance we attributed to the current timber sale. We also did not have site specific information on surface soil texture. Soil texture influences water infiltration and hydrologic function, but surface soil texture information is not specific to each timber sale area. This should be a key piece of information associated with monitoring efforts. Unfortunately, it may take several years to gather sufficient data to validate the model for all the landtypes and harvest seasons represented. Despite the lack of model validation, we have established a framework by which other decision support tools and risk rating assessments can be constructed based on landscape characteristics and seasonality for proposed management activities.

4.5 Management Implications

Developing an accurate risk rating system and decision support tool to model soil response to management activities can be accomplished using current, consistently applied soil monitoring protocols, landtype (or soil) surveys, and geo-spatial data that is often readily available. Consistent application of soil monitoring protocols and database development are key components of this process and critical to an effective soil monitoring program. All harvest operations produce some type of soil disturbance and using a risk rating system as a portion of the overall risk analysis of proposed projects is an efficient, cost-effective step in identifying areas more susceptible to DSD causing activities. Identifying areas more susceptible to high impact (i.e. ground-based) harvest techniques allows land managers to develop alternative strategies to meet management objectives and can help prioritize allocation of monitoring resources. Tools such as this one that incorporate a risk rating system can play a crucial role in project planning and are a key component of adaptive management strategies.

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CHAPTER 5: DETRIMENTAL SOIL DISTURBANCE ASSOCIATED WITH TIMBER HARVEST SYSTEMS ON NATIONAL FORESTS IN THE NORTHERN REGION

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Abstract

Maintaining site productivity on forested lands within the National Forest System is a Federal mandate. To meet this mandate, soil conditions on timber harvest units within the Northern Region of the USDA Forest Service cannot exceed a threshold of 15% areal extent of detrimental soil disturbance (DSD; defined as a combination of compaction, puddling, rutting, burning, erosion, and displacement). The objectives of this study were to collate post-harvest soil monitoring data and to statistically document the areal extent of DSD resulting from timber harvest systems in the Northern Region. Current and legacy post-harvest soil monitoring data on National Forests throughout the Northern Region were collected to determine whether timber harvest systems (ground-based, skyline, or helicopter) used in the Northern Region resulting in DSD levels in excess of the mandated 15% areal extent. Statistical models developed in this study showed significant differences in the areal extent of DSD following timber harvest operations among ground-based, skyline, and helicopter harvest systems; among harvest seasons; and among National Forests. The frequency of DSD harvest operations followed the general trend of ground-based>skyline>helicopter. Winter ground-based harvest resulted in a significantly lower areal extent of DSD than summer ground-based harvest. Differences among Forests may have been caused by unique physiographic and ecological characteristics and distinct survey methods. However, despite significant differences in the amount of DSD resulting from similar timber harvest systems, none of the harvest systems that we evaluated on the National Forests consistently resulted in mean disturbance levels in excess of the 15% areal extent threshold.

Research Summary

The National Forest Management Act of 1976 (NFMA) mandates that management systems “will not produce substantial and permanent impairment of the productivity of the land.” In response to this mandate, soil quality standards were developed for each Region of the USDA Forest Service. To comply with the NFMA mandate in the Northern Region, detrimental soil disturbance (DSD; a combination of compaction, rutting, severely burned soil, displacement, erosion, and soil mass movement) must not exceed 15% of the areal extent of a timber harvest unit when harvest and site preparation activities are complete. In the Northern Region, monitoring of post-harvest soil disturbance levels has been achieved using several methods since the soil quality standards were last revised in 1999. Despite the lack of a common monitoring protocol, the shared objective of all soil monitoring methods has been to find the areal extent of detrimentally disturbed soil on the harvest unit in order to determine the extent to which harvest activities meet the Regional standard.

We collected current and legacy soil monitoring data that was gathered post-1999 from throughout the Northern Region for all timber harvest systems in order to evaluate the differences in the areal extent of DSD resulting from ground-based, skyline, and helicopter harvest systems over different harvest seasons. Where sufficient data were available, we also evaluated the areal extent of DSD resulting from different harvest systems/harvest seasons for the individual Forests in the Northern Region.

Using a statistical model developed in this study, we came to the following conclusions:

1. The mean areal extent of DSD does not exceed the 15% threshold for any harvest system in the Northern Region, based on the data we collected and were given.

2. Significant differences in the areal extent of post-harvest /post site preparation DSD result from different harvest systems. The trend in DSD for the Northern Region harvest systems is ground-based>skyline>helicopter.
3. The areal extent of DSD is significantly higher as a result of ground-based summer harvest than ground-based winter harvest.
4. Harvest method that listed “tractor” as the equipment type used lacked enough precision for definitive conclusions about DSD resulting from ground-based equipment.
5. Significant variation exists in the areal extent of DSD post-harvest among National Forests in the Northern Region (and by extension, the soil disturbance monitors) utilizing similar harvest systems and harvest seasons.
6. The institutional bias in the Northern Region that directs soil monitoring efforts toward harvest units that are more susceptible to DSD is justified.
7. The applicability of large-scale assessments to determine the impact to the soil resource and its productive capacity is limited because of disparate sampling protocols that are implemented over a wide-range of climatic, geographic, and soil characteristics.

Land managers can reasonably predict that the areal extent of post-harvest DSD on proposed skyline and helicopter harvest units will fall under the 15% threshold on harvest units with minimal pre-existing DSD. In addition, the Forest Service stands to benefit from the adoption of a common soil monitoring protocol that standardizes a common monitoring method, when pre- and post-harvest soil monitoring occurs, and delineates the soil disturbance resulting from harvest activities and from site preparation activities.

5.1 Introduction

Maintenance of soil productivity is a statutory mandate of the National Forest Management Act (NFMA) of 1976. The NFMA and the administrative National Forest System Land and Resource Management Planning Act (USDA-FS 1982) related to maintenance of soil productivity are general statements that gives managers significant flexibility in how soil and site productivity are maintained. Efforts to determine the extent to which management activities undertaken by the USDA Forest Service were meeting legal mandates relative to soil productivity led to the first soil quality standards (SQS) in North America.

Forest Service Manual 2500 (USDA-FS 2010) and the SQS (USDA-FS 1999) developed for the Northern Region of the Forest Service describe specific definitions, policy, and direction for meeting mandates and directives set forth in NFMA and the Planning Rule. The Northern Region SQS (USDA-FS 1999) were last revised in 1999. The objectives of the SQS are to "meet direction in the National Forest Management Act of 1976 and other legal mandates, and to manage Forest System lands under ecosystem management principles without permanent impairment of land productivity and to maintain or improve soil quality" (USDA-FS 1999). This policy is based on the assumption that detrimental soil disturbance (DSD) must reduce vegetative growth by more than 15% before it is detectable during routine measurements (Powers et al. 1990). However, it has also come to mean that the areal extent of DSD should be less than 15% to maintain site quality (Powers et al. 1998). To meet the policy direction, cumulative levels of soil impacts considered detrimental to land productivity must not exceed 15% of the areal extent of any given management unit. Soils are considered to be detrimentally impacted when disturbance thresholds (set by each USDA

Forest Service Region) are exceeded for compaction, displacement, rutting, severe burning, surface erosion, loss of surface organic matter, and soil mass movement. The assumption is that the magnitude of these impacts is dependent on the ecological interaction between local climate and soil physical, chemical, and biological properties and processes. However, at the time these standards were developed, little research had been completed to validate the impacts of these soil disturbances on forest productivity (e.g., vegetative regrowth after harvesting) (Page-Dumroese et al. 2000) or on how individual soil types might respond to various management systems. Areas not managed for vegetation and water resources such as permanent roads, harvest landings, mines, developed recreation areas, and administrative sites were exempted from the SQS.

The USDA Forest Service SQS describe a systematic process by which data are collected to determine if soil management objectives to maintain long-term productivity are achieved (Neary et al. 2010). Howes et al. (1983) provided a protocol for quantitative forest soil monitoring that was used in the Pacific Northwest Region, but a rapid qualitative assessment was favored to reduce the monitoring burden and to allow more assessment capacity (Howes 2001, Curran et al. 2005). Page-Dumroese et al. (2009) developed the Forest Soil Disturbance Monitoring Protocol, which has been adopted for nationwide use by the USDA Forest Service. This protocol standardizes how soil data are collected so that sites can be compared at both temporal and spatial scales. Previously, post-harvest soil disturbance monitoring data had been observed and documented using several different formats and field methods since the SQS were revised in 1999. Although the format has varied over time, the common objective has been to document the extent of DSD in various timber harvest units. The objectives of this study were to collate the post-harvest soil monitoring data and to statistically document the areal extent of DSD resulting from ground-based, skyline, and helicopter timber harvest systems in the Northern Region of the USDA Forest Service.

5.2 Methods

5.2.1 Data collection

Data for the areal extent of post-harvest and post-site preparation DSD were collected from 409 individual timber harvest units from 11 National Forests in the Northern Region (Figure 5.1). Only data collected after the last revision of the SQS (post 1999) were considered for this study. Data were provided by each of the National Forests in report or field data sheet form, and we collected additional data in the summer of 2009 to fill obvious gaps. Additional data was collected using the Forest Soil Disturbance Monitoring Protocol (Page-Dumroese et al. 2009). The data set included DSD information from ground-based, skyline, and helicopter harvest systems from each of four harvest seasons (spring, summer, fall, and winter; Table 5.1).

