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Title: Applications of Soil Science in Forest Landscape Planning: Challenges and Opportunities in the 21st Century

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ABSTRACT

Soils and other resource programs in both public land management agencies and private industry are continually being adapted to the challenges of evolving knowledge and experience in the field of forestry. This dissertation explores new ways of thinking about and using soils information in forest planning and management, with a focus on Pacific Northwest lands. At the core of this work are the concepts of soil quality, in particular, the applications of inherent and dynamic soil quality.

These soil quality concepts can be used as both a planning tool to improve our understanding and assessment of land-use decisions and as an assessment tool to evaluate the sustainability of different management practices. The result is two very different types of soil interpretations based on inherent and dynamic soil quality concepts which are applied at different times and for different purposes during forest planning and management.

Forest planning soil interpretations that are based upon inherent soil quality are used primarily to make land use allocations and related decisions. These interpretations are applied up-front in the forest planning process and are based on the fact that different

soils vary widely in their inherent capacity to perform various ecological and utilitarian functions. By both recognizing different soil types in the local landscape and understanding how those various soils naturally function, managers can use inherent soil interpretations to better match land management objectives to soil types that have a high capacity to meet those objectives. Matching soil potentials to the appropriate land management actions in this manner helps to assure management actions will be both attainable and sustainable over the long term.

Soil interpretations that are based upon dynamic soil quality differ from those based upon inherent soil quality in that dynamic soil interpretations are primarily used to assess the sustainability of management practices. These interpretations identify different soils' resistance and resilience to disturbances and use soil-based indicators of key soil functions to make assessments of the effects of different disturbances.

A conceptual "forest planning and management model" is presented that illustrates applications of these soil quality concepts in the forest planning process. Concepts and practical applications of the conceptual model are illustrated in current forest level planning projects within the US Forest Service (FS) Region 6. Soil disturbance monitoring was also conducted in recently managed areas and used to both provide a practical procedure for monitoring soil porosity changes and to present a case for updating current directives and guidelines for FS Region 6 Soil Quality Standards.

It is my hope that this work will be of value to both soil scientists and other forest resource specialists and managers. Perhaps one of the more significant contributions that may come of this work is that it may help soil scientists and others to be inspired through a better understanding of the "value added" when soils information is considered in new and effective ways. It is also my hope that this work provides some of the practical ideas and tools necessary to take advantage of opportunities to apply knowledge of the soil resource in future forest planning and management.

Applications of Soil Science in Forest Landscape Planning: Challenges and Opportunities in the 21st Century

by
Terry Lee Craigg

A DISSERTATION

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Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Terry Lee Craigg, Author

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CONTRIBUTION OF AUTHORS

Dr. Paul W. Adams is one of the coauthors of the Journal of Forestry manuscript "Soil Matters: Improving Forest Planning and Management with Soils Information and Expertise." Dr. Adams greatly improved the quality of all of the reports in this dissertation by assisting me with developing concepts, repeated review and editing of chapters, contributing text, providing relevant literature, data interpretation, preparing publications based on journal specifications and submitting manuscripts for publication.

Karen A. Bennett is also one of the coauthors of the Journal of Forestry manuscript "Soil Matters: Improving Forest Planning and Management with Soils Information and Expertise." For each of the chapters in this dissertation, she provided thought provoking edits and suggestions; taking the time to meet, discuss, and help develop the concepts for this work.

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Chapter 1 : General Introduction

Terry L. Craigg

Introduction

The overall focus of this Ph.D. project has been on the use of soils information in forestry. This work was prompted by my past experiences working as a U.S. Forest Service soil scientist and the desire to be able to better integrate soils information into forest planning and management.

Chapter 2 of this dissertation provides the foundation for helping forest managers discover more expansive ways of using soil information in forest planning in the manuscript "***Soil Matters: Improving Forest Planning and Management for Diverse Objectives with Soil Information and Expertise***." In this manuscript the broader role of the soil practitioner is discussed, highlighting the value of soil information in forest planning. A conceptual model of a forest planning and management cycle is used to illustrate applications of soil data both early and throughout the forest planning process. The use of soil resource information in forestry is then further discussed for a case study implemented on the Sisters Ranger District of the Deschutes National Forest, which applies the conceptual model in a practical planning application. The intent of this work is to raise awareness of the value of soils information in forestry and help forest managers better understand how soils information can be more effectively used in forest planning.

Although an argument has been made (Chapter 2) for matching inherent soil quality and potentials to land management objectives early in the process to improve forest planning, it is also recognized that many complex concepts of soil quality can be difficult to understand and even more difficult to apply in planning. Chapter 3 of this dissertation addresses this issue in the manuscript ***"Using Soil Surveys to Refine Ecologically Based Forest Land Management Interpretations during Project Level Planning in the Eastern Oregon Cascade Range."*** In this manuscript, an expanded set of practical considerations and examples were developed for the "Green Ridge" project level forest planning project located on the Sisters Ranger District of the Deschutes National Forest. The interpretations developed for this study offer elaboration and proof of the value of those concepts introduced in Chapter 2. Examples help illustrate the value added” in considering soil information early in the forest planning process to address a variety of forest objectives including wildlife habitat enhancement, improved watershed hydrologic function, vegetation treatments to restore resilient forest conditions, and applications of prescribed fire to restore resilient forest conditions.

Evaluations of soil condition assessments remain an important part of sustainable forest management. One of the common soil disturbance concerns with equipment operations is soil compaction which, among other soil changes, can result in undesirable changes in soil porosity. Porosity changes are well documented in forest soils research, and concerns about related impacts led to a focus on changes in soil porosity and soil organic matter as the two primary disturbance indicators for the U.S. Forest Service Long Term Soil Productivity studies (Powers, 1991). While the importance of maintaining soil porosity is well recognized, direct measurements of soil porosity are not commonly made due to the difficulties in making these measurements and instead soil bulk density measurements are often used to calculate or infer porosity changes. Chapter 3 of this dissertation ***“A Practical Method for Measuring Soil Porosity Changes Resulting from Forest Management”*** describes a simplified method for measuring changes in soil pore size distribution using a modification of the water desorption method described in Methods of Soil Analysis (Klute, 1986). The procedure does not require sophisticated laboratory equipment and thus offers a practical alternative for making such measurements in local facilities to generate a more refined understanding of important soil changes.

Chapter 5 further investigates soil condition assessments in the manuscript ***“US Forest Service Soil Quality Standards: A case for updating current directives and guidelines in Region 6.”*** This study began with a review of the current FS Forest Soil Disturbance Monitoring protocol (Page-Dumroese et al., 2009), used to assist with the quantification of visual soil condition classes within managed areas. While this protocol provides a statistically based systematic method for determining area extent of different visual soil condition classes, the determination as to which soil condition classes represent an important alteration in key soil functions is not specified and instead left to those doing the monitoring. There are currently few tools and limited guidance available to assist soil scientist and others with interpreting these visual soil disturbance monitoring results.

In Chapter 5 the FS Region 6 SQS were next applied in an operational setting at five locations throughout the Region representing six soil types. Forest soil disturbance monitoring was conducted in an operational setting in a manner typical of that used by a FS staff member working on a Forest or Ranger District (Howes et al., 1983; Howes, 2006; Page-Dumroese et al., 2009). Field evaluations included identification and descriptions of different visual soil condition classes within treatment units and measurements of soil quality indices within visual soil condition classes. The data were then assessed with interpretation of measured changes based on the current FS SQS for R6, quantification of area extent of soil condition classes, and a determination as to whether or not treatment areas meet the intent of current standards. Key ecological processes and soil functions were next reviewed along with soil quality indicators used to make assessments of change. Selected soil based indicators were measured in recently managed areas for different soil types within Pacific Northwest forests and results were evaluated based on different soil indicator measurements. The intent of this work is to (1) demonstrate the importance of measuring soil indicators to better understand and interpret visual soil condition classes, and (2) make a case for developing a “Strategic Soil Database” that can be used to evaluate visual soil condition classes within different soil types and identify those soil condition changes that have important effects on key soil functions.

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Chapter 2 : Soil Matters: Improving Forest Landscape Planning and Management for Diverse Objectives with Soils Information and Expertise

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Abstract

Most forest managers would agree that soils are a fundamental resource of forest lands, yet many planning and management decisions continue to be made without a detailed and spatially explicit understanding of this unique and vital resource. We discuss the value of soil data and interpretations in forest planning. We emphasize that soil types differ widely in their inherent capacity to perform various ecological functions as well as in their dynamic response to and recovery from disturbances; concepts that can greatly enhance the quality of forest management decisions. We make a case for applying these concepts by introducing an adaptive management model that targets the use of soil information during forest planning and management. Our goal is to help bridge the gap between soil science and decision making by helping forest managers better understand the value of soil information in project planning. A case study highlights applications and potential benefits.

Introduction

The theme of a recent SAF National Convention, “Silviculture Matters,” seemed to state the obvious about the importance of forest management, but such focused attention can provide valuable reminders, examples and fresh thinking about the technical underpinnings of well-practiced forestry. Such is the case for soils, which are the most fundamental resource of forest lands, greatly contributing to nearly all other forest resource functions and values. Yet despite a substantial evolution of investigation and expertise in forest soils in the U.S. (Gessel 1978, Fisher et al. 2005, Binkley and Fisher 2013,), the use of soils information and expertise does not seem to have come close to reaching its potential in helping improve current forest planning and management. Here we discuss the value of soils data and the role of the soil resource in forestry, using some examples from the US Forest Service (FS) and its Region 6. Although our discussion and the following examples focus on the FS and the Pacific Northwest, we feel this information has comparable value in forest planning and management on other public and private lands, particularly where there are diverse management objectives on larger landscapes.

After several decades of growth in soil science research, education, and professionals, concerns were raised in the 1980s about dropping enrollments in undergraduate soil science degree programs and serious shortages of adequately trained soils professionals (McCracken 1987). More recently, Fisher et al. (2005) noted a significant decline in requirements for a forest soils class in undergraduate forestry curricula, and a similar negative trend in forest soils expertise among forestry faculty. These issues appear to have directly or indirectly impacted the FS: Between 1993 and 2012, the number of Region 6 soil scientist positions decreased by 63%, and the national trend in FS soils staffing also has been strongly negative (Zimmerman 2012). In addition, the role of many soil scientists has become focused on monitoring and interpreting soil disturbance from forest operations (USDA Forest Service 2009). This relatively narrow focus stems from the National Environmental Policy Act of 1969 (NEPA) and the National Forest Management Act of 1976 (NFMA) requirements, which shifted attention to assessments of potential management impacts and efforts to protect soil and other resources. Specific guidelines to limit soil disturbance from operations were thus developed (e.g., Cornell et al. 1977, Boyer 1979) and added to administrative manuals (e.g., USDA Forest Service 1983). The original Soil Quality Standards (SQS) have been further refined by different FS Regions over the past few decades, including the Region 6 supplement to the Forest Service Manual (USDA Forest Service 1991).

The overall goal of the FS SQS was to direct National Forest land management in ways that would avoid permanent impairment of the land's productivity, consistent with the mandate of the NFMA. The FS SQS greatly increased the awareness of soil disturbance concerns, and more recently the FS developed national monitoring protocols to quantify soil disturbance within activity areas (Page-Dumroese et al. 2009), with additional soil-based indicators proposed to help identify degraded soil conditions

(Burger and Kelting 1998, Powers et al. 1998, Schoenholtz et al., 2000). A notable consequence of this soil disturbance assessment activity has been the citing of FS soil standards in lawsuits and administrative appeals by groups opposed to forest management (e.g., Ecology Center v. Austin in Montana, and League of Wilderness Defenders – Blue Mountains Biodiversity Project v. Bosworth, Civil No. 04-405-AS, in Oregon). This broader issue of legal opposition to FS management activities is well documented (Miner et al. 2014), and helps explain the current level of attention given to the assessment and control of soil disturbance. Although such litigation has often delayed or restricted implementation of FS management projects, it also reflects the high importance of and concern about soils as a fundamental resource in forest ecosystems. Increased attention to the value of soils by the interested public should provide added incentive for engaging soil scientists in management solutions for agency lands.

The need to assess and limit soil impacts cannot be ignored, but its dominance in National Forest decisions in recent decades has also led to a diminished awareness of the broader value of soil information in FS planning and management decisions. It is notable that in the 1960s the FS significantly increased its soil and other resource specialist staff to help meet the mandates of the Multiple Use Sustained Yield Act (MUSYA) of 1960 (Fedkiw 1999, MacCleery 2011). At that time, soil specialists primarily supported timber harvesting, road construction, and subsequent reforestation projects with soil inventories and management interpretations, but soils information also was recognized as valuable in managing for a variety of forest values. For example, Roger Reiske, then a FS regional soil scientist, offered in the Journal of Forestry an inspiring and forward-looking discussion of the value and use of soils information in forest management planning, with examples that included wildlife, watershed and recreation objectives (Reiske 1966).

Although much progress in both forest management and forest soil science has been made over the years, it can be argued that many applications of soils information in forest planning that Reiske proposed decades ago have not been consistently used nor have they been adequately expanded for the diverse management needs of today.

Increased emphasis on soil disturbance assessments is likely one of the more important factors contributing to this lack of a proactive approach by soil scientists. Other factors may include the roles and expectations of administrators and the structure and dynamics of interdisciplinary planning teams, most of whom may not recognize the value of soils information in upfront planning. For the soil resource to reach its full potential in forest planning, the soil scientist and other forestry professionals need to carefully think about their concept of soil quality and its applications (Sims et al. 1997). Thus we offer below an adaptive management approach to the use of soil information in project planning as well as some more contemporary ideas and examples, which we hope will help inspire a renewed interest in the use of soils information and expertise in forest management planning. An initial discussion of current soil quality concepts helps reveal how they can be better integrated into forest planning and management, particularly on National Forests and other forest lands with diverse land use and resource objectives.

Soil Quality and Diverse Management Objectives

A half-century ago, management of National Forests expanded from the basic timber and water supply focus set by the Organic Act of 1897 and the Weeks Act of 1911 to include diverse, compatible values as directed by the MUSYA. Subsequent environmental laws such as the Clean Water Act of 1972 and subsequent amendments (CWA) and the Endangered Species Act of 1973 (ESA) prompted additional management considerations. Thus, many of today’s forest management decisions are not only related to growing trees, but also include other resource concerns such as maintaining water quality, unique habitats, and hazardous fuels reduction (Fisher et al. 2005). Similarly, planning and management for National Forests now occurs primarily in an interdisciplinary setting with a number of specialists representing different disciplines and forest resource values. The team is challenged to design and implement a management plan for a given planning area that includes multiple and sometimes competing objectives (Noss et al. 2006, Maron and Cockfield 2008, Rieman et al. 2010).

Soil resource information can facilitate this planning and management process by matching the desired objectives to areas of soils that have the best potential to support those objectives over the long term. The expectation is that management actions will be more sustainable and better able to meet the intent of the planners.

Foresters often use potential natural vegetation patterns and estimates of the historic range in variability of vegetation to assess local site characteristics and potentials (Pfister and Arno 1980, Morgan et al. 2008). While valuable in helping to understand the dynamic nature of ecosystems, this approach is sometimes limited by a lack of historical data and or difficulties interpreting the historic record. Land use history, fire suppression, natural events and management practices can each alter local vegetation conditions to a degree that masks or distorts true site potentials and limitations thereby resulting in unreliable assumptions for forest planning and management (Morgan et al. 2008). Soil characteristics can provide much more reliable and stable indicators than vegetation for interpreting site potentials and responses to management prescriptions (Abella et al. 2013, Gilliam et al. 1993).

The concept of soil quality has been used as a tool to improve understanding and assessments for both land use decisions and the sustainability of different management practices (Doran and Parker 1994, Karlen et al. 2001). To better understand how the soils information can be useful in forest planning and management, it is helpful to further clarify the concept of soil quality by distinguishing two unique and important categories of soil quality, inherent and dynamic soil quality (Karlen et al. 2001), which provide different types of information for planning and decision making.

Inherent Soil Quality

Inherent soil quality reflects the soil's basic capacity to perform different soil functions that support a variety of land uses or resource objectives. These inherent soil qualities normally are not significantly altered by management activities and thus can be mapped and described in soil resource inventories. This reflects the fact that a given local soil type is the result of five dominant, soil-forming processes, including climatic influences, soil and surface organisms, local topography/geomorphology, geology/parent materials, and time for soil development (Jenny 1941). The resulting soil characteristics uniquely integrate these local environmental influences and reflect the soil's inherent capacity for performing a variety of soil functions. Examples of inherent soil attributes include soil depth, texture, amounts of rock in the soil, thickness and types of soil horizons, and depth to a water table. Examples of inherent soil quality interpretations are shown in Table 2.1. In landscape planning, an understanding of the various soil types and how these attributes result in different functional capacities can be used to better design sustainable management actions by matching planned actions to the right soil.

Different soils can vary widely in their inherent capacity to perform various ecological functions. For example, Abella et al. (2014) noted that thinning and grazing treatments applied in a ponderosa pine forest restoration study in northern Arizona showed different responses in species richness and productivity depending upon soil type. Other examples include the identification of droughty soil types, which can be helpful in prioritizing stand treatments based on stocking levels, site potentials, and risk of insect and disease problems. Where watershed values are especially important, soils that capture and store large quantities of water can be identified and managed to maintain or enhance their ability to moderate peak flows and water temperatures in nearby streams. By both recognizing different soil types in the local landscape and how those various soils function, managers can better match land management objectives such as timber production, fuels reduction, favorable hydrologic function, and habitat enhancement to soils with a high capacity to meet those objectives.

Table 2.1 Management interpretations for inherent soil qualities in planning for various resource objectives on forest lands in central Oregon.

Resource Management Objectives		**Opportunities and Limitations Based on Inherent Soil Quality**	**Applications in Planning Management Actions**
Maintain, restore or improve stand conditions and associated vegetation in native forest types.	Forest health and resilience of drier forest types to insect epidemics and drought.	Inherent water supplying capacity varies among soils and can be estimated using data for mean and extreme precipitation, evapotranspiration, and water infiltration, retention and drainage within the soil profile.	Soil quality information is used to both refine tree stocking prescriptions and prioritize areas for treatment, based on expected drought stress and related increased risk of insect or disease.
	Desirable tree mosaic patterns in dry ponderosa pine forest stands.	The volcanic origin of many forests soils and the underlying rocks often results in complex soil patterns, with depths varying from very shallow to very deep. Local tree and stand productivity vary similarly.	Understanding and recognizing these diverse soil areas is used to refine local tree marking and related decisions about appropriate tree densities and design and number of openings.
	Desirable types and extent of riparian vegetation.	Soils that historically supported desirable riparian vegetation such as aspen often have thick, dark surface horizons. These soil features persist long after the removal or alteration of the original vegetation.	Identification and qualities of soils that historically supported aspen and other desirable vegetation are used to target locations for restoration projects and refine techniques to enhance success.
Maintain, restore or improve soil water storage, stream flows and aquatic habitats in local forest watersheds.		Capture, storage and release of water from rain and snowmelt within a watershed are greatly influenced by soil qualities that can vary widely, including organic and mineral layers, infiltration, permeability, depth, texture, porosity, and landscape position.	Identification of soils with higher and lower capacities for capturing and storing water is used to prioritize areas for vegetation management as well as to refine treatment prescriptions.
Maintain, restore or improve vegetation for local wildlife species.	White headed woodpecker (*Picoides albolarvatus*) habitat.	Soils that historically supported woodpecker habitat (i.e., open stands of widely spaced, large ponderosa pine) often have thick dark surface horizons that developed from heavy understory grass cover. These soil features persist long after	Soil maps and local investigations are used to identify areas of soils with “mollic epipedons,” where desirable woodpecker habitat can be effectively developed and maintained.

		the removal or alteration of the original vegetation.	
	Mature and old-growth forest habitat.	Soils with higher moisture and nutrient supplying capacities are likely to better develop and maintain mature and old-growth forest vegetation over the long term.	Soil quality information is used to identify locations, including recently disturbed areas, where desirable habitat can be grown and maintained over time.

Dynamic Soil Quality

Dynamic soil quality, on the other hand, reflects how the functional capacity of soils may be altered in response to natural or human caused disturbances (Seybold et al. 1998). Unlike inherent soil attributes, the dynamic characteristics of the soil are more vulnerable to changes from management actions that disturb soils. Some examples of these disturbances and resulting changes in dynamic soil properties include a reduction in the depth of organic-rich surface horizons resulting from soil displacement, an increase in soil strength or resistance to root penetration as a result of compaction by vehicles, and soil physical and chemical changes due to intense burning. Examples of dynamic soil quality assessments are listed in Table 2.2. Assessments of changes and trends in dynamic soil quality can provide a valuable tool for directing soil protection, mitigation, or restoration efforts as well as for measuring long-term sustainability of management practices.

Concerns within the FS over changes in dynamic soil quality resulting from forest management prompted National Forest land managers and FS research scientists to cooperatively establish the North American Long Term Soil Productivity (LTSP) experiment in the late 1980’s (Powers et al. 1991). This effort has since expanded to 62 research sites and numerous additional affiliated sites within the United States and Canada and is now the world’s largest organized research network addressing forest management and sustained productivity issues. Treatment design is based on two site properties considered most likely to impact long-term site productivity: soil organic matter and soil porosity (Powers et al. 1990). Study sites cover a broad range of climates, tree species, and soil types and 10 to 15 year results have now become available for some of the older instillations (Sanchez et al. 2006, Scott et al. 2014). While initial study results show limited effects to site productivity resulting from core treatments, it is important to note that these are early results of a long-term study and other measured changes (e.g., soil nutrient status) from the treatments may be revealed as monitoring continues.

Different soils also vary in their immediate and subsequent response to disturbances (Seybold et al. 1999). A soil that is *resistant* to a given disturbance can retain important functional characteristics even when disturbance occurs. A soil that is *resilient* can be altered by disturbance but recover more quickly in its functions, while a soil that is *neither* resistant nor resilient can have long-term impacts to its functions after disturbance. For example, Scott et al. (2014) looked at changes in three ecosystem services: stand volume production, mineral soil C storage, and understory diversity on thirteen LTSP study sites located in the southeastern United States. While results showed minor impacts to these ecosystem services at most study sites, a small number of nutrient deficient sites did show negative effects resulting from treatments.

A soil's inherent qualities often can also help predict a soil's resistance and resilience to different disturbances. For example, although soil texture or soil rock content may not be changed by management they sometimes influence a given soils' resistance or resilience to compaction due to variability in inherent load-bearing capacity. By recognizing differences in soils resistance and resilience to disturbance, managers can better design soil protection measures for disturbances that might impact desired soil functions, while also not being overly restrictive.

Table 2.2 Interpretations of dynamic properties of forest soils, including applications to monitoring of soil effects for adaptive management and sustainability.

Ecological Process	**Key Soil Functions**	**Dynamic Soil Quality Indicators and Common Management Concerns**	**Applications in Monitoring and Adaptive Management**
Forest Vegetation Growth and Composition	Soil drainage and aeration	Soil porosity, color and color patterns (mottling). Soil compaction or other disturbance from vehicle traffic may reduce drainage and aeration.	Monitor soil porosity and/or color for changes that reflect significant impacts to soil water and air movement. As needed, modify extent, type or timing of vehicle traffic.
	Root growth and plant community composition	Soil resistance to penetration (strength), bulk density, structure. Soil compaction or other disturbance from vehicle traffic may reduce root growth and/or alter vegetation composition.	Monitor soil strength, density and/or structure for changes that significantly impact root growth and/or vegetation. Modify extent, type or timing of vehicle traffic; use deep tillage to restore soil penetrability.
Hydrologic Cycle	Infiltration	Soil infiltration rate. Soil compaction or other disturbance from vehicle traffic may reduce infiltration.	Monitor soil infiltration and runoff for significant changes and effects. Modify extent, type or timing of vehicle traffic; use surface tillage to restore infiltration.
	Water storage and release	Soil porosity and permeability. Soil compaction or other disturbance from vehicle traffic may alter porosity and reduce permeability.	Monitor soil porosity for changes that significantly impact water movement and availability for root uptake. Modify extent, type or timing of vehicle traffic.
Nutrient Cycling	Surface woody debris, fine litter and duff accumulation	Size, amount and quality of woody material; extent, depth and quality of surface litter and duff layers. Harvest utilization levels and debris or fuels management (piling and/or burning) may alter amount and quality of surface materials.	Monitor surface woody debris, litter and duff for characteristics appropriate for vegetation type and successional stage. Modify debris management or other practices that result in undesirable amounts or conditions.
	Nutrient availability	Depth and quality of soil A horizon; amounts of plant-available nutrients in rooting zone. Harvest utilization levels and debris or fuels management (piling and/or burning) may alter nutrient availability.	Monitor depth and condition of A horizon and/or soil nutrient levels for changes that significantly impact tree and plant growth. Modify management practices that alter soil nutrient inputs, amounts and/or availability.

Applying Soil quality to a Forest Planning and Adaptive Management Model

To effectively apply the concept of soil quality and related information in the forest planning and management process, land managers need to identify the management objectives early and have maps and interpretations available for the inherent and dynamic qualities of the soil types within a planning area. The conceptual model in Figure 1.1 reflects how such soils information is integrated early and the discussion that follows expands on the use and value of soil information.

Figure 2.1 A forest planning and adaptive management model that integrates the concepts of inherent and dynamic soil quality.

Integration of soils information into forest planning begins as the interdisciplinary planning team initially identifies the broad land management objectives (A) for a planning area. For example, the forester may have both ecological and economic targets that require commercial harvest while also promoting desirable stand structure or complexity, whereas the fisheries biologist highlights a need to maintain local cold water habitat for an ESA-listed fish species. The fuels planner seeks to reduce the risk of stand replacement wildfire to protect the urban interface and the wildlife biologist identifies needs or requirements for minimum canopy cover over a percentage of the landscape, habitat corridors, and forage for an important local species. Understanding the landscape and forest-specific context of these broader objectives is necessary before identifying and refining more specific management actions that are matched to soils that can best sustain such actions.

With soil types identified on the landscape and an understanding of their functions and qualities, managers can next identify opportunities and limitations based on soil quality (B). Thus, management actions are matched to soils with higher potentials for achieving the objectives and sustaining those actions. The success of this approach requires that local soil types have been well identified and mapped, and that interpretations of their potentials and limitations are available for consideration early in the planning process. As this step is completed, potential areas where the desired management actions are expected to be more effective and sustainable can be displayed spatially as maps.

These maps provide the basis for the interdisciplinary planning team (C) to next work together to strategize and integrate land management objectives and actions. At this stage, the interdisciplinary planning team often must consider tradeoffs and make compromises as management objectives have higher or lower compatibility within the planning area. The understanding of different soil functions and qualities can help staff in various disciplines improve specific resource management decisions and design actions that are both sustainable and effectively integrate diverse and sometimes competing management objectives.

At the project design and implementation (D) stage, planners experienced in field operations and project design develop the specifications and schedules for actions in specific locations. Resource specialists also are often involved or provide operating standards or guidelines that will protect or enhance resources of local concern. For example, a ground-based timber harvest plan typically will include directives to use existing or planned skid trails to limit soil disturbance that may impact dynamic soil quality and related functions such as soil drainage. Knowledge of the resistance and resilience of different soil types to disturbances can be applied to project design (Seybold et al. 1999), including the refinement of more general guidelines to target more effective actions and mitigation without being overly restrictive. During project implementation, managers and sometimes resource specialists oversee the operation and give the operator feedback to achieve the desired onsite results.

Ecosystem responses (E) are revealed through monitoring and more detailed evaluation of resource responses to individual and cumulative project actions. Monitoring of resource conditions and responses to treatments requires data collection, analysis, and interpretation of results. Success requires that monitoring be robust to scrutiny while also meeting the needs of both the resource managers and other stakeholders. To better address this need Larson et al. (2013) suggest an active adaptive management approach to monitoring that includes the use of basic principles of experimental design, thus enabling efficient and confident learning about complex forest responses to management.

Effectiveness monitoring of resource responses occurs after treatments have been implemented; however, important monitoring questions can and should be developed early in the planning process and include input from both the interdisciplinary planning team as well as other stakeholders (Larson et al. 2013). This approach can help build trust both internally and externally for future projects. The ecosystem response can be assessed at both the landscape and local scale (e.g., stand by stand) and also with a temporal context that considers resource responses both immediately following an activity and for some extended period afterwards. For example, soil compaction from a ground-based thinning project can result in immediate changes in soil bulk density but more extended monitoring of tree growth may show an absence of significant impacts when planned skid trails are used to limit the extent of compaction (Miller et al. 2007).

Adaptive management is next used to apply monitoring results and adjust future management activities in ways that incorporate what was learned (Bormann et al. 2007). With local as well as broad-scale monitoring at both short and extended intervals, it is easier to gain useful knowledge and apply adaptive management more effectively. Not only can this knowledge be used in local planning and project design, in some instances it can also help update agency guidelines for forest resource management.

A Local Example: Sisters Area Fuels Reduction Planning Area

The forest planning and adaptive management model described above provides a framework for highlighting the value of soils information and expertise in planning and management. However, because the accompanying discussion and examples were relatively general, the following real-world example helps illustrate the added value in using soils information in project planning. The following example and discussion for dry forest management incorporates many of the management strategies and treatment recommendations recently suggested for other federal forest lands in Oregon and Washington; including FS, National Park Service, and Bureau of Land Management lands (Franklin and Johnson 2012).

Sisters Area Fuels Reduction (SAFR) is an approximately 32,000 acre planning area located within lower elevation ponderosa pine (*Pinus ponderosa*) forest of the Deschutes National Forest near the town of Sisters, Oregon (Figure 2.2). With 72 percent of the National Forest lands within the SAFR planning area identified for treatment, the SAFR project was one of the first large scale planning projects on the Sisters Ranger District to address the need for accelerated rates of treatment over a broader landscape as suggested by Franklin and Johnson (2012). These predominantly dry ponderosa pine forest ecosystems have been greatly modified over the past 100 years (Hessburg et al. 2005, Noss et al. 2006). Stand conditions now include young plantations, 60 to 100 year old stands, and uneven age stands with various tree cohorts. An environmental assessment of the area, which included a variety of restoration treatment prescriptions, was completed in 2008 and many planned activities have been implemented (USDA Forest Service 2008)

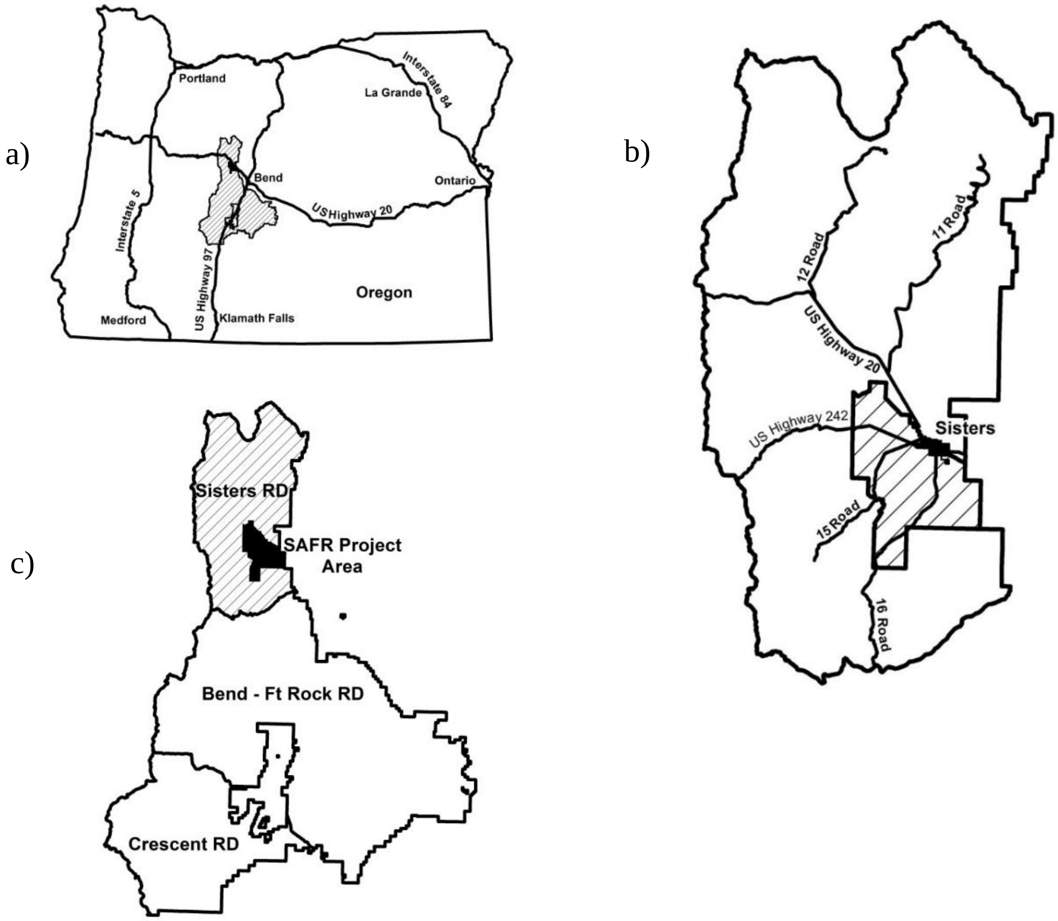

Figure 2.2 Sisters Area Fuels Reduction (SAFR) project area location: a) Deschutes National Forest (crosshatch) in Oregon, b) Sisters Ranger District (crosshatch), and c) SAFR project (crosshatch) within Sisters District.