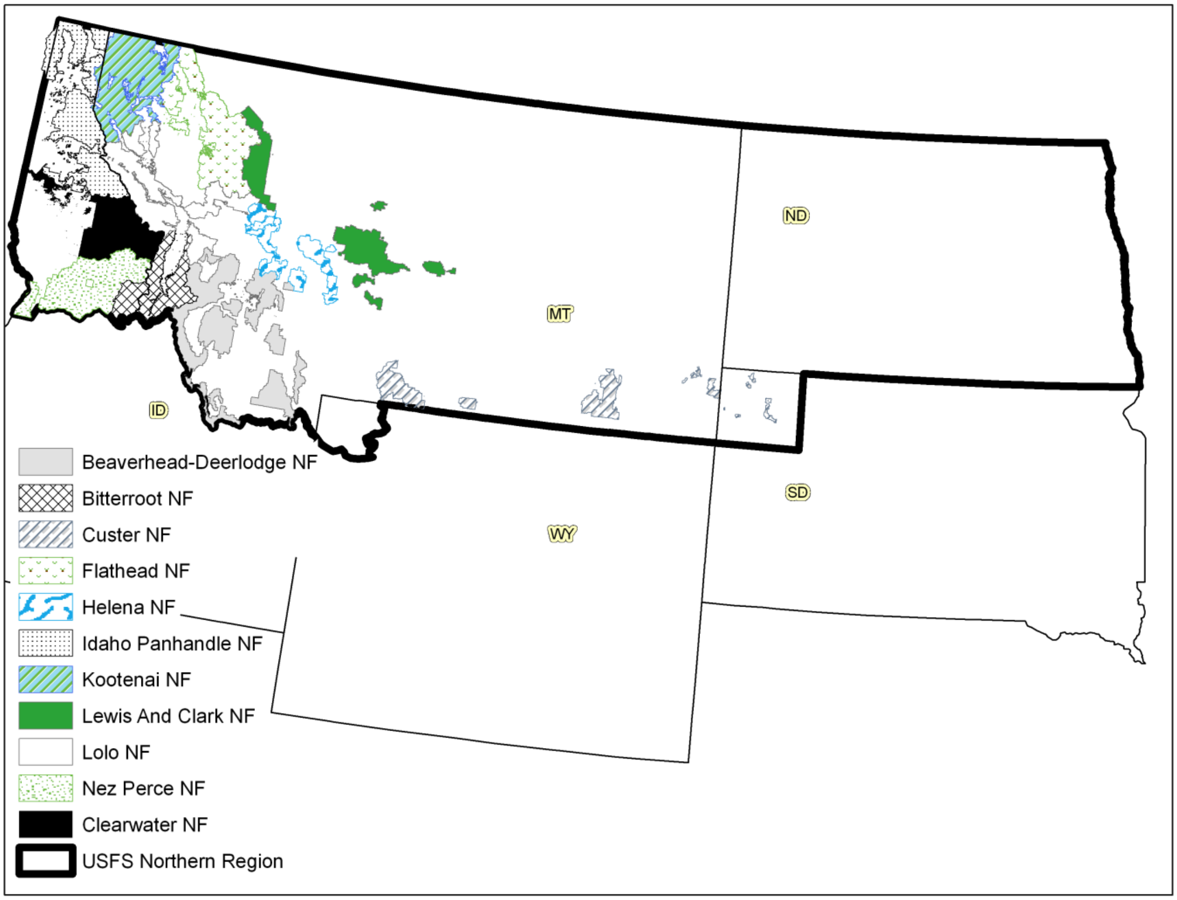

FIGURE 5.1. National Forests of the Northern Region included in this study.

TABLE 5.1. Number of timber harvest units associated with individual National Forests by harvest system.

Forest	**Ground (non-winter)**	**Ground (winter)**[a]	**Skyline**	**Helicopter**	**Total**	**% of total**
Beaverhead-Deerlodge	4	0	0	0	4	<1
Bitterroot	4	5	1	2	12	2.9
Clearwater	11	0	10	0	21	5.1
Custer	12	2	0	0	14	3.4
Flathead	22	19	0	1	42	10.3
Helena	2	7	2	0	11	2.7
Idaho Panhandle	10	9	5	0	24	5.8
Kootenai	118	78	9	10	215	52.6
Lewis and Clark	3	1	0	0	4	<1
Nez Perce	0	0	0	2	2	<1

[a] Winter harvest is designated as having harvest operations that were completed during December, January, or February.

5.2.2 Detrimental soil impacts definition

Existence of one, or a combination of any, of the attributes listed below can indicate detrimental soil conditions. After management activities of harvesting and site preparation, 85% of the activity area (harvest unit) must be in a satisfactory condition (without detrimental impacts). The Northern Region SQS define detrimental impacts as the following (USDA-FS 1999):

Compaction: a 15% increase in the natural bulk density. Cumulative effects of multiple site entries should be considered.

Rutting: wheel ruts at least 2” (5 cm) deep in wet soils.

Displacement: removal of $\geq$1” (2.5 cm) of any surface horizon, usually the A horizon, from a continuous area greater than 100 ft^2 (9.2 m^2).

Severely burned soil: physical and biological changes to the soil resulting from high-intensity burns of long duration as described in the Burned-Area Emergency Rehabilitation Handbook (FSH 2509.13).

Surface erosion: rills, gullies, pedestals, and soil deposition.

Soil mass movement: any soil mass movement caused by management activity.

5.2.3 Monitoring methods

Soil scientists on each of the National Forests used any available methods for determining when detrimental soil conditions existed in harvest units. Typically, monitors traversed harvest units on random or pre-selected transects representative of the area. Periodic sample points were collected along each transect. The number of sample points in each unit, number of units monitored, level of site stratification (slope, aspect etc.), and how much of the area is traversed is at the discretion of each soil scientist. Quantitative or qualitative methods, such as measuring a 15% increase in bulk density, could be applied using any method available at the time of data collection and ranged from collecting bulk density cores (e.g., Blake and Hartge 1986) to using the “shovel test” (sliding a tile spade into the soil to determine a change in soil resistance to penetration relative to a site-specific control [unharvested or unimpacted] soil). Because of the discretionary nature of soil disturbance collection and also because of the lack of soil monitoring data on some National Forests, we were unable to stratify sites by soil texture, depth to bedrock, rock fragment content, cover type and amount, or other site features for DSD modeling. In addition, only a few locations collected pre-harvest data to provide a baseline for comparison. There was no time standard after harvest and site preparation operations ceased for monitoring to take place.

5.2.4 Description of harvest systems

Ground-based harvest systems

1. Harvest systems were considered ground-based if the following equipment was used during harvest operations: rubber-tired skidders (RTS) yarding bole only or whole tree segments that were hand fell (“hand fell + RTS”) or machine fell (“machine fell + RTS”).
2. Harvester/Forwarder or cut to length systems (“Harvester/Forwarder”).
3. Tractor was often used as a default category when soil monitors are unsure of the ground-based equipment used. “Tractor” includes rubber-tired skidders or tracked vehicles yarding hand felled or machine felled timber.

4. Harvest units that were ground-based, machine fell, and lacked a specific yarding machine were recorded as "machine fell + ground skid."

Skyline harvest systems

Harvest systems were considered to be skyline if the following equipment was used during harvest operations: stationary machines that yard whole tree or bole only segments to a central landing location by means of a cable suspending at least one end of the tree segment. Units that were hand fell and skyline yarded were recorded as "skyline", units that were machine fell and skyline yarded were recorded as "machine fell + skyline."

Helicopter harvest systems

Harvest systems were considered helicopter logged if the whole tree or bole only segments were yarded to a central landing area by a helicopter. Helicopter units that were hand fell were recorded as "helicopter." Helicopter units that had post-harvest site preparation (i.e., fuel treatments) conducted by machines were recorded as "helicopter + machine fuels."

Harvest season

Harvest season for each unit was assigned based on the month in which harvest operations were completed. Spring harvests were completed in March, April, or May; summer harvests were completed in June, July, or August; fall harvests were completed in September, October, and November; and winter harvests were completed in December, January, and February.

Post-harvest site preparation

While most forest sites within the Northern Region have some type of post-harvest site preparation done before soil monitoring occurs, we were unable to separate the impacts of logging from those of site preparation.

5.2.5 Statistical Analysis

All analyses were evaluated using a SAS PROC GLM procedure (SAS Institute 2008). A linear multiple regression analysis was used to test for significant effects ($\alpha = 0.05$) of harvest season, harvest system, the National Forest on which harvest occurred, and the interaction between the Forest and harvest season (Forest*season) on the areal extent of DSD. Statistical models were used to generate least squares means to evaluate the areal extent of DSD across Northern Region Forests and within each Forest. A square root transformation was applied to DSD values to create a normally distributed data set.

5.3 Results

5.3.1 Region-wide

All harvest systems

National Forest, harvest system, and harvest season were significant factors in predicting the amount of DSD resulting from timber harvest activities across the Region for all harvest systems (p-value<0.0407; Table 5.2).

TABLE 5.2. ANOVA table listing model variables and probability values for a Regional analysis of DSD.

Variable	**p-Value**
Forest	<0.0001
Harvest system	<0.0001
Harvest season	0.0407

As expected, helicopter harvesting, where no post-harvest site preparation was performed using ground-based machines, resulted in significantly less DSD (0.2%) than units harvested by either skyline or ground-based systems (3.8% and 8.2%, respectively) (Figure 5.2). In addition, hand-felling with skyline systems resulted in significantly less DSD (1.9%) than harvesting with ground-based systems (8.2%). There were no differences in the areal extent of DSD between those units mechanically fell + skyline versus those that were harvested with ground-based equipment. Winter harvest units had significantly less areal extent of DSD (7.6%) than summer harvest units (9.6%).

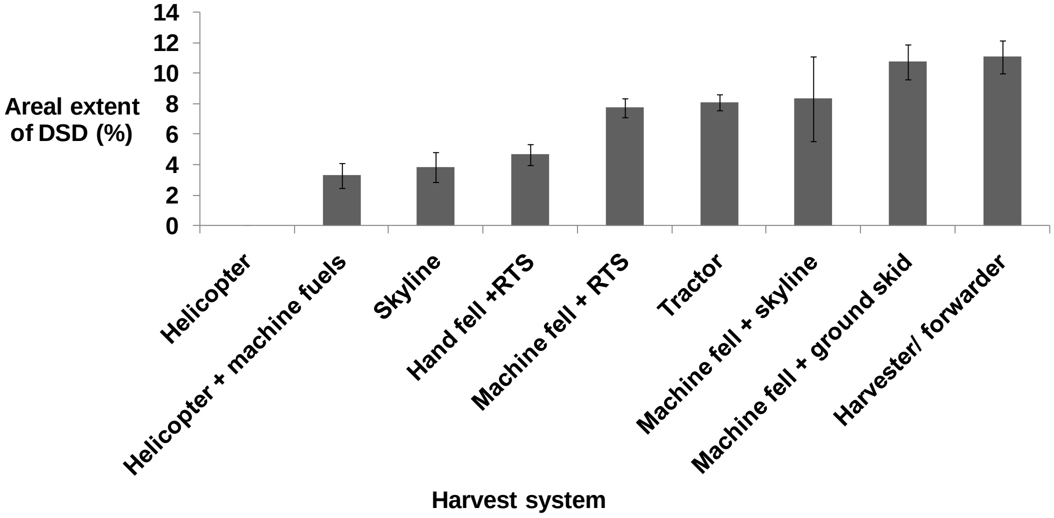

FIGURE 5.2. Detrimental soil disturbance values by harvest system for all National Forests surveyed in the Northern Region. Graphed values are mean values reported on untransformed data. Error bars represent the standard error associated with the mean values.

Ground-based harvest

Three of the four model variables (Forest, Harvest season, Forest*season) had a significant effect on the areal extent of DSD due to ground-based harvest in the Northern Region (Table 5.3). The type of ground-based equipment used during harvest operations was not a significant factor.

TABLE 5.3. ANOVA table listing model variables and probability values for Regional analysis of DSD due to ground-based timber harvest.

Variable	**p-Value**
Forest	<0.0001
Harvest system	0.1478
Harvest Season	0.0055
Forest*season	0.0011

For ground-based harvest operations, there were differences in the amount of DSD by different harvest seasons (p = 0.0055). The areal extent of DSD was higher during the summer and fall (9.9% and 9.2%, respectively) than during winter or spring (7.0% and 6.0% respectively) (Figure 5.3). Additionally, differences in the areal extent of DSD during the same season depended on the National Forest where the harvest took place (Figure 5.4). For example, summer harvesting on the Lewis and Clark National Forest exceed 25% areal extent, whereas on the Custer National Forest it was less than 5%.

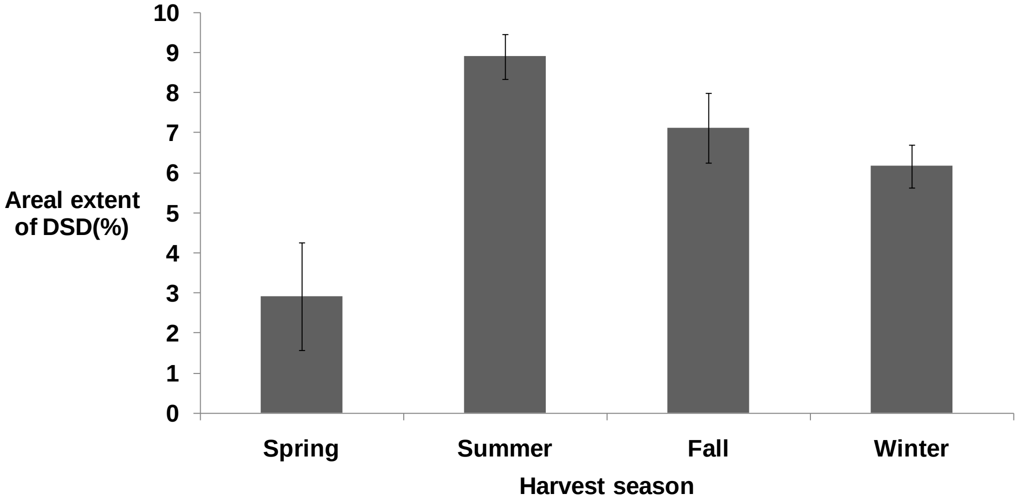

FIGURE 5.3. Areal extent of DSD resulting from ground-based harvest in the Northern Region by season. Graphed values are mean values reported on untransformed data. Error bars represent the standard error associated with the mean values.

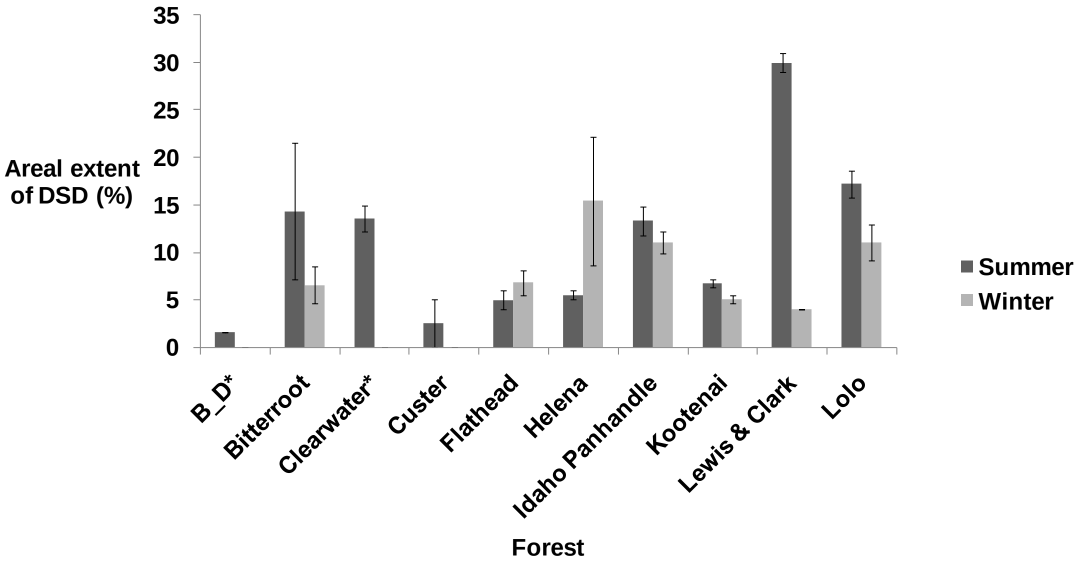

FIGURE 5.4. Areal extent of DSD for ground-based harvest on individual National Forests in the Northern Region during the summer and winter seasons. *No data was available from the Beaverhead Deerlodge (B_D) or Clearwater National Forests for ground-based winter harvest. Graphed values are mean values reported on untransformed data. Error bars represent the standard error associated with the mean values.

5.3.2 Individual forests

Beaverhead-Deerlodge National Forest

- Areal extent of DSD values was limited to four ground-based harvest units. Three harvests were completed in the fall, and one was completed in the summer (Table 5.1).
- Mean values for DSD were significantly higher for the fall harvest season units (p = 0.0125) than for the summer harvest season units (17.7% and 1.6%, respectively).

Bitterroot National Forest

- Data consisted of nine ground-based harvest units (five of which were harvested in winter), two helicopter units, and one skyline unit (Table 5.1).
- There were no differences in the mean values for areal extent of DSD associated with the helicopter and skyline harvest units (0.0% and 2.0%, respectively). Mean values

of areal extent of DSD for ground-based harvest (7.4%) were higher than helicopter harvest (0.0%) ($p = 0.0012$).

- High levels of DSD variability resulted in no significant difference in the reported mean values for areal extent of DSD resulting from summer (11.9%) and winter (5.1%) ground-based harvest ($p = 0.1099$).

Clearwater National Forest

- Data consisted of 11 ground-based harvest units and 10 skyline units, all harvested in summer (Table 5.1).
- Summer harvesting resulted in no differences among the ground-based harvest systems ($p = 0.8970$).
- Mean values of the areal extent of DSD resulting from skyline harvest were lower ($p < 0.0001$) than from ground-based harvest.
- Reported mean values for the areal extent of DSD resulting from harvester/forwarder, machine fell+RTS, and skyline harvest systems were 13.5%, 12.9%, and 1.0%, respectively.

Custer National Forest

- Data consisted of 14 ground-based harvest units, two of which were harvested in winter (Table 5.1).
- There were no differences by season in the areal extent of DSD from ground-based harvest ($p > 0.2146$) and mean areal extent of DSD from ground-based harvest was 0.05%.

Flathead National Forest

- We analyzed data from 42 harvest units. Forty-one units were ground-based units and one was harvested by helicopter. Of the 41 ground-based harvest units, 19 were winter harvested (Table 5.1).
- There were no significant differences in the areal extent of DSD levels between summer and winter harvest. However, winter harvesting produced significantly more DSD (4.9%) than harvest operations that were completed in the spring (0.3%) ($p = 0.0228$).
- There were no significant differences in areal extent of DSD between ground-based harvest (3.8%) and helicopter harvest (0%).

Helena National Forest

- Data was from 11 harvest units. Nine were ground-based units and two were skyline units. Seven of the ground-based harvest units were completed in winter (Table 5.1).
- There was no difference in the areal extent of DSD levels between winter (10.7%) and summer (5.5%) ground-based harvests.
- The areal extent of DSD disturbance was significantly less following skyline harvesting than following ground-based harvest ($p = 0.0479$).
- Areal extent of DSD from ground-based logging was 9.4% and from skyline logging it was 2.0%.

Idaho Panhandle National Forest

- We analyzed data from 24 harvest units. Nineteen were ground-based units and five were skyline units. Nine of the ground-based units were completed in the winter (Table 5.1).

- There was no difference in the areal extent of DSD levels following ground-based harvest between winter (10.8%) and summer (13.0%) harvests.
- Harvest units listed by monitors as “tractor” resulted in higher levels of areal extent of DSD than those harvested by skyline systems, both mechanically and hand felled ($p = 0.0261$ and 0.0227, respectively). However, the areal extents of DSD resulting from other harvest systems were not significantly different from one another.
- The mean areal extents of DSD resulting from all harvest systems on this Forest are listed in Appendix A.

Kootenai National Forest

- This data set was the largest and consisted of 215 harvest units. Of the 215 harvest units, 196 were ground-based harvested, 9 were skyline harvested, and 10 were helicopter harvested. Seventy-eight of the ground-based units were completed in the winter (Table 5.1).
- There was less areal extent of DSD resulted from winter ground-based harvest (4.36%) than from summer ground-based harvest (6.15%) ($p = 0.0237$). Helicopter harvesting resulted in less areal extent of DSD than any other harvest system employed ($p \leq 0.0197$).
- Skyline harvest resulted in less areal extent of DSD (2.5%) than units that were mechanically felled and ground skidded (8.4%) ($p = 0.0241$).
- There were no differences in DSD between the other various skyline and ground-based harvest systems.
- The average areal extents of DSD resulting from all harvest systems on the Kootenai National Forest are listed in Appendix A.

Lewis and Clark National Forest

- Data was limited to four harvest units. All harvest units were ground-based and one was completed in the winter (Table 5.1).
- The areal extent of detrimental soil disturbance was less from winter ground-based harvesting (4.0%) than from summer or fall ground-based harvesting (29.92% and 31.92%, respectively) ($p = 0.0054$ and 0.0048, respectively).

Lolo National Forest

- Data consisted of 60 harvest units. Fifty-six units were harvested with ground-based systems and 4 units were skyline harvested. Twenty-six of the 56 ground-based units were completed in the winter (Table 5.1).
- There was less areal extent of DSD from winter ground-based harvest (8.6%) than from summer ground-based harvest (16.3%) ($p<0.0001$). The areal extent of DSD resulting from skyline harvest (4.53%) was less than from all other harvest systems ($p<0.0498$).
- There was no difference in the areal extent of DSD resulting from machine fell+skyline or from ground-based harvest systems ($p<0.3923$).

Nez Perce National Forest

- Data was limited to two helicopter harvest units. Both units had pre-harvest DSD from prior management and recreational activities.
- Average pre-harvest areal extent of DSD on the two harvest units was 4.58%--well below the 15% areal extent limit. All DSD was attributed to the pre-harvest conditions on the units. The helicopter harvest did not increase in the areal extent of DSD.