Treatments within the planning area had multiple objectives, including improved forest health and resistance to insect epidemics, drought, and serious wildfires in the wildland-urban interface (WUI) (US Government 2003), while also providing quality wildlife habitat and other ecosystem services. Landscape treatments included thinning, shrub mowing, and prescribed burning to restore unique stand-level spatial patterns that serve important ecological functions, such as disturbance, regeneration, and habitat diversity (Hessburg et al. 2005, Johnson et al. 2008, Stephenson et al. 2011). Prescriptions included creating heterogeneous tree spatial patterns while conserving older trees regardless of tree size (Franklin and Johnson 2012). Desired tree spatial patterns and related heterogeneity were planned using a “mosaic thinning” process designed at two distinct scales (Stringer 2008).

Plans included a fuel reduction strategy with treatments to: a) reduce hazardous fuels, b) create defensible space adjacent to private lands, and c) provide safer travel routes should a fire occur. However, the planning area also contains mule deer (*Odocoileus hemionus*) winter range management allocations (USDA Forest Service 1990) where the forest understory often includes antelope bitterbrush (*Purshia tridentata*) that is important for sustaining deer herds during winter (Burrell 1982, Griffith and Peek 1989). This resulted in competing management objectives, i.e., the need to reduce fuels and improve forest health versus retaining or enhancing winter forage and other habitat components.

Soil Characteristics Reveal Opportunities and Limitations

Reconstructions of pre-settlement stand patterns can be useful in managing ponderosa pine and mixed conifer forests (Larson and Churchill 2012, Churchill et al. 2013). These authors emphasize, however, that these spatial patterns can vary by soil type. Thus, the Deschutes NF Soil Resource Inventory (SRI) (Larsen 1976) was used to identify three general soil groups within the SAFR planning area to help assess and match stand-level tree spatial patterns (Figure 2.3). One soil group is found on lava plains where soils have developed in shallow to deep pumice or in volcanic ash over an older residual soil on basaltic lavas. General productivity of these soils is reflected in the site index values (100 year base) between 70 and 85 for ponderosa pine (Larsen 1976). A wide range of soil depths, from very shallow to very deep, results in substantial tree spatial heterogeneity from the diverse soil carrying capacities. Linear arrays of larger trees often follow deeper soils formed on the edges of underlying bedrock, and higher stand densities are found where deeper soils are more extensive relative to more shallow soils. Openings occur in areas of shallow soils and the amount, size, and patterns of openings are determined by the extent of shallow soils in a given area.

A second soil group includes soils formed in relatively deep volcanic ash over glacial outwash. Productivity of these soils is somewhat lower than the first group, with site index values (100 year base) between 60 and 75 for ponderosa pine. These soils have relatively high moisture supplying capacities and the consistent nature of the underlying outwash results in tree patterns that are less variable than with the first soil group. Tree clumps and openings still can occur but overall the stands have less spatial heterogeneity because soil depth and moisture are less variable.

The third soil group is similar to group 2, with volcanic ash over glacial outwash, but the ash is thinner and there are more coarse fragments in the surface soil compared to the other soil groups. The result is low moisture availability and a mix of ponderosa pine and western juniper (*Juniperus occidentalis*) with low productivity (Larsen 1976). The droughty soils contribute to lower stand densities and more openings than with group 1 or 2 soils, and removal of competing juniper can strongly alter the spatial patterns of residual trees after treatment. Some of these shallow, rocky soils also provide somewhat fire resistant areas where scattered, older junipers are well-established and other vegetation is limited.

To help plan thinning and fuel reduction treatments that also maintain desirable winter forage, the characteristics of the three soil groups were integrated with local micro- and macro-climate information to refine predictions of amounts and types of understory. The somewhat higher elevation and precipitation of the group 1 soils area result in understory greenleaf manzanita (*Arctostaphylos patula*) and snowbrush (*Ceanothus velutinus*) but little or no bitterbrush. Brush control in these areas requires aggressive treatments and is only maintained when trees reach canopy closure. Group 2 soils are found in a somewhat lower precipitation zone but their relatively high moisture supplying capacity can support substantial bitterbrush. Thinning, mowing and burning treatments on these soils typically result in quick recovery of desirable bitterbrush forage. The droughty soil group 3 supports an understory mixture of sagebrush (*Artemisia tridentata*) and some bitterbrush. In these areas prescribed fire treatments reduce the shrub component while increasing bunchgrass (*Festuca idahoensis*) in the understory. Thinning the overstory trees on these droughty soils can increase available soil water while promoting bitterbrush in the understory.

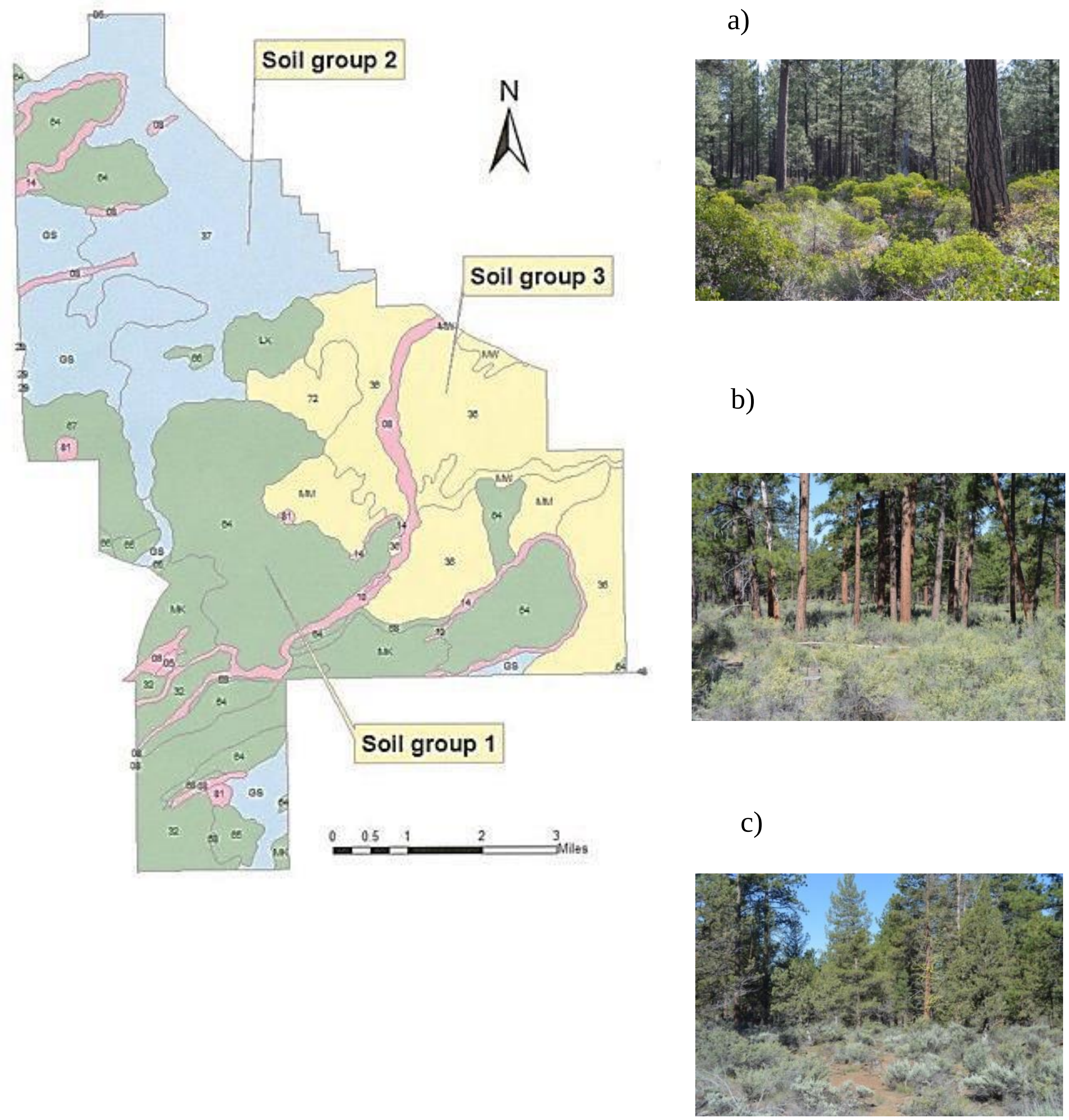

Figure 2.3 Major soil types within the SAFR project planning area, with photos of characteristic vegetation for: a) Soil group 1, b) Soil group 2, and c) Soil group 3.

Interdisciplinary Strategy for Land Management Actions

Tree density targets were initially determined from both reference conditions in areas that still had an old growth tree component and from management tools such as stand density index (SDI) (Reineke 1933). Recognition and understanding of the three major soil groups were then used to refine treatment prescriptions and implementation guidelines. Thus, in group 1 soil areas, variable soil depths are used to make better choices about retention and removal of trees to achieve the desired landscape heterogeneity. Locations and extent of shallow soils help determine the areas and shapes of openings, whereas identification of deeper soils can help locate areas for retaining wildlife cover where soils are more likely to sustain desirable cover levels.

The relative uniformity of the group 2 soils provides more flexibility for design and placement of tree clumps and openings, whereas management in areas of the droughty group 3 soils provides unique limitations in both carrying capacity and species composition. Targets for residual trees on group 3 soils must consider the related overstory and understory interactions, including the effects of juniper removal. Although juniper control is often desirable, there are areas of old growth juniper within the planning area that consist of small one or two acre patches within the larger landscape. These small patches have droughty, rocky, shallow soils that support very little understory vegetation. This makes these areas somewhat fire resistant allowing juniper to establish and thrive while providing important habitat diversity across the landscape.

Soils information also can be used to strategically plan and focus primary understory fuel treatments on soils less suitable for bitterbrush production, and to modify treatments in other areas to retain or promote bitterbrush on soils that can better support the species. Because soil group 1 is less suitable for bitterbrush these areas are treated more aggressively to reduce brush fuels and encourage residual tree growth. In areas of soil group 2, where a variety of treatments can yield good responses by bitterbrush, treatments are scheduled in a sequence and pattern that allow treated areas to recover before adjacent areas are treated. To maintain a bitterbrush component in areas of soil group 3, stands are thinned to lower densities and prescribed burning sometimes is restricted to avoid converting the understory to bunchgrass.

Soils Information for Project Design and Implementation

In this step, information about inherent soil qualities and dynamic responses to disturbances can help identify differences in soil resistance and resilience to disturbances and expected effects on key soil functions (Page-Dumroese et al. 2007). The fine ash soils in the SAFR planning area have inherently high porosity making them resistant to reduced aeration and infiltration from compaction, however they can show large reductions in soil penetrability (Craigg and Howes 2007) at levels that can restrict root growth (Siegel-Issem et al. 2005). Operationally, soil monitoring has shown that the added strength of compacted soils can sometimes allow equipment activity to proceed without further disturbance, even when the soils are moist. Again, soils information and expertise help identify such trade-offs.

Monitoring Ecosystem Responses and Adaptive Management

Post-treatment monitoring has confirmed expectations of desirable stand patterns and vegetation responses where key soil differences were considered. Treatments in areas of group 1 soils have reduced much of the brush while also retaining habitat in suitable areas. In areas of group 2 soils, bitterbrush responses were positive following thinning, mowing and burning that reduced stand densities and created both small and large canopy openings. Treatments on these soils also significantly reduced and delayed recovery of less desirable manzanita that was originally present. Some areas of group 3 soils that were thinned, mowed, and burned were converted largely to a bunchgrass understory, whereas other unburned treatment areas retained a bitterbrush component. Other notable differences and trade-offs were observed, e.g., bunchgrass-dominated treatment areas contained a variety of understory forbs that provided additional forage value to mule deer when not covered by snow (Monty Gregg, USDA Forest Service wildlife biologist, personal communication).

On September 12, 2012 the Pole Creek Fire started about 12 miles southwest of Sisters, Oregon, and after several weeks it eventually burned into the SAFR planning area. Several SAFR treatment units located between the fire and the Sisters community that had been previously thinned, mowed, and burned were successfully back-burned to assist with the suppression efforts (Jinny Reed, USDA Forest Service fuels planner, personal communication).

Conclusions and Outlook

With the soil quality concepts, adaptive management model, and real world example of the SAFR Project presented here, we hope that forestry professionals will recognize the value of soils information in planning and management decisions involving diverse resources on a large forest land base. We believe that forest managers can make better planning and management decisions through wider awareness, understanding and application of local soils information. Our experience suggests that to use soils information to its full potential and assure sustainability, this information should be considered early in the planning process to help match soils to the desired management objectives, related actions and expected treatment responses. Management planning for diverse benefits also invariably involves some tradeoffs and compromises, and knowledge of soil resources can assist these decisions. By recognizing the wide differences among soils in their capacity for important ecological functions and in their responses to disturbances, managers can help assure adequate measures are being taken to protect soil function while not being overly restrictive. As planned projects are implemented, soils and other resource monitoring can validate expectations or direct effective modifications when planning future management actions.

Although soil science continues to be recognized as an important discipline in natural resource management, more can and should be done to increase the awareness of the soil resource (Drohan et al. 2010). We are also concerned that current and near-future staffing in larger forest management organizations such as the FS does not consistently provide adequate soils expertise and experience for important planning efforts on forest lands (Zimmerman 2012). Emphasis of the importance of a soils program in forest management decisions starts with leadership at national, regional, and state levels of a public or private organization. Recent administrative direction within public agencies has given more emphasis to growing issues such as ecological restoration and climate change (e.g., Bosworth and Brown 2007, Tidwell and Brown 2011). Increased “executive-level” leadership within important disciplines such as soils could help to communicate the importance of the soil resource and the need for soils staffing comparable to that for other key resources.

Because significant constraints on the number of specialized staff is likely to continue, other approaches may also be helpful in promoting the effective integration of soils information in the planning and design of land management actions. One approach is to provide formal training and certification in forest soils for existing staff, similar to FS programs for silviculture and other key areas (Walker 2014). Staffing of many of the other disciplines within the FS has also declined in recent years (Zimmerman 2012), and this cross training approach suggested for the soil resource may prove useful in other resource areas as well. As with other major resource specializations, training and certification programs cannot serve as a full substitute for staff with professional degrees from university soil science programs. However, soils training and certification can provide valuable awareness and understanding among staff and interdisciplinary planning teams with diverse backgrounds, as well as clarify key concepts and terminology that facilitate effective communication and applications in management planning. The Natural Resource Conservation Service, for example, has soil scientists whose primary responsibility is to develop soil resource inventories, maps and interpretations that can be understood and used by both soil scientists and non-soil scientists to make informed resource management applications. The agency also has Soil Conservationists who then use that information to help landowners make appropriate land management decisions. Using a similar approach in forestry organizations, staff certification in forest soils could help create effective teams of “Forest Soil Conservationists,” especially if the training targeted a variety of resource disciplines that can benefit from soils information (e.g., hydrology, silviculture, range, wildlife, fisheries, and fuels). The training could include understanding the types of available soil information, how to access and integrate that information with a spatial database, and how various soil interpretations can be further developed and applied in forest planning. The forest planning and adaptive management model presented here could also be used to further organize and refine an effective forest soils training and certification program.

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Chapter 3 : Using Soil Surveys to Refine Ecologically Based Forest Land Management Interpretations during Project Level Planning in the Eastern Oregon Cascades

Terry L. Craigg

Abstract

Natural resource programs in public agencies are continually adapting to the challenges of evolving knowledge and experience in the field of forestry. As a result many of today's forest land management decisions are not related to just growing trees, but include other resource issues such as restoring resilient forest conditions, habitat enhancement, and improved water quality. One of the challenges facing resource managers is the development of ecologically based land management strategies that address the various opportunities and resource issues across large complex landscapes. Knowledge of the soil resource can assist this process by matching different land management objectives to soils that have the highest potential for supporting those objectives. The result is management strategies that are both sustainable and better able to meet the intent of the planners because management actions are occurring on soil types that have high potential for attaining resource objectives. Here those concepts are applied to a forest restoration planning project within a portion of the dry forest province of the Northwest Forest Plan located on the Deschutes National Forest in central Oregon. Soil survey data was used to help refine ecologically based treatment prescriptions that address a variety of forest level land management objectives.

Introduction

The Northwest Forest Plan (NWFP) (USDA Forest Service & BLM 1994), was drafted over two decades ago with a goal of maintaining and creating connected or interactive old-growth forest ecosystems on federal lands within the range of the Northern Spotted Owl (*Stix occidentaolis caurina*). Forest landscapes within the range of the NWFP exhibit broad scale variations in inherent growth potentials, disturbance regimes and other important ecological functions.

The NWFP's success has been questioned in the dryer provinces of the plan due to losses of old growth forest to wildfire (Spies et al., 2006). While losses of old growth forest to stand replacement wildfire are consistent with early assumptions (Spies, 2006), the rate of loss in the eastern and southern dry provinces of the plan are higher than expected, threating the existence of these forests and species associated with them (Moeur et al., 2005).

Another concern in dry forest provinces is that retention strategies intended to protect the threatened northern spotted owl, may be in conflict with the goal to restore old-growth forest types (Lehmkuhl et al., 2015). Prior to fire suppression, dry forest of the Inland Northwest were burned predominantly by frequent low- and mixed-severity fires (Agee, 1993; Hessburg et al., 1994). These fires favored large fire tolerant tree species of ponderosa pine, Douglas-fir, and western larch (Heyerdahl et al., 2001; Merschel et al., 2014) and helped maintain low tree densities, clumped tree spatial patterns, and simple canopy layering (Hessburg et al., 2005).

Past management and fire suppression have resulted in many of these dry forest types being modified from their historic structure, composition, and function (Hemstrom, 2001; Reinhardt et al. 2008; Merschel et al., 2014). Restoration of dry forest back to historical open old-growth results in a forest structure that is less suitable for owl habitat compared to the thick dense forest that developed as a result of fire exclusion (Lee and Irwin, 2005).

A challenge now facing resource managers is the development of ecologically based treatment prescriptions that address these various land management issues while at the same time balancing different and often competing land management objectives across large landscapes (Craigg et al. 2015). To address this challenge, a landscape classification system is needed that interprets the inherent potentials of different landscape areas and partitions the landscape into land management subunits that reflect different land management opportunities and limitations.

A forest planning and adaptive management model that integrates the concepts of inherent and dynamic soil quality was presented in Chapter 2 (Craigg et al., 2015). The following refinements of ecologically based forest land management interpretations illustrate the application of the first two steps of that model. Specifically the identification and refinement of “Land Management Objectives” based upon trends of concern identified in a recent watershed analysis, and the use of the soil inventory to identify “Opportunities & Limitations Based on Soil Quality.”

Different soils within a landscape result from the integration of five dominant soil-forming factors, including climatic influences, soil and surface organisms, local topography, geology/parent materials, and time for soil development (Jenny 1941). Different soil types, resulting from the integration of these soil forming factors contribute to landscape heterogeneity by integrating these biophysical landscape attributes into meaningful landscape subunits. In addition soil inventories describe the characteristics of different soils in a given area, classify those soils according to a standard classification system, delineate the boundaries of the soils on a soil map, and provide interpretive soil data sets (USDA NRCS). By doing this soil surveys provide a stable resource for interpreting soil potentials and partitioning landscapes into meaningful subunits based on their different anticipated responses to disturbances and management (Craigg et al. 2015).

In this study we tested the value of a soil survey data set and mapping for stratifying a planning area and identifying land-management strategy areas that can be used to help refine ecologically based treatment prescriptions in a forest level planning project located on the Sisters Ranger District of the Deschutes National Forest in central Oregon. Broad land management objectives were initially identified based upon landscape trends described in a Lower Metolius watershed analyses completed by a US Forest Service Ranger District interdisciplinary team prior to initiation of the planning project. Objectives were further refined through a review of current relevant literature. A soil survey was then used to partition the landscape into land management subunits by making predictions about different inherent site potentials, disturbance regimes, and other important ecological functions. Vegetation data sets, wildlife habitat mapping, and hydrologic indicators were used to help validate predictions and these predictions were then used to present land management interpretations that can be used to help refine ecologically based treatment prescriptions being developed for different forest stands..

Methods

Overview of the Green Ridge planning area

The Sisters Ranger District of the Deschutes National Forest in central Oregon initiated the Green Ridge landscape planning project in 2015. The Green Ridge project included 24,690 acres within the larger approximately 100,000 acre Lower Metolius watershed and was named after the green ridge volcanic landscape, located at the northeast end of the Sisters Ranger District (legal: T16 and 17S, R9 and 10E, all sections, Willamette Meridian, Jefferson County, Oregon) (Figure 3.1). The Green Ridge landscape formed on the eastern flanks of an ancient shield volcano that gently slopes to the east (Hales 1974). Elevations within the project range from 5100 ft down to 2930 ft. Common to the region, precipitation trends follow elevation gradients with a mean annual precipitation in the higher elevations at the western end of the project area receiving 30 to 35 inches and precipitation dropping in the eastern end of the planning area to around 20 inches. The volcanic landform has been dissected by a number of small perennial and intermittent streams that flow to the east (Figure 3.1).

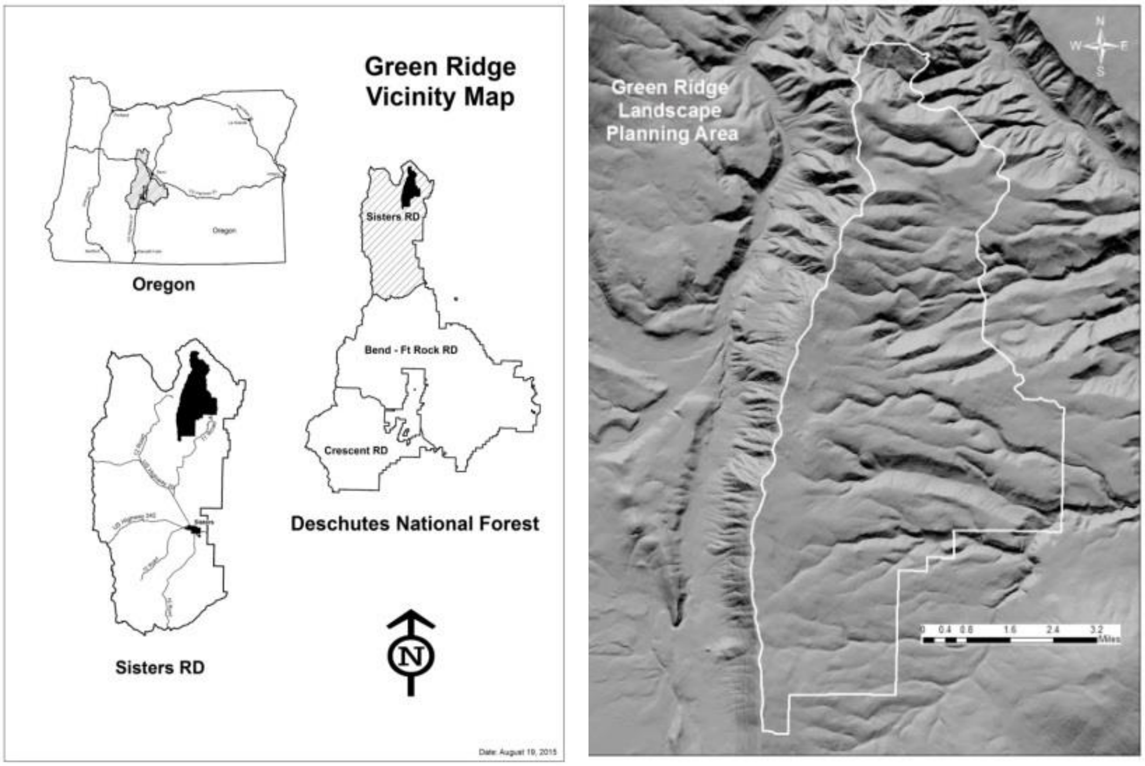

Figure 3.1 Vicinity map for the Green Ridge planning area and landscape topography of the Green Ridge planning area.

Forest Management Direction

The Deschutes National Forest Land and Resource Management Plan (LRMP) as amended guide all natural resource management activities and provides standards and guidelines for the Deschutes National Forest (USDA Forest Service 1990). Those LRMP land allocations located within the Green Ridge planning area are listed in Table 3.1.

Table 3.1 Deschutes LRMP management areas.

LRMP Management Area	**Acres in Project Area**
Deer Habitat	1,801
General Forest	18,718
Metolius Heritage	2,395
Metolius Special Interest	116
Metolius Wildlife-Primitive	827
Old Growth	833
Total Project Area	24,690

In addition to management direction found in the LRMP, the project area is managed under the Northwest Forest Plan (NWFP) (USDA FS and USDI BLM 1994). The NWFP amended the LRMP in 1994 and the planning area contains three NWP allocations (Table 3.2).

Table 3.2 Northwest Forest Plan land allocations.

Northwest Forest Plan Land Allocations	**Acres in Project Area**
Administratively Withdrawn Areas	992
Late Successional Reserves	9,496
Matrix	14,202
Total Project Area	24,690

Administratively Withdrawn Areas: areas usually allocated for their visual, backcountry, or other natural resource values. Management emphasis precludes scheduled timber harvest.

Late Successional Reserves: areas allocated to protect and enhance conditions of late-successional and old-growth ecosystems, which serve as habitat for related species including the northern spotted owl.

Matrix: areas where most timber harvest and other silvicultural activities would be conducted with suitable forest lands, according to standards and guidelines. Most scheduled timber harvest takes place in the matrix.

Land Management Objectives and Watershed Trends of Concern

To develop land management objectives for the Green Ridge planning area, the Sisters Ranger District formed an Inter-disciplinary Team (IDT) consisting of specialists in forestry, wildfire fuels, wildlife, hydrology, soil science, botany, fisheries, cultural resources, and recreation. The IDT completed the Lower Metolius Watershed Analysis (WA) which included lands within an adjacent to the Green Ridge planning area prior to the initiation of the Green Ride project as required by the NWFP. The watershed analysis provided a landscape level assessment that was intended to guide project planning (USDA Forest Service 2016). The analysis examined historic conditions as well as recent disturbances and identified the following trends of concern in the Green Ridge project area: (i) changes in forest structure, species composition, and stand density levels leading to forest health concerns (ii) high fuel loads and changes in fire behavior leading to increased risk and occurrence of wildfire (iii) the need to grow and maintain nesting, roosting, and foraging habitat for Northern Spotted Owl as well as habitat for other wildlife Management Indicator Species (MIS) (iiii) and alteration of hydrologic functioning of perennial and intermittent streams impacting habitat for native fish and causing degradation of riparian habitats and hardwoods.

The watershed trends of concern were used to identify land management objectives for the planning area. With an understanding of the landscape and forest-specific context of these broader objectives, management actions were next matched to soils with a higher potential for both achieving objectives and sustaining those actions. Refinements to land management interpretations were then discussed for each of the objectives.

Soil Survey Information

A soil inventory for the Green Ridge planning area was completed in 2002 and includes a portion of the larger Upper Deschutes River Area Soil Survey that covers parts of Oregon’s Deschutes, Jefferson, and Klamath Counties (USDA NRCS 2002). The soil survey is a publication of the National Cooperative Soil Survey, a joint effort of the United States Department of Agriculture and other Federal agencies, State agencies, and local agencies. Soil maps were developed at a scale of 1:24,000 and have been digitized in accordance with the Soil Survey Geographic (SSURGO) database standards (USDA NRCS 2010). A map of the soil mapping units identified in the Green Ridge planning area is displayed in Figure 3.2.

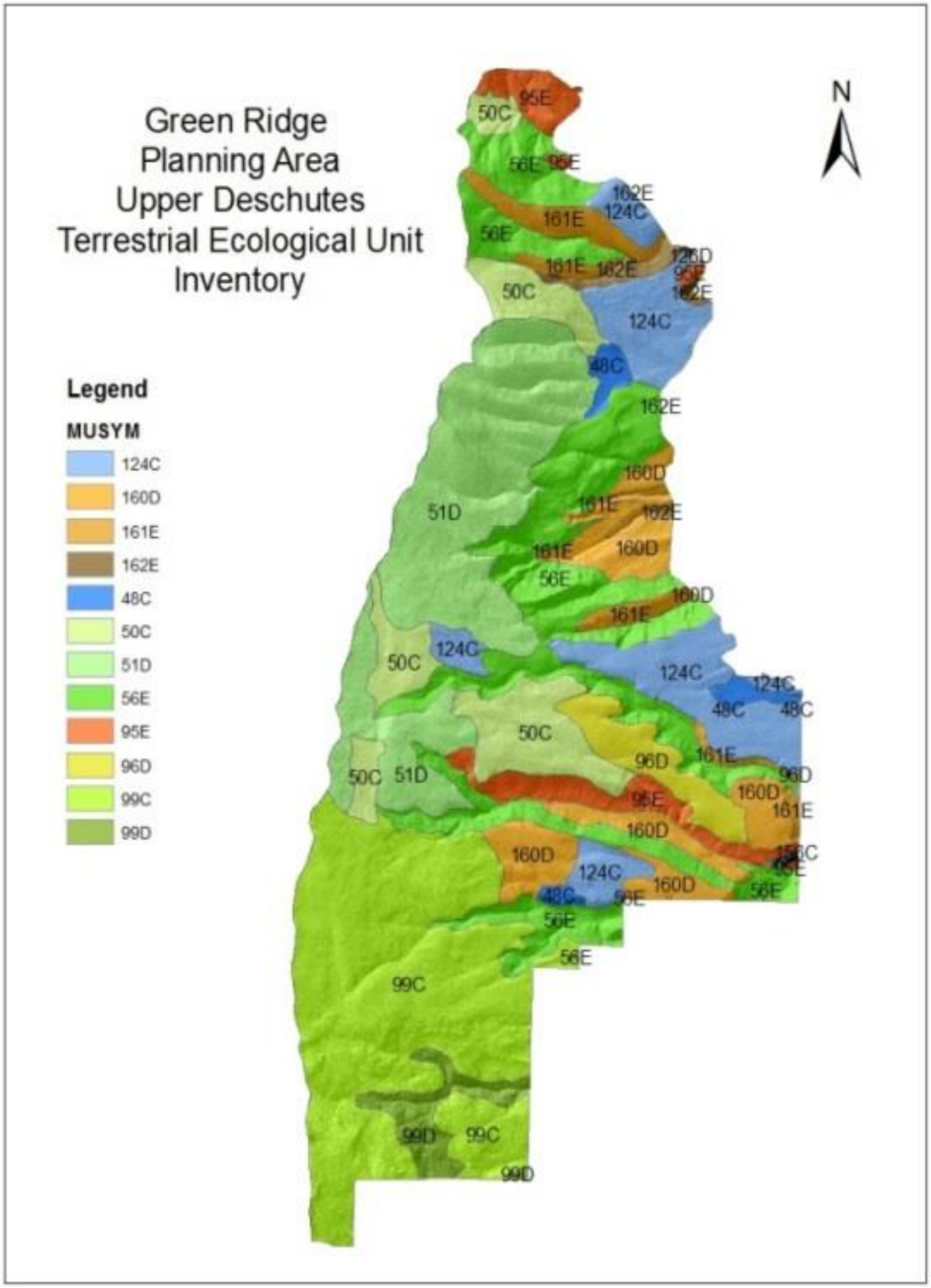

Figure 3.2 Upper Deschutes River Area Soil Survey for the Green Ridge planning area.