5.4 Discussion

5.4.1 Regional analysis

All harvest systems

Consistent with other studies (Bockheim et al. 1975, Miller et al. 2004), the areal extent of DSD following timber harvest in the Northern Region of the Forest Service was greatest from ground-based equipment, followed by skyline and helicopter harvest systems when all harvest systems are included in the model. While there were isolated instances where the areal extent of post-harvest DSD exceeded the mandated 15% threshold on a per unit basis, no timber harvest system resulted in mean values in excess of the 15% threshold. We only had pre-harvest DSD data for few harvest units. The lack of pre-harvest data made it difficult to differentiate the areal extent of DSD that resulted from prior entry with DSD that resulted from the most current harvest entry. Therefore, unless we noted pre-harvest DSD in the Results section (e.g., Nez Perce National Forest), we assumed that the levels of DSD were caused by the current harvest practice.

In practical monitoring efforts, compaction was often the most obvious and principal form of soil impact resulting from harvest activities (Hatchell et al. 1970, Dickerson 1976). Compaction increases bulk density, decreases water and air movement into and through the soil, restricts root growth, and increases surface runoff and erosion (Reinhart 1964, Greacen and Sands 1980, Rab 1996). However, changes in soil attributes following harvest activities, and their subsequent effect on vegetative growth vary by soil type and climatic regime (Reisinger et al. 1992, Page-Dumroese et al. 2000, Powers et al. 2005).

The susceptibility of soil to any detrimental change is predicated on soil moisture (Froehlich 1972), soil type (Hatchell et al. 1970), and organic matter content (Howard et al.

1981) at the time of harvesting. In addition, the number of machine passes, the volume and axle weight of timber hauled, post-harvest site preparation, and characteristics of the harvest equipment influence the degree of detrimental soil impacts (Williamson and Neilsen 2000). For instance, Bockheim et al. (1975) found that ground-based harvesting resulted in more DSD than skyline or helicopter harvest on a similar soil type. However, it is difficult to draw conclusions about the level of DSD resulting from harvest operations over geospatially large and diverse areas without considering the controlling factors. The elevation profiles and associated precipitation patterns along with the heterogeneity in soil types within and between individual National Forests suggest that the areal extent of DSD resulting from similar harvest systems will vary significantly among locations. This might help explain the variability in DSD reported for similar harvest types among National Forests.

Aside from site characteristics, there are other considerations that are not easily quantified and accounted for in statistical modeling that impact the variability in DSD levels among National Forests. Equipment operator skill and experience have been found to play an important role in the areal extent of DSD resulting from harvest operations (Pinard et al. 2000, Stone 2002). This may become an even greater issue with the continuing decline in the timber industry. For example, as experienced operators retire or move to other occupations, lack of steady employment may deter qualified individuals from filling these roles in the future. On National Forests that are not in close proximity to actively managed corporate timber lands, this may lead to a deficit in skilled equipment operators. Perhaps equally important to the reduction of DSD by knowledgeable operators is the skill and experience of the sale administrator who oversees active timber sales. Knowledge of local conditions as well as operator tendencies are important in keeping DSD levels below the mandated 15% of areal extent in an activity area. This knowledge is especially important during ground-based winter harvest operations. As winter harvest conditions become sub-optimal (e.g, during snow melt) and the soil moisture content increases, DSD is more likely to occur and the areal extent of that disturbance increases. It is imperative at this point of the harvest operation that the sale administrator monitors harvest operations closely and halts harvest operations until site conditions become less susceptible to high disturbance levels.

Other variables that influence the amount and type of disturbance noted during soil monitoring are: time elapsed since harvest, type of site preparation operations, when the soil monitoring occurs relative to operations, training and experience of the monitoring personnel, existence of pre-harvest data for a baseline assessment, and if the harvested site was stratified to reflect changes in site characteristics (slope, aspect, soil, vegetation, etc.) (Page-Dumroese et al. 2006).

Our research showed that there are significant differences in the amounts of DSD that result from similar harvest techniques among National Forests. When considering how and when to monitor, resource professionals should take into account the unique local attributes of weather patterns, soil texture, surface organic matter, and soil moisture conditions , and the individual contractors involved with the harvest activities. Effective communication between all resource professionals (timber sale administrators, silviculturists, forestry technicians, hydrologists, etc.) is necessary to successfully achieve management objectives can be successfully achieved.

Ground-based harvest systems

Ground-based harvest systems have high potential to create damage under some conditions. Based on other studies, we expected that harvest season would be a significant factor in the areal extent of DSD resulting from ground-based timber harvesting (Klock 1975, Page-Dumroese et al. 2006, Johnson et al. 2007). Winter ground-based harvests often result in less areal extent of DSD than during other seasons when performed under ideal conditions, and they are often used as a best management practice (Miller et al. 2004, Page-Dumroese et al. 2006, Johnson et al. 2007, Page-Dumroese et al. 2010) because they minimize soil damage. However, there were two exceptions to that trend in our data. DSD resulting from ground-based harvest was higher during the winter harvest season than the summer harvest season on both the Flathead and Helena National Forests. This was partly explained by the small sample size and several instances where the areal extent of DSD exceeded the 15% threshold for a harvest unit (see the discussions on Flathead and Helena National Forests).

Ground-based harvest operations that were completed in the spring resulted in the least amount of total DSD. The low levels of DSD resulting from ground-based harvest in the spring were likely an anomaly of how we delineated harvest season within the analyses, and they further emphasize the importance of optimal winter harvest conditions and the role that local weather patterns play in maintaining them. The seasonal designation used in this study was based entirely on the month that harvest operations were completed. The eight ground-based spring harvest units in our data set were all completed in early March. Spring operations had minimal impact under the existing conditions at the time of observation (Figure 5.3). In our experience, ground-based harvest operations that were ongoing in March were indicative of either high-elevation, above-average snow pack, and/or below-average temperatures. In short, optimal snow pack and temperature conditions for ground-based winter harvesting help preserve organic horizons, water infiltration, and root structure (Williamson and Neilsen 2000). Winter conditions also reduce the occurrence of soil compaction and rutting.

During the collection and analysis of this monitoring data, we noted that the term "tractor" was often used as a catch-all term when soil disturbance monitors were unsure of the exact equipment used for ground-based timber harvest. Every effort was made to determine the exact piece (or pieces) of equipment that was used on each ground-based harvest unit that did not have a clear equipment notation. However, this data was unavailable on some units. This likely explains why we could detect no statistically significant differences in the areal extent of DSD among the various ground-based harvest equipment types. The lack of precision in the data set regarding the ground-based harvest equipment employed leaves us hesitant to draw any conclusions as to the relative areal extent of DSD resulting from different ground-based harvest equipment. Greater precision in the monitoring and recording process regarding different equipment is necessary to determine if there are differences in the areal extent of DSD resulting from each equipment type.

5.4.2 Individual Forest analysis

The amount of soil monitoring data available from each of the National Forests across the Northern Region varied considerably due to many factors, including the disparity in timber harvest levels among the National Forests, how much emphasis was placed on pre- and post-harvest soil monitoring, and how sites were selected to be monitored. The amount of legacy data (data collected in hard copy form prior to the utilization of computer based spreadsheets) in each National Forests' database also played a significant role in the amount and type of data available for this study. National Forest data were heavily weighted toward ground-based harvest. This was due, in part, to the relative distribution of the timber harvest system that was employed and management expectations that ground-based harvesting would cause the greatest areal extent of soil impacts. In addition, on some National Forests, there were no helicopter-logged units and few skyline harvested units. Another factor was the institutional bias toward monitoring soil disturbance on sites that are most likely to result in higher levels of DSD (personal correspondence with Meredith Webster, Northern Region Soil Program Manager). A more complete analysis was possible for forests that included these factors (i.e., units logged with other than ground-based systems, pre-harvest or legacy data available, and monitoring occurring in all harvest systems). The following discussion of the individual National Forests is limited to those with noteworthy or unusual results.

Beaverhead-Deerlodge

On this National Forest, the average areal extent of DSD for fall harvesting is relatively high and was likely a result of one harvest unit with 45% areal extent of DSD and a small sample size (n = 3). It was unclear whether the 45% was due to an excessive amount of skid trails, wet soil, driving across the entire site, or some other factor.

Bitterroot National Forest

There was no difference in the areal extent of DSD resulting from helicopter and skyline harvest systems. This is likely because there were only two helicopter harvest units monitored (Table 5.1). Additionally, although there was no statistical difference in monitoring results between winter and summer ground-based harvest, it is worth noting that the areal extent of DSD resulting from summer ground-based harvest was more than two times the level of DSD resulting from winter ground-based harvesting.

Custer National Forest

The areal extent of DSD on the Custer National Forest resulting from timber harvest activities was the lowest of any Forest at 0.05%. This is especially remarkable considering that all harvest activities were completed with ground-based equipment. Relatively arid conditions, coarse-textured soil, and strong communication between the operator and sale administrator about the desired post-harvest conditions possibly played a role in the resulting levels of areal extent of DSD. Ground-based operations conducted on fairly coarse-textured soil result in conditions that are fairly resilient after harvest operations and may not impact vegetative productivity (Powers 2006).

Flathead National Forest

Although there were no significant statistical differences in the areal extent of DSD between winter and summer ground-based harvest operations, the Flathead National Forest was one of two Northern Region National Forests where the average areal extent of DSD was higher in winter than in summer (Figure 5.1). On the Flathead, this anomaly was attributed to two winter ground-based units that exceeded the 15% areal extent of DSD threshold. In contrast, there were two spring ground-based units that resulted in 0% and 1% areal extent of DSD. These data again emphasize the need to monitor local weather conditions carefully when winter harvest operations are underway. A cold snap in March can produce weather that is more conducive to successful “winter” harvest than a warm spell in December, January, or February.

Helena National Forest

Opposite the trend of higher DSD during summer ground-based harvests, Helena National Forest showed nearly twice the areal extent of DSD following winter logging than that observed during summer. However, due to variation in the DSD observations, this difference was insignificant (p = 0.2548). The Helena National Forest was one of two Forests where ground-based winter harvest resulted in more DSD than ground-based summer harvest (Figure 5.4). This was due, in part, to the small sample size associated with summer ground-based harvest (Table 5.1) and to the large areal extent of DSD resulting from winter ground-based harvest on two units. It is possible that the areal extents of DSD associated with the two winter harvest units reflect disturbance resulting from fire, recreation, or some other management activity not associated with the timber harvest but not explicitly noted in the monitoring data.