Classifying mixed-conifer forest types

The vegetation classification proposed by Merschel et al. (2014), was used to classify mixed-conifer forest types within the planning area. This system identified different forest potentials by first separating types based upon historical forest structure and composition. It next interpreted current forest structure and species composition to predict successional trajectories following recent changes in land management.

Mapping mixed-conifer forest types

Forest types described by Merschel et al. (2014) were assigned to different soil series based upon important differences in environmental gradients of topography, elevation, and climate. Persistent Shade tolerant were identified as occurring in cold/wet environments, while Recent Grand fir and Recent Douglas-fir types occurred in warm/moist environments, and Persistent Ponderosa pine types occurred in warm/dry environments. Soil series data sets and soil map unit descriptions were used to identify these different landscape attributes and assign mixed-conifer forest types to soil series. Slope class, dominant aspect, and landform elevations were assigned to soil series based upon soil map unit descriptions which identified those attributes. Different climatic gradients were next divided based upon soil temperature regime, mean annual precipitation class, and soil water holding capacity. This information along with environmental descriptions of the type of environment described by Merschel et al. (2014), were then used to assign a forest type to an individual soil series.

Results

Soil series

Eight soil series were identified in the planning area (Table 3.3).

Table 3.3 Soil series names and taxonomic classifications for the eight soil series mapped within the Green Ridge planning area.

Soil series name	**Taxonomic classification**
Glaze	Ashy over loamy-skeletal, mixed Xeric Vitricryands
Gap	Ashy over loamy, mixed Xeric Vitricryands
Prairie	Ashy over loamy, mixed Xeric Vitricryands
Windego	Ashy over loamy-skeletal, mixed, frigid Alfic Vitrixerands
Smiling	Ashy over loamy, mixed, frigid Vitrixerands
Flarm	Fine, mixed, frigid Ultic Palexeralfs
Parrego	Fine-loamy, mixed, frigid Ultic Haploxeralfs
Thorn	Loamy-skeletal, mixed, frigid Lithic Mollic Haploxeralfs

The Glaze soil series occur on the north aspects of large incised drainages in the planning area. While Gap and Prairie soils occur on the south aspects of these drainages and on lava plains in the southern portion of the planning area (Table 3.4). The Gap, Glaze, and Prairie soil series also occur in areas of colder “cryic” soil temperature regimes and higher precipitation zones predominately on the western side of the planning area (Table 3.5). These soil series have deep (40 to 60 inches) and moderately deep (20 to 40 inches) soil profiles consisting of volcanic ash soil parent materials with varying amounts of soil coarse fragments (fragments > 2mm) throughout their profiles (Table 3.6).

Soil Taxonomy: What's in a name?

A soil's taxonomic name provides detailed information about a soil's complex structure, horizons, and traits, thereby providing clues as to how a given soil functions within different ecosystems. For example, the taxonomic name of the first five soils in Table 3 end in the letters "ands" indicating they are in the Andisols soil order. Andisols commonly form in volcanic ash or similar soil parent materials; they are dominated by glass and/or colloidal weathering products such as allophane. Andisols differ from other soils in that they typically have lower bulk densities, higher porosities, and weak structural development. "Cryic" indicates a colder soil temperature regime and shorter growing season compared to the slightly warmer "frigid" temperature regime and "xeric" indicates a xeric soil moisture regime with warm dry summers and cool wet winters. "Vitri" indicates these soils made it into the Andisols soil order by having large amounts of volcanic glass. "Ashy over loamy" indicates a cap of volcanic ash over a more crystalline soil material below and "skeletal" indicates a soil with over 35% coarse fragments (materials > 2 mm) in much of the soil profile.

The remaining three soils in Table 1 end in the letters "alfs" indicating they are in the Alfisols soil order. Alfisols are moderately leached soils that have relatively high fertility. These soils often form under forest and have a subsurface horizon in which clays have accumulated. "Xeralfs" have a xeric soil moisture regime. "Pale" indicates older Alfisols having more development in the soil profile while "Haplo" indicates the more common Alfisols. "Ultic" is an indication of high profile leaching while "Mollic" indicates higher organic carbon and base saturation in the surface horizons. "Lithic" indicates a soil that is 20 inches or less deep. "Fine" indicates a soil having between 35 and 60 percent clay while Fine-loamy" indicates 18 to 35 percent clay in the fine earth fraction of the soil.

The Windego, Smiling, and Flarm, soil series occur on the lower elevation drainages and lava plains (Table 3.4). These soil series occur in the slightly warmer “frigid” soil temperature regime and lower precipitation zones on the eastern side of the planning area (Table 3.5). All of these soils have very deep soil profiles (> 60 inches) containing volcanic ash soil parent materials (Table 3.6). The Windego soils have large amounts of soil coarse fragments giving them lower available water holding capacities compared to the Smiling and Flarm soils. Unlike the previous soils the Flarm soils have clay loam sub-surface horizons and are seasonally wet soils located within and adjacent to the Smiling soil series.

The Parrego and Thorn soil series occur on ridge tops and south facing drainages. These series are also located in areas having the slightly warmer “frigid” soil temperature regime and in lower precipitation zones on the eastern side of the planning area (Table 3.5). Parrego soils have moderately deep soil profiles while Thorm soils have shallow soil profiles (< 20 inches). Both soils have clay loam sub-surface horizons and both have large amounts of soil coarse fragments in their soil profiles giving them relatively low available water holding capacities compared to other soils in the planning area (Table 3.6).

Table 3.4: Landform elevation and topography for different soil series.

Soil series	Landform elevation	Dominant aspect	Dominant slope class %
Glaze	Large incised drainages	North	15-50
Gap	Large incised drainages and lava plains	South and East	0-30
Prairie	Large incised drainages and lava plains	South and East	0-50
Windego	Lower elevation drainages and lava plains	South and East	30-50
Smiling	Lower elevation drainages and bedrock lava plains	East	0-50
Flarm	Lower elevation bedrock lava plains	East	0-15
Parrego	Lower elevation ridgetops and south facing drainages	South and East	15-30
Thorm	Lower elevation ridgetops and south facing drainages	South	15-50

Table 3.5: Soil temperature regime and mean annual precipitation for different soil series.

Soil series	Soil temp regime	Mean annual precipitation (inches)
Glaze	Cryic	30-35
Gap	Cryic	30-35
Prairie	Cryic	30-35
Windego	Frigid	20-30
Smiling	Frigid	20-25
Flarm	Frigid	20-25
Parrego	Frigid	20-25
Thorm	Frigid	20-25

Table 3.6: Soil texture, depth, and available water holding capacity for individual soil series.

Soil series	Soil texture		Soil depth	Available water holding capacity (inches)
	Surface horizon	Sub-surface horizons		
Glaze	Sandy loam	Extremely stony loam	Deep (40-60 inches)	5
Gap	Sandy loam/loam	Clay loam	Deep (40-60 inches)	8
Prairie	Sandy loam	Cobbly loam	Moderately deep (20-40 inches)	4
Windego	Sandy loam	Very cobbly clay loam	Very deep (>60 inches)	6
Smiling	Sandy loam	Clay loam	Very deep (>60 inches)	10
Flarm	Loam	Clay loam	Very deep (>60 inches)	10
Parrego	Sandy loam	Cobbly clay loam	Moderately deep (20-40 inches)	3
Thorm	Sandy loam	Extremely stony loam	Shallow (10-20 inches)	2

Soil mapping units

Twelve soil mapping units were mapped in the Green Ridge planning area including two soil map unit consociations, two map unit associations, and eight map unit complexes (Table 3.7). Soil mapping units represent one to three soil series with some having a component of rock outcrop (see text box 2). All of the mapping units are phased based upon slope breaks and mapping unit 162E is also phased based upon climate.

The soil survey map unit

Soil map units represent a set of geographic areas for which a common management strategy is suitable. A soil map unit is typically composed of one or more noncontiguous polygons, distributed throughout the soil survey area. The size of a map unit varies depending upon the level of detail at which the survey was conducted. Forest lands are typically mapped at a scale of 1:24000 and map units can range in size from approximately two acres to thousands of acres in size.

A map unit is typically composed of one or more "map unit components." A map unit component is typically a "soil series" but can also include a "soil taxonomic classification" or some kind of non-soil entity like "rock outcrop." "Major" soil components are part of the map unit name. For example, "Glaze-Prairie-Rock outcrop association, 30 to 50 % slopes." Although map units contain components, those components are not delineated within the map unit. There are also dissimilar inclusions of other components in a map unit. Generally these inclusions do not exceed 15 to 25 % of the map unit.

Three different types of soil map units are used in soil surveys. They include soil map unit "consociations, complexes and associations." In a consociation, delineated areas are dominated by a single soil series. Complexes and associations consists of two or more dissimilar components occurring in a regular repeating pattern across a landscape. They differ in that the components of a map unit complex cannot be separated at a scale of 1:24000 while the major components of a map unit association can be separated at that scale but the mapper chooses not to separate them. For example, a typical map unit association may include three components which occur on a north aspect, south aspect, and ridge top and the pattern repeats across the landscape, while these could be separated into individual map unit consociations, the mapper chooses to map them as an association.

Table 3.7 Soil mapping units and soil map unit components mapped within the the Green Ridge planning area.

Soil Map Unit #	**Soil Map Unit Name**	**Soil Map Unit Components and Percentage**
56E	Glaze-Prairie-Rock outcrop association, 30 to 50% slopes	Glaze soil and similar inclusions 35% Prairie soil and similar inclusions 35% Contrasting inclusions 15%
51D	Gap-Glaze association, 15 to 30% slopes	Gap soil and similar inclusions 45% Glaze soil and similar inclusions 40% Contrasting inclusions 10%
50C	Gap sandy loam, 0 to 15% slopes	Gap soil and similar inclusions 90% Contrasting inclusions 10%
99C	Prairie-Gap complex, 0 to 15% slopes	Prairie soil and similar inclusions 45% Gap soil and similar inclusions 45% Contrasting inclusions 10%
99D	Prairie-Gap complex, 15 to 30% slopes	Prairie soil and similar inclusions 45% Gap soil and similar inclusions 45% Contrasting inclusions 10%
162E	Windego-Smiling complex, cool, 30 to 50% slopes	Windego soil and similar inclusions 55% Smiling soil and similar inclusions 30% Contrasting inclusions 15%
161E	Windego-Smiling complex, 30 to 50% slopes	Windego soil and similar inclusions 55% Smiling soil and similar inclusions 30% Contrasting inclusions 15%
160D	Windego-Parrego complex, 15 to 30% slopes	Windego soil and similar inclusions 45% Parrego soil and similar inclusions 40% Contrasting inclusions 15%
124C	Smiling sandy loam, 0 to 15% slopes	Smiling soil and similar inclusions 90% Contrasting inclusions 10%
48C	Flarm-Smiling complex, 0 to 15% slopes	Flarm soil and similar inclusions 45% Smiling soil and similar inclusions 45% Contrasting inclusions 10%
95E	Parrego-Rock outcrop-Windego complex, 30 to 50% slopes	Parrego soil and similar inclusions 35% Rock outcrop 25% Windego soil and similar inclusions 25% Contrasting inclusions 15%
96D	Parrego-Thorn-Rock outcrop complex, 15 to 50% slopes	Parrego soil and similar inclusions 35% Thron soil and similar inclusions 25%

Classifying Mixed-conifer Forest Types

Merschel et al. (2014), identified the following four mixed-conifer forest types based upon historical forest structure and composition: (i) Persistent Shade Tolerant (ii) Recent Grand fir (iii) Recent Douglas-fir and (iiii) Persistent Ponderosa pine (Table 3.8).

Table 3.8: Classification of mixed-conifer forest types and environmental setting as described in Merschel et al. (2014).

Classification of forest types based on historical and modern composition and structure (Merschel et al., 2014)	**Environmental setting of forest types**
Persistent Shade Tolerant	Cold/wet environments
Recent Grand fir	Warm/moist environments
Recent Douglas-fir	Warm/dry environments
Persistent Shade Tolerant	Warm/dry environments

Once classified, forest types were next interpreted to predict successional trajectories following recent changes in land use (Table 3.9). Persistent Shade tolerant types were described as historically having high stand densities, a mixture of conifer species, and longer fire return intervals compared to other types (Merschel et al., 2014). This has resulted in low departure from historic forest conditions. In contrast Recent Grand fir and Recent Douglas-fir forest types showed high departure from historic conditions. Past management and fire suppression have resulted in an increased in both stand densities and tree species conversion from fire resistant species such as ponderosa pine to thick understories of fire sensitive grand fir and Douglas-fir. Persistent Ponderosa pine types showed moderate departure from historic conditions. While increases in shade tolerant tree species has not occurred in this forest type, past management and fire suppression has resulted in an increase in densities of ponderosa pine.

Table 3.9: Mixed-conifer forest types and successional trajectories following recent changes in land management.

Forest type (Merschel et al., 2014)	**Successional trajectories following recent changes in land management**		
	Historical stand conditions	**Fire return interval relative to different forest types**	**Departure from historic stand conditions**
Persistent Shade Tolerant	High stand densities and a mixture of conifer species	Longer fire return intervals	Low departure from historic forest conditions due to longer historic fire return intervals.
Recent Grand fir	Low stand densities of ponderosa pine and Douglas-fir	Short fire return intervals	High departure from historic forest conditions due to past management and fire suppression resulting in an increase in both stand densities and shade tolerant tree species.
Recent Douglas-fir	Low stand densities of ponderosa pine and Douglas-fir	Short fire return intervals	High departure from historic forest conditions due to past management and fire suppression resulting in an increase in both stand densities and shade tolerant tree species.
Persistent Shade Ponderosa pine	Low stand densities of predominantly ponderosa pine	Short fire return intervals	Moderate departure from historic due to past management and fire suppression resulting in an increases in ponderosa pine stand density.

Mapping Mixed-conifer Forest Types

Persistent Shade Tolerant and Recent Grand Fir types were identified in areas of the colder cryic soil temperature regime and higher precipitation zones while the Recent Douglas-fir and Persistent Ponderosa Pine types were identified in areas of warmer frigid soil temperature regimes in the lower precipitation zones. In addition to these soil series attributes, information from the soil mapping unit descriptions were also used to assign different forest types. For example, in the colder\wetter portion of the planning area slope and aspect were used to assign Persistent Shade Tolerant forest types to colder north aspects while Recent Grand Fir types were assigned to other aspects.

Other soil attributes in addition to environmental gradients of climate, temperature, and topography were also used to justify the assignment of forest types to soil series. For example, soil texture, depth, and the resulting available water holding capacity (AWHC) for different soil series was interpreted along with different precipitation zones to help determine the effect of available water supplying capacity of different soils on forest type potential. AWHC for different soils ranged from 2 to 10 inches depending upon soil texture, depth, and amounts of coarse fragments (materials > 2 mm). Shallow to moderately deep Throm and Parrego soil series, with large amounts of stones and cobbles in their sub-surface horizons, resulted in only 2 to 3 inches of AWHC in these soil series. Low AWHC along with the lower precipitation zone of these areas further justified the warm/dry Persistent Ponderosa Pine forest type. The considerably higher AWHC of 6 to 10 inches in the Windego, Smiling, and Flarm soil series, was offset by the lower precipitation zone, again justifying the warm/dry environments of the Recent Douglas-fir forest types (Table 3.10).

Table 3.10 Soil series and soil map unit criteria used to assign mixed-conifer forest types to soil series.

Soil series	**Forest type (Merschel et al., 2014)**	**Elevation**	**Topography**		**Climate**		
		Landform elevation	**Dominant aspect**	**Dominant slope class %**	**Mean annual precip (inches)**	**Soil temp regime**	**Soil water holding capacity (inches)**
Glaze	Persistent shade tolerant	Large incised drainages	North	15-50	30-35	Cryic	5
Gap	Recent grand fir	Large incised drainages and lava plains	South and East	0-30	30-35	Cryic	8
Prairie	Recent grand fir	Large incised drainages and lava plains	South and East	0-50	30-35	Cryic	4
Windego	Recent grand fir	Lower elevation drainages and lava plains	South and East	30-50	20-30	Frigid	6
Smiling	Recent grand fir	Lower elevation drainages and bedrock lava plains	East	0-50	20-25	Frigid	10
Flarm	Recent grand fir	Lower elevation bedrock lava plains	East	0-15	20-25	Frigid	10
Parrego	Persistent ponderosa pine	Lower elevation ridgetops and south facing drainages	South and East	15-30	20-25	Frigid	3
Thorm	Persistent ponderosa pine	Lower elevation ridgetops and south facing drainages	South	15-50	20-25	Frigid	2

Discussion

Management Interpretations and Refinements of Ecologically Based Land Management Objectives

Wildlife Habitat Northern Spotted Owl

Management Objectives

The Northern Spotted Owl (NSO) (*Strix occidentalis caurina*) is believed to have historically inhabited most forest throughout southwestern British Columbia, western Washington and Oregon, and northwestern California. Loss of habitat due to timber harvesting, land conversions, natural disturbances such as wildfire, and competition from encroaching barred owls, a species native to eastern North America, has led to a decline of spotted owls throughout much of their historic range. The NSO was listed as threatened under the Endangered species Act in 1990 (USDA Forest Service 1990) and in 1994, the Northwest Forest Plan (USDA FS and USDI BLM 1994) was adopted to protect the spotted owl as well as a number of other species inhabiting late-successional forests in Washington, Oregon, and California. More recently, a revised recovery plan for the NSO was approved on June 28, 2011 (USFWS 2011) that describes a strategy and management actions to restore NSO habitat through active landscape scale management.

Identification of soils and site potentials on which NSO habitat can be best grown and sustained over the long term can assist land managers in deciding where on the landscape NSO habitat should be grown and maintained, verses other areas that may be better managed for other purposes. Addressing this question is particularly relevant in the lower productivity east side forest types where many sites are not capable of growing and sustaining forest structural components for NSO habitat over the long term. Due to the high risk of existing NSO habitat burning in a wildfire in east side forests, it is also important to be able to predict which areas have soils and site potentials that could be managed for future NSO habitat and which areas do not.

Existing Conditions

Northern spotted owl surveys were conducted in the Green Ridge planning area in 2014 and 2015. Three nesting pair of NSO were located and mapped within the planning area and two additional nesting owl pairs were confirmed on the western edge adjacent to the planning area. The NSO recovery plan (USFWS 2011) and critical habitat rule (USFWS 2012) identify the essential functions served by spotted owl habitat as nesting/roosting, foraging, (NRF) and dispersal. In the Green Ridge planning project stand structural components meeting NRF habitat was defined as multi storied stands with a minimum of 40 percent canopy cover that have undergone some self-pruning in the lower canopy and also have a component of dead and down wood. Dispersal habitat was defined as stands with a minimum of 30 percent canopy cover that have a minimum 11 inch average tree diameter at base height (DBH) (Green Ridge NEPA analysis 2016).

Within the planning area, 969 acres of existing NRF habitat was located and mapped during the 2015 field season (Table 3.8). The amount of existing NRF habitat was found to be reduced due to recent wildfires and past regeneration harvest that have occurred within the planning area (USDA Forest Service 2016).

Opportunities and Limitations based on Soil Quality

Restoration plans included maintaining existing NRF habitat where it currently exist, determining areas that have a high potential for growing and maintaining future NRF habitat over the long term, and managing those high potential areas not currently supporting NRF habitat for future NRF habitat. Goals also include managing for NSO dispersal habitat that provides connectivity of stands, thereby providing security for NSO movement across the planning area.

Soil mapping units 56E and 51D occur in large incised drainages draining west to east across the planning area. Soils include a soil association of the Glaze soil series occurring on north aspects identified as having an approximate UMZ SDI of 234, and Gap or Prairie soil series on south aspects identified as having an UMZ SDI of 256 and

215 respectively. Drainage bottoms are narrow and constitute a minor component of the mapping unit. Aspect appears to be a strong driver determining forest type potential in these soil mapping units. Glaze soils on north aspects have the potential to support the more productive Persistent Shade Tolerant forest types that also have a high potential for supporting sustainable NRF habitat. Gap are Prairie soils occurring on predominantly south aspects support Recent Grand Fr forest types and the more productive Gap soils are considered to have a high potential for supporting NSO dispersal habitat.

Soil mapping units 50C, 99C, and 99D occur on gently sloping lava plains in the higher elevation, higher precipitation zones of the planning area. Soils include a soil complex of Gap and Prairie soil series that both support Recent Grand Fir forest types. Gap soils with their deep soil profiles (40 to 60 inches), few rock fragments in the soil profile, and higher water supplying capacity can support the higher stands densities associated with NSO dispersal habitat. Prairie soils which are moderately deep (20 to 40 inches) and have over 35 percent rock fragments in their soil profile, are not considered suitable for growing NSO dispersal habitat.

To help confirm these assumptions, areas identified as existing NRF habitat in the 2015 field survey were stratified by soil mapping unit and results are displayed in Table 3.11 and Figure 3.3. Approximately half of the existing NRF habitat was located on the Persistent Shade Tolerant forest types growing on the Glaze soils occurring in the steep north aspects of soil mapping unit 56E. While additional NRF habitat was identified within other soil mapping units in the planning area, the percentage is lower compared to the relative area of these map units within the planning area. The assumption was made that while some NRF habitat does exist in other areas it may be growing on small inclusions of more productive soils within these areas. A second assumption is that while these sites are capable of growing NRF habitat it may not be sustainable on less productive soils over the long term.

Table 3.11: Areas identified as existing NRF habitat stratified by soil mapping unit.

Map unit symbol	**Acres in planning area**	**% of planning area**	**Acres NRF mapped**	**% of total NRF mapped**
56E	4953	20	484	50
99C	6240	25	200	20
160D	1736	7	172	18
50C	2007	8	78	8
Other	9753	40	35	4
Total	24,689	100	969	100

Soil mapping unit 51D also contains areas of Glaze soils on steeper north aspects; however, no NRF habitat was identified in these areas. Reasons could include the fact that approximately three quarters of this soil mapping unit has burned in recent wildfires and that much of the remainder of the areas underwent regeneration harvest and are currently occupied by young plantations (Figure 3.3).

The Gap and Prairie soil series located in the higher precipitation zones of the planning area supporting Recent Grand Fir forest types have the potential to supporting the minimum 30 percent tree canopy levels needed for NSO dispersal habitat. Soil mapping units support these forest types include the south aspects in soil mapping units 56E and 51D and most of soil mapping units 50C, 99C, and 99D.

Refinements to Land Management Interpretations

Due to the strong correlation between the Glaze soil series occurring on north aspects and the Persistent Shade Tolerant forest types. Glaze soils in soil mapping units 56E and 51D could be prioritized for maintaining existing NRF habitat where it currently exist as well as managing areas where it does not exist for future habitat. Vegetation treatments to reduce risk of loss of NRF habitat to wildfire could be planned and strategically located adjacent to NRF habitat to help protect these areas. Areas of Glaze soils that currently have a component of large fire resistant ponderosa pine, Douglas-fir, and western larch could be thinned from below and in some cases treated with prescribed fire to promote the health and development of the large tree component for future NRF habitat.

Areas of Glaze soils that have undergone recent regen harvest and are currently dominated by pole size ponderosa pine could be prioritized for thinning to promote future large tree structure. Openings could also be created in these young stands and a variety of tree species associated with Persistent Shade Tolerant forest types such as Douglas-fir and western larch could be planted to increase tree species diversity for future NRF habitat. Glaze soils in areas of recent wildfire could also be prioritized for planting to increase tree species diversity for future NRF habitat.

Areas of Gap and Prairie soils supporting Recent Grand Fir forest types occurring on south slopes of soil mapping units 56E and 51D and areas of soil mapping units 50C, 99C, and 99D, that currently meet the required minimum of 30 percent canopy cover for dispersal, could be managed for dispersal habitat. In some cases, these stands may benefit from thinning from below removing smaller diameter trees and thereby increasing the average DBH of these stands to or above the minimum requirement of 11 inches average DBH required for dispersal habitat while also improving the resilience of these overstocked stands to disturbance.

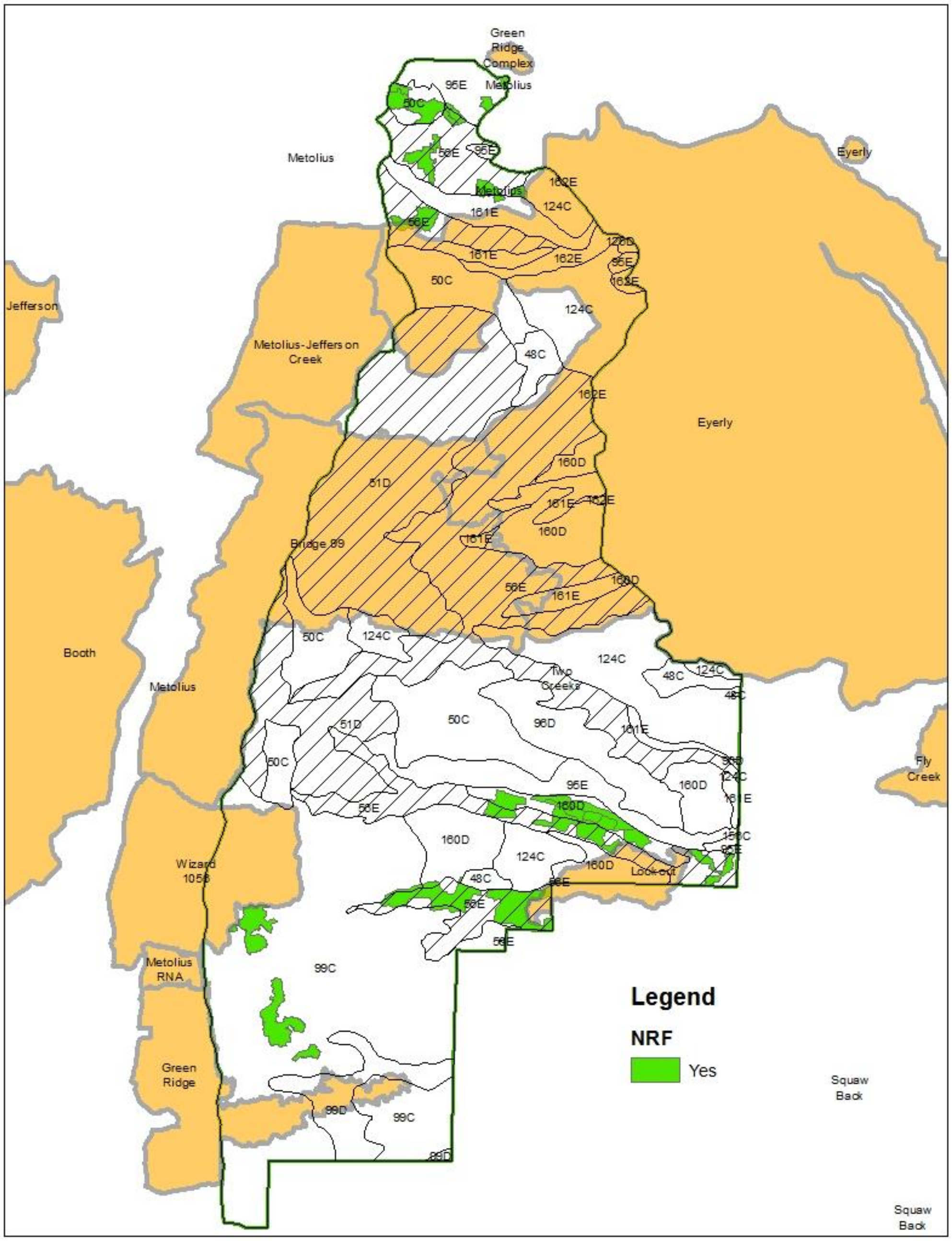

Figure 3.3 Northern Spotted Owl nesting roosting and foraging habitat (NRF) stratified by soil mapping unit.

Mule Deer Habitat

Management Objectives

Mule deer (*Odicoleus hemionous)* and black-tail deer (*Odicoleus columbianus*) are distributed throughout western North America occupying a wide diversity of climatic regimes and vegetation associations (WAFWA 2004). While both species occur in Oregon, in general, deer west of the Cascade Mountains are black-tailed deer while those east of the Cascades are mule deer. To better manage deer populations in Oregon, the Oregon Department of Fish and Wildlife (ODFW) has divided the state into Wildlife Management Units (WMU's) and established heard management objectives (MO) based on deer winter populations. Core components of deer habitat are consistent water, food, and cover that is interspersed in such a way that a population can derive necessary nutrition and cover to survive and reproduce (WAFWA 2004). In eastern Oregon, shrubs make up a significant portion of the deer dietary needs, in particular antelope bitterbrush (*Purshia tridentate*). In addition to adequate forage, mule deer hiding cover is also an importnat habitat attribute that provides escapement from predation as well as avoidance from harassment potential by hunters and other recreation use.

The identification of areas capable of growing high quality bitterbrush for deer forage and an understanding the various responses and recovery of bitterbrush to thinning and prescribed fire, can assist managers in developing vegetation treatment prescriptions that better meet deer habitat needs. Placement of hiding cover in areas capable of growing and sustaining high quality cover is another important project design consideration.

Existing Conditions

Within the Green Ridge planning area, the Deschutes National Forest Land Resource Management Plan (DES LRMP) identifies 1,801 acres of land allocation Deer Winter Range (Table 3.12). Deer Winter Range allocations are located on in the warmer, lower elevation, lower precipitation zone portion of the planning area. Dominant forest types include Recent Douglas-fir and Persistent Ponderosa Pine. Soil types in these areas supporting an understory of bitterbrush include the Windego, Smiling, Flarm, Parrego, and Thorm soil series. Extent of these forest and soil types in the planning area is about twice as large as the Deer Winter Range land allocation (Figure 3.4).

Historic frequent low intensity fire intervals of 7 to 10 years in these forest types periodically regenerated understory brush in these forest types, thus improving the palatability of the brush for mule deer forage. A lack of frequent fire as a result of fire suppression over the past century has resulted in much of this area being converted to a brush component that is older and decadent with low forage palatability. The exception is areas that have burned in recent wildfires. Approximately one third of the 3,000 acres of soils supporting a component of bitterbrush was burned in the 2002 Eyerly fire (Figure 3.4). Brush in these areas has reestablished with a mixture of bitterbrush and manzanita. Manzanita is less desirable than bitterbrush from a forage stand point. Increases in manzanita in these historically bitterbrush forest types may be due to stand replacement fire resulting in a loss of over story trees and the associated increases in available water due to both lack of interception caused by over story trees and decreased transportation from over story vegetation. Mule deer hiding cover in these areas has also been greatly reduced as a result of recent wildfire.

Opportunities and Limitations based on Soil Quality

Restoration plans include recognizing areas that support bitterbrush understories that are providing an important forage component for mule deer. Management goals include better understanding variations in brush response to treatments on different soil types and using that knowledge to plan different treatment methods and schedules that will provide the opportunity to treatment these stands while still providing a mule deer forage component in some areas. Manage goals also include identifying areas with the potential to grow and maintain high quality mule deer hiding cover.

Soil types in these areas supporting an understory of bitterbrush include the Windego, Smiling, Flarm, and Parrego soil series. Extent of these forest and soil types in the planning area is about twice as large as the Deer Winter Range land allocation (Figure 3.4). Soil mapping units with a potential to support bitterbrush understories and different soils potential for providing wildlife hiding cover are displayed in Table 3.12. Soil attributes used to develop this interpretation included soil profile depth, amounts of coarse fragments within different soil profiles, and the resulting soil water holding capacity (Table 3.6).

Soil mapping units 162E, 161E, and 160D occur on sloping lava plains with small incised drainages in the lower elevation lower precipitation zones of the planning area. Soils include a soil complex of the Windego and Smiling soil series that support recent Douglas fir forest types and Parrego soil series that support Presistent ponderosa pine forest types. The Windego and Smiling soils have deep soil profiles and relatively high available water holding capacity giving them a higher site potential compared to the Parrego soils (Table 3.6). Therefore, these soils have the highest potential for growing bitterbrush. These soils are also expected to show rapid brush recovery within a couple of years following vegetation treatments such as mowing and prescribed burning. The higher productivity Windego and Smiling soils are also the areas where higher stocking levels can be sustained for deer hiding cover. Soil mapping units 124C and 48C are also soil map unit complexes of predominately Smiling soils and a minor component of Flarm soils.

Soil mapping units 95E and 96D occur on ridgetops and droughty south facing drainages in the eastern end of the planning area. Soils include soil mapping complexes of the Parrego, Windgo, and Throm soil series that support primarily Persistent Ponderosa Pine forest types with some areas of Recent Douglas-fir occurring on Parrego soils. The moderately deep and shallow Parrego and Thorm soils respectively, with large amounts of soil coarse fragment in the soil profile, have low available water holding capacity compared to the Windego and Smiling soils (Table 3.6). These soils therefor have a lower potential to grow and support bitterbrush and are expected to show slow recovery following treatments like mowing and prescribed burning. Flarm soils have a seasonal water table within 12 inches of the soil surface in the spring causing bitterbrush to be replaced by plant species like rose and twinflower that are more adapted to a wetter environment.

Table 3.12 Bitterbrush potentials, bitterbrush recovery following vegetation treatments, and potential to grow wildlife hiding cover by soil type.

Soil mapping units	**Soil series**	**Bitterbrush potential**	**Bitterbrush recovery following treatment**	**Hiding cover potential**
162E, 161E,160D	Windego	High	Rapid	High
	Smiling	High	Rapid	High
	Parrego	Moderate	Slow	Moderate
124C, 48C	Smiling	High	Rapid	High
	Flarm	Low	Slow	Low
95E, 96D	Parrego	Moderate	Slow	Moderate
	Windgo	High	Rapid	High
	Thorm	Not suited	N/A	Not suited

Refinements to Land Management Interpretations

Thinning to reduce tree basal area in overstocked stands will increase water and light reaching the forest floor and should result in an increase in bitterbrush response in those forest types supporting a bitterbrush understory. Mowing and burning in these forest types should improve brush palatability and improve the forage value in these areas. The Windego and Smiling soils in soil map units 162E, 161E, 160D, 124C, and 48C are expected to show a quick brush response to thinning, mowing, and burning treatments. These are also the areas were bitterbrush can be best grown and maintained for deer forage. To maintain a continuous component of forage within these areas treatments could be spread out over a number of years, thus allowing brush to recover from treated areas before adjacent areas are treated.

The Parrego and Thorn soils in soil map units 95E and 96D have a lower potential for supporting both over story trees and understory brush. Mowing and burning treatments in these soil types are expected to result in slow brush recovery compared to other areas. Experience in similar low productive potential sites on the Forest has shown that treatments of understory brush with prescribed fire can result in removal of the brush and result in an understory dominated by bunchgrass in these areas of low productivity. Treatment options for maintaining some bitterbrush in these areas include mowing brush in a mosaic pattern leaving some brush and not prescribed burning to allow quicker recovery of treated areas.

The more productive Windego and Smiling soils in soil map units 162E and 161E located within narrow draws running east and west through the planning area may provide opportunities to manage for stand structures suitable for wildlife connectivity corridors across the planning area. Due to their high site potential, areas of Windego and Smiling soils also provide the best opportunities for creating a mosaic of wildlife clumps within larger landscapes for big game cover.

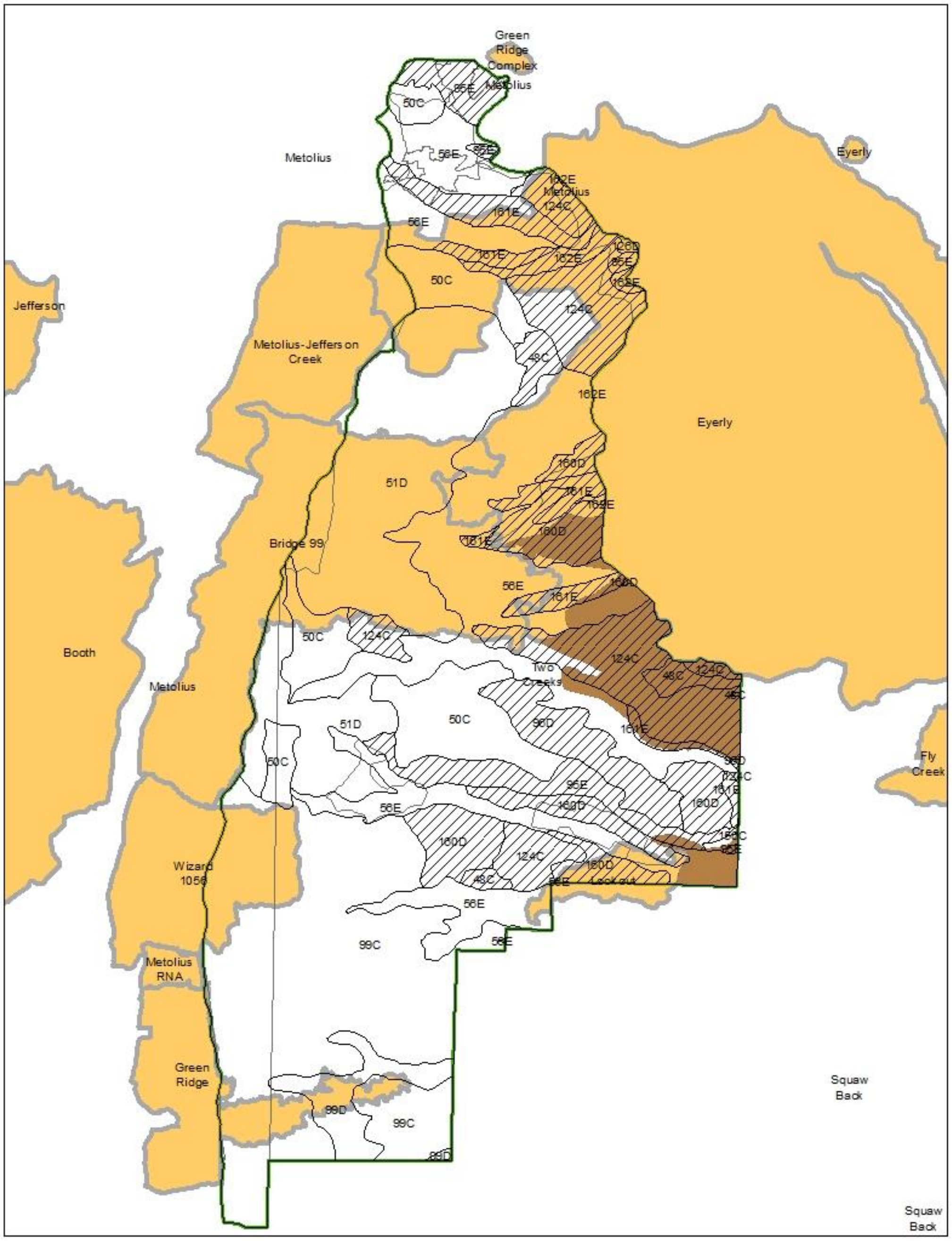

Figure 3.4 Mule deer habitat Forest Plan land allocation and soil types with the potential to support bitterbrush.

Landscape Hydrologic Function

Land Management Objectives

The concept that streamflow in forested watersheds results from subsurface flow rather than overland flow grew out of studies conducted at the Coweeta Hydrologic Laboratory (Hewlett 1961). From this work the “Variable Source Area” (VSA) concept for explaining how water from precipitation moves through forested watersheds to streams was developed nearly 50 years ago (Hewlett and Hibbert 1967). The basic assumption is that soils within vegetated forest have infiltration capacities that are seldom exceeded by rainfall intensities. Therefore, rather than resulting from surface flow, water from precipitation and snowmelt infiltrates into the soil and moves to streams through subsurface flow coming to the surface in a relatively small zone adjacent to the stream that expands in width during a storm and shrinks in width following a storm.

More recent studies and field evidence of water source, flowpath, and age in forest watersheds have identify watershed factors in addition to the VSA that affect runoff response. For example, Kirchner (2003) noted catchments within watersheds store water for considerable periods of time but then release it promptly during storm events indicating flow, source, and age of water are considerations needed for a robust process description of watershed function. McDonnell (2003) suggested a view of the watershed as a series of cryptic reservoirs that have coupled unsaturated and saturated zones connecting vertically and laterally in time and space in linear and non-linear ways. If functioning properly, these water storing areas can act to moderate peak storm flows, provide additional low season stream flows, and provide cool groundwater to streams systems later into the summer months.

By recognizing the morphological components of a landscape that contain important water storing areas and better understanding moisture fluxes that move across and through areas of the watershed managers can better plan vegetation treatments that maintain and enhance water storage and release.

Existing Conditions

Named streams within the planning area include the headwaters of Meadow Creek, Six Creek, and Prairie Farm Creek. These small, first order streams, occur in deeply dissected drainages that run from west to east in the southern half of the planning area. Most of their reaches are intermittent with the exception of short perennial reaches in Six Creek and Prairie Farm Creek. None of these drainages have burned in recent wildfires. There are a number of smaller hydrologically connected ephemeral channels in the northern half of the planning area, some of which have burned in recent wildfires. In this analysis the landscape areas adjacent to streams and ephemeral channels were identified as important VSA's for supplying flows to drainages (Figure 3.5).

A second set of hydrologically connected catchments within the planning area consist of areas of Smiling soils that occur on ash capped volcanic plateaus underlined by un-fractured bedrock (Figure 3.5). The bedrock in these areas appears to be perching water in the volcanic ash materials allowing water to flow laterally into adjacent smaller areas with soils that have spring time seasonal water tables within a few inches of the soil surface (Flarm soils). Seasonal saturation in these Flarm soils is also evident in their soil redoxomorphic features which include mottles and gleyed soil colors. These areas are also associated with seeps and springs coming out of the sides of areas along some parts of the plateaus. Roughly a quarter of these areas have burned in recent wildfires and currently support early seral vegetation. The remainder of this area supports overstocked stands of Recent Douglas-fir forest types.

Opportunities and Limitations based on Soil Quality

Restoration plans include identifying important hydrologically connected areas of subsurface flow and catchments and prescribing vegetation treatments that maintain and enhance water storage and release in these areas.

Soil mapping was used to initially identify different morphological features within the planning area that contain different water storage potentials and partitioned those areas into the following land management subunits.

1. Drainages functioning as variable source areas adjacent to intermittent or perennial streams (MU 56E)
2. Draws functioning as variable source areas adjacent to ephemeral drainages (162E, 161E, 160D, 51D, 95E)
3. Volcanic plateaus functioning as water storing areas with thick ash caps underlined with un-fractured bedrock often associated with small seasonal wetlands and adjacent seeps and springs (MU 124C, 48C)
4. Other landscape areas that are less directly hydrologically connected to drainages or wetlands (50C, 99C, 99D)

Refinements to Land Management Interpretations

Landscape treatments of thinning and prescribed burning to reduce tree stocking levels can reduce interception and evapotranspiration rates of trees and other vegetation in over stocked stands and may help to retain more snow longer into the spring. This in turn can increase water storage, particularly in hydrologically connected catchments of ash capped volcanic plateaus occurring over un-fractured bedrock, thereby extending release longer into the dry season. Drainages and draws functioning as VSA’s adjacent to intermittent, perennial, and ephemeral drainages can also benefit from thinning to reduce stand densities. Thereby making more water available to streams through subsurface flows.

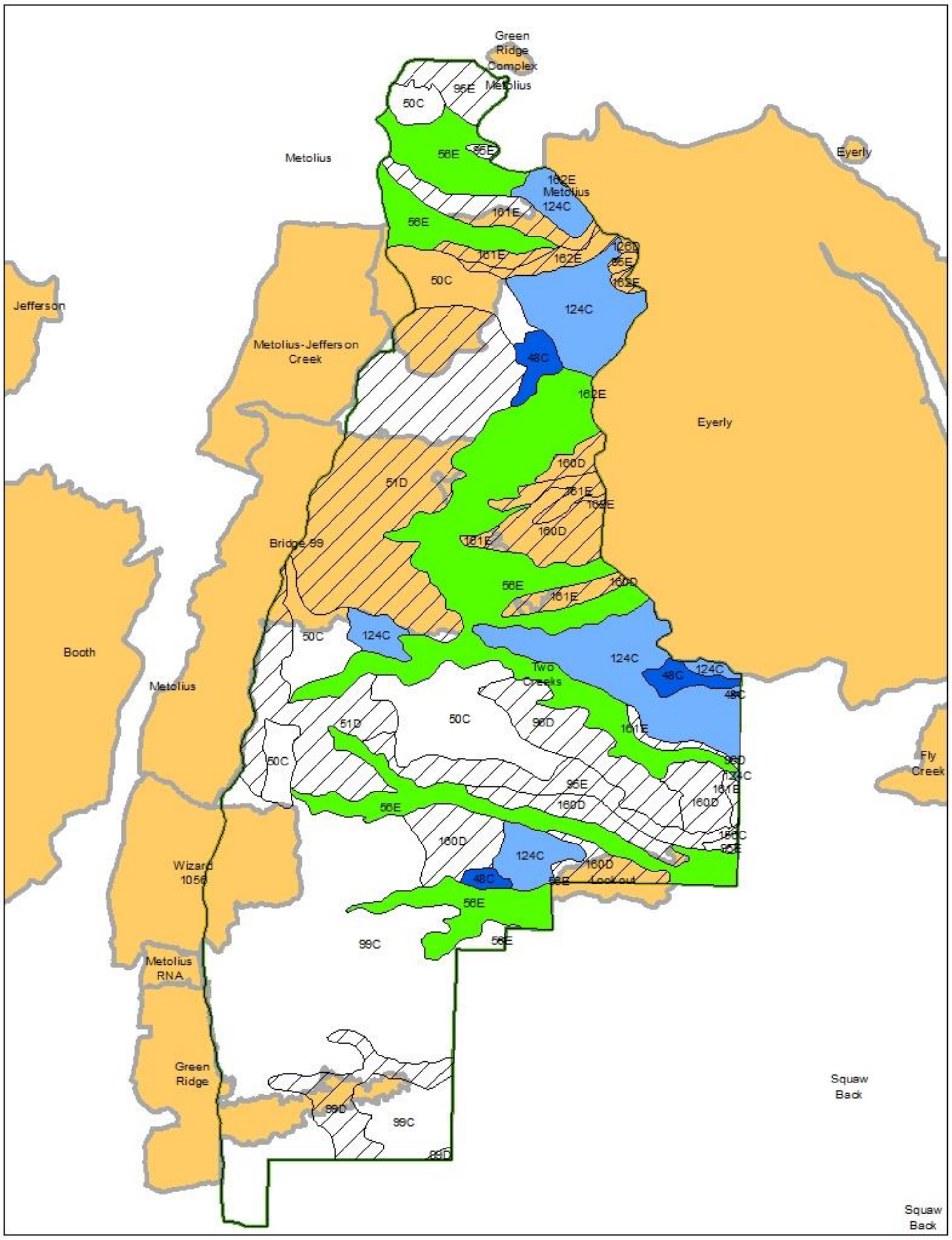

Figure 3.5 Landscape hydrologic variable source area and volcanic plateaus underlined by un-fractured bedrock with associated small wetlands.

Vegetation Treatments to Restore Resilient Forest Conditions

Land Management Objectives

Dry forest landscapes consisting of mixed conifer forest types comprise extensive areas of the eastern Oregon Cascade Range (Franklin and Dyrness, 1988). Past selective harvest and clear cutting, altered fire regimes, recent fires and insect and disease agents have reduce these forests resistance and resilience to disturbances in both the short- and long-term (Hessburg et al., 2007; Stine et al., 2014; DeRose and Long, 2014). Harvest practices and fire suppression over the past decades have reduced the numbers of older trees, resulted in increases in the density of smaller trees, and created a dominance of shade-tolerant trees (Arno et al., 1997; Perry et al., 2004; Merschel et al., 2014). The resulting high fuel loading, increaseed tree competition, and greater landscape-level continuity in many forest stands (Franklin and Agee, 2003), has led to a higher risk and occurrance of large scale disturbances like stand-replacement wildfire and increased susceptibility to insect and disease (Hessburg et al., 2005, 2007; Hemstrom, 2001; Reinhardt et al., 2008; Spies et al., 2006; Littell et al., 2011).

Historic Range of Variability (HRV) is a term that has been used to describe the natural fluctuation in pattern of components of ecosystems over time (Stine et al., 2014). HRV serves as a framework for understanding the ecological system in question and serves as a general reference point that can be useful for setting management goals (Landres et al., 1999). The assumption is that past conditions and processes can provide context and information that drove variability in ecological systems in the past. Objectives for restoring resilient forest conditions, identified in the Lower Metolius Watershed Analysis, were based on an HRV analysis for the watershed (USDA Forest Service, 2016). Forest health objectives identified in the watershed analysis included creating stand structures that are more consistent with forest reference conditions of species composition, structure, and age/size classes, thus improving forests resistance and resilience to disturbances. Objectives also include reducing the effects of insect and disease in order to increase the longevity of mature and old forest and promote growth of younger age classes.

Questions facing resource managers include; what types of forest management treatments are needed to create desired stand structures that are more consistent with reference conditions of vegetation species composition, structure, and age/size classes thus resulting in forest that are more resistant and resilient to disturbance? Also, what types of forest treatments will reduce the risk of a large scale wildfire and the negative effects of insects and disease?

Existing Conditions

Past vegetation management activities in the project area have included timber harvest, small tree thinning, firewood cutting, and prescribed fire. Regeneration cuts have created small even aged blocks dominated by pole-sized trees in approximately one quarter of the planning area. Almost all stands within the planning area have been entered as some point over past decades. Past selective logging has removed a large proportion of the ponderosa pine large tree component from all mixed conifer forest types in the planning area and past selective logging combined with fire suppression has resulted in over stocking and tree species conversion in much of the planning area (Merschel et al., 2014). In addition, over the past two decades roughly a third of the planning area has burned in recent wildfires (USDA Forest Service 2016).

The most dramatic changes in species composition and stand structure have occurred in the Recent Grand fir and Recent Douglas-fir forest types (Merschel et al., 2014). It has been noted that mature fire resistant ponderosa pine historically occurred in all four of the forest types described by Merschel et al. (2014), suggesting that historic fires were frequent and predominantly low severity in these areas. It was also noted that while shade tolerant species of Douglas-fir and grand fir commonly established prior to fire exclusion in the Persistent Shade Tolerant forest types, they did not become established in their current high densities in Recent Douglas-fir and Recent Grand Fir types until after fire exclusion. This was attributed to Douglas-fir and grand fir only showing moderate to high resistance to fire once they have attained adequate size and bark thickness (Howard and Aleksoff 2000; Steinberg 2002) and the assumption that recent fire exclusion, thus allowed these young fire sensitive shade tolerant species to become established in Recent Douglas-fir and Recent Grand Fir types (Merschel et al., 2014).

Based on these findings it has been suggested that the speed and therefore the degree of change in the four forest types following fire exclusion varied in terms of both current stand structure and species composition (Merschel et al., 2014). Large Douglas-fir and grand fir became established in the Persistent Shade Tolerant Type prior to fire exclusion suggesting that historic fire intervals were somewhat longer in this forest type and thus, this forest type was considered to be the least departed from historic. Because Douglas-fir and grand fir are sensitivity to fire at a young age, recent fire exclusion has allow these shade tolerant species to become established in large numbers in the Recent Douglas-fir and Recent Grand fir forest types. Thus these types show the highest departure from historic conditions in terms of infilling and species conversion. Infilling of shade tolerant trees was found to be less common in the Persistent Ponderosa Pine forest types, rather the response of this forest type to fire exclusion was the increase in smaller diameter ponderosa pine.

Opportunities and Limitations based on Soil Quality

Restoration plans include vegetation thinning, mowing, and burning treatments to reduce stand density and create stand structures that are more consistent with reference conditions of species composition, structure, and age/size classes, thereby improving forest resistance and resilience to disturbances.

Forest types described by Merschel et al., (2014) were assigned to different soil mapping units based upon impotent differences in environmental gradients of topography, elevation, and climate. Soil series and soil mapping unit descriptions were used to identify these different landscape attributes. Departure in terms of the effects of past management and fire exclusion on existing stand structure and species composition was shown to vary by forest type (Merschel et al., 2014). Thus, silvilculture prescriptions and fuel treatments intended to restore resilient and resistant forest conditions, would be expected to also vary with forest type.

Glaze soils on north aspects in soil mapping units 56E and 51D support Persistent Shade tolerant forest types. These forest types were found to historically have high stand densities, a mixture of conifer species, and longer fire return intervals compared to other types (Merschel et al., 2014). This has resulted in a low departure from historic forest conditions in these stands (Table 3.13).

In contrast Recent Grand fir and Recent Douglas-fir forest types were found to have high departure from historic conditions. Past management and fire suppression have resulted in an increase in both stand densities and tree species conversion from fire resistant species such as ponderosa pine to thick understories of fire sensitive grand fir and Douglas-fir. Silviculture prescriptions in these areas could emphasis removal of less fire tolerant younger trees and promoting the growth and health of fire resistant species. Persistent Ponderosa pine forest types were identified as having moderate departure from historic condition primarily due to increases in stand density of ponderosa pine. In these areas thinning prescriptions could emphasis the creation of historic mosaic patterns of ponderosa pine occurring in different size clumps and small openings (Table 3.13).

Table 3.13 Successional trajectories of different forest types following recent changes in land management.

Soil map units	**Soil series**	**Forest type (Merschel et al., 2014)**	**Successional trajectories following recent changes in land management**		
			Historical stand conditions	**Fire return interval relative to different forest types**	**Departure from historic stand conditions**
56E, 51D	Glaze	Persistent Shade Tolerant	High stand densities and a mixture of conifer species	Longer fire return intervals	Low departure from historic forest conditions due to longer historic fire return intervals.
56E, 50D, 50C, 99C, 99D	Gap and Prairie	Recent Grand fir	Low stand densities of ponderosa pine and Douglas-fir	Short fire return intervals	High departure from historic forest conditions due to past management and fire suppression resulting in an increase in both stand densities and shade tolerant tree species.
162E, 161E, 160D, 124C, 48C	Windego, Smiling and Flarm	Recent Douglas-fir	Low stand densities of ponderosa pine and Douglas-fir	Short fire return intervals	High departure from historic forest conditions due to past management and fire suppression resulting in an increase in both stand densities and shade tolerant tree species.
95E and 96D	Parrego and Thorn	Persistent Shade Ponderosa pine	Low stand densities of predominantly ponderosa pine	Short fire return intervals	Moderate departure from historic due to past management and fire suppression resulting in an increases in ponderosa pine stand density.

High tree stocking increases tree stress and reduces tree vigor and the ability to resist insects and disease (Hessburg et al. 1994). The upper management zone (UMZ) provides a site-specific density threshold, above which forest health conditions and large tree health are likely to deteriorate. Different parts of the project area can support different stand densities, depending upon their different soil and site potentials. Thus, there is an opportunity to adjust target SDI maximum values representing the UMZ for different biophysical locations to better optimize tree growth and maintain healthy forest. Table 3.13 displays the different site potentials and SDI values for each of the major soil series in the planning area.

Table 3.13 Site index and upper management zone by soil series.

Soil map units	**Soil series**	**Site index**	**Upper management zone**	**Basal area/acre 10 inch dbh**	**Basal area/acre 20 inch dbh**	**Basal area/acre 30 inch dbh**
56E, 51D, 50C, 99C, 99D	Glaze	100	234	127	149	164
	Gap	106	256	139	163	179
	Prairie	95	215	117	138	151
162E, 161E, 160D, 124C	Smiling	92	204	111	131	144
	Windgo	85	179	98	114	126
	Parrego	80	161	88	103	113

Site carrying capacity, stand density index (SDI), and upper and lower management zones (UMZ, LMZ).

All growing sites have a fixed quantity of resources and growing space, when upper limits of site potential are reached for a given site, inter-tree competition results in loss of plant growth and/or tree mortality. Stand density index (SDI) is a measure of stand density that provides an index of forest health concerns that can be used to help predict; levels of tree competition, risk of insect and disease, fire hazard, habitat stability, as well as other important resource questions (Reineke, 1933; Cochran et al., 1994; Powell, 1999; Powell, 2010; Franklin et al., 2013). Measurements of SDI are broken up into "zones" that are used to assess relative growth and inter-tree competition. Full stocking (also called normal) is a zone where tree vigor is slowed to the point where trees are self-thinning and have an increased likelihood of mortality agents. Below full stocking, are the upper and lower management zones (UMZ and LMZ) where partial to full competition occurs and inter-tree competition and mortality agents are less likely to result in tree mortality. In addition, different tree species respond differently to inter-tree competition and, as such, different SDI values are calculated (Cochran 1994; Powell 1999). Managing for species with lowest SDI values on a site ensures all other tree species are accounted for.

Logging systems are also an important consideration for determining opportunities and limitations within the planning area. Unlike much of the Deschutes NF which has a dominance of relatively low sloping topography. The Green Ridge planning area landscape has a considerable proportion of steeper slopes. Over the past couple of decades the Forest has used a slope break of 30% to separate ground based tractor ground from that which would require other logging systems such as cable or helicopter. While cable logging systems are somewhat common on the steeper slopes of the west side forests, these systems have not been used extensively on the Deschutes within the past few decades. The relatively large areas of steeper topography in the Green Ridge planning area justifies at least the consideration of for the use of cable logging systems in some areas.

Based on the criteria discussed above, a restoration treatment consideration matrix was developed for different forest health treatments by soil mapping unit (Table 3.14).

Table 3.14 Restoration treatment consideration matrix identifying silviculture and logging system considerations for forest health treatments by soil mapping unit.

Soil map units	**Soil series**	**Forest type**	**Departure from historic (stand structure/tree species composition**	**Slope class/ logging systems**	**Considerations for forest health treatments**
56E, 51D	Glaze	Persistent shade tolerant	Low departure	MU 56E 30 to 50% MU 51D 15 to 30%	Low departure from historic, slopes over 30%
	Gap	Recent grand fir	High departure (tree species composition and structure)		High departure from historic, opportunities include reduce stand densities and removal of shade tolerant tree species. Logging systems: Cable systems may be required in areas of slopes over 30%.
	Prairie	Recent grand fir	Moderate departure (tree species composition and structure)		
50C, 99C, 99D	Gap	Recent grand fir	High departure (tree species composition and structure)	MU 50C and 99C 0 to 15% MU 99D 15 to 30%	High departure from historic, opportunities include reduce stand densities and removal of shade tolerant tree species. Logging systems: opportunities for tractor ground based systems.
	Prairie	Recent grand fir	Moderate departure (tree species composition and structure)		
162E, 161E, 160D	Windego	Recent Douglas fir	High departure (tree species composition and structure)	MU 162E and 161E 30 to 50% MU160D 15 to 30 %	High departure from historic, opportunities include reduce stand densities and removal of shade tolerant tree species. Moderate departure from historic in ponderosa pine, opportunities to reduce stand densities. Logging systems: Cable systems may be required in areas of slopes over 30%.
	Smiling	Recent Douglas fir	High departure (tree species composition and structure)		
	Parrego	Persistent ponderosa pine	Low departure (due to low site productivity)		
124C, 48C	Smiling	Recent Douglas fir	High departure (tree species composition and structure)	MU 124C and 48C 0 to 15%	High departure from historic, opportunities include reduce stand

	Flarm	Recent Douglas fir	Moderate departure (due to seasonal water table)		densities and removal of shade tolerant tree species. Logging systems: opportunities for tractor ground based systems.
95E, 96D	Parrego	Persistent ponderosa pine	Low departure (due to low site productivity)	MU 95E 30 to 50% MU 96D 15 to 50%	Moderate departure from historic in ponderosa pine, opportunities to reduce stand densities. High departure from historic, opportunities include reduce stand densities and removal of shade tolerant tree species. Logging systems: Cable systems may be required in areas of slopes over 30%.
	Windego	Recent Douglas fir	High departure (tree species composition and structure)		
	Thorm	Juniper woodland	Low departure: stand structure (due to lower site productivity)		

Refinements to Land Management Interpretations

Persistent Shade Tolerant forest types that occur in soil mapping units 56E and 51D on Glaze soils in areas of steep north aspects, were identified as forest types having a low departure from historic stand conditions and thus could be considered a low priority for restoration treatments. Recent Grand Fir forest types in these mapping units, occurring on the Gap and Prairie soils, that are located on predominantly south aspects, may provide opportunities for restoration treatments. Slope classes greater than 30% in these areas could limit opportunities for using tractor ground based equipment.

Due to their large departure in tree species composition and stand structure, and tractor ground based harvest capabilities, Gap and Prairie soils supporting Recent Grand Fir forest types in soil mapping units 50C, 99C, and 99D could be a high priority for thinning prescriptions that reduce densities of less fire tolerant grand fir species. There is also an opportunity to thin stands to variable densities based upon placement of higher stand densities in areas of the more productive Gap soils and lower stand densities in areas of the less productive Prairie soils.

Areas of Windego and Smiling soils supporting Recent Douglas-fir forest types in soil mapping units 162E, 161E and 160D also show high departure in tree species composition and stand structure compared to other forest types and therefore are also high priorities for restoration treatments. Soil mapping unit 160D has a larger percentage of the area that is under 30 percent slope and thus could provide more tractor ground based treatment opportunities.

Persistent Ponderosa Pine forest types occurring in soil mapping units 95E and 96D on Parrego soils were identified as forest types having moderate departure for historic stand conditions. Over stocking is the primary cause for this departure from historic condition in this forest type. Slope classes greater than 30% in these areas could limit opportunities for using tractor ground based equipment.

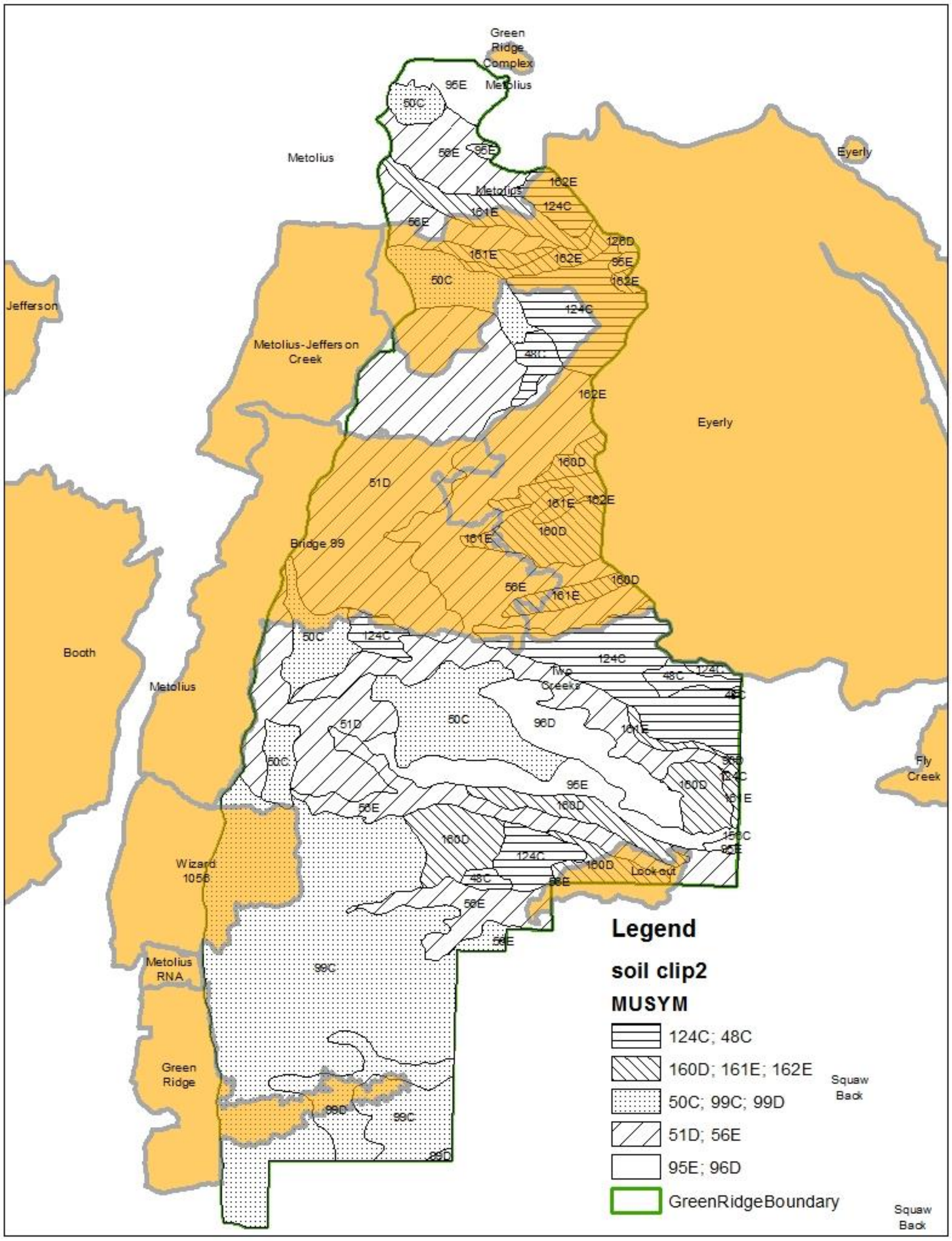

Figure 3.6 Soil mapping unit groupings stratified by priority for forest health treatments.