5.5 Conclusion

Across the Northern Region, no timber harvest system consistently resulted in mean DSD in excess of the mandated 15% areal extent within a timber harvest unit. There are, however, statistically significant differences in the amount of DSD resulting from ground-based, skyline, and helicopter timber harvest systems. Significant differences also exist in the areal extent of DSD resulting from ground-based harvest in winter versus summer. The Forest Service is justified in its institutional bias toward monitoring harvest units that are at risk from higher impact harvest (e.g., ground-based harvesting). Where pre-harvest soil monitoring reveals low areal extent of DSD on planned skyline and helicopter harvest units in the Northern Region, land managers can reasonably predict that post-harvest levels of DSD will likely fall under the 15% of areal extent threshold.

Ultimately, the utility of the soil monitoring data is dependent upon the accuracy with which they reflect conditions on the ground. For a wide-scale synthesis of soil monitoring data to be successful, it is imperative that the sample size of monitoring points within a harvest unit be adequate to represent the amount of soil disturbance caused by harvest equipment. Inadequate sample size and the melding together of disparate methods, soil types, and climatic regimes limit the applicability of individual Forest data for to large-scale assessments such as this one. In addition, a goal of soil monitoring should be to separate the impacts of pre-harvest from post-harvest as well as the impacts of additional site preparation such as prescribed fire or slash piling. With the adoption of a common method (see Page-Dumroese et al. 2009) and the development of a national soil monitoring database, the applicability of any analysis increases so that best management practices can be further refined. In addition, a national database of data that are collected in a similar manner will provide a decision support tool that will help determine which units are most at risk from harvesting or site preparation impacts and where scarce monitoring resources can be directed.

5.6 Acknowledgements

We thank all the forest soil scientists in the Northern Region for providing soil monitoring data from the forests included in this paper. Without their dedicated assistance, we wouldn't have been able to evaluate the impacts of harvest operations. We also thank the countless summer employees who helped collect monitoring data. Most of all, we acknowledge the help and financial support of Meredith Webster and the Northern Region.

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Appendix A

TABLE 5.4. Mean areal extent of DSD for each harvest system by Forest. Numbers in parentheses indicate the number of harvest units used to calculate mean values.

Harvest System	B_D*	Bitterroot	Clearwater	Custer	Flathead	Helena	Idaho Panhandle	Kootenai	Lewis & Clark	Lolo	Nez Perce
Helicopter	-	0.0% (2)	-	-	0.0% (1)	-		0.0% (7)	-	-	-
Helicopter + machine fuels	-	-	-	-	-	-		2.3% (3)	-	-	4.6% (2)
Skyline	-	2.0% (1)	1.0% (10)	-	-	2.0% (2)	4.5% (2)	2.5% (9)	-	4.5% (3)	-
Hand fell + RTS	-	-	-	-	-	-		4.6% (3)	-	-	-
Machine fell + RTS	12.05% (4)	-	12.9% (6)	.05% (14)	-	9.4% (9)	9.9% (5)	5.4% (109)	30.0% (2)	15.8% (11)	-
Tractor	-	7.4% (9)	-	-	3.9% (41)	-	26% (1)	4.9% (75)	14.7% (2)	11.7 (45)	-
Machine fell + skyline	-	-	-	-	-	-	5.6% (3)	5.6% (2)	-	20.0% (1)	-
Machine fell + ground skid	-	-	-	-	-	-	12.5% (6)	8.3% (6)	-	-	-
Harvester/ forwarder	-	-	13.5% (5)	-	-	-	11.2% (7)	5.6% (3)	-	-	-

* Beaverhead- Deerlodge National Forest

CHAPTER 6: PRODUCTIVITY MAINTENANCE AS A BARRIER TO ACTIVE MANAGEMENT

Abstract

Maintenance of soil productive capacity is a common management objective on public lands in the United States and related activities are governed under a host of laws and regulations. The USDA Forest Service has developed its own policies intended to meet these legal requirements. Impacts to soils resulting from timber harvest operations range on a continuum from detrimental to positive increases in growth, depending on site-specific characteristics and climatic regime. Current policy leaves the agency subject to challenges on soil productivity issues. Litigation on soil issues has constrained the agency's ability to engage in management activities and could continue to do so. The following analysis provides an overview of conditions and trends that lead to existing policies regarding maintenance of soil productive capacity and management activities, identifies specific definitions that seem to encourage legal challenges, provides alternatives to existing policy, and suggests a monitoring procedure that recognizes site variability. Revising current policy and definitions could perhaps reduce legal challenges on soil issues, and provide forest land managers the flexibility necessitated by variable site conditions in the Northern Region.

6.1 Introduction

Maintenance of soil productivity is a statutory mandate of the *National Forest Management Act of 1976* (NFMA) and its implementing regulations, which the USDA Forest Service (USDA-FS) often calls the “planning rule” (USDA-FS 1982). These laws are general statements that provide managers considerable discretion in how the maintenance of soil productivity is achieved. Specific definitions, policy and direction on how to meet NFMA requirements for soil productivity maintenance are described in *Forest Service Manual 2500* (FSM) and the *Soil Quality Standards* (SQS) developed for the USDA-FS Northern Region, or Region One (USDA-FS 1999).

The goal of soil policies in the USDA-FS Northern Region is to maintain soil productivity while allowing the Forest Service to engage in active management on National Forest System (NFS) lands to meet a variety of management objectives, including soil productivity maintenance. The concern with the agency’s current soil policy is twofold: first, a strict interpretation of current definitions leaves the agency with limited options for meeting the *NFMA* mandate and the directives of *Forest Service Manual 2500*. Second, the current policy does not provide an avenue to consider the wide range of natural variability in site characteristics inherent in the region, instead treating all sites similarly.

The USDA-FS Northern Region encompasses more than 9 million acres of timberlands, and includes 12 National Forests (Fig. 6.1). The range in elevation and precipitation patterns both ensure considerable variation in site characteristics and forest types throughout the region.

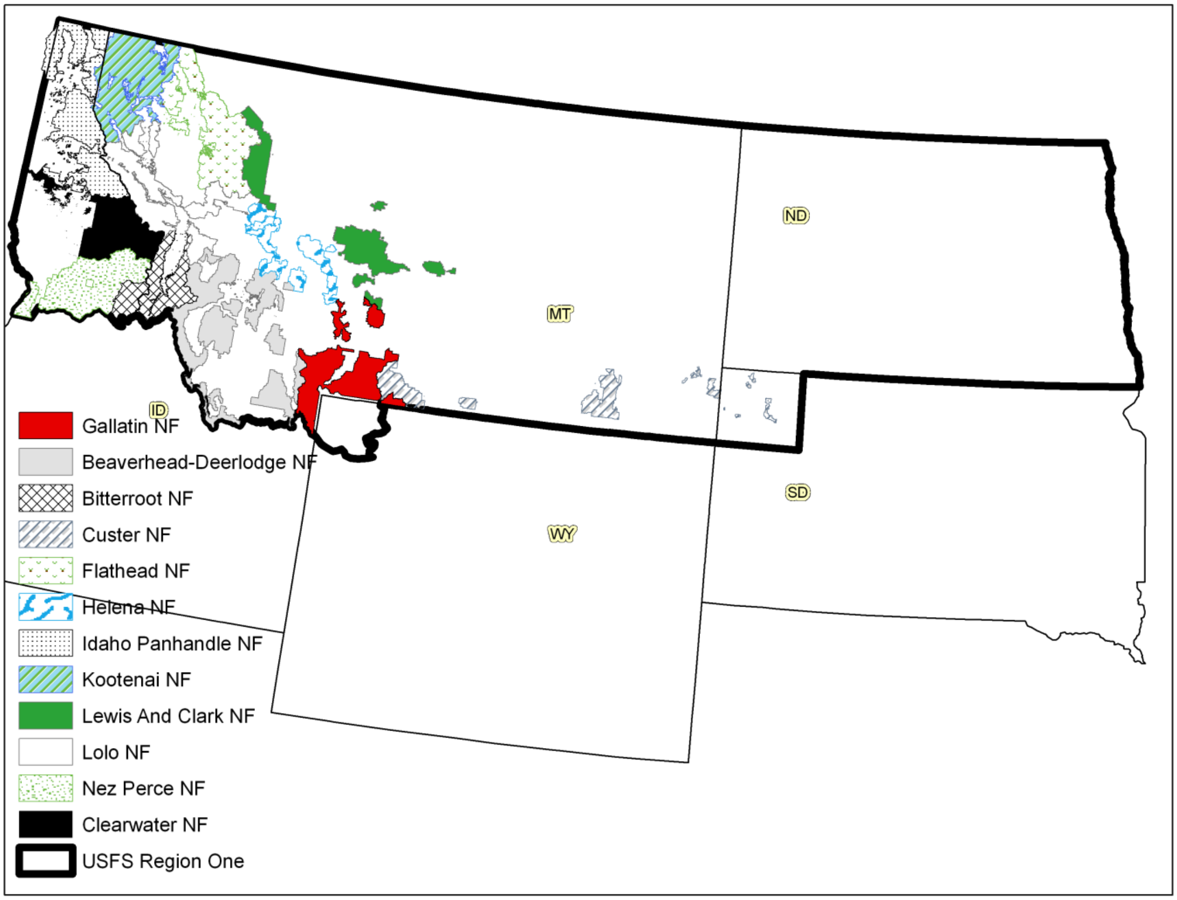

FIGURE 6.1. National Forest System units included in the USDA-FS Northern Region (Region One)

The objectives of this paper are to:

- Identify current soil productivity maintenance policy and litigation in the USDA-FS Northern Region.
- Identify potential litigation problems associated with soil productivity maintenance the agency faces under current policy and definitions.
- Suggest options for modifying current policy and definitions to reduce potential litigation.

- Suggest a soil disturbance monitoring approach that will create managerial flexibility consistent with variable conditions.

Current soil productivity maintenance policy and direction in the USDA-FS Northern Region is problematic. This paper takes a "policy sciences" approach to improving the problem situation by analyzing the policy decision context as well as the social context that exacerbates the problem (see Clark 2002, O'Laughlin 2004). This paper suggests improving the problem situation with two things: 1) minor changes to *Forest Service Manual 2500*, and 2) provide managers an opportunity to use their professional training and experience by building in site specific concerns when documenting soil disturbance due to active or proposed management activities.

6.2 Problem Statement

Projects proposed in the USDA-FS Northern Region have been litigated in reference to soil issues. Further litigation has the potential to significantly restrict the Forest Service's options for active management. Strictly defined, "permanent" and "substantial" impairment is caused by detrimental soil disturbance (USDA-FS 2010, USDA-FS 1999). Unless the term "detrimental" is removed from the definitions of "permanent" and "substantial" the agency is vulnerable to legal challenges based on the *NFMA* productivity mandate that management activities "will not produce substantial and permanent impairment of the land" (NFMA 1976 §6(g)(3)(C)).