Applications of Prescribed Fire to Restore Resilient Forest Conditions

Land Management Objectives

Fire was historically a very influential disturbance agent in forest of the eastern Cascade Range (Hessburg et al. 1994). Prior to fire suppression, dry forest of the Inland Northwest were burned predominantly by frequent low- and mixed-severity fires (Agee, 1993; Hessburg et al., 1999). The resilience of these forests was enhanced by frequent fires that cycled nutrients and reduced competition for surviving trees and vegetation (Kauffman, 1990). These types of fires helped to maintain low tree densities, clumped tree spatial patterns, and simple canopy layering (Hessburg et al., 2005). These low- and mixed-severity fires also favored large fire tolerant tree species of ponderosa pine, Douglas-fir, and western larch (Merschel et al., 2014). Fire suppression/exclusion and selective logging of large, fire-resistant trees has now led to a condition of high fuel loading and tree species conversion from large fire resistant species to smaller less fire resistant species in many of these forests. This has resulted in an increased occurrence of high-severity wildfires which are now much more common in these dry forest landscapes (Everett et al., 2000; Hessburg et al., 2005).

Inherent Fire Regime refers to a classification of the historical role fire played across a landscape, and describes the historical fire conditions under which vegetative communities evolved and are maintained (Agee 1993). Fire regimes are classified based on the average number of years between fires combined with the expected severity of the fire. These data reflect and support fire and landscape management goals identified in regional directives like the National Cohesive Wildland Fire Management Strategy, the Federal Wildland Fire Management Policy, and the Healthy Forests Restoration Act. Issues such as cost of implementing fuel treatments, short windows for implementing prescribed burns, and smoke management often limit the amount of acres within a planning area that can be prescribed burned within a given period of time. Inherent Fire Regimes can be useful for both helping assesse current forest conditions in terms of fuel loading and in the prioritization of different areas for prescribed burn treatments.

Questions facing resource managers include: With resources and other issues limiting the use of prescribed fire in the planning area which stands will benefit most from prescribed fire. And where on the landscape should prescribed fire be prioritized as a treatment that stimulates ecological processes in unique ways that cannot be duplicated with mechanical treatments?

Existing Conditions

Over the past two decades roughly one third of the planning area has burned in recent wildfires. Fires in much of this area have been stand replacement but fires in some areas have resulted in a low to moderate burn severity. In areas that have not recently burned, fire suppression/exclusion has interrupted the historic low to mixed-severity fire regimes within and adjacent to the planning area, leading to a change in forest structure, species composition, densities, and fuel accumulation. As a whole, much of the planning area contains a high density of ladder fuels from small trees and understory shrubs which contribute to stand replacement conditions in the event of a fire (USDA Forest Service 2016).

In areas that have not recently burned, stocking levels and tree species composition are outside of the HRV. The most dramatic changes have occurred in the Recent Grand fir and Recent Douglas-fir forest types due to overstory removal of ponderosa pine and fire suppression and exclusion causing increases in young, less fire resistant tree species. These conditions can preclude the growth and development of the more fire resistant large diameter ponderosa pine over the long term due to competition for site resources such as water, nutrients, and growing space. Increases in densities of younger grand fir/Douglas-fir and subsequent development of shade intolerant trees as ladder fuels put the existing overstory old ponderosa pine trees at risk to high intensity wildfires (USDA Forest Service 2016).

Opportunities and Limitations based on Soil Quality

Restoration plans include identifying stands that would most benefit from prescribed burning treatments that stimulate ecological processes that cannot be duplicated with mechanical treatments alone. Then prioritizing areas for treatment based upon limitations of cost, short burn windows, smoke management, and limited personnel for implementing burning.

Two of the five recognized Inherent Fire Regime Groups are represented within the Green Ridge planning area (Figure 3.7). Approximately one third of the planning area is classified as Fire Regime I. Fire regime I historically exhibited a fire frequency return interval of 0-35 years, with low to mixed severity fire disturbance perpetuating fire resilient plant species and forest conditions. The remaining two thirds of the planning area is identified as Fire Regime III. Fire frequency return intervals in Fire Regime III extends beyond 35 years and is associated with mixed conifer stands containing both fire resilient and fire sensitive plant species (Agee 1993; Hessburge et al., 1999).

It is recognized that forest resistance and resilience to disturbances of all forest types that have not burned in a recent wildfire would be improved as a result of some type of vegetation treatment followed by treatments of prescribed fire. Limited resources and competing land management objectives like NSO habitat; however, limit the area extent that prescribed burning can be used. To help prioritize areas for burning, a restoration treatment priority matrix was developed to assign priority ratings for prescribed burning treatments by soil mapping unit (Table 3.15).

Table 3.15 Restoration treatment priority matrix used to assign priority ratings for prescribed burning treatments by soil mapping unit.

Soil map units	Soil series	Forest type	Fire regime	Fire Frequency (years)	Fire Severity	Departure from historic	Priority for Rx fire
56E, 51D	Glaze	Persistent shade tolerant	III	35-200	Mixed/low	Low	Low
	Gap	Recent grand fir	III	35-200	Mixed/low	High	Moderate
	Prairie	Recent grand fir	III	35-200	Mixed/low	High	Moderate
50C, 99C, 99D	Gap	Recent grand fir	III	35-200	Mixed/low	High	Moderate
	Prairie	Recent grand fir	III	35-200	Mixed/low	High	Moderate
162E, 161E, 160D	Windego	Recent Douglas fir	I	0-35	Low/mixed	High	High
	Smiling	Recent Douglas-fir	I	0-35	Low/mixed	High	High
	Parrego	Persistent ponderosa pine	I	0-35	Low/mixed	Low	Low
124C, 48C	Smiling	Recent Douglas-fir	I	0-35	Low/mixed	High	High
	Flarm	Recent Douglas-fir	I	0-35	Low/mixed	High	High
95E, 96D	Parrego	Persistent ponderosa pine	I	0-35	Low/mixed	Low	Low
	Windego	Recent Douglas-fir	I	0-35	Low/mixed	High	High
	Thorm	Juniper woodland	I	0-35	Low/mixed	Low	Low

Fire Regime I: Generally low-severity fires replacing less than 25% of the dominant overstory vegetation; can include mixed-severity fires.

Fire Regime III: Generally mixed-severity; can also include low severity

Refinements to Land Management Interpretations

Due to their lower departure from historic and their longer historic fire return interval, Glaze soils in soil mapping units 56E and 51D could be a low priority for prescribed fire treatments. While the Gap and Prairie soils in soil mapping units 56E, 51D, 50C, 99C, and 99D were identified as having a high departure from historic conditions, departure in due to over stocking and recent increasing of shade tolerant tree species. Mechanical treatments that reduce overstocking by removing much of the shade tolerant tree species should address a large portion of this condition. While burning prescribed under burning could further reduce fuel loading the longer fire return intervals in these areas indicated that burning may not be as high a priority as in other areas.

Smiling and Flarm soils occurring within soil mapping units 124C and 48C that supporting Recent Douglas-fir and occur on gently sloping landscapes could be a high priority for prescribed fire treatments for the following reasons. The more frequent historic fire return interval of Fire regime I, high departure from historic, increased opportunities for mechanical thinning to occur due to slopes less than 30% allowing for ground based tractor logging systems, the potential to improve water storing potential in these area with vegetation treatments that have the potential to reduce interception of precipitation and reduce high levels of transportation due to high stocking levels.

Smiling and Windgo soils occurring within soil mapping units 162E, 161E, and 160D could also be prioritized for prescribed fire treatments, however, slopes over 30% may limit the ability to implement pre-fire vegetation treatments and the logistics of burning. Parrego and Thorm soils occurring within soil mapping units 95E and 96D could be identified as low priority for prescribed burning due to their lower productivity and low departure from historic conditions.

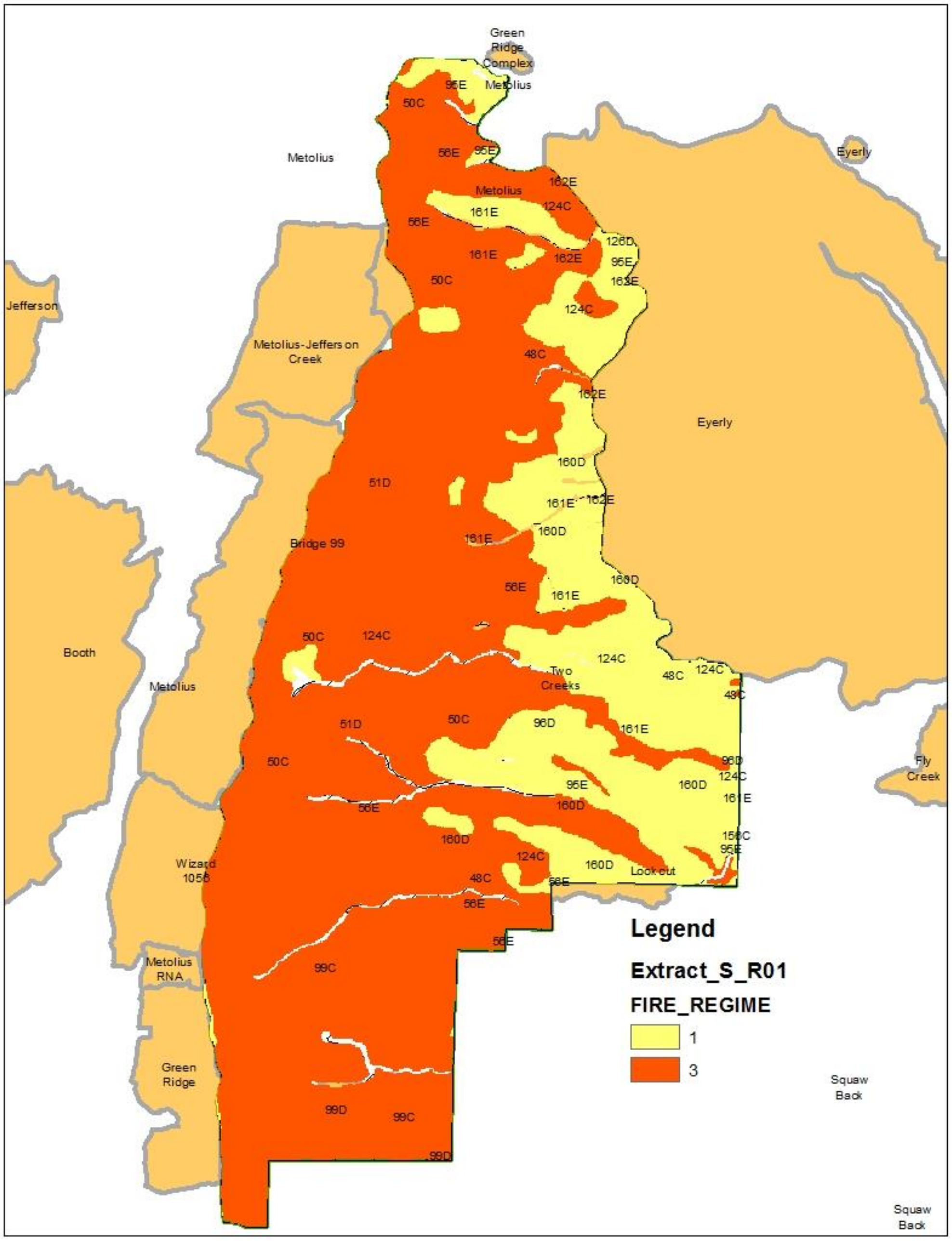

Figure 3.7 Inherent Fire Regimes for the Green Ridge planning.

Conclusion

The many complex concepts of soil quality can be difficult to understand and even more difficult to apply in forest planning. Using soil information to refine ecologically based treatment prescriptions for project level forest planning requires forest managers understand both the soil resource and the multiple land management objectives of interest. This knowledge can then be used to interpret the biophysical setting during project level planning and partition the landscape into broad land-management subunits based upon different land management objectives and inherent site potentials. Management strategies leading to a desired future condition can then be identified for individual land-management subunits and ecologically based treatment prescriptions developed for individual stands based upon current stand conditions and guided by the broader ecological functions identified at the larger landscape scale.

The preceding examples and discussions were intended to provide a detailed real-world illustration of how soils information can be used in forest planning to help match desired land management objectives to soils that have the potential to both attain and sustain objectives over the long term. To effectively apply the concept of soil quality and related information in the forest planning and management process, land managers will need to identify management objectives early in the planning process and have maps and interpretations available for inherent and dynamic qualities of the soil types within a planning area. Understanding the landscape and forest-specific context of the broader land management objectives is necessary before identifying and refining more specific management actions that area matched to soils that can best sustain such actions. Thus, to be successful at this process land managers will need to have a good understanding of both those land management objectives and the soil resource.

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Chapter 4 : A Practical Procedure for Measuring and Interpreting Soil Porosity Changes Resulting from Forest Management

Terry L. Craigg

Abstract

Changes in soil bulk density, soil strength and soil pore size distribution are commonly used indices for assessing physical soil disturbances resulting from forest harvest operations. Each of these soil indices provide somewhat different information about physical changes occurring in the soil as a result of management disturbance. While changes in soil porosity and pore size distribution have long been recognized as an important index for making soil quality assessments, they have not been directly measured extensively during operational soil monitoring. One possible reason is the perceived difficulty in making the measurement. A modified water desorption method for measuring changes in soil porosity resulting from harvest equipment operations provides a practical option for making such measurements at local facilities without the need for sophisticated laboratory equipment. Once soil macroporosity and bulk density have been measured for an individual soil type, a correlation can then be established to reasonably predict soil porosity changes from measurements of soil bulk density. In contrast to measurements of soil bulk density and soil strength alone, measured changes in total soil porosity and soil pore size distribution can help forest managers further refine their understanding of important changes occurring in different soil types as a result of physical soil disturbances. Results can also be used to develop meaningful forest management project design criteria and, when necessary, effective mitigation measures for operations.

Introduction

Forest harvest equipment operations have the potential to negatively affect key soil functions that are important for the maintenance of long term soil productivity and favorable watershed conditions. One of the more commonly recognized and managed soil disturbances is soil compaction (Adams, 2005). Soil compaction can result in an alteration of basic soil properties such as soil density, soil strength, total pore volume, pore size distribution, and macropore continuity (Greacen and Sands, 1980).

A number of studies have noted the negative effects of soil compaction on tree growth (Cochran and Brock, 1985; Helms and Hipkin, 1986; Froehlich et al., 1986). More recent studies have shown variable growth responses to soil compaction depending upon climate and soil type (Gomez et al., 2002; Ares et al., 2005; Miller et al., 2007; Heninger et al., 2002). In addition to vegetation responses, different soils vary in their susceptibility and resilience to compaction (Seybold et al., 1999). These results highlight the importance of having site-specific soil quality assessments for interpreting different soil and ecosystem responses.

Assessment of soil disturbances such as compaction requires consideration of soil changes that affect important soil functions. Because individual soil functions can be difficult to quantify directly, indices of change are typically used to evaluate these effects. Physical soil-based indices used to assess soil compaction include changes in soil bulk density, soil strength, and soil porosity (Powers et al., 1998). Measurements of soil bulk density and soil strength have been used extensively to quantify soil changes resulting from compaction (Miller et al., 2001). Although vital for soil moisture, drainage and aeration functions, direct measurements of changes in soil porosity are not commonly made, possibly due to the perceived difficultly in making those measurements.

Soil bulk density is defined as the mass per unit volume of the soil and represents the ratio of the mass of solids to the total volume of the soil (Soil Survey Staff, 1996). When soils compact bulk density typically increases. A common procedure used to measure soil bulk density changes is a double-wall core sampler of known volume (Blake and Hartge, 1986). Higher soil bulk densities have been correlated with reduced growth of tree roots, with some variability among species (Daddow and Warrington, 1983; Minore et al., 1969). Increases in mineral soil bulk density are also sometimes used to estimate soil porosity changes that can effect movement of air or water within the soil. While soil porosity can be calculated from soil bulk density and an assumed soil particle density, this calculation only provides a general index of changes in total porosity. It does not provide a direct measure of the soil pore size distribution shifts that also occur when soils compact and which can impact specific moisture, drainage or aeration functions.

Soil strength describes the soil hardness or the resistance of the soil to deformation (Scott, 2000), and when soils compact soil strength or the resistance of the soil to penetration commonly increases. These increases can be readily quantified using a recording cone penetrometer, which is capable of recording, at predetermined intervals, the force required to push a probe into and through the soil. Soil strength measurements can be interpreted as the soil resistance levels that may be encountered as roots grow and expand spatially in the soil. Levels above which roots of some tree species begin to be affected have been suggested in the range of 2000 to 2500 kPa (Siegel-Issem et al., 2005; Greacen and Sands, 1980). In some soils, particularly those with higher clay content, penetrometer measurements can be highly dependent on soil moisture content; thus, field sampling for comparative purposes is often done when soils are near field capacity.

Soil porosity refers to the volume within the soil consisting of pore spaces of varying sizes that are filled with either water or air. The porosity of different soils varies depending upon soil texture, organic matter content, depth in the soil profile, and soil management (Scott, 2000). Soil porosity can be characterized in terms of the amount, size, configuration, and distribution of soil pores. These attributes of soil porosity influence a number of important soil physical functions including the retention and transport of solutions, gases, and heat.

Each of the three described soil indices, i.e., soil bulk density, soil strength, and soil porosity, provide somewhat different information about important soil changes occurring when soils become compacted. Thus, assessments of soil compaction that include measurements of soil porosity along with soil bulk density and soil strength can better inform land managers about the resistance and resilience of different soil types to compaction and potential effects of observed soil changes on key soil functions.

Soil pore sizes are commonly divided into three functional size classes related to their water retention properties (Luxmoore, 1981; Cary and Hayden, 1973). "Macropores" are soil voids of sufficiently large size (>15 um radius) that capillary water cannot bridge their diameters following gravitational drainage. "Mesopores and Micropores" include the smaller soil voids (<15 um radius) that remained filled with capillary water when gravitational water has drained and the soil is at field capacity. Soil compaction typically results in a decrease in total soil pores, a decrease in macropores, and an increase in mesopores and micropores (Scott, 2000). These changes can affect the soil air-water balance (Siegel-Issem, et al. 2005; Startsev and McNabb, 2009) and in some cases reduce water infiltration capacity and increase runoff (Startsev and McNabb 2000).

A soil's pore size distribution can be determined indirectly in non-shrink-swell soils (i.e., those without high amounts of certain clay minerals) from the water retention curve (also known as the characteristic curve) (Scott, 2000). Typically the procedure for determining the water retention curve, and in turn the pore size distribution of a soil, is to equilibrate samples at a chosen range of negative pressures or potentials and then determine their moisture contents. Commonly used apparatus for making these measurements include suction tables, pressure plates, and vacuum desiccators (Loveday, 1974; Puckett et al., 1985; Coleman and Marsh, 1961). The method used depends, at least in part, on the desired range of matric potentials and in turn the pore sizes that are of interest.

For assessments of soil porosity changes from soil compaction it is beneficial to be able to separate the data for larger macropores from the smaller mesopores and micropores. Two methods for determining water retention and soil pore size distribution down to 15 um radius include the Buchner funnel and the porous suction plate methods. The Buchner funnel apparatus, introduced by Bouyoucos (1929), consists of a Buchner funnel with filter paper in the bottom to support the soil sample. This method was later adapted by Haines (1930) to demonstrate patterns of soil moisture absorption and release and is sometimes referred to as the Haines apparatus. The apparatus was later improved by fitting the funnel with a porous ceramic plate (Russell, 1941; Danielson and Sutherland, 1986). To increase the number of samples that could be run at one time, Loveday (1974) constructed a ceramic porous suction plate apparatus that was capable of holding several soil core samples. The use of core samples is important as a means for maintaining the integrity of soil structure and porosity as they existed in the field.

The objective of the study described in this chapter was to investigate the use of a modified Buchner funnel apparatus for measuring and interpreting forest soil porosity changes resulting from compaction. The method does not require the use of more elaborate and costly laboratory equipment (e.g., large ceramic plates and powered suction pumps) and therefore can be used in field offices where only a minimum of facilities are available. Soil bulk density and soil strength were measured in addition to soil porosity and results used to further assess the added value of making soil porosity measurements along with these other soil measurements. Statistical prediction of soil porosity changes from a measured change in soil bulk density was also investigated. Management implications include a discussion of the susceptibility of different soils to compaction, notable soil changes that can affect key soil functions, implications for equipment operation scheduling, and potential soil restoration opportunities.

Methods

Sample Site Descriptions

Six forest soils representing a range of soil taxonomic classes in Oregon were chosen for this study (Table 4.1). Sampling locations were located on the Mt. Hood, Deschutes, and Malheur National Forests (Figure 4.1). Each of the sampling locations consisted of a vegetation management unit (activity area) that was recently harvested under a thinning prescription. Three of the thinning units were harvested using track-mounted harvesters and rubber-tired skidders and three of the units were harvested using harvester/forwarder equipment. For sampling purposes three soil disturbance classes were recognized in the track mounted harvester/skidder thinning units: (1) No soil disturbance, (2) Harvester off-trail track, and (3) Skid trails. In harvester/forwarder thinning units two soil disturbance classes were recognized: (1) no soil disturbance, and (2) harvester/forwarder trails. A number of standard protocols for visually assessing soil disturbance have been developed by both forest industry and the US Forest Service (Scott, 2007; Howes, 1983; Page-Dumroese et al., 2009; Napper et al., 2009). Visual soil disturbance criteria identified in these documents was considered in the development of the visual disturbance classes for this study.

Table 4.1 Soil taxonomy and potential natural vegetation types for sampling areas in Oregon.

Forest/Ranger District and Timber Sale Unit	**Soil Taxonomy**	**Potential Natural Vegetation**
Mt Hood NF, Estacada RD, Ladee Flats Sale, Unit 1	Fine silty, mixed, mesic Typic Dystroudepts	**Tsuga heterophylla/ Berberidaceae mahonia – Gaultheria shallon*
Mt Hood NF, Barlow RD, Star Sale, Unit 1	Fine silty, mixed, frigid Vitrandic Dystroxerepts	***Abies grandis/ Symphoricarpos mollis*
Deschutes NF, Sisters RD, Metolius Land Trust Sale, Unit 5	Ashy-skeletal, glassy over amorphic Humic Vitricryands	****Pinus ponderosa/ Purshia tridentate/ Festuca idahoensis*
Deschutes NF, Sisters RD, Glaze Sale, Unit 6	Ashy over loamy, glassy over mixed, superactive, frigid Humic Vitrixerands	****Pinus ponderosa/ Purshia tridentate/ Festuca idahoensis*
Malheur NF, Prairie City RD, Dads Sale, Unit 2	Loamy-skeletal, isotic, frigid Vitrandic Haploxerolls	*****Pinus ponderosa/Carex inops*
Malheur NF, Prairie City RD, Craw Sale, Unit 126	Ashy over loamy-skeletal, glassy over mixed, superactive, frigid Alfic Vitrixerands	*****Pseudotsuga menziesii/Chimaphila umbellata*

***as described in Halverson, N.M. 1986**
****as described in Topin, C. 1988**
*****as described in Simpson, M. 2007**
******as described in Hall, F.C. 1973**

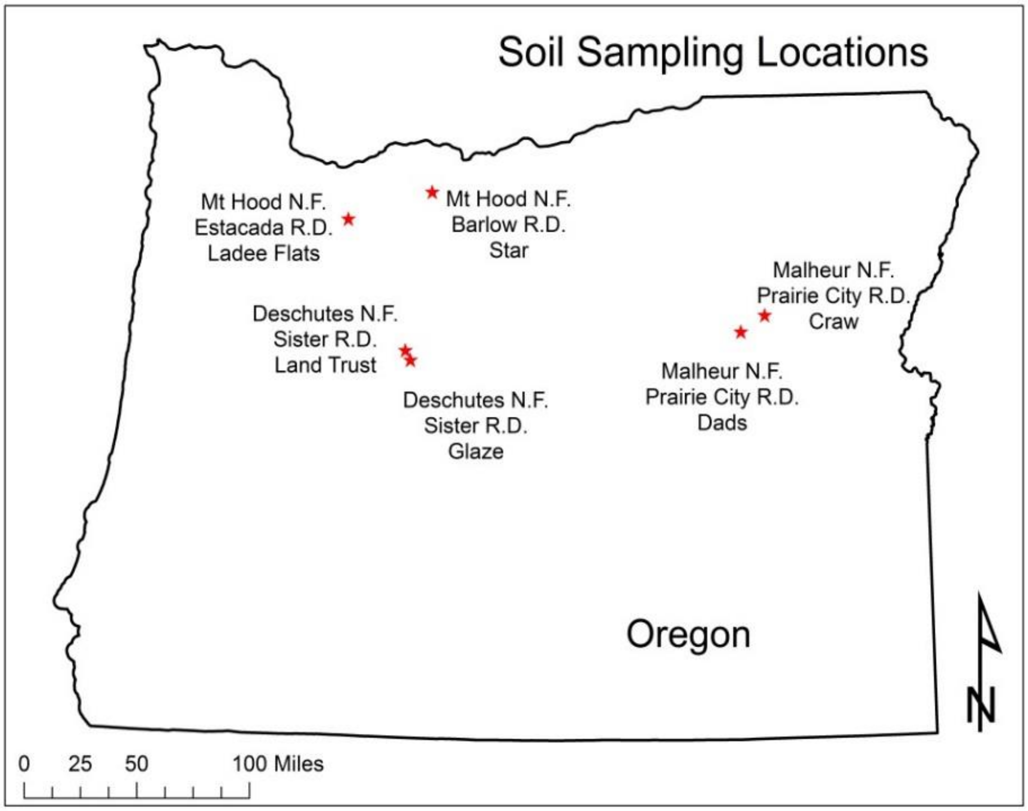


Figure 4.1 Soil sampling locations.

Modified Water Desorption Method for Measuring Soil Porosity

Intact soil cores for measuring both soil porosity and soil bulk density were collected using a hammer driven double-wall soil core sampler (Blake and Hartge, 1986). Soil cores measuring 8.25-cm x 6-cm (diameter x length) were centered at a 15 cm depth to characterize the 10 to 20 cm soil depth. This sampling depth represents a zone in which changes in soil physical properties were expected to be high, yet avoided the surface 0 to 10 cm that may have undergone some initial short-term recovery (Page-Dumroese, 2006; Powers et al., 2005). Three soil cores were collected in each of the different soil disturbance classes within sampled stands.

Intact soil cores were collected during a time of year when soil moisture levels were still relatively high, i.e., mid- to late-spring. Collecting soil cores when soils were moist provided a couple of advantages. Higher soil moisture levels created lower soil strengths for driving the core sampler more easily into the ground. Soil moisture also improved soil sample quality by providing cohesion in soils that had weaker soil structure, allowing the core to retain its structure while it was extracted from the soil and when the sampling ring was extracted from the soil core sampler. In soils that had stronger structure, soil moisture helped to avoid excessive fracturing of soil peds in the core while the metal soil core was being driven into the ground.

Soil pore size distribution of the sample cores was determined using a modification of the water desorption method described in Methods of Soil Analysis (Danielson and Sutherland, 1986) in which the equivalent radius of the largest pore that will be filled with water is a function of the soil water pressure through the capillarity equation. The mathematical relationship between these parameters is:

$$r = (2\sigma \cos \theta)/(\rho_w g h)$$

Where r is the equivalent radius of the pore (cm), σ is the surface tension (kg/s^2), θ is the contact angle between the water and the pore wall (usually assumed to be zero), ρ_w is the density of water (kg/m^3), g is the gravitational acceleration (m/s^2), and h is the soil water suction (cm of water). Thus, a measurement of the water retention curve can be used to show the amount of pore space that has pores smaller than a given effective size derived from a given applied suction (h) (Scott 2000).

To make the measurement, a hanging water column was created by connecting a Buchner funnel with a porous ceramic plate in the bottom to approximately 3 meters of

5/16 inch OD plastic tubing. The other end of the tubing was then connected to a 30 ml plastic burette (Figure 4.2). Both the funnel and burette were placed on a vertical bar at approximately equal heights with the tubing suspended between them. The tubing, burette and the volume of the funnel below the porous plate were then filled with water and any air bubbles removed. The porous ceramic plate (ave. pore size = 5 um) was then saturated by raising the burette slightly above the funnel, creating a small head of water.

Once the porous plate was saturated, any water in the funnel above the porous plate was poured out, and the soil core was placed directly on the plate in the funnel. The soil core was next saturated by raising the burette a few centimeters above the Buchner funnel thus applying a small head of water to the soil core. This allowed the soil core to wet up slowly, minimizing air pockets. After the core was saturated (approximately 24 hours), a level was used to adjust the 20 ml mark on the burette level with the center mark on the soil core in the funnel. Excess water between the soil core and the glass funnel and any water in the burette above the 20 ml mark was then removed using a syringe with a piece of small diameter tubing.

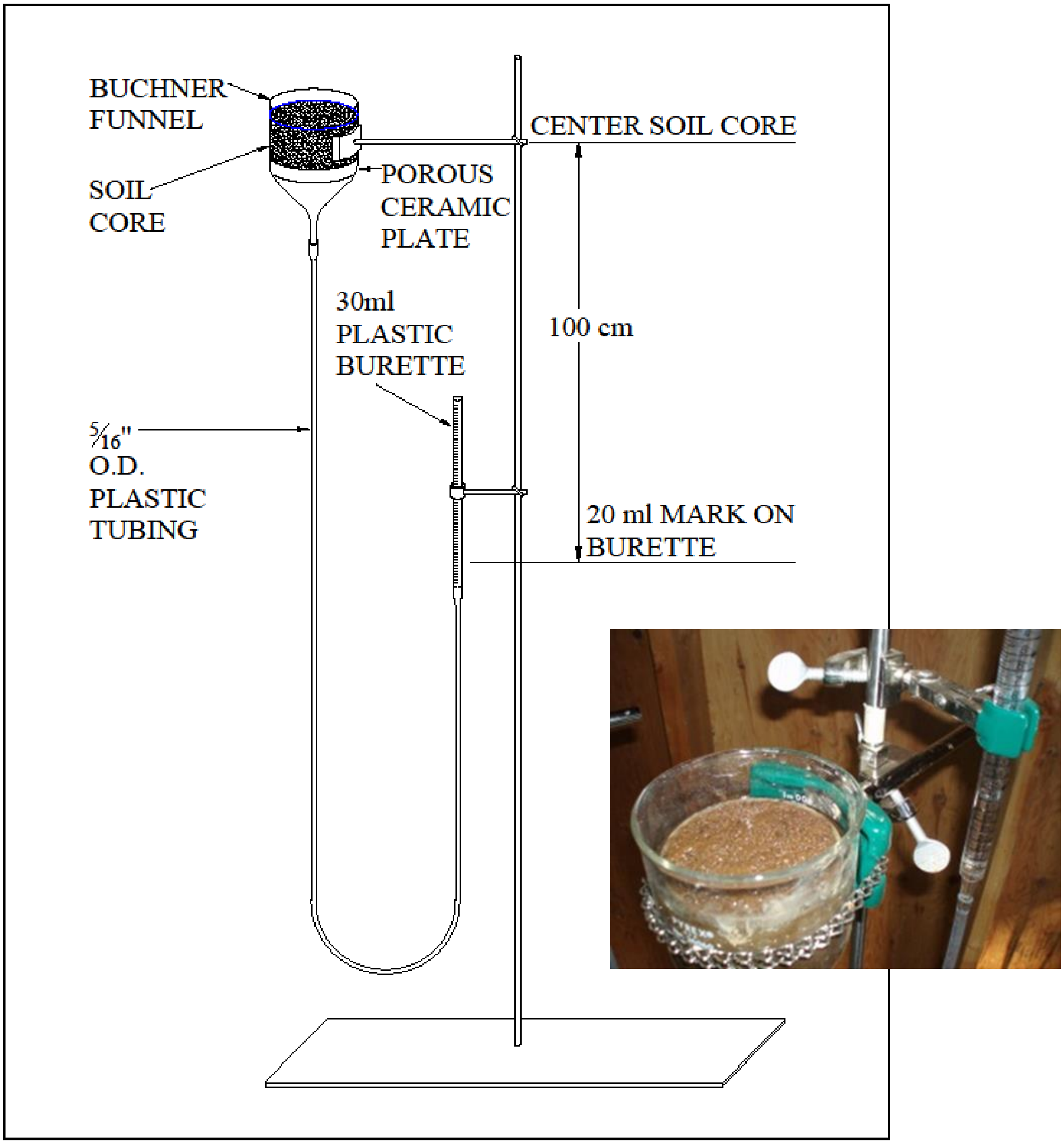


Figure 4.2 Modification of the water desorption method for measuring soil porosity and soil bulk density described in Methods of Soil Analysis (Danielson and Sutherland, 1986). The photo insert shows a Buchner funnel with soil core.