6.3 Social Context of the Problem

Since 2004, the Bitterroot, Lolo, and Idaho Panhandle National Forests of the Northern Region have been sued by environmental groups or coalitions including the WildWest Institute, Ecology Center, and Lands Council. Included in the plaintiff's litigation were claims related specifically to soil disturbance issues, and the extent to which the forests were in violation of legal mandates specified in the *NFMA* (*e.g.*, Lands Council v. Powell 2004, Ecology Center, Inc. v. Austin 2005, WildWest Institute v. Bull 2008). Court rulings in these three cases were mixed. The Ninth Circuit Court of Appeals awarded summary judgment to the Lands Council and Ecology Center, but found for the Forest Service in WildWest v. Bull (2008).

In Lands Council v. Powell (2004), the Ninth Circuit court held that the Forest Service harvest plan violated *NFMA* provisions because the plan did not adequately address sections of the forest plan developed by the Idaho Panhandle National Forest dealing with soil quality standards. The harvest plan in question in Lands Council v. Powell (2004) estimated the post harvest soil quality (determined by the areal extent of detrimental soil disturbance on a timber harvest unit at the close of the sale contract) using a spreadsheet model based on soil quality monitoring results taken from throughout the forest. The Ninth Circuit ruled this methodology inadequate, and held that the USFS's "reliance on … spreadsheet models, unaccompanied by on-site verification of the models predictions, violated *NFMA*" (Lands Council v. Powell 2004). A year later, in Ecology Center v. Austin (2005), the Ninth Circuit affirmed its previous ruling. Claims against the Forest Service in this case included arguments that the USFS soil quality analysis was flawed because the Lolo National Forest had evaluated soil conditions on the basis of maps, aerial reconnaissance, and computer modeling without directly monitoring the proposed activity area. The Ninth Circuit noted this was a "nearly identical claim" it addressed in Lands Council v. Powell (2004) when it awarded summary judgment to Lands Council. Court rulings in these two cases both resulted in delaying management activities and effectively forced the USDA-FS to produce new NEPA documentation and selection of alternatives consistent with the Ninth Circuit decision.

In WildWest v. Bull (2008), the plaintiff claimed that the *Northern Region Soil Quality Standards* were "facially unreliable" and as such were not adequate for determining whether the cumulative impacts to soils on the proposed harvest area would, in fact, cause detrimental impacts to more than 15% of the activity area. The Ninth Circuit declined to rule on the merits of this claim, but rejected it because the challenge was not raised in the original litigation heard in the District Court (WildWest Institute v. Bull 2008).

6.4 Decision Context

The *NFMA of 1976* is a statutory law that was promulgated as an amendment to the *Forest and Rangeland Renewable Resources Planning Act of 1974* (RPA 1974). It mandates that management systems "will not produce substantial and permanent impairment of the productivity of the land" (NFMA 1976 §6(g)(3)(C)).

The regulations for implementing the *NFMA* are often referred to as the "planning rule." These regulations are administrative law prescribing "how land and resource management planning is to be conducted on USDA Forest Service System lands" (USDA-FS 1982, §219.1(a)) and directs that all management prescriptions shall "conserve soil and water resources and not allow significant or permanent impairment of the productivity of the land" (USDA-FS 1982, §219.27(a)(1)).

Forest Service Manual 2500 (USDA-FS 2010) is an internal document that provides policy and direction for complying with requirements of statutory and administrative laws. It defines substantial soil impairment as "detrimental changes in soil properties (physical, chemical, or biological) that result in the loss of the inherent ecological capacity or hydrologic function of the soil resource that last beyond the scope, scale, or duration of the project causing the change" (USDA-FS 2010, Chapter 2550.5). Permanent soil impairment is defined as "detrimental changes in soil properties (physical, chemical, and biological) that result in the loss of the inherent ecological capacity or hydrologic function of the soil resource that lasts beyond a land management planning period" (USDA 2010, Chapter 2550.5). This period is typically 15 years in the USDA-FS Northern Region (personal correspondence with Meredith Webster, Northern Region Soil Program Leader, Mar. 31, 2010).

The *Northern Region Soil Quality Standards* (USDA-FS 1999) provide benchmarks for soil disturbance above which are considered to be detrimental. Disturbances considered are the effects of compaction, displacement, rutting, severe burning, surface erosion, loss of surface organic matter, and soil mass movement. To meet soil quality standards in the Northern Region, detrimental soil disturbance must not exceed 15% of the areal extent of the management area.

The implications of current policy in *Forest Service Manual 2500* stem from agency definitions of "permanent and substantial soil impairment" as "detrimental changes" (USDA-FS 2010). Application of a strict view of this definition while referencing the soil quality standards to define “detrimental” could be construed to mean that the USDA-FS is in violation of the *NFMA* mandate if, for example, a 5 cm. rut exists on a timber harvest unit at the close of the sale contract. However, there is a low probability that timber harvest and site preparation operations can be undertaken without resulting in some level of soil disturbance. Consequently, the potential for some detrimental soil disturbance as it is defined in the soil quality standards to be incurred during timber harvest operations is unavoidable for any harvest systems except helicopter harvest (Chapter 5). Helicopter harvest units that have track machines on the ground for site preparation also result in some detrimental soil disturbance as defined in the SQS (Chapter 5).

6.5 Analysis of Current Policy

6.5.1 Trends

Recent trends in the effort to achieve timber harvest objectives while meeting site productivity mandates involve both changes to Forest Service policy and an increase in low impact harvest systems. The *Northern Region Soil Quality Standards* were revised by the agency in1999 to achieve the following objectives:

- “… meet direction in the *National Forest Management Act of 1976*, and other legal mandates”
- “… manage the National Forest System (NFS) lands under ecosystem management principles without permanent impairment of land productivity” and
- “ … maintain or improve soil quality” (USDA-FS 1999).

The *Forest Service Manual (FSM 2500)* was updated in 2010 with two objectives:

- "… maintain or restore soil quality on National Forest System lands" and
- "… manage resource uses and soil resources on National Forest System lands to sustain ecological processes and function so that desired ecosystem services are provided in perpetuity" (USDA-FS 2010).

Recent operational trends include use of equipment that has lower impact on the land than previous timber harvest machinery. To meet soil quality standards in the Northern Region, detrimental soil disturbance must not exceed 15% of the areal extent of the management area (USDA-FS 1999). Detrimental soil disturbance due to timber harvest activities is related directly to the harvest system employed, the season of harvest, and the individual Forest on which it occurs (Chapter 5). With few exceptions, detrimental soil disturbance occurs in timber harvest operations. Past practices included dozer piling of slash, as well as building of skid trails using cut and fill construction. Such practices incurred high levels of detrimental soil disturbance. More recently a reduction in detrimental soil disturbance associated with timber harvest due to the use of grapple piling techniques for slash and fuels treatments, as well as low impact harvest systems (i.e., helicopter and skyline) has helped reduce detrimental soil disturbance associated with timber harvest. The development of best management practices (BMPs), and timber sale or stewardship contracts requiring minimum snow floors for ground-based winter harvest operations, have also contributed to the reduction in detrimental soil disturbance. Reports from National Forests in the Northern Region indicate that harvest operations on "second entry" harvest units that utilize existing skid trails show little (0-3%) increase in detrimental soil disturbance (Bitterroot N.F. 2007, 2008; Idaho Panhandle N.F. 2008). These trends indicate that soil disturbance resulting from timber harvest have declined with changes in harvest equipment and the development of BMPs, and suggest that the trend toward lower disturbance levels resulting from harvest operations may continue as BMPs are refined to reflect increasing knowledge.

6.5.2 Factors affecting current policy

Soil monitoring associated with timber harvest and site preparation techniques provides a protocol for quantitative forest soil monitoring, but a rapid qualitative assessment was favored in order to reduce the monitoring burden and allow more assessment capacity (Howes et al. 1983, Howes 2001, Curran et al. 2005). While qualitative assessments provide greater assessment capacity they are inherently subjective and need to be validated by quantifiable, ecologically relevant variables (Curran et al. 2005, DeLuca and Archer 2009). While the current monitoring protocol gives the agency a tool to gauge the extent to which it is meeting legislative mandates, its qualitative nature may ultimately leave the agency more vulnerable to litigation challenging the extent to which they are in compliance with *NFMA* mandates if qualitative monitoring results are not correlated with quantifiable, ecologically relevant variables.

The *Northern Region Soil Quality Standards* (SQS) direct the process by which data is collected to establish whether management activities are in compliance with long-term soil productivity mandates (Neary et al. 2010). The SQS are based largely on examples given as possible criteria for detrimental thresholds in *USDA Forest Service Handbook 2509.18*. Examples of possible disturbance thresholds include an increase in bulk density of >15%, a reduction in porosity of >10%, or forest floor removal along with 25mm of mineral soil. The

Handbook contained a note stating these examples were not intended for actual SQS (Neary et al. 2010). Directions for determining threshold values, areal extent, sample size and variability and data collection were also given in the Handbook. The handbook suggested that detrimental soil disturbance is that which occurs on greater than 15% of an activity area, and this qualitative unsupported criterion became the standard for the Northern Region and several others (Neary et al. 2010).

6.5.3 Projections

Decision-makers for the Northern Region are currently considering a revision of the SQS. The proposed revisions would be more effective if they included some recognition of the variability inherent in the region due to diverse physical characteristics across more than 9 million acres. For instance, top soil mixing may ultimately prove to be detrimental in areas that have an ash cap, as commonly found in northern Idaho and northwestern Montana. The same top soil mixing in National Forests east of the continental divide, where no ash cap is present, may not prove detrimental. Soil quality standards that allow for site specificity would accomplish two goals: 1) help the agency meet its legislative mandate to document soil disturbance resulting from management activities while still maintaining soil productivity, and 2) provide field monitors some flexibility by basing the determination whether soil disturbance is detrimental on site conditions. Mandates regarding productivity maintenance and monitoring could then be satisfied while allowing the agency to undertake management activities to meet other objectives.

6.6 Alternatives to Current Policy

Potential alternatives to the current policy relating to soils include: 1) maintaining the current policy; 2) revising the *National Forest Management Act* (§6(g)(3)(C); 3) revising *Forest Service Manual 2500*, *Chapter 2550.5*; and/or 4) revising the *Northern Region Soil Quality Standards*. These four potential alternatives are evaluated below based on the following criteria: biophysical feasibility, social acceptability, ethical considerations, economic feasibility, and administrative practicality.

6.6.1 Maintain current policy

Since the goal is to reduce soil disturbance to maintain soil productivity and hydrologic function, the current policy may be successful if it results in successful litigation blocking all harvest activity. The *NFMA* mandates that management systems "will not produce substantial and permanent impairment of the productivity of the land" (NFMA 1976 §6(g)3(C)). New litigation, based on the revised *Forest Service Manual 2500*, has the potential to have a crippling effect on management activities due to the way it defines "permanent" and "substantial" soil impairment. If current policies continue, the options the agency has for active management will decrease.

While policies promoting passive management due to litigation are acceptable to some stakeholders, others argue for active management. Historic management activities have created a landscape where current conditions leave forests vulnerable to insect and disease outbreaks and catastrophic wildfire. Policies that leave federal agencies vulnerable to litigation on resource issues limit the economic feasibility of proposed projects, and have led to a reduction in the work force of people with the knowledge and skill to accomplish management objectives.

6.6.2 Revision of the National Forest Management Act

The *NFMA* mandates that management systems “will not produce substantial and permanent impairment of the productivity of the land” (NFMA §6(g)(3)(C)). On its own merit, this statement is not only reasonable, it is imperative that its intent be met for sustaining the mix of goods and services Forest Service managers are mandated to provide under the *Multiple-Use Sustained-Yield Act of 1960* as referenced in the *NFMA* (NFMA 1976 §2(3)). However, the issue is not with protecting land productivity, but rather what constitutes substantial and permanent impairment. Regardless of how this point is clarified, revisions to *NFMA* would not meet the intended objective of maintaining long-term soil productive capacity.

6.6.3 Revision of Forest Service Manual 2500

Chapter 2550.5 of *Forest Service Manual 2500* defines substantial soil impairment as a “detrimental change in soil properties that last beyond the scope, scale, or duration of the project causing the change.” “Permanent” soil impairment is defined as “detrimental changes in soil properties that last beyond a silvicultural rotation or land management planning period”, which is typically 15 years in the Northern Region of the USFS (personal correspondence with Meredith Webster, Northern Region Soil Program Leader, Nov. 12, 2009). Strictly applying the definitions of substantial and permanent soil impairment, while referencing the soil quality standards, could be construed to mean that the USFS is in violation of *NFMA* mandates if detrimental disturbance as it is defined in the SQS (e.g. rutting > 5cm. in wet soil, compaction >15%) exists on a timber harvest unit at the close of the sale contract. Such a literal interpretation of the SQS definition of detrimental soil disturbance is likely to result in litigation with potential bans on all operations because of the high potential for such insignificant damage to occur during harvest operations and be defined as "detrimental" according to SQS (Chapter 5). Using the more broad interpretation (changes that last beyond a silvicultural rotation) may provide the most leeway for interpretation, but long-term studies on the changes to productivity from soil impairing activities and recovery time have not been conducted in the Northern Region.

Revising the definitions for permanent and substantial impairment in *Chapter 2550.5* of *Forest Service Manual 2500* would allow the agency to meet the mandates set forth in the *NFMA* while at the same time strengthening its legal stance when it comes to the variety of operations they conduct. Meeting the mandates set forth in *NFMA* will maintain ecological function, remain politically desirable, and meets the ethical responsibilities associated with land stewardship. The recommended revisions could improve the economic viability and reduce administrative burdens of proposed management projects by reducing time and monetary resources required to respond to litigation.

6.6.4 Revision of the Northern Region Soil Quality Standards

The soil quality standards define thresholds for detrimental soil disturbance in the Northern Region. Although the current policy is administratively convenient, litigants have contested the current standards as "facially unreliable" (WildWest Institute v. Bull 2008). Revising the standards to recognize the inherent variability across approximately 9 million acres of timberlands in the USDA-FS Northern Region would provide soil scientists and managers with some flexibility in determining what constitutes detrimental soil disturbance. Allowing soil scientists and managers to account for site specific conditions would meet *NFMA* mandates to maintain productivity. Proposed projects that were justified on site specific characteristics would not only improve the agencies' legal position, it would strengthen the case for active management objectives during the public involvement phase of the environmental analysis process required by the *National Environmental Policy Act* (NEPA 1969). This could ease engagement in the planning process for stakeholders by addressing site specific concerns that could avoid litigation altogether.

6.7 Recommendations

A combination of the above alternatives is the best strategy for meeting the goal of maintaining soil productivity, while allowing a range of management activities to meet various objectives without costly litigation. First, the definitions for "permanent and substantial soil impairment" given in *Forest Service Manual 2500* need to be revised. This internal document provides USDA-FS managers with policy and direction for legal compliance with the agency's legislative mandates. A simple revision of the definitions in *Chapter 2550.5* of *Forest Service Manual 2500* can be efficiently accomplished without public comment provided the issue is not controversial (personal correspondence with Meredith Webster, Northern Region Soil Program Leader, March 31, 2010). It becomes a controversial topic that requires public comment once this issue has been litigated on, and would then require more time and resources to change. Removing "detrimental" from the definition would preclude litigation on the grounds that any violation of the current standard for detrimental soil disturbance could be found to be illegal. A strict interpretation of the current wording in the manual has the potential to halt any proposed management activities based on the definitions of permanent and substantial soil impairment.

The second step in a combined strategy would be to revise the soil quality standards to allow for site specific conditions in response to current scientific understanding. Chapter three demonstrates that delineating areas based on site characteristics can be useful for predicting the susceptibility of soils to disturbance due to ground-based harvest systems. One possible approach to meet the need for site specificity is to monitor soil conditions based on the ecological site type of the management area, similar to the approach used in monitoring rangelands through ecological site descriptors (ESDs). The ESDs for forest habitats is currently a work in progress and adopting this system will depend on the completion of ESD surveys. Once completed, the ESD would provide the tools necessary to delineate site types within the Northern Region. Given the lack of long term data, a qualitative assessment of the extent to which ecological functions are performing based on the ESD would still be necessary. Due to the inherent subjectivity of qualitative assessments, and the paucity of data correlating qualitative measurements of soil disturbance with vegetative response, the agency will remain vulnerable to litigation based on differences of opinion, but the financial resources allocated for soil disturbance monitoring make large scale quantitative soil monitoring assessments impracticable. Thus, revision of the soil quality standards should be regarded as a continual process. As long term data becomes available from the North American Long Term Soil Productivity (LTSP) study sites and similar studies, the soil quality standards should be revised to reflect increases in knowledge, and to take advantage of the best available science. To move forward, qualitative assessments of soil disturbance must be supported by a rigorous training program to ensure consistent application of a standardized soil monitoring protocol. Ultimately, the soil quality standards will need to be correlated to ecologically significant site-specific variables based on the best available science produced from studies that by their nature are long term, evolving projects.

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CHAPTER 7: CONCLUSIONS

7.1 Summary of Results

The first objective in this project was to determine if soil disturbance monitoring data collected under disparate monitoring protocols can be used to correlate disturbance levels to harvest systems and site physical characteristics (Chapter 3). After transposing soil disturbance data collected under disparate protocols into the four class system defined by the Forest Soil Disturbance Monitoring Protocol (Page-Dumroese 2009) we developed a mean soil disturbance (MSD) metric for analysis. We were able to show significant differences among harvest systems using MSD as a metric for disturbance levels. Ground-based harvest resulted in the most disturbance, followed by skyline and helicopter harvest systems. This was consistent with published results (Bockheim et al. 1975). However, we were not able to correlate disturbance levels to site physical characteristics. Variation in the soil disturbance monitoring data resulting from disparate collection methods lacked the necessary precision to correlate disturbance to site characteristics using MSD as a metric. We concluded from the results of this study that correlating soil disturbance levels to site characteristics will require a standard soil monitoring protocol that is consistently applied.

The second objective in this project was to utilize soil disturbance monitoring data that had been collected using a consistent protocol to produce a model predicting the areal extent of detrimental soil disturbance resulting from ground-based harvest based on landscape characteristics and season of harvest (Chapter 4). Using soil monitoring data collected using a consistent protocol on the Kootenai National Forest we were able to produce a predictive model useful as a risk analysis tool identifying areas more susceptible to increased detrimental soil disturbance levels during winter and non-winter ground-based harvest activities based on landscape characteristics. This model can be used to efficiently identify areas where alternative harvest systems may be appropriate to maintain soil productivity while still meeting other management objectives. Study results show that winter harvest typically results in lower levels of detrimental soil disturbance, and suggests that sub-optimal winter harvest conditions may have been a significant factor in increased disturbance levels on landtype 328 on the Kootenai National Forest. We concluded from this study that it is possible to correlate disturbance levels to site physical characteristics using consistently collected soil disturbance monitoring data, landtype surveys, and geo-spatial data.

The third objective in this project was to evaluate the areal extent of detrimental soil disturbance resulting from timber harvest operations in the Northern Region (Chapter 5). There were significant differences in the areal extent of detrimental soil disturbance resulting from helicopter (0.2%), skyline (3.8%), and ground-based (8.2%) harvest across the Northern Region. Season of harvest was also a significant factor controlling the areal extent of detrimental soil disturbance. Summer ground-based harvest resulted in more detrimental soil disturbance (9.9%) than winter ground-based harvest (7.0%). There was a significant amount of variation among National Forests in the Region using similar harvest systems during the same season of harvest, although mean levels of detrimental soil disturbance across the Northern Region were under 15% for all harvest systems.

The fourth objective in this project was to provide an analysis of policy related to soil disturbance in the Northern Region (Chapter 6). We concluded from this analysis that there are two steps the Forest Service should consider taking to meet site productivity mandates while still allowing a range of management activities to meet various objectives; 1) revise the definitions for “permanent and substantial” soil impairment in Forest Service Manual 2500

(USDA-FS 2010), and 2) revise the Northern Region Soil Quality Standards to allow for site-specific conditions in response to current scientific understanding.

Based on the results of these projects we offer the following suggestions:

1. Adopt a common soil disturbance monitoring protocol. Data collected using a common, consistently applied monitoring protocol will provide soil disturbance monitoring data with the precision necessary to develop risk rating systems based on site-specific features. Using the methodology described in Chapter 4 risk rating systems can be used to allocate scarce monitoring resources and identify areas conducive to specific harvest systems.
2. Modify timber sale contract language for winter harvest operations to include language that requires skid trails be cleared of snow and allowed to “freeze-up” before harvest operations begin.
3. Soil monitoring data should include the specific ground-based harvest equipment used in harvest operations. Ground-based equipment specifics are a missing, critical piece of information that is necessary to correlate disturbance levels to equipment type and refine BMPs for ground-based harvest operations.
4. Modify the definitions of “substantial” and “permanent” in Forest Service Manual 2500. Removing the term “detrimental” from these definitions would not tie them to unsubstantiated definitions in the Soil Quality Standards.
5. Modify the Northern Region Soil Quality Standards. The standards should define detrimental soil disturbance thresholds over a range of site-specific conditions, based on current scientific knowledge.