Suction was then applied to the base of the saturated soil core by raising the center mark on the soil core above the 20 ml mark on the burette to a height of 100 cm. Based on the capillary equation the suction required removing water from soil pore sizes 30 um and larger is -10 kPa or a water column 100 cm high. Negative 10 kPa is a suction that is commonly used to indicate “field capacity” of a soil and the 30 um soil pore size therefore can be used to represent a break between aeration porosity and water-holding porosity. To maintain the desired suction on the soil core, water was periodically removed from the burette down to the predetermined 20 ml mark and the volume of water removed noted. While suction was being applied to the soil core aluminum foil was placed over the funnels to minimize any evaporation. Once the suction was stabilized (i.e., no more water flowed out of the soil core) the total volume of water removed was noted. The equivalent radius of the largest soil pores filled with water was then calculated to be 30 um using the capillary equation (Scott, 2000). This measurement of soil pores 30 um and greater was then used to represent soil macroporosity in the sample.

Following the stabilization of the applied suction of 100 cm, the soil cores were removed from the funnels and weighed. Next they were placed in a drying oven set at 105 C for 24 hours and reweighed. This measure of soil porosity was then used to represent the total soil (meso plus micro) porosity.

In this study nine soil core samples were processed at one time and the time required for running those samples was approximately four days. Not all of that time was spent actively working on analyzing the samples. Actual time required to set up and processes the nine samples was estimated to be about six hours. This included setting up the water columns and saturating the cores, applying the suction to the cores and measuring and removing water from the burette, removing the cores from the funnels, weighing the cores, placing them in a drying over, and weighing/sieving soils and soil coarse fragments.

Soil Bulk Density Measurements

Measurements of soil bulk density were determined with the same soil cores used to measure soil porosity. Soil bulk density was determined on both an oven-dry whole soil basis and a fine fraction basis because both measurements are useful for interpreting soil bulk density changes. Comparisons of changes in soil bulk density can be confounding if comparisons of changes are made only on a whole soil basis. This is because of variations in the amount of coarse fragments in individual samples and the fact that soil coarse fragments typically weigh two to three times that of an equal volume of soil. Thus, to facilitate comparisons, soil bulk density comparisons were made on a soil fine fraction basis, to reduce the bias of coarse fragments.

Soil bulk density was initially assessed on a whole soil basis as the weight of the whole soil fraction divided by the volume of the soil core. To determine soil bulk density on a fine fraction soil basis, soils were sieved using a number 10 sieve to remove the coarse fragments. Coarse fragments were then weighed and the volume of the coarse fragments determined by displacement in water. Soil bulk density was then determined a second time based on the fine fraction of soil, excluding the weight and volume of soil coarse fragments (Soil Survey Staff, 1996).

Soil Strength Measurements

At each of the sampling locations soil penetration resistance was also measured on-site using a *Rimik CP 40* (Note: Mention of trade names does not constitute and endorsement) recording cone penetrometer. Thirty cone penetrometer readings at randomly located areas were selected and then measured within each of the different soil disturbance classes. The penetrometer was set to record soil resistance at 1.5 cm increments to a depth of 73.5 cm. Soil cone penetrometer measurements were then downloaded into a spreadsheet for statistical analysis. Measurements were made in the spring when soil moisture levels were still high, with bulk soil samples also taken to quantify gravimetric water content at time of measurement.

Statistical Analysis

Microsoft Excel statistical package (Excel 2010 version) was used to perform a one-way analysis of variance (ANOVA) to compare measured soil parameter means. An alpha level of 0.05 was used to identify significant differences. Statistical analysis was performed for each of the locations separately. Treatments were not replicated within a location and it is recognized that applying inferential statistics to treatments comparisons at a single location represents pseudoreplication. Individual treatment units were, however, carefully selected at each location to assure soil types within a harvest unit were as uniform as possible.

Results

Total Soil Porosity

Total soil porosity of undisturbed soils ranged between 0.56 and 0.72 (m^3/m^3) and, following compaction, decreased between 4 and 23% in areas of harvester/skidder operations and between 9 and 18% in areas of harvester/forwarder operations (Tables 4.2 and 4.3). Decreases in total soil porosity in disturbed areas were significant ($P<0.05$) for most but not all of the soils tested. The Mt. Hood soils showed the greatest decrease in total soil porosity and the Deschutes soils the least amount of change.

Table 4.2 Total soil porosity (m^3/m^3) as related to soil disturbance level for harvester/skidder operations and harvest location.

Visual soil disturbance class	**Mt Hood NF, Estacada RD, Ladee Flats Sale, Unit 1**		**Mt Hood NF, Barlow RD, Star Sale, Unit 19**		**Deschutes NF, Sisters RD, Metolius Land Trust Sale, Unit 5**	
	Total soil porosity (m^3/m^3)	**% difference in soil porosity**	**Total soil porosity (m^3/m^3)**	**% difference in soil porosity**	**Total soil porosity (m^3/m^3)**	**% difference in soil porosity**
1	0.72 (0.02) a	-	0.59 (0.02) a	-	0.61 (0.01) a	-
2	0.69 (0.02) a	- 4	0.45 (0.02) b	- 23	0.56 (0.05) a	- 9
3	0.57 (0.02) b	- 21	0.47 (0.03) b	- 22	0.56 (0.03) a	- 9

Soil disturbance classes (1) No soil disturbance, (2) Harvester off trail track, (3) Skid trails. Total porosity values shown are means +/- one standard error in parentheses, (n = 3). Within a location and soil type means followed by the same letter are not significantly different at $P < 0.05$.

Table 4.3 Total soil porosity (m^3/m^3) as related to soil disturbance level for harvester/forwarder operations and harvest location.

Visual soil disturbance class	**Deschutes NF, Sisters RD, Glaze Sale, Unit 6**		**Malheur NF, Prairie City RD, Dads Sale, Unit 2**		**Malheur NF, Prairie City RD, Craw Sale, Unit 126**	
	Total soil porosity (m^3/m^3)	**% difference in soil porosity**	**Total soil porosity (m^3/m^3)**	**% difference in soil porosity**	**Total soil porosity (m^3/m^3)**	**% difference in soil porosity**
1	0.56 (0.02) a	-	0.60 (0.01) a	-	0.67 (0.01) a	-
2	0.51 (0.01) b	- 9	0.50 (0.02) b	- 18	0.59 (0.01) b	- 12

Soil disturbance classes (1) No soil disturbance, (2) Harvester forwarder trails. Total porosity values are means +/- one standard error in parentheses, (n = 4). Within a location and soil type means followed by the same letter are not significantly different at $P < 0.05$.

Soil Macroporosity

Soil macroporosity in undisturbed soils ranged from 0.21 and 0.36 m^3/m^3 and represented between 32 and 56% of the total soil porosity. In areas of harvester/skidder operations soil compaction decreased macroporosity between 18 and 65% and reduced macropores to between 23 and 42% of the total porosity (Table 4a). In areas of harvester/forwarder operations soil compaction decreased macroporosity between 36 and 60% and reduced macropores to between 14 and 32% of the total porosity (Table 4.4 and 4.5). All of the soil disturbance classes showed a significant decrease in macroporosity ($P<0.05$).

Table 4.4 Soil macroporosity (m^3/m^3) as related to soil disturbance level for harvester/skidder operations and harvest location.

Visual soil disturbance class	**Mt Hood NF, Estacada RD, Ladee Flats Sale, Unit 1**			**Mt Hood NF, Barlow RD, Star Sale, Unit 19**			**Deschutes NF, Sisters RD, Metolius Land Trust Sale, Unit 5**		
	Soil macro porosity (m^3/m^3)	**% diff in soil macro porosity**	**% soil macro porosity**	**Soil macro porosity (m^3/m^3)**	**% diff in soil macro porosity**	**% soil macro porosity**	**Soil macro porosity (m^3/m^3)**	**% diff in soil macro porosity**	**% Soil macro porosity**
1	0.36 (0.03) a	-	50	0.30 (0.01) a	-	51	0.34 (0.01) a	-	56
2	0.29 (0.01) b	- 18	42	0.12 (0.03) b	- 60	27	0.19 (0.04) b	- 44	34
3	0.14 (0.03) c	- 61	24	0.11 (0.04) b	- 65	23	0.22 (0.02) b	- 37	39

Soil disturbance classes (1) No soil disturbance, (2) Harvester off trail track, (3) Skid trails. Macroporosity values shown are means +/- one standard error in parentheses, (n = 3). Within a location and soil type means followed by the same letter are not significantly different at $P < 0.05$.

Table 4.5 Soil macroporosity (m^3/m^3) as related to soil disturbance level for harvester/forwarder operations and harvest location.

Visual soil disturbance class	**Deschutes NF, Sisters RD, Glaze Sale, Unit 6**			**Malheur NF, Prairie City RD, Dads Sale, Unit 2**			**Malheur NF, Prairie City RD, Craw Sale, Unit 126**		
	Soil macro porosity (m^3/m^3)	**% diff in soil macro porosity**	**% Soil macro porosity**	**Soil macro porosity (m^3/m^3)**	**% diff in soil macro porosity**	**% Soil macro porosity**	**Soil macro porosity (m^3/m^3)**	**% diff in soil macro porosity**	**% Soil macro porosity**
1	0.25 (0.03) a	-	45	0.28 (0.02) a	-	46	0.21 (0.01) a	-	32
2	0.16 (0.01) b	- 36	32	0.12 (0.03) b	- 57	24	0.09 (0.02) b	- 60	14

Soil disturbance classes (1) No soil disturbance, (2) Harvester forwarder trails. Macroporosity values shown are means +/- one standard error in parentheses, (n = 4). Within a location and soil type means followed by the same letter are not significantly different at $P < 0.05$.

Soil Bulk Density

Soil bulk densities in undisturbed soils and calculated on a fine fraction basis ranged between 0.63 and 1.06 (Mg/m^3) and following compaction, increased between 6 and 65% in areas of harvester/skidder operations and between 10 and 24% in areas of harvester/forwarder operations. (Tables 4.6 and 4.7). Increases in soil bulk density in disturbed areas were statistically significant ($P<0.05$) for most but not all of the soils tested. In areas of harvester/skidder operations soil bulk density was significantly higher than the undisturbed in two of the three locations and off-trail tracks had significantly lower bulk density than the skid trails in two out of three locations. In areas of harvester /forwarder operations, soil bulk density was significantly higher compared to undisturbed areas for all three soils. The Mt. Hood soils, derived from residuum and colluvium parent materials weathered from volcanic rock, showed the highest increases in soil bulk density. The Deschutes soils and Malheur soils, derived from volcanic ash soil parent materials, showed smaller changes in soil bulk density as a result of disturbance.

Table 4.6 Soil bulk density (Mg/m^3) as related to soil disturbance level for harvester/skidder operations and harvest location.

Visual soil disturbance class	Mt Hood NF, Estacada RD, Ladee Flats Sale, Unit 1		Mt Hood NF, Barlow RD, Star Sale, Unit 19		Deschutes NF, Sisters RD, Metolius Land Trust Sale, Unit 5	
	Soil bulk density (Mg/m^3)	**% difference in bulk density**	**Soil bulk density (Mg/m^3)**	**% difference in bulk density**	**Soil bulk density (Mg/m^3)**	**% difference in bulk density**
1	0.63 (0.02) a	-	0.92 (0.04) a	-	0.82 (0.06) a	-
2	0.67 (0.02) a	6	1.18 (0.05) b	24	0.84 (0.16) a	3
3	1.04 (0.11) b	65	1.28 (0.08) c	38	0.95 (0.07) a	16

Soil disturbance classes: (1) No soil disturbance, (2) Harvester off trail track, (3) Skid trails. Bulk density values shown are means +/- one standard error in parentheses, ($n = 3$). Within a location and soil type, means followed by the same letter are not significantly different at $P < 0.05$.

Table 4.7 Soil bulk density (Mg/m^3) as related to soil disturbance level for harvester/forwarder operations and harvest location.

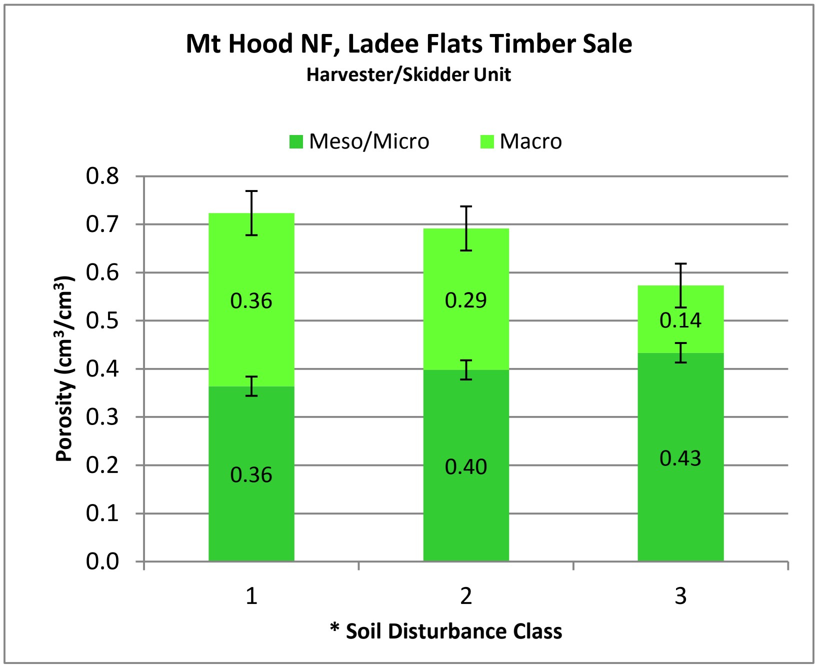
Visual soil disturbance class	Deschutes NF, Sisters RD, Glaze Sale, Unit 6		Malheur NF, Prairie City RD, Dads Sale, Unit 2		Malheur NF, Prairie City RD, Craw Sale, Unit 126	
	Soil bulk density (Mg/m^3)	**% difference in bulk density**	**Soil bulk density (Mg/m^3)**	**% difference in bulk density**	**Soil bulk density (Mg/m^3)**	**% difference in bulk density**
1	1.06 (0.04) a	-	0.93 (0.02) a	-	0.72 (0.02) a	-
2	1.20 (0.03) b	10	1.12 (0.03) b	18	0.86 (0.02) b	24

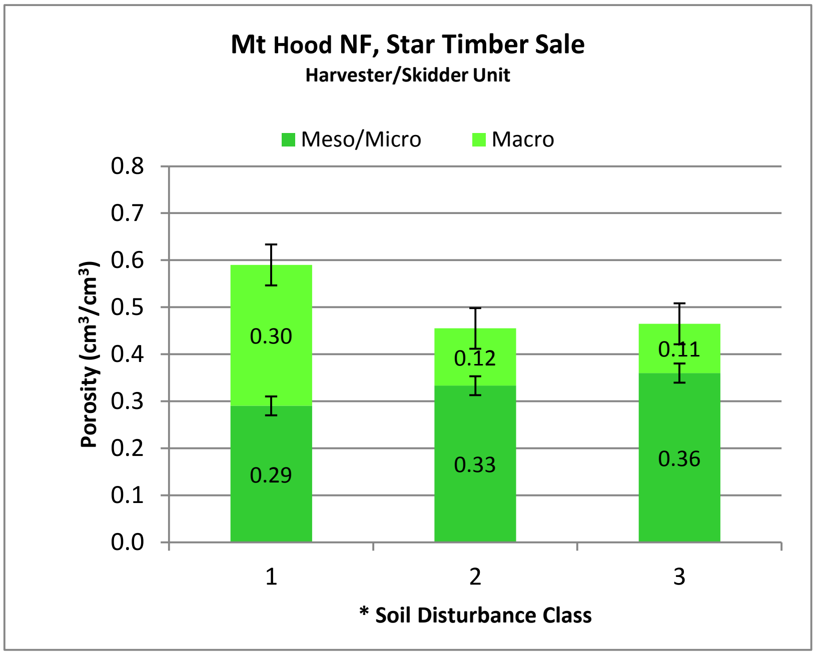
Soil disturbance classes: (1) No soil disturbance, (2) Harvester/forwarder trails. Bulk density values shown are means +/- one standard error in parentheses, ($n = 4$). Within a location and soil type, means followed by the same letter are not significantly different at $P < 0.05$

Predicting Soil Porosity Changes from Soil Bulk Density

Changes in soil bulk density resulting from compaction can be measured in less time than it takes to measure changes in soil pore size distribution. Thus, predicting important soil porosity changes from a measured change in soil bulk density could improve monitoring efficiency. Results from this study show that when these soils compact there is both a loss in total soil porosity and a shift in soil pore size distribution from larger macro pores to smaller meso and micro pores. Thus, an interpretation of effects of soil porosity changes on soil moisture, drainage and aeration functions requires knowledge of both total soil porosity changes and the shift in soil pore size distribution that occur when soils become compacted. Both these porosity changes are reflected in the change in soil macroporosity. Thus, a method that predicts the amount of macroporosity change when soil becomes compacted would provide the information needed to identify important effects on key soil functions.

A pattern of reductions in total soil porosity and shifts in soil pore sizes resulting from soil compaction are illustrated in Figure 4.3. The figures show both a loss of total soil porosity occurring when soils become compacted and a rearrangement of soil pore sizes resulting from the reduction in aeration porosity (macropores). Results also illustrate the variation by soil type in both total soil porosity losses and the shift in pore size distribution when compaction occurs.

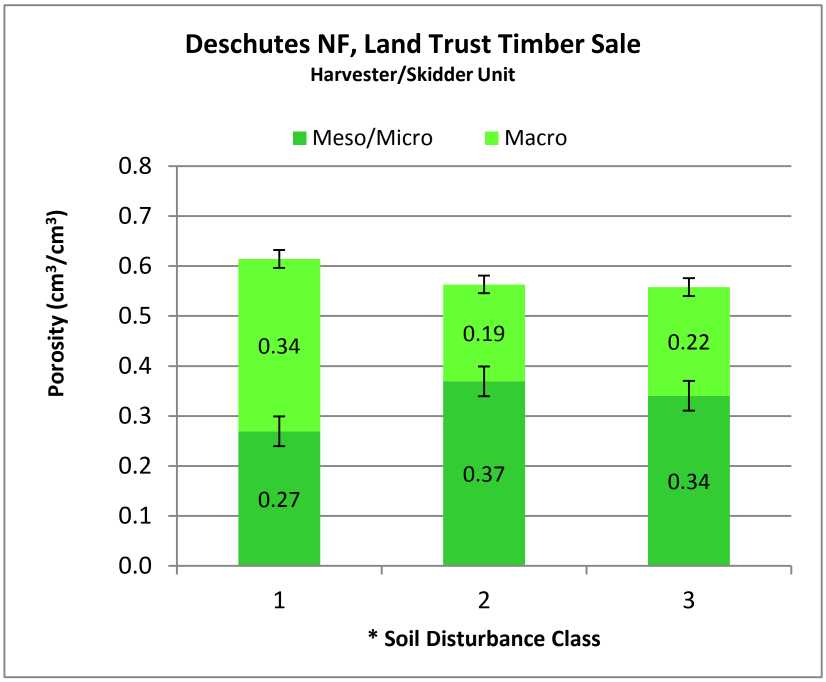


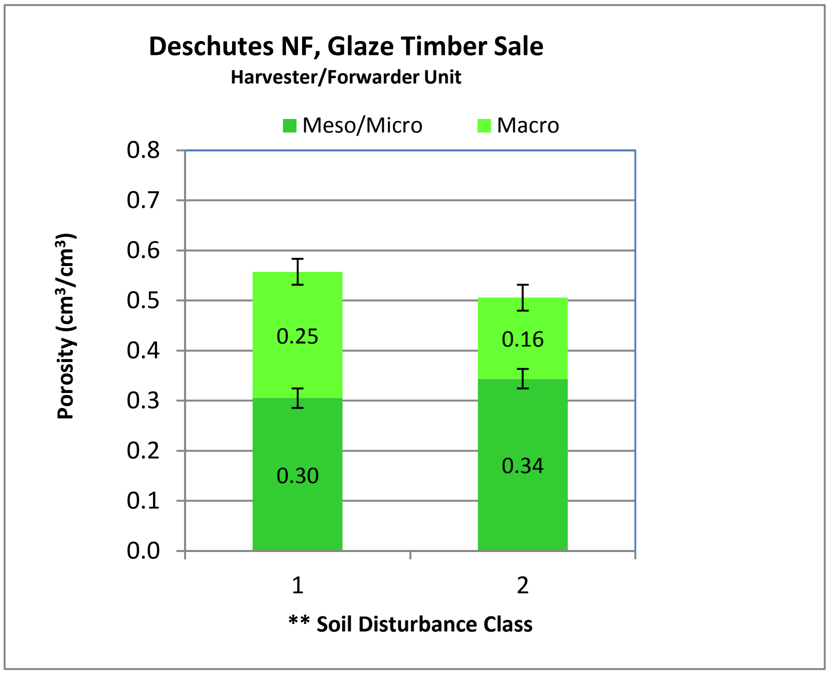


*Soil disturbance classes “Harvester/Skidder” (1) No soil disturbance, (2) Harvester off trail track, (3) Skid trails.
**Soil disturbance classes “Harvester/Forwarder” (1) No soil disturbance, (2) Harvester forwarder trails.

Figure 4.3 Soil pore size distribution as related to soil disturbance level and harvest equipment type and harvest location (error bars represent one standard error).

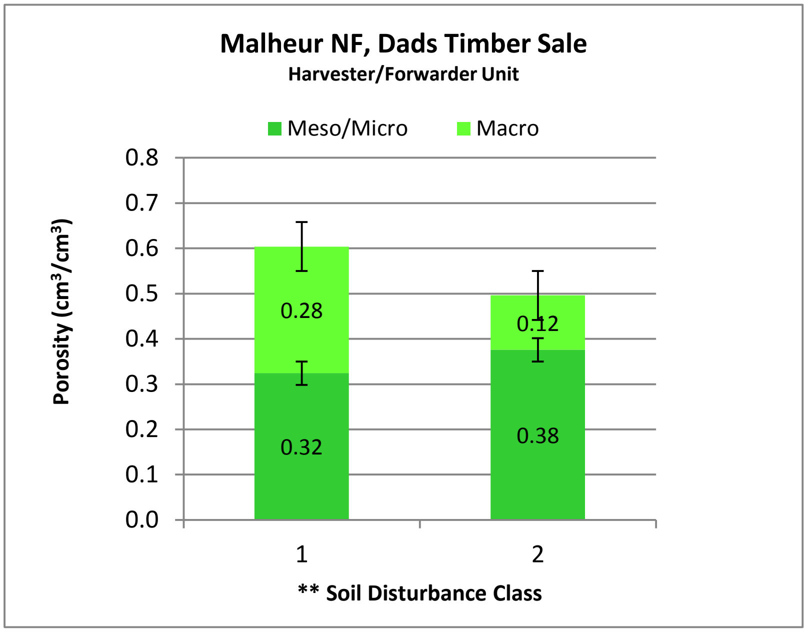
Figure 4.3 continued

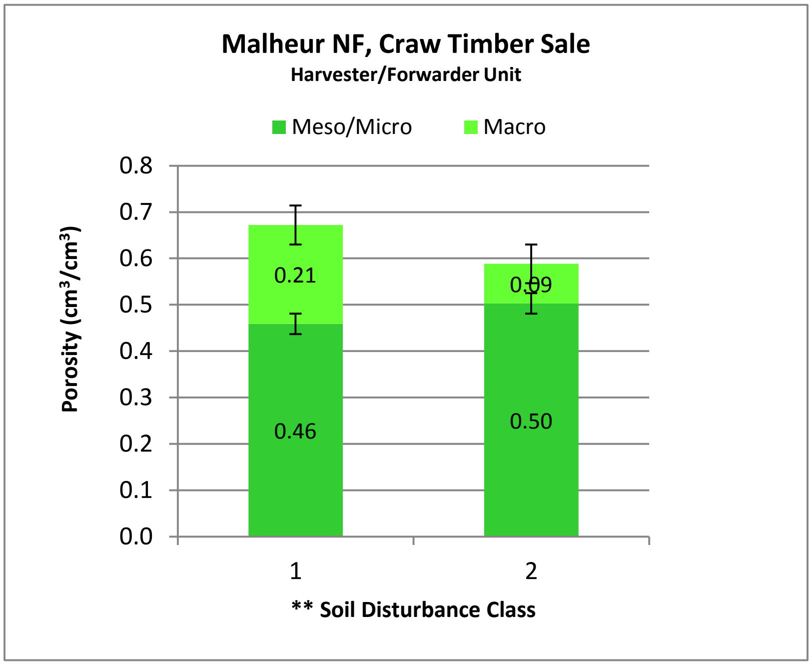




*Soil disturbance classes “Harvester/Skidder” (1) No soil disturbance, (2) Harvester off trail track, (3) Skid trails.
**Soil disturbance classes “Harvester/Forwarder” (1) No soil disturbance, (2) Harvester forwarder trails.

Figure 4.3 continued





*Soil disturbance classes “Harvester/Skidder” (1) No soil disturbance, (2) Harvester off trail track, (3) Skid trails.
**Soil disturbance classes “Harvester/Forwarder” (1) No soil disturbance, (2) Harvester forwarder trails.

Total soil porosity can be determined from a measurement of the dry soil bulk density and a measurement of soil particle density (Blake and Hartge, 1986). The mathematical relationship between these parameters is:

$$f = 1 - \rho_b/\rho_p$$

Where f is the total porosity (m^3/m^3), ρ_b is the soil bulk density (kg/m^3), and ρ_p is the soil particle density (kg/m^3) (Scott, 2000). While soil porosity can be calculated from soil bulk density and soil particle density, this calculation only provides an index of changes in total porosity. It does not provide a direct measure of the soil pore size distribution shifts that also occur and may impact specific moisture, drainage or aeration functions. A correlation of measurements of soil macroporosity as a function of soil bulk density could provide a useful model for predicting changes in soil macroporosity from a measured change in soil bulk density.

In Figure 4.4, the linear relationship between the soil bulk density and macroporosity of a combined data set of all six soils tested explained 39% of the variation in the data on losses in macroporosity resulting from soil compaction. While this indicates a general trend in the reduction in macroporosity as soil bulk density increases, the accuracy of the predicted change was less than ideal due to the variability in the data set as a result of total soil porosity and soil pore size distribution shifts occurring at different degrees in different soil types.

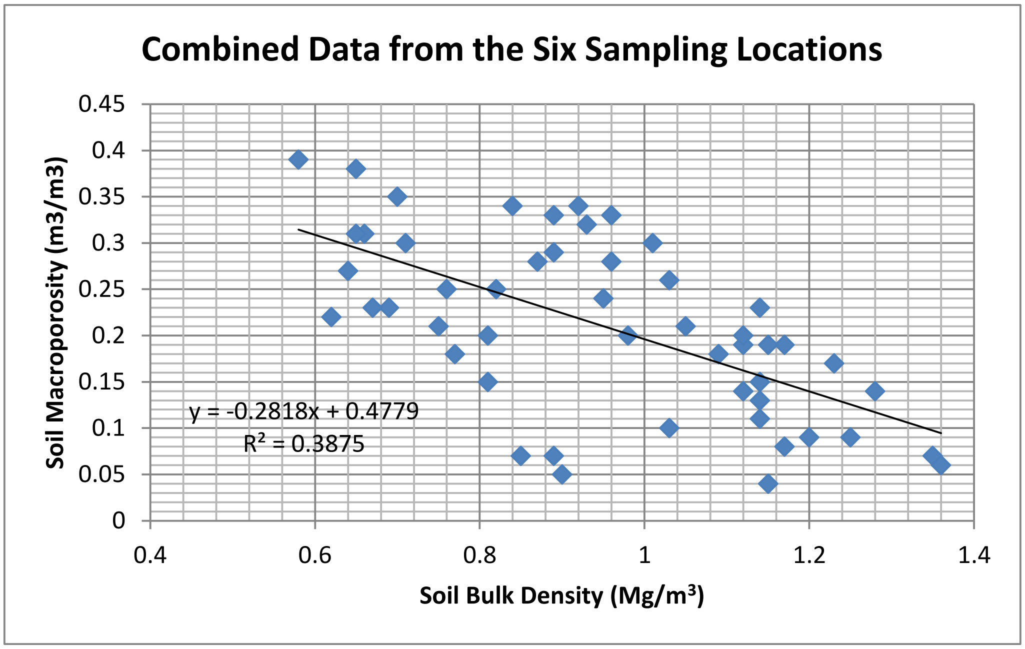
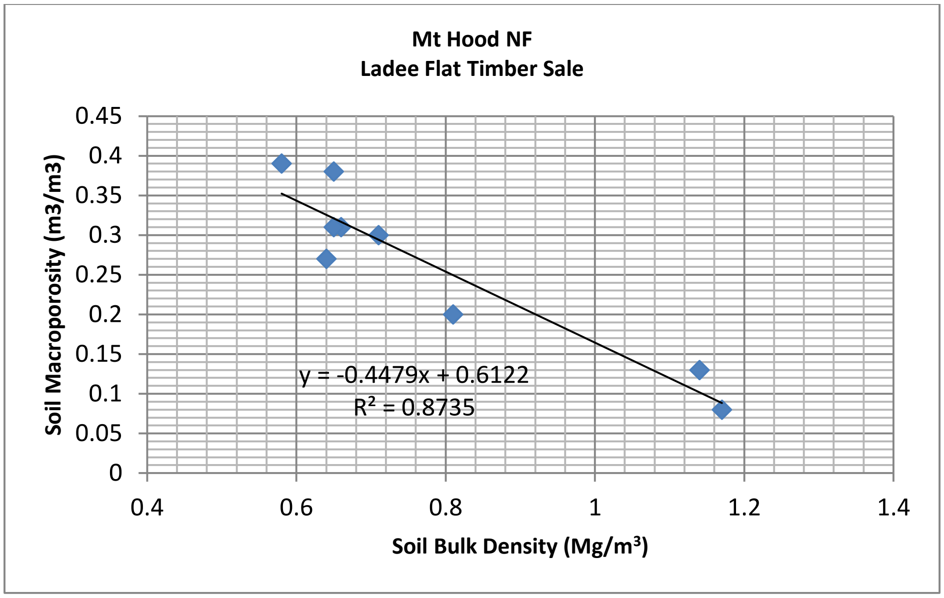


Figure 4.4 Decrease in soil macroporosity as a function of increasing soil bulk density.

Thus, it appears difficult to develop a single equation for these diverse soil types that can be used to reliably predict changes in soil porosity from measurements of soil bulk density with a high level of accuracy. Correlations between soil macroporosity and soil bulk density for individual soils did show an improvement in predictability of changes in macroporosity in five out of the six soils tested (Figure 4.5). Based on these results it appears it is possible, in most cases, to make reasonable predictions of changes in macroporosity from a change in soil bulk density once a correlation coefficient is determined for an individual soil type using the water desorption method.



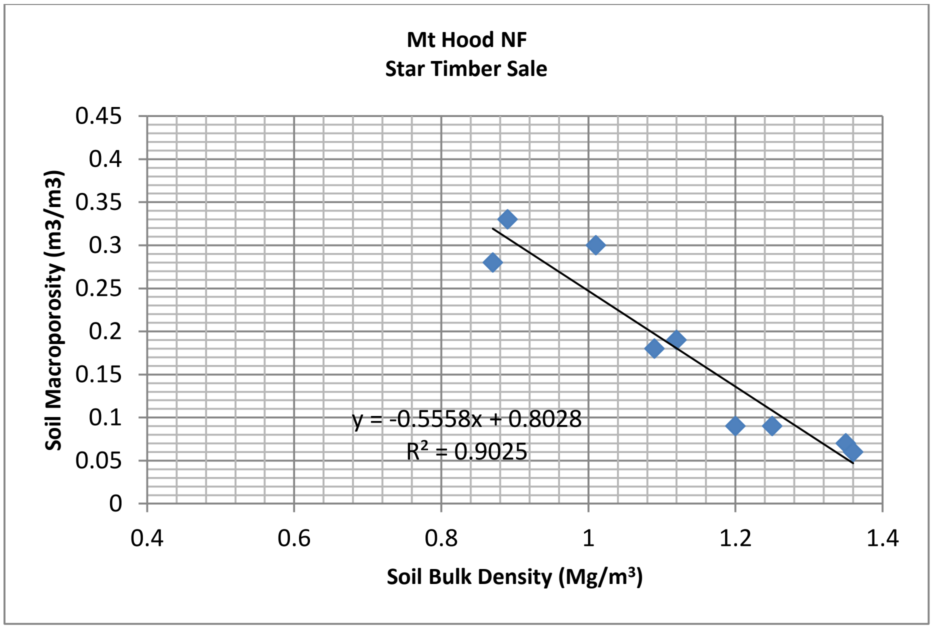
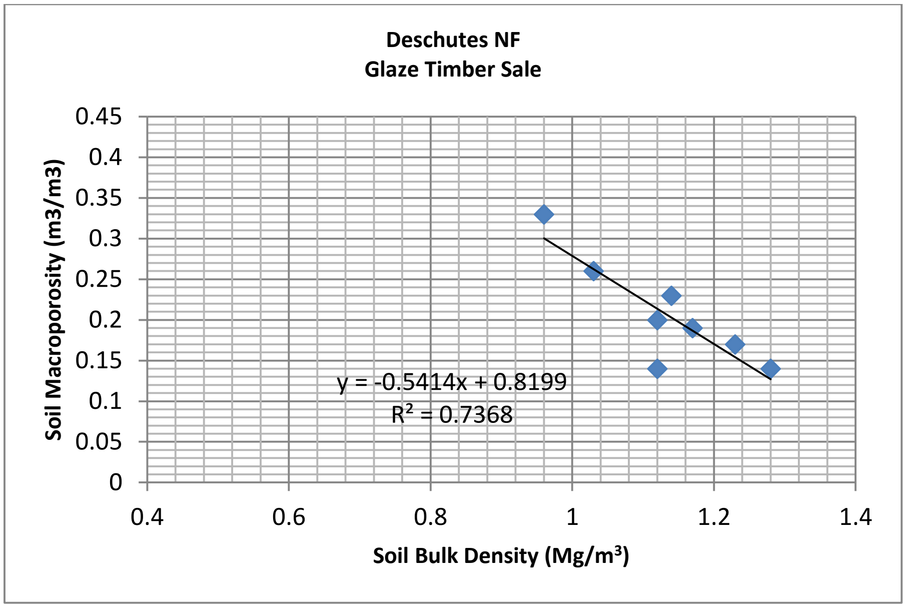


Figure 4.5 Decrease in soil macroporosity as a function of increasing soil bulk density for individual soil types.

Figure 4.5 continued



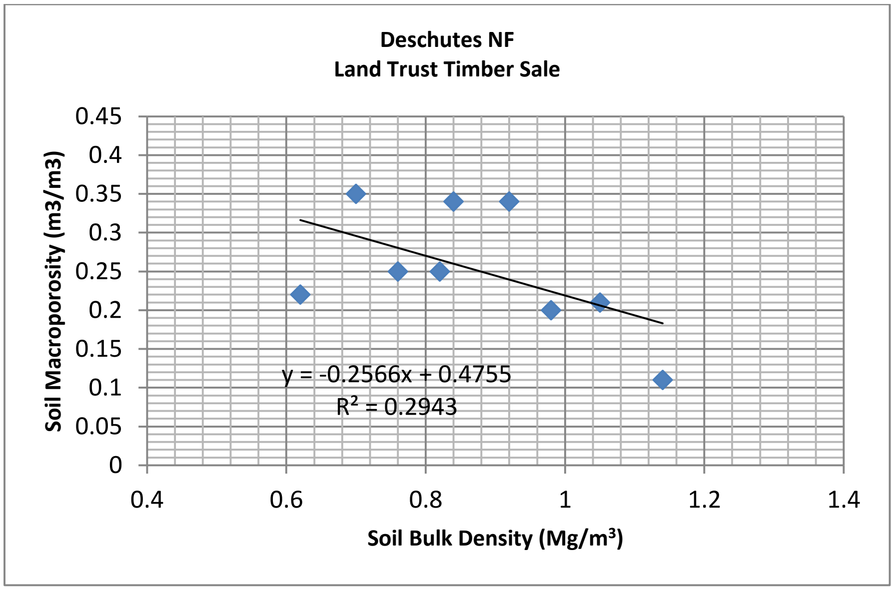
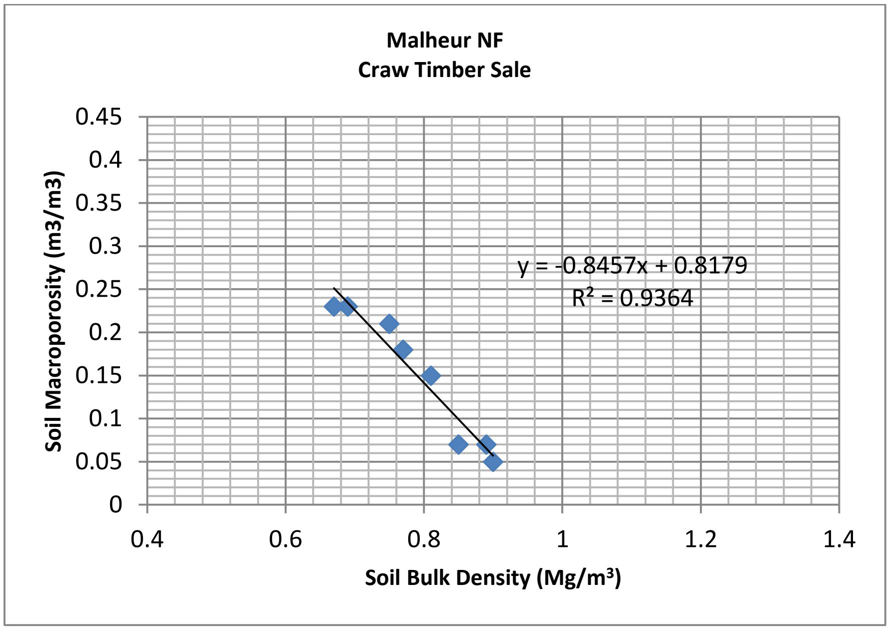
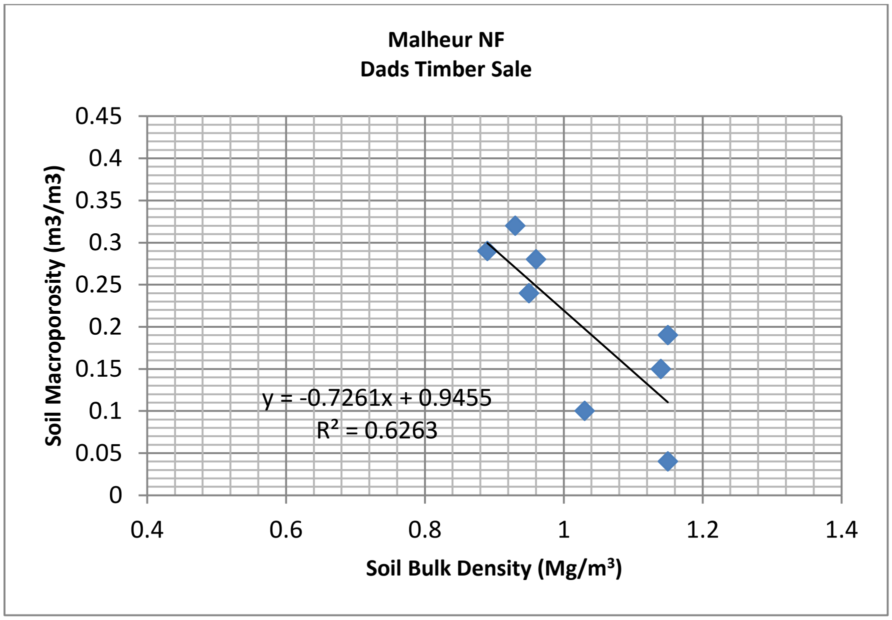


Figure 4.5 continued





Available Water Supplying Capacity

In addition soil porosity changes, the water desorption method also provided a direct measurement of changes in available water capacity (AWC) resulting from compaction. In areas of compacted soils AWC was between 9 and 37% higher, reflecting a shift in pore size distribution when soils compact from macropores to mesopores (Tables 4.8 and 4.9). However, not all differences were statistically significant, despite a consistent pattern of higher values in the disturbed areas.

Table 4.8 Available water capacity cm^3/cm^3), defined here as water held at < -10kPa tension, as related to soil disturbance level for harvester/skidder operations and harvest location.

Visual soil disturbance class	**Mt Hood NF, Estacada RD, Ladee Flats Sale, Unit 1**		**Mt Hood NF, Barlow RD, Star Sale, Unit 19**		**Deschutes NF, Sisters RD, Metolius Land Trust Sale, Unit 5**	
	Available water capacity	**% difference in available water capacity**	**Available water capacity**	**% difference in available water capacity**	**Available water capacity**	**% difference in available water capacity**
1	0.36 (0.02) a	-	0.29 (0.01) a	-	0.27 (0.01) a	-
2	0.40 (0.02) a	11	0.33 (0.01) a	14	0.37 (0.03) b	37
3	0.43 (0.01) a	19	0.36 (0.02) a	24	0.34 (0.02) b	26

Soil disturbance classes (1) No soil disturbance, (2) Harvester off trail track, (3) Skid trails. Available water capacity values shown are means +/- one standard error in parentheses, (n = 3). Within a location and soil type means followed by the same letter are not significantly different at $P < 0.05$.

Table 4.9 Available water capacity (cm^3/cm^3), defined here as water held at < -10kPa tension, as related to soil disturbance level for harvester/forwarder operations and harvest location.

Visual soil disturbance class	**Deschutes NF, Sisters RD, Glaze Sale, Unit 6**		**Malheur NF, Prairie City RD, Dads Sale, Unit 2**		**Malheur NF, Prairie City RD, Craw Sale, Unit 126**	
	Available water capacity	**% difference in available water capacity**	**Available water capacity**	**% difference in available water capacity**	**Available water capacity**	**% difference in available water capacity**
1	0.30 (0.02) a	-	0.32 (0.01) a	-	0.46 (0.02) a	-
2	0.34 (0.01) b	13	0.38 (0.02) b	19	0.50 (0.02) a	9

Soil disturbance classes (1) No soil disturbance, (2) Harvester forwarder trails. Available water capacity values shown are means +/- one standard error in parentheses, (n = 4). Within a location and soil type means followed by the same letter are not significantly different at $P < 0.05$

Changes in soil porosity have been shown to affect the amounts of water storage in the soil (Gomez et al., 2002; Siegle-Issem et al., 2005). For example, Gomez et al. (2002) noted that soil compaction significantly increased the amount of plant available water (-0.03 to -1.5 MPa) between the 0 and 45 cm soil depth. It was also noted that this was associated with an increase in cumulative stem volume for ponderosa pine on a sandy soil texture, no increase on a loam soil, and a decrease in growth on a clay loam soil when compared to undisturbed soils.

Soil Strength

In the spring of 2014 when soil penetrometer measurements were made, total gravimetric soil moisture contents (GWC) were near or above field capacity (Tables 4.10 and 4.11). Soil strength in the non-compacted areas showed a similar pattern for all soils, gradually increasing with soil depth to between 1000 and 2000 kPa (Figure 4.6). In compacted areas changes in soil strength varied with soil type. The Andisol soils on both sale units on the Deschutes NF showed the largest increase in soil resistance, with resistance increasing to greater than 4000 kPa in the 10 to 30 cm depth then dropping to lower differences in resistances deeper in the soil profile. The Inceptisol soils on the Mt

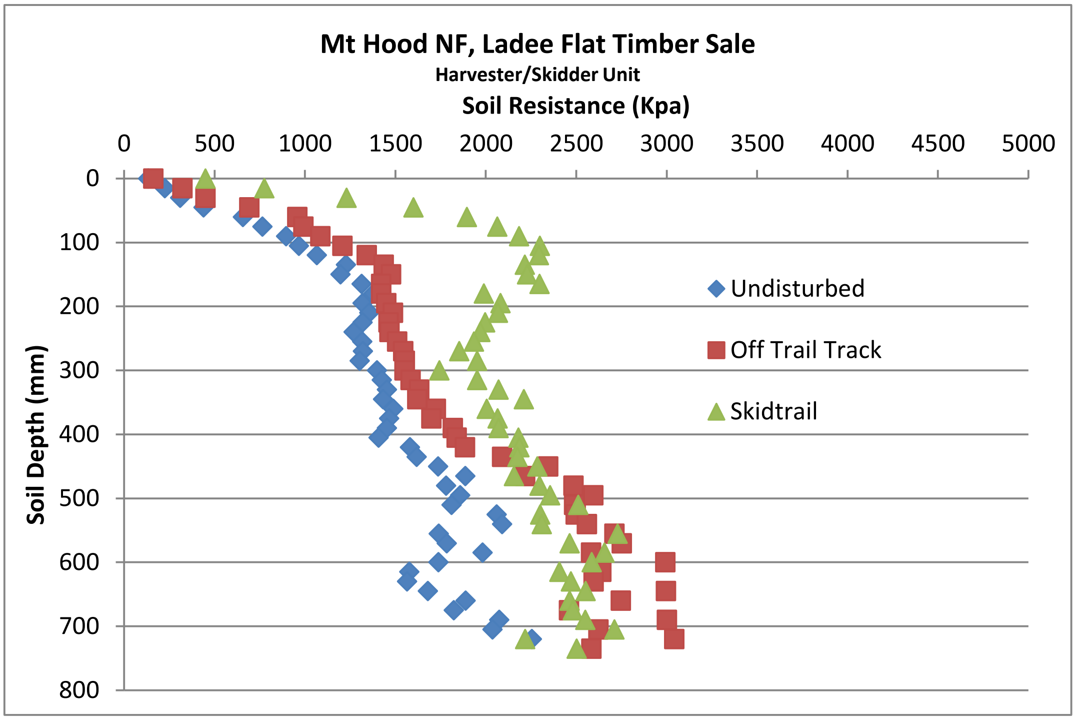
Hood NF showed a similar pattern but maximum resistances were in the range of 2000 to 3500 kPa. The Andisol soil and Mollisol soil both on the Malheur NF showed little difference in soil resistance between the undisturbed and compacted areas. Slightly higher soil resistances in the undisturbed areas of the Mollisol soils compared to the disturbed soils were likely due to a thick grass mat on the surface of the Mollisols which was broken up in disturbed areas of the unit.

Table 4.10 Comparisons of gravimetric water content (GWC) when penetrometer measurements were made and at field capacity soil moisture (-10kPa tension), as related to harvester/skidder operations and harvest location.

Mt Hood NF, Estacada RD, Ladee Flats Sale, Unit 1		**Mt Hood NF, Barlow RD, Star Sale, Unit 19**		**Deschutes NF, Sisters RD, Metolius Land Trust Sale, Unit 5**	
GWC at time of penetrometer measurements (g/g)	**Soil moisture at field capacity (m^3/m^3)**	**GWC at time of penetrometer measurements (g/g)**	**Soil moisture at field capacity (m^3/m^3)**	**GWC at time of penetrometer measurements (g/g)**	**Soil moisture at field capacity (m^3/m^3)**
0.68	0.36	0.36	0.29	0.38	0.27

Table 4.11 Comparisons of gravimetric water content (GWC) when penetrometer measurements were made and at field capacity soil moisture (-10kPa tension), as related to harvester/forwarder operations and harvest location.

Deschutes NF, Sisters RD, Glaze Sale, Unit 6		**Malheur NF, Prairie City RD, Dads Sale, Unit 2**		**Malheur NF, Prairie City RD, Craw Sale, Unit 126**	
GWC at time of Penetrometer Measurements	**Soil moisture at field capacity (m^3/m^3)**	**GWC at time of Penetrometer Measurements**	**Soil moisture at field capacity (m^3/m^3)**	**GWC at time of Penetrometer Measurements**	**Soil moisture at field capacity (m^3/m^3)**
0.26	0.30	0.48	0.32	0.66	0.46



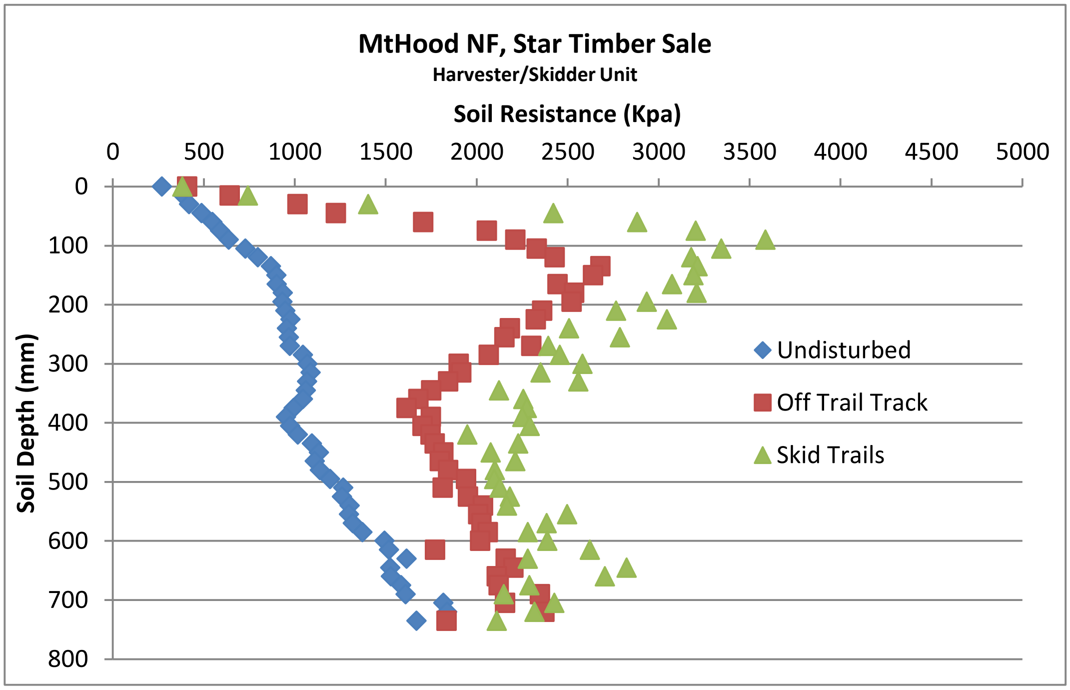
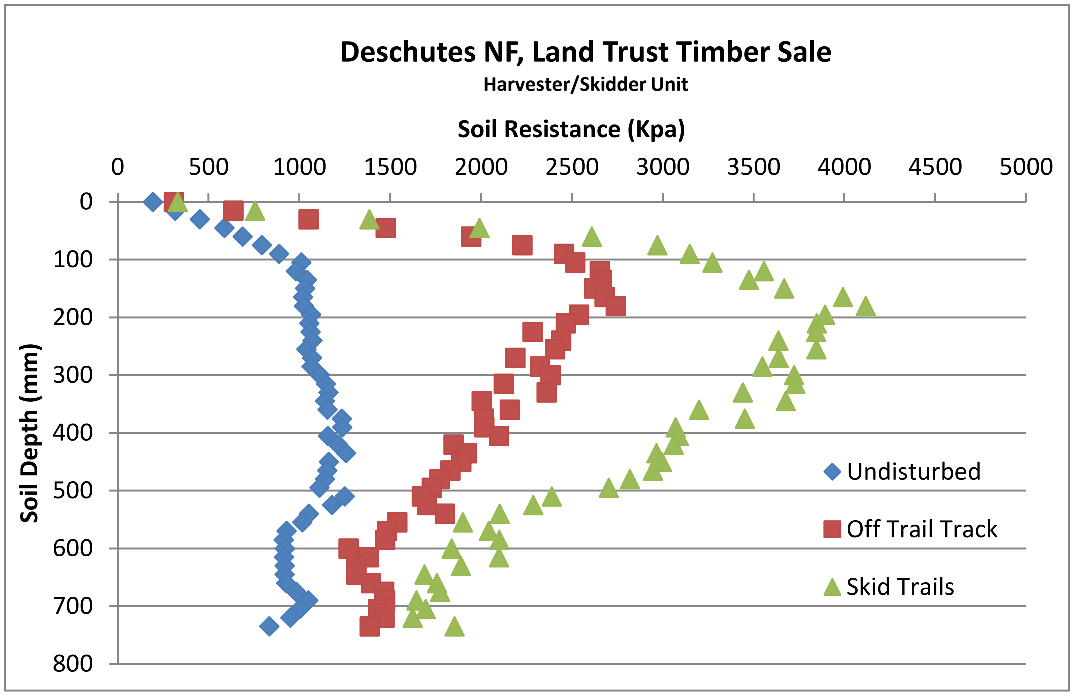


Figure 4.6 Soil strength as related to soil disturbance level and harvest equipment type.

Figure 4.6 continued



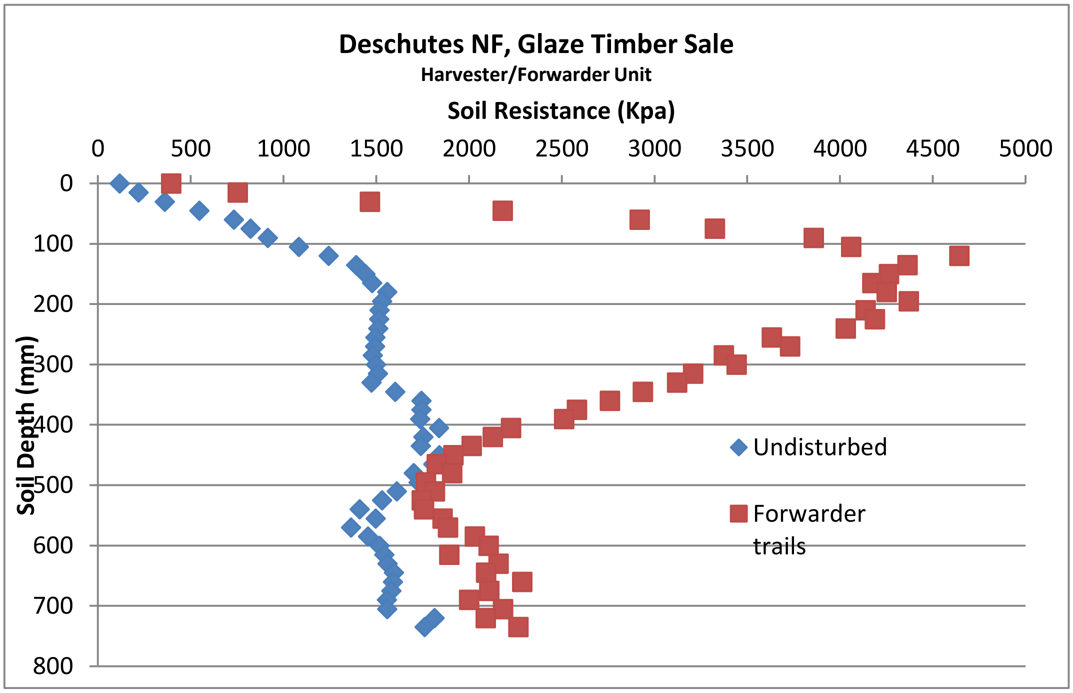
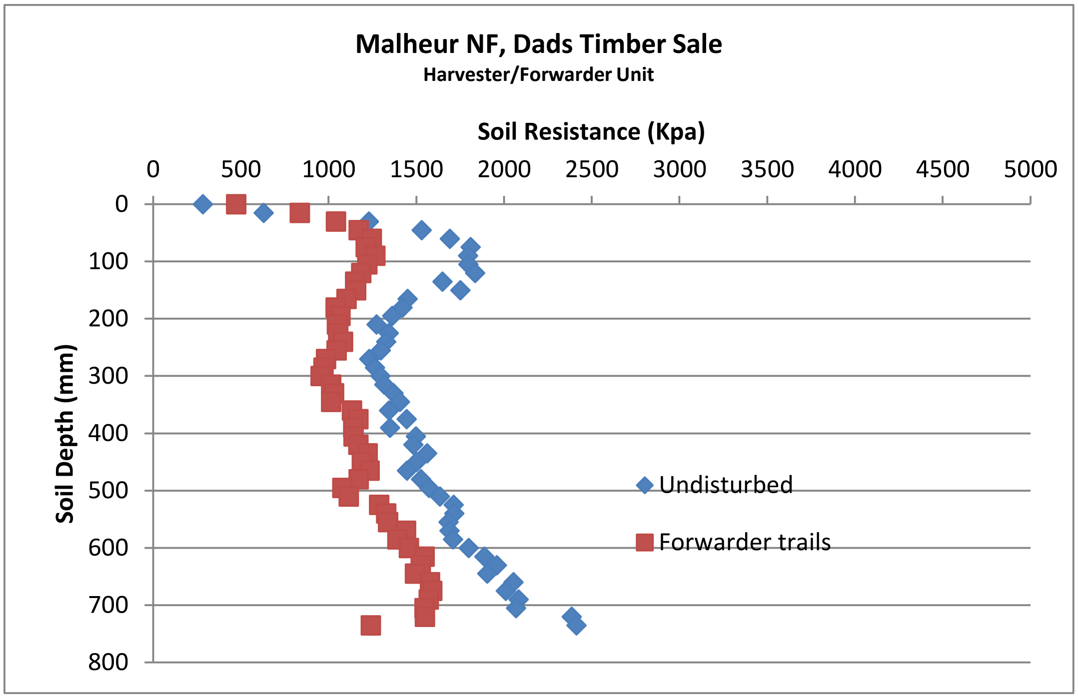
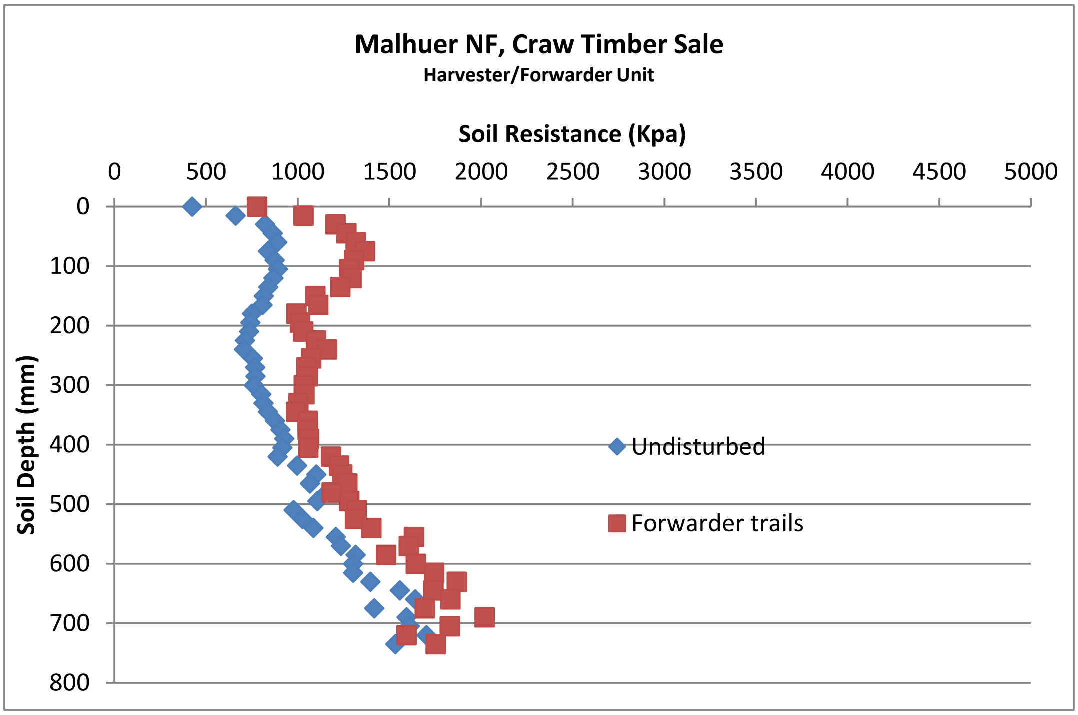


Figure 4.6 continued





Laboratory studies have shown that an increase in soil strength above 2 MPa, resulting from soil compaction, may result in a reduction of plant root growth (Siegel-Issem et al., 2005; Greacen and Sands 1980). Compared to soil bulk density, measurements of soil strength provide a more direct measure of root limiting levels of soil resistance. Increases in soil resistance resulting from compaction varied by soil type, with the Deschutes and Malheur soils exceeding root-limiting levels determined by other researchers (Siegel-Issem et al., 2005, Greacen and Sands, 1980), whereas soil resistances in compacted areas of the Malheur soils were well below root-limiting levels.

Soil Management Interpretations

Soil porosity

Decreases in total soil pores, macropores, and an increase in mesopores and micropores can negatively affect the soil air-water balance (Siegel-Issem et al., 2005; Startsev and McNabb, 2009) and in some cases reduce water infiltration capacity and increase runoff (Startsev and McNabb, 2000). Several studies have investigated the effects of soil porosity changes on key soil functions through the alteration of air and water flow into and through the soil. Root elongation in radiata pine (*pinus radiata*) seedlings was found to be nearly zero when soil matric potentials were high and air-filled porosity was < 0.05 cm^3/cm^3. Increasing air-filled porosity to 0.15 cm^3/cm^3 resulted in root elongation increasing sharply (Zou et al., 2001). A reduction in aeration porosities below 0.1 cm^3/cm^3 was also proposed as a root growth-limiting threshold by Grable and Siemer (1968) and Siegel-Issem et al. (2005) identified 10 percent aeration porosity as a threshold below which tree seedling root growth may become inhibited.

Assuming that compaction levels on harvester trails were similar at each of the sample locations, the crystalline mineralogy of the Mt Hood soils appeared more susceptible to losses of total porosity and macroporosity compared to the Andisol soils on the Deschutes NF which were derived from volcanic ash. In a study of soil compressibility and shear strength McNabb and Boersma (1993) found a similar pattern for low bulk density Andisols in the Pacific Northwest, which were less compressible than the crystalline mineralogy soils commonly found in areas other than central Oregon and Washington. The resistance of Andisols was attributed to significantly higher shear strengths, specifically the angle of friction. Although the Malheur soils were derived from volcanic ash soil parent materials, they were susceptible to soil macroporosity losses similar to that of the Mt Hood soils. This may be due to the finer volcanic ash materials in the Malheur soils compared to volcanic ash on the Deschutes.

Risk of negative effects to key soil functions such as soil air-water balance and reduced water infiltration capacities may be higher in the Mt Hood soils compared to the other soils due to their udic soil moisture regime and the increased risk of saturated soil conditions for long periods compared to the Deschutes and Malheur soils that have a xeric soil moisture regime.

Soil bulk density

Minore (1969) investigated the effects of increased soil bulk density on seven Northwestern tree species and found root growth responses of tree seedlings varied by species and soil bulk density. Results showed that all seven tree species grew through soils having a bulk density of 1.32 Mg/m^3, three of the tree species did not growth through soils at bulk density 1.45 Mg/m^3, and none of the tree species were able to grow through soils with 1.59 Mg/m^3 bulk densities. Soil bulk densities measured in this current study were well below those root limiting levels tested by Minore, but his work remains important in showing variable species responses to compaction.

Soil strength

Levels above which roots of some tree species begin to be affected by increases in soil resistance have been suggested in the range of 2000 to 2500 kPa (Siegel-Issem et al., 2005; Greacen and Sands, 1980). Increases in soil strength in the Deschutes volcanic ash soils were well above the 2 MPa levels identified by these researchers. Such high soil resistances could negatively impact key soil functions and in turn site productivity in these soil types. Operationally, the resulting high soil resistances even when soils are near field capacity indicate that these soils could support equipment operations during moist to wet soil conditions without causing excessive rutting or puddling of the soil. On these soils, equipment operational periods could extend over longer periods of time compared to the other soil types. These volcanic ash soils would also be expected to benefit from soil restoration measures like soil tillage (subsoiling) to reduce soil resistance in compacted areas.