7.2 Management Implications

Scientific advancements and changing societal mores have led to the development of policies and best management practices that have changed forestry practices dramatically over the latter part of the 20th century (Allen et al. 1999). Implicit in these changes is the recognition of the critical role soils have in sustainable forestry and to a greater degree, the maintenance of naturally functioning and productive ecosystems (Powers et al 1990, Powers et al. 2005). Management activities, including timber harvest, cause some degree of soil disturbance (Grigal 2000). Disturbance levels resulting from timber harvest operations range on a continuum from minimal (i.e. helicopter) to higher impact (i.e. ground-based) depending on harvest method (Chapter 3, Chapter 5), site-specific characteristics (Chapter 4), and season of harvest (Chapter 5). The effect that disturbance has on subsequent forest growth also ranges on a continuum from negative to positive impacts, with changes in site-specific attributes being driven by local climate, time, and initial site conditions (Laffan et al. 2001, Page-Dumroese et al. 2010). For example, Powers et al. (2005) reported vegetation growth increases of 40% resulting from severe compaction of sandy soils. The same severe compaction treatment on clay soils resulted in a reduction in vegetation growth of 50%. These changes in vegetative response were due primarily to the relative change in plant available water holding capacity, which increased in the sandy soil and decreased in the clay soil (Powers et al. 2005). Maintenance of soil productivity and hydrologic function is imperative to maintaining productive landscapes (Ares et al. 2005, Curran et al. 2005a). However, maintaining productive landscapes will be increasingly difficult in the future as population growth places increasing demand for forest products on a shrinking forest land base (Thorud 1983).

Timber harvest operations on National Forest System lands generally comply with an array of laws, regulations, and directives designed to protect site productivity. Post harvest monitoring data indicates that timber harvest operations consistently result in soil disturbance levels below the threshold currently considered to be detrimental (Chapter 5). The rare exceptions to this suggest that minimizing timber harvest impacts to soils can be achieved by limiting harvest activities to periods when the soil moisture content reduces soil susceptibility to disturbance causing activities (i.e. dry or frozen soils) and by active monitoring of harvest operations by timber sale administrators (Chapter 5). Current scientific knowledge suggests that applying these regulations uniformly across heterogeneous landscapes is not scientifically justified, despite the best of intentions during policy development (Page-Dumroese et al. 2000). Our results show that harvest impacts to soil are site-specific, and depend on the interaction between physiography, geology, vegetation, and climate on site (Chapter 4). The paramount questions may be: 1) what level of disturbance is truly detrimental given site conditions, and 2) under what conditions are those types of disturbances likely to occur. Concurrent with these questions is the effect multiple management entries may have throughout stand rotations. Solutions are elusive due to several disturbance factors on an operational scale. For instance, rutting, compaction, and displacing the forest floor and upper layer of the mineral soil commonly occur simultaneously, making it difficult to determine what factor most controls subsequent vegetation growth (Page-Dumroese et al 2000). Determining which disturbance factor controls site productivity is difficult to identify and is likely to be geographically limited in scope (Heninger et al. 2002). If the effects of soil disturbance are cumulative, as suggested by Page-Dumroese et al. (2010), then time may ultimately prove to be the factor controlling the long-term maintenance of site productivity. Heninger et al. (2002) noted that the effect of high impact disturbance did not significantly affect seedling height growth after a relatively short time frame (7 years). The lack of long term data precludes making definitive statements about the cumulative effects of multiple entries on productivity (Powers et al. 2005). Results from the ongoing LTSP studies are critical to understanding the time frame required between harvest entries to maintain site productivity given different site characteristics (including climate). Unfortunately, these are long-term questions that will likely require another generation of research to answer.

Adoption of a universal soil disturbance monitoring protocol by land managers interested in maintaining site productivity will help determine site-specific factors controlling extent and severity of disturbance (Chapter 3, Chapter 4). However, disturbance monitoring data should be recognized by administrators responsible for framing policy as one of the tools necessary to show a relationship between disturbance causing activities, site productivity, and changes in hydrologic function (Curran et al. 2005b) and needs to be tied to some ecologically relevant variable to be useful (DeLuca and Archer 2009).Vegetation growth, site organic matter, and soil porosity are all examples of ecologically relevant variables that could be correlated with soil disturbance monitoring data. Soil disturbance monitoring classification is an instrument that facilitates the consistent and structured transfer of this knowledge (Curran et al. 2005b).

There are differences in disturbance levels between timber harvest systems. Our work shows ground-based harvest operations cause more disturbance than harvest systems that partially suspend logs or trees (overhead skyline systems), or helicopter harvest systems that fully suspend logs or trees in the yarding process (Chapter 3, Chapter 5). These results have been corroborated by researchers for over 35 years (Bockheim et al. 1975). Observations suggest that soil disturbance levels will also vary among ground-based harvest systems. However, there is currently little research available to support this claim (Page-Dumroese 2006). The reason for this contradiction may stem from soil disturbance monitors being unaware of the type of ground-based harvest equipment employed on a harvest unit. Ground-based harvest equipment is often denoted as “tractor” or simply “ground-based” on field data sheets and electronic databases. These general categories do not lend themselves to the precision necessary to differentiate disturbance resulting from ground-based harvest systems (Chapter 3, Chapter 4, Chapter 5). Recording ground-based equipment specifics in the data collection process will ultimately enable researchers to better understand how soils react to differences in ground-based harvest equipment in local conditions. The dissemination of this knowledge will improve scientifically driven recommendations to policy makers and help resource professionals in revising best management practices. Determining soil susceptibility to different ground-based harvesting equipment is critical for developing site-specific strategies for minimizing soil disturbance as a result of ground-based harvest operations (Miller et al. 2010).

Inherently diverse forests respond differently to disturbances and inferring the relationship between disturbance thresholds and productivity is difficult due to differences in growth response following disturbance in diverse regions (Powers et al. 1998). Therefore, it would be beneficial for resource managers to develop a system of soil quality standards that recognizes the variation that is inherent across diverse landscapes (Miller et al. 2010). Developing a system of soil quality standards that allows for site-specific thresholds of acceptable disturbance levels can be accomplished while still exercising precautionary principles, and has the potential to reduce some of the criticisms that the current system is insensitive to site- specific conditions (Curran et al. 2005b). Burger et al. (2008) suggests that the soil variables to monitor as indicators of site productivity should be site-specific due to the variation in soil physical properties and attributes. For instance, the presence of an ash-cap in the soil profile is an example of a site-specific attribute that should be considered. Maintaining the ash cap is a concern for managers in the Inland Northwest of the United States due to their critical role in forest productivity and susceptibility to disturbance (Johnson et al. 2007). To progress, soil disturbance monitoring data must be collected consistently and the visual indicators of disturbance must be correlated to ecologically relevant variables. This is supported by Heninger et al. (2002) who maintain that the effect of soil disturbance on tree growth will vary between sites and that an interaction exists between management practices and location that drives vegetative growth response to disturbance causing activities. Heninger et al. (2002) suggests this interaction between management practices and location is the rule, rather than the exception. Heninger et al. (2002) further cautions that there is no justification for extrapolating the effect of soil disturbance on tree growth from one soil and climatic regime to sites with dissimilar soil and climatic regimes. Ultimately, site-specific correlation among management practices, disturbance levels, vegetation health and forest productivity should be required for site-specific soil quality guidelines. Such correlations will allow flexibility to meet changes based on the current understanding.

The information in this thesis adds to current knowledge about monitoring the impact of timber harvest systems on soils. Soil disturbance monitoring data recorded using disparate protocols that lack clear definitions of disturbance produce results that are too variable to draw meaningful conclusions from. Greater consistency and precision is necessary to determine the impact physical site characteristics have on the severity and extent of soil disturbance resulting from timber harvest operations (Chapter 3). In contrast, results from a consistently applied soil disturbance monitoring protocol can be useful for developing models predicting the susceptibility of soil to disturbance from harvest operations. Curran et al. (2005b) maintains that forests are inherently diverse and that soil susceptibility to disturbance-causing activities is determined by site characteristics and climatic settings. Our results in Chapter 4 support the position taken by Curran et al. (2005b) by showing that soil susceptibility to disturbance depends on landtype, slope, aspect, and season of harvest on the Kootenai National Forest. The risk rating model developed in this thesis, based on landscape characteristics, provides a framework that can be applied to other regions and allows for site-specific predictions of post-harvest soil disturbance levels based on physical site characteristics and season of harvest (Chapter 4). The practical application of risk rating systems is suggested by Miller et al. (2010) as a means to arrive at management activities most appropriate for local conditions.

Research results that show differences in soil disturbance levels between ground-based, skyline, and helicopter harvest systems are not novel concepts. The important conclusions from the results described in Chapter 5 are: 1) there are differences in harvest impacts among National Forests using similar harvest systems over the same harvest season, furthering arguments for adoption of a common soil disturbance monitoring protocol, and 2) soils on post-harvest logging units are in satisfactory condition in the Northern Region except in isolated and extreme cases.

Policies that meet productivity mandates while still tolerating active management are difficult to initiate due to the variation in response to disturbance across diverse landscapes. The current one-size-fits-all approach to delineating detrimental soil disturbance does not recognize the variability in potential site productivity and resilience to disturbance due to differences in physical site characteristics and climate in the Northern Region. Miller et al. (2010) note that consistent predictions of when and under what conditions management activities will cause, as the NFMA (1976) puts it, “substantial and permanent impairment of productivity of the land” are not supported by current science and knowledge. The lack of data validating these predictions increases the difficulty resource managers have in meeting productivity mandates while still engaging in active management (Curran et al. 2005b). In addition, Chapter 6 suggests that by tying “substantial” and “permanent” to soil quality standards that are not site-specific, forest managers in the Northern Region are vulnerable to legal challenges.

Much of the discussion on soil disturbance and its impacts on site productivity revolve around the question of how much disturbance is truly detrimental to future productivity under a given set of conditions. More research is needed to define the variables that control site-specific responses to soil disturbance to answer this long-term fundamental question. The USDA Forest Service has provided a critical background for the key role soils play in functioning ecosystems, and should be commended for their support of researchers seeking knowledge of critical factors that maintain long-term soil productivity.

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