The Malheur volcanic ash soils showed little change in soil strength following equipment operations and therefore increases in soil resistance from compaction would not be expected to have negative effects on key soil functions. Operationally these soils have relatively low soil resistance when soil moistures are near field capacity indicating that equipment operations during these moist conditions could result in excessive soil rutting and possibly undesirable soil puddling that alters soil structure. Powers et al. (1998) discuss the effect of increasing soil resistance as soils dry out over the summer months and the effects of higher soil resistance in disturbed areas reducing the length of the growing season. These soils do dry out later in the summer as indicated by their xeric soil moisture regime. As they dry out soil resistance is expected to increase and, if soil resistance in the disturbed trails increases faster than in non-disturbed areas, root limiting conditions could occur sooner in the compacted trails.

The Mt Hood residual soils showed increases in soil strength resulting from disturbance that was intermediate between those higher levels found on the Deschutes and the very low levels found on the Malheur. Such increases in soil resistance may be expected to have some effect on key soil functions but not to the extent of that on the Deschutes. Operationally, the increase in soil resistances should have at least some benefit in supporting equipment operations when soils are moist. These sites have an udic soil moisture regime indicating precipitation is more evenly distributed over the year compared to the xeric soil moisture regime. This could have some benefit in reducing the soil drying effect that can result in higher soil resistances compared to the xeric soil moisture regime at the other monitoring locations.

Conclusion

Results indicated that changes in soil bulk density, soil porosity, and soil strength varied widely by soil type, and thus could not be generalized. These findings are consistent with other observations that impacts from ground-based forest harvest operations are dependent upon various factors, some of which include the type of harvest equipment used, operator experience, soil conditions, and soil type (Heninger et al., 1997).

The modified water desorption procedure provided a practical procedure for measuring and interpreting soil porosity changes resulting for forest management. Soil porosity measurements provided information in addition to changes in soil bulk density and soil strength to better inform land managers about the degree of soil changes occurring and potential changes in key soil functions. The method does not require the use of more elaborate and costly laboratory equipment and therefore can be used in field offices where only a minimum of facilities are available. Once soil macroporosity and soil bulk density have been measured for an individual soil type, a correlation can be established to reasonably predict soil porosity changes from measurements of soil bulk density. This approach provides a practical alternative for assessing important changes in pore size distribution resulting from forest management.

While these results appear to be consistent between soils and treatments, it is recognized that this method still needs comparison and validation against standard laboratory pressure plate measurements to fully support its use. Some of the variables that may affect its accuracy include precision in measuring the height of the water column and consistency of the temperature of the water in the column. Care in the collecting of soil cores to assure that soil structure is maintained is also probably one of the more important steps in the procedure to help assure accurate results.

By helping determine which soil types are more or less sensitive to management disturbances that may affect soil function, the effects of those disturbances on those key soil functions can be better analyzed. Results in turn can be used to develop meaningful project design criteria and, when necessary, mitigation measures for operational periods. When needed, this information may also be useful for justifying and developing prescriptions for soil restoration activities within areas of sensitive soil types.

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Chapter 5 : US Forest Service Soil Quality Standards: A case for updating current directives/guidelines in Region 6

Terry L. Craigg

Abstract

Soil productivity plays a primary role in maintaining essential ecosystem functions; therefore, it is important for forest managers to be able to evaluate the effects that forest management activities can have on this vital component of soil quality. The US Forest Service (FS) has addressed this issue through their development of FS "Soil Quality Standards" (SQS) to assess and limit soil disturbances and changes in soil quality resulting from forest management operations. Regional FS directives and guidelines outlined in the FS SQS have been in place for nearly four decades. FS SQS serve as limits that maintain soil quality based upon current research and professional judgment, and are expected to be reevaluated and updated as additional information becomes available. It has been nearly two decades since the Pacific Northwest FS Region 6 (R6) standards and guidelines were last reviewed and updated.

To evaluate the soil monitoring approach and SQS currently being used by the FS R6, forest soil disturbance monitoring was conducted on five National Forests in Oregon and Washington within operational settings in a manner typical of that used by a manager on an R6 Forest or Ranger District. Results from these diverse sites indicated that the visual soil conditions commonly assessed with disturbance do not consistently reflect actual measurements of detrimental soil conditions as defined within the FS R6 SQS. Results also strongly suggest that measurement and evaluation of relevant physical and chemical soil-based indicators are essential for effective interpretation of visual soil disturbance classes. Additional soil indices not currently included in FS R6 SQS were also investigated to help identify needs and opportunities for updating and refining directives and guidelines based on the overall data analysis and interpretations. Recommendations include the development of a FS Region 6 strategic soil data base, compiled and stratified by soil taxonomic classes known to influence management, which could provide a concise and readily accessible reference for more effective answers to questions about the different effects of different soil disturbances.

Introduction

The concept of soil quality has been used as a tool to improve understanding and assessments of both land-use decisions and the sustainability of different management practices (Doran and Parker 1994, Karlen et al., 2001). The term “dynamic soil quality” reflects how the functional capacity of soils may be altered in response to natural or human caused disturbances (Seybold et al. 1998). When one or more soil properties are altered to a point where a soil can no longer function at its full potential for a defined purpose, the dynamic soil quality is said to be reduced or impaired (Larson and Pierce, 1991, Doran and Parker, 1994, Karlen et al., 2001).

The Pacific Northwest Region of the US Forest Service (FS) has a long history of concern about potential negative soil impacts resulting from forest management activities (Adams, 2005). In the 1970’s a key western regional document discussing federal forest policy concluded that prudent land management should limit the extent and degree of soil disturbances from operations (Cornell and others, 1977), and specific soil protection guidelines emerged for the Pacific Northwest soon after (Boyer, 1979). These guidelines subsequently were formally adopted into administrative handbooks and manuals (e.g., USDA Forest Service, 1983), and further refined by different FS Regions over the past few decades. In the Pacific Northwest Region (R6) the most recent revision is reflected in the regional supplement to the Forest Service Manual (FSM 2520, R-6 Supplement No. 2500-98-1) and is commonly referred to as the FS Soil Quality Standards (SQS) (USDA Forest Service 1998). Since their inception, the FS SQS have greatly increased the awareness of soil disturbances that result from forest management that may affect important ecosystem functions.

In a review of FS assessments of soil disturbances, Powers (2002) noted that the FS SQS are meant to serve as early warnings, are based on current knowledge, and are intended to be updated as new information becomes available. In the late 1980’s, concerns within the FS over changes in dynamic soil quality resulting from forest management prompted National Forest managers and FS research scientist to cooperatively establish the North American Long Term Soil Productivity (LTSP) experiment (Powers, 1991). This effort has been the world's largest organized research network addressing forest management and sustained productivity issues. One of the main goals of this study has been to help refine and validate the FS SQS. More recently a National Soil Disturbance Monitoring Protocol was also implemented to quickly identify and quantify visual soil disturbances within project activity areas (Page-Dumroese et al., 2009), with additional soil-based indicators proposed to help identify degraded soil conditions (Burger and Kelting, 1998; Powers et al., 1998; Schoenholtz et al., 2000; DeLuca and Archer, 2009).

Questions persist, however, about whether the FS standards and guidelines and the soil disturbance monitoring protocol effectively identify soil changes that cause key impacts such as tree growth reductions and increased runoff (e.g., Miller and Anderson, 2002; Miller et al., 2010). Page-Dumroese, et al. (2000) applied selected FS Regional SQS over a climate and elevation gradient of soils in the Pacific Northwest and found that a single limit for a soil property applied across a diversity of soil types was not adequate for assessing a soil change.

A notable consequence of these soil disturbance assessments has been challenges by groups opposed to forest management that the FS is not meeting its own standards and guidelines for the soil resource (Miner et al., 2014). In some instances this broader issue of legal opposition to FS management activities and the resulting soil disturbances has prompted a shift in National and some Regional SQS directives and guidelines away from the measurable standard threshold approach to a less quantifiable description of desired future conditions (USDA Forest Service, 1983; USDA Forest Service, 2012).

Past criticisms of the FS SQS have included statements that standards and guidelines focus primarily on surface disturbances, and that criteria focuses on qualitative rather than quantitative assessments (Powers et al., 1998). Some of the shortcomings commonly cited include the lack of well-established relationship between standards and guidelines and soil productivity, subsoil conditions are not adequately considered in assessments, and weak integration of processes (e.g., interactions between different soil variables are seldom considered). These concerns will be discussed further here in a review of relevant literature addressing soil quality changes from soil disturbances as well as in relation to observations from new monitoring and data collection from five R6 study sites. The overall analysis provides some significant and current direction for constructive refinement of the existing FS R6 SQS.

US Forest Service Approach to Operational Soil Monitoring

Within the FS, assessments of soil disturbances are made through a stratification process in which visually recognizable soil disturbance categories that can be easily verified by probing the soil are initially described and quantified within an activity area (Howes, 2006; Craigg and Howes, 2007). Individual visual soil disturbance categories typically describe areas with one or a combination of disturbances that repeat across an activity area and that are assumed large enough in extent and distribution to affect soil function (Craigg and Howes, 2007). In 2009, the National Soil Disturbance Monitoring Protocol was developed to provide a statistically based systematic method for making this assessment (Page-Dumeroese et al., 2009).

The protocol for stratifying visual soil disturbances across an activity area provides a rapid method for quantifying different types of soil disturbances over large acreages and is recognized by the FS as a primary step in the soil assessment process. Describing and quantifying the amounts of different visual disturbance classes, however, does not in itself indicate whether or not a soil disturbance is detrimental in terms of the soil's ability to function in a desirable manner. For visual soil disturbance classes to be meaningful a determination must also be made as to whether or not these disturbances represent a true change in important response variables such as vegetative site productivity and hydrologic function. Because individual soil functions can be difficult or time-consuming to quantify directly, soil-based indicators of change are used to evaluate these processes (Powers et al., 1998; Burger and Kelting, 1998; DeLuca and

Archer, 2009). These assessments of soil-based indicators thus provide a quantitative link between visual soil disturbance classes and those disturbances that are considered to negatively affect important soil functions (USDA Forest Service, 1998).

Determining appropriate soil-based indices for evaluating different soil disturbance categories requires the identification of those key soil functions that may be negatively affected by a disturbance. For example, if surface soil has been displaced, a reduction in its ability to supply nutrients may be the key soil function of concern, whereas in areas of compacted soils, changes in root penetration as well as soil air and water movement may be important. Descriptions of soil functions affected by a given disturbance allows for the selection of appropriate soil-based indicators to assess important changes in key soil functions. On National Forest System lands, soil disturbances are considered “detrimental” when a measured soil index extends beyond a defined threshold identified in the Regional FS SQS (Powers et al., 1998).

In addition, the FS R6 SQS also set limits for the allowable areal extent of detrimental soil disturbance that can occur before standards and guidelines are exceeded. In FS R6, the allowable amount of soil disturbance identified to be detrimental is limited in extent to no more than 20% of an activity area. An activity area is defined as “the total area of the activity, and feasible unit for sampling and evaluating” and is referenced in the R6 FS Manual (USDA Forest Service, 1998). These area extent limits include permanent features of the transportation system such as roads and landings as well as logging systems. In activity areas that exceed this extent limit either as a result of previous or current activities, restoration plans must be in place before new projects are implemented.

The FS R6 SQS emphasize both observable and measurable soil characteristics that field personnel can use to monitor effectiveness of activities in meeting soil management objectives (USDA Forest Service, 1998).

This chapter is organized in to three parts. To build a case for updating current SQS directives/guidelines in FS Region 6, I begin in Part 1 with a review of the current soil monitoring protocol and visual assessment methods described in the FS “Forest Soil Disturbance Monitoring Protocol” (FSDMP) (Page-Dumroese et al. 2009) and discuss issues and opportunities for refinements. Part 2 next provides an evaluation of the current FS R6 SQS through a review of operational monitoring data supplemented by additional soil measurements collected from a range of locations in FS Region 6. The case is further supported in Part 3 with a discussion of how measurements of soil-based indicators provide a foundation for improving the interpretations of visual soil disturbances as they reflect effects on key soil functions. In the conclusion recommendations are provided for updating current directives/guidelines in FS Region 6.

Part 1: A review of the FS Forest Soil Disturbance Monitoring Protocol

In 2009 the FS released a Forest Soil Disturbance Monitoring Protocol (FSDMP) to assist with the quantification of visual soil condition classes within managed areas (Page-Dumroese et al. 2009). Volumes I and II of the FSDMP provide soil monitoring methods for the collection of visual soil disturbance data, statistical procedures for data analysis, and data storage components for a national soil disturbance data base. The FSDMP defines soil quality for public lands in the United States in terms of the “maintenance of soil productive capacity.” This definition was derived from interpretations of the Multiple Use and Sustained Yield Act of 1979, the Forest and Rangeland Renewable Resources Planning Act of 1974, and the Forest Management Act (NFMA) of 1976. The FSDMP acknowledges the challenges in the developing meaningful soil quality standards that address the full range of variability found in forest soils and strives to establish a monitoring protocol that is practical to use and provides meaningful information (Page-Dumroese et al. 2009).

In the FSDMP it is recognized that soil quality cannot be measured directly and therefore must be defined in terms of the functional elements of the soil that sustain biological productivity, in particular indicators that define those functions (Page-Dumroese et al. 2009). To address this issue the fundamental properties of soil porosity and site organic matter as discussed in Powers et al. (2005) are cited as site response variables that could, if altered by disturbances, alter soil quality by changing the ability of roots to support leaf mass and primary productivity (Powers et al. 1998).

The FSDMP addresses the same soil disturbances identified in current FS R6 SQS as well as the potential negative effects that those disturbances can have on site productivity and hydrologic responses (Page Dumerose et al. 2009). The protocol acknowledges the need for standardization of methods for making assessments that allow for consistent comparison and interpretation of results. The protocol also relies on the use of common definitions for terms for describing disturbances (Curran et al. 2005) as well as standardization of methods used to make assessments (Reeves et al., 2013; Howes et al. 2006, Page Dumerose et al. 2009).

For consistency, the FSDMP provides a standard set of visual soil disturbance classes that describe the degree of change from natural or pre-activity conditions (Page-Dumroese et al. 2009). This is consistent with other soil monitoring protocols developed over the past decade which have attempted to replace point observations of soil disturbances with a defined set of visual soil disturbance classes (Howes 2006). Describing and quantifying these sets of visual soil disturbance classes has several advantages over point observations of a soil disturbance. For example, visual soil disturbance classes provide a means of recognizing only those disturbances that have an extent and distribution that may have a significant effect on soil function. Visual soil disturbance classes also avoid the need to separate out several different soil disturbances that might be occurring in the same area, such as soil compaction and soil displacement that sometimes are found in the same disturbed area.

The FSDMP describes four soil disturbance classes that increase in severity of impact, ranging from class 0 to class 3 (Page-Dumroese et al. 2009). While the obvious advantage of this type of approach is consistency among concurrent observations, there are some disadvantages to this approach as well. One issue is the loss of flexibility for recognizing specific soil conditions that can result from different types of harvest equipment, soil types, soil conditions, as well as other important factors. In some cases two or three visual soil disturbance classes may be adequate for describing the different types of disturbance that have occurred, and in other cases more than four categories may be needed. If fewer visual soil disturbance classes are adequate for describing a disturbed area, this can save time and the expense of making unnecessary measurements.

An alternative to a standard set of visual soil disturbance categories would be to provide a standard set of descriptions of soil visual indicators and management activities, much like what has been done under the FSDMP unique monitoring strategies section of Volume II, Table 3. The individual doing the monitoring could then choose those soil disturbances that apply to their location and build their own site-specific set of visual soil disturbance classes. This would still provide the consistency of standardized descriptions while also allow for the flexibility of determining only the number of visual classes needed for an individual location.

Summary

The FSDMP establishes a standard inventory, monitoring, and assessment tool, based on common terms, and is intended to allow for consistent data sharing and interpretation. However, the determination as to which soil disturbances and condition classes represent an important alteration in key soil functions is not specified and instead left to those doing the monitoring. There are currently few tools and limited guidance available to assist soil scientists and others in interpreting these soil disturbance monitoring results. To help address this gap, I will next review key ecological processes and soil functions along with soil-based indicators that can be used to make determinations of important changes.

Part 2: Evaluation of current FS R6 SQS

To evaluate the current FS R6 SQS, forest soil disturbance monitoring and data collection were conducted in operational settings on five National Forests in Region 6. Soil monitoring was initially implemented in a manner that would be typical of that used by a FS manager working on a Forest or Ranger District in Region 6 (Howes, 1983; Page-Dumroese et al., 2009). Evaluations included identification of defined visual soil disturbance classes and quantification of area extent of different soil disturbance classes.

To establish physical and biological linkages for interpreting the practical consequences of the visual soil disturbances, the more basic evaluation of visual soil disturbance monitoring was supplemented by quantitative measurements of soil characteristics. Critical thresholds for soil-based indicators are identified in the FS R6 SQS (USDA Forest Service, 1998) with the intent of using those indicators to interpret visual soil disturbances and determine whether or not they meet the definitions of detrimental conditions. However, in R6 few forest managers are measuring these indices as a part of their monitoring and data collection program (K. Bennett, personal communication). Instead they apparently are basing their assumptions of detrimental soil disturbances solely on a visual soil disturbance classes that may or may not meet the definition of detrimental conditions in the FS R6 SQS.

Methods

Site Descriptions

Five locations with six distinctly different soil types within FS Region 6 (Oregon and Washington) were chosen for this study (Figure 5.1). Each of the five sampling locations consisted of a vegetation management unit (activity area) that was harvested (thinned) within the past few years. The study sites include four soil orders that reflect udic and xeric soil moisture regimes and mesic, frigid, and cryic soil temperature regimes (Table 5.1). Slopes at all sampling locations were less than 30 percent and ground-based harvest was conducted with mechanized harvester and skidding equipment. Soils at each of the locations occur over extensive areas of these National Forests and the forests they support are likely to continue under active management in the near future.

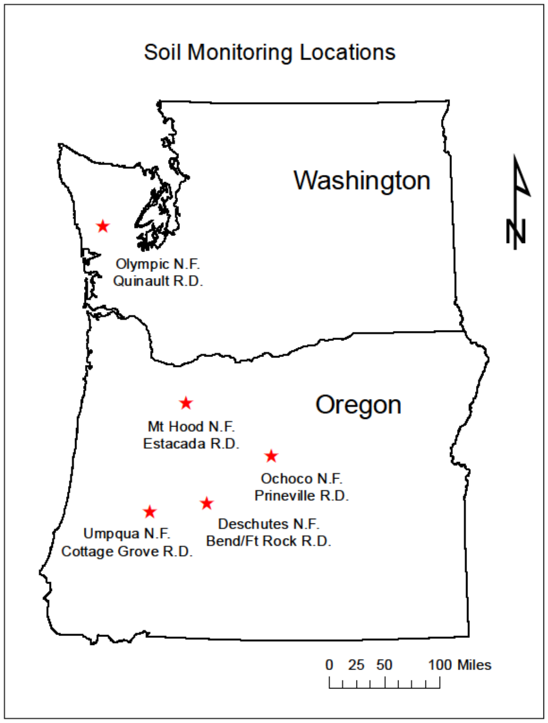


Figure 5.1 Map of five soil monitoring and sampling locations with six soil types within FS Region 6.

Table 5.1 Vegetation and soil classifications for five monitoring and sampling locations.

Forest/Ranger District	**Soil Taxonomy**	**Potential Natural Vegetation**
Mt Hood NF, Estacada RD	Fine-silty, mixed, mesic Humic Dystrudepts	**Tsuga heterophylla/Berberidaceae mahonia – Gaultheria shallon*
Olympic NF, Quinault RD	Medial, ferrihydritic, isomesic Typic Fluvudands	*Tsuga heterophylla*
Umpqua NF, Cottage Grove RD	Coarse-loamy, mixed, mesic Typic Haploudalfs	*Pseudotsuga menziesii*
Deschutes NF, Bend Ft Rock RD	Ashy-pumiceous, glassy Xeric Vitricryands	***Pinus ponderosa/ Purshia tridentate/ festuca idahoensis*
Ochoco NF, Prineville RD (clay soil)	Fine, smectitic, frigid Vertic Palexerolls	***Pseudotsuga menziesii/ Purshia tridentata*
Ochoco NF, Prineville RD (ash soil)	Ashy, glassy over mixed Xeric Vitricryands	***Pseudotsuga menziesii/ Purshia tridentata*

*as described in Halverson, N.M. 1986
*as described in Simpson, M. 2007

FS Region 6 Soil Quality Standards

The FS R6 SQS provide both “critical threshold” changes for different soil-based indicators and a minimum areal extent for non-detrimentally impacted soil conditions (USDA Forest Service, 1998). These critical thresholds are policy-based and intended to provide an administrative limit beyond which soil disturbances are considered excessively detrimental to the soils ability to function in a desirable manner. However, important changes in key soil functions resulting from soil disturbances most likely do not change abruptly at such a threshold, but rather change gradually over a range of disturbance conditions in part due to the common heterogeneity of a given soil area mass.

On National Forest System lands in FS Region 6, soil disturbance is considered to be detrimental when a measured soil indicator is either higher or lower than a specific threshold defined in the R6 FS SQS (Table 5.2). To meet the intent of the FS SQS, at least 80% of an activity area must be maintained in an acceptable soil quality conditions (no detrimental soil conditions) following a ground disturbing activity.

Table 5.2 Summary of FS Region 6 SQS for detrimental soil conditions (USDA Forest Service 1998).

FS Region 6 Soil Quality Standards
Detrimental Compaction • Volcanic Ash/Pumice Soils (Soils with Andic Properties): bulk density increase >20% above undisturbed level. • Other Soils: bulk density increase > 15% above undisturbed level, a macropore reduction >50%, and/or a reduction to <15% macropores.
Detrimental Displacement • Defined as the removal of more than 50% of the soil A horizon for an area greater than 100 square feet, which is at least 5 feet in width. Soil assessment methods include visual observations.
Detrimental Puddling • Occurs when the depth of ruts or imprints is six inches or more. Soil deformation and loss of structure are observable and usually bulk density is increased. Soil assessment methods included visual observations and depth measurements of soil puddling.
Detrimental Burned Soil • Occurs when the mineral soil surface has been significantly changed in color, oxidized to a reddish color, and the next one-half inch blackened from organic matter charring by heat conducted through the top layer. The detrimentally burned soil standard applies to an area greater than 100 square feet, which is at least five feet in width. Soil assessment methods include visual observations.
Detrimental Surface Erosion • Visual evidence of surface loss in areas greater than 100 square feet, rills or gullies and/or water quality degradation from sediment or nutrient enrichment. Soil assessment methods include visual observations.
Detrimental Soil Mass Wasting • Visual evidence of landslides associated with land management activities.

Identification of visual soil condition categories

Based on field reconnaissance, three visual soil condition classes were developed for the vegetation management activity areas in this study (Table 5.3). A number of standard protocols for visually assessing soil disturbance have been developed by both forest industry and the FS (Scott, 2007; Howes et al., 1983; Napper et al., 2009; Page-Dumroese et al., 2009). The intent of these protocols was to allow harvest managers, machine operators, and foresters to recognize and control the amount of soil disturbance from ground-based equipment operations. These standard protocols were also intended to improve the precision of observations between both the same observer and concurrent observers (Miller et al., 2010). The visual soil condition classes described for this study reflect an integration of the observed soil disturbances, soil disturbance criteria described in the FS R6 SQS (USDA Forest Service, 1998), as well as criteria described in other standard soil disturbance protocols.

Table 5.3 Visual soil disturbance classes developed for this study.

Visual Soil Condition Classes
Soil condition class 1 (Undisturbed) • Surface soil disturbance: ○ No evidence of soil compaction, puddling, or soil displacement; i.e. no past equipment operation, rutting, trails.
Soil condition class 2 (Off trail track) • Surface soil disturbance: ○ Wheel tracks or depressions evident but depth of ruts or imprints was less than six inches deep. ○ Forest floor layers (soil O horizons) may be present and intact, partially intact, or missing. ○ Surface soil may be intact or partially intact and may be mixed with subsoil. • Soil compaction: ○ Compaction evident with increased resistance in the 0 to 30 cm depth when shovel or prove is pushed into the soil.
Soil condition class 3 (Skid trails) • Surface soil disturbance: ○ Forest floor layers (soil O horizons) missing. ○ Evidence of mixing of surface soil A horizon with lower soil horizons. ○ Wheel tracks or depressions evident with ruts greater than 6 inches deep in soils having a perudic soil moisture regime (Olympic NF site). • Soil compaction ○ Compaction evident with increased resistance in the 0 to 30 cm depth when a shovel or probe is pushed into the soil.
Additional comments: • Soil condition classes assigned when one or more of the bulleted criteria are met for an individual condition class. • At the time of monitoring none of the activity areas had been burned. • No evidence of soil erosion or mass wasting was noted. • Inherent soil moisture regimes were determined to be unaffected by management activities.

Quantifying area extent of soil disturbance classes

The extent of areas with different soil disturbance classes was quantified using a randomly oriented square grid with one grid-intersection every two acres overlain on the activity area. At each grid-intersection a 100-ft transect randomly oriented along different azimuths was determined. The three defined soil disturbance classes were then identified and measured along each transect and lengths occupied by each category recorded. A mean of the area extent of each disturbance class was then computed for the entire activity area (Howes et al., 1983; Page-Dumroese et al., 2009).

The primary soil disturbance noted at the six monitoring locations was soil compaction resulting from equipment operations**.** Ruts greater than six inches deep were observed in skid trails at the Olympic NF location, indicating a FS-defined detrimental soil condition in visual soil disturbance class 3 (USDA Forest Service, 1998). While minor soil displacement was observed on some heavily used skid trails, excessive amounts of soil displacement that would qualify as detrimental by the FS was not observed at any of the five study locations. The only burning that occurred at any of the study locations was the burning of slash piles on landings that were already considered to have detrimental soil impacts from compaction. No evidence of soil erosion or mass wasting was observed at any of the study locations.

Measurements of soil indicators

Once the soil condition classes were identified and their area extent measured, they were next sampled to determine whether they actually represent an important change in dynamic soil quality. To make those determinations, soil-based indicators were applied to reveal the degree of soil disturbance and whether or not critical limits identified in FS SQS had been exceeded. Given that the primary soil disturbance noted at the six monitoring locations was soil compaction from equipment operations, soil bulk density and porosity changes and related thresholds identified in FS Region 6 SQS were a primary focus for assessing detrimental soil changes (USDA Forest Service, 1998).

Measurements of soil porosity and soil bulk density

At each study site and disturbance class, intact soil cores for measuring both soil porosity and soil bulk density were collected using a hammer-driven, double-wall soil core sampler (Blake and Hartge, 1986). Soil cores measuring 8.25-cm x 6-cm (diameter x length) were centered at a 15 cm depth to characterize the 10 to 20 cm soil depth. Three soil cores were collected in each of the different soil disturbance classes within sampled stands. Changes in soil pore size distribution were determined from the water retention curve (Danielson and Sutherland, 1986; Chapter 3) in which the equivalent radius of the largest pore that will be filled with water is a function of the soil water pressure defined by the capillarity equation. The mathematical relationship between these parameters is:

$$r = (2\sigma \cos \theta)/(\rho_w gh)$$

where r is the equivalent radius of the pore (cm), σ is the surface tension (kg/s^2), θ is the contact angle between the water and the pore wall (usually assumed to be zero), ρ_w is the density of water (kg/m^3), g is the gravitational acceleration (m/s^2), and h is the soil water suction (cm of water). Thus, a measurement of the resulting water retention curve can be used to show the amount of pore space that has pores smaller than a given effective size derived from a given applied suction (h) (Scott, 2000).

The soil bulk density of each soil core was then determined on an oven-dry, whole soil basis. Soils from the cores were then sieved using a number 10 sieve to remove coarse fragments from the soil cores. Coarse fragments were weighed and the volume of the coarse fragments determined by displacement in water. Soil bulk density was then determined a second time based on the fine fraction of soil, excluding soil coarse fragments (Blake and Hartge, 1986; Chapter 4).

Results

Evaluation of current FS SQS

The area extent of the most highly disturbed visual soil disturbance class (class 3), typically associated with skid trails and landings, ranged from 8 percent to 18 percent of the activity area extent depending upon monitoring location (Table 5.4). Visual soil disturbance class 2, typically associated with harvester tracks leading off of skid trails, ranged from 8 to 25 percent of the activity area. A 95% confidence interval was calculated around the estimate of the mean for visual soil disturbance class 1 (undisturbed). If it is assumed that visual soil disturbances classes 2 and 3 indicate a detrimental soil disturbance as defined in the FS SQS, the data (95% confidence intervals) for the Umpqua, Deschutes, and Ochoco NF sites indicate that these sites have maintained the 80% non-detrimental soil condition areal extent and thus meet the FS R6 standard. In contrast, the data for the Mt Hood and Olympic NF sites show that FS R6 standard has not been met.

Table 5.4 Area extent of different visual soil condition classes for harvest units at the five soil monitoring locations in Oregon and Washington FS Region 6 (a 95% confidence interval was calculated around the estimate of the mean for visual soil disturbance class 1).

Forest/Ranger District	**% Area by visual soil disturbance class**		
	1	2	3
Mt Hood NF, Estacada RD	65 +/- 6	25	10
Umpqua NF, Cottage Grove RD	76 +/- 5	10	14
Olympic NF, Quinault RD	65 +/- 6	17	18
Deschutes NF, Bend Ft Rock RD	76 +/- 10	9	15
Ochoco NF,Prineville RD	84 +/- 4	8	8

Soil indicator measurements of bulk density and porosity were next used to evaluate whether or not visual soil disturbance classes 2 and 3 actually exceeded critical thresholds identified in the FS R6 SQS thereby representing a “detrimental” soil condition (Table 5). Three of the soils monitored in this study are classified as Andisols and thus exhibit unique andic soil properties. The R6 FS SQS identify two different soil bulk density thresholds considered to represent a detrimental soil condition depending upon whether or not a soil has andic soil properties. The first change considered to be detrimental is a 15 percent or greater increase in soil bulk density over the undisturbed level for non-andic soils. Non-andic soils are also considered to be detrimentally disturbed in R6 if soil compaction causes their macroporosity to be reduced by 50 percent or more and if total macroporosity is reduced below 15 percent by volume (Table 2). Because andic soils typically have low inherent soil bulk densities and more porosity than other soils, andic soils are not considered to be detrimentally impacted by management activities unless they show a 20 percent or greater increase in soil bulk density over the undisturbed level. Unlike non-andic soils, andic soils also do not have a standard for assessing changes in soil porosity (Table 2).

Although the operations and visual disturbances observed in the various locations were similar in many respects, measurements of soil bulk density and macroporosity changes showed that disturbances at only half of the study sites exceeded FS SQS thresholds for detrimental compaction (Table 5). Andic vs non-andic soil type appeared to be an important factor in determining whether or not current soil thresholds were exceeded, with all of the non-andic soils exceeding standards while none of the andic soils exceeded the standards.

In general, soil bulk density measurements better predicted important changes in soil macroporosity in the non-andic soils compared to the andic soils (Table 5). However, a measured change in bulk density alone still appeared to be a poor indicator of a change in soil macroporosity that exceeded the FS R6 SQS. For example, soil compaction resulted in soil bulk density increases beyond the 15% threshold in soil condition classes 2 and 3 of both the Mt Hood and Umpqua soils, whereas soil macroporosity was reduced by more than 50% only in soil condition class 3 of the Mt Hood. Increases in soil bulk density in condition classes 2 and 3 of the Ochoco (clay soil) were well below the 15% bulk density threshold, yet soil macroporosity was reduced by greater than the 50% limit and reduced below the 15% total macroporosity threshold identified in R6 SQS (Table 5.5). None of the andic soils exceeded the 20% increase in soil bulk density limit. Even if one applies the non-andic SQS of 15% increase in soil bulk density to andic soils, only one site and disturbance level on andic soils exceeded one of the limits (e.g., bulk density by 1%). This pattern demonstrates the resistance of andic soils to bulk density increases. Although there is no macroporosity standard for andic soils, measurements of macroporosity in these soils were all within in the allowable ranges for non-andic soils following disturbance (Table 5.5).

Table 5.5 Measured changes in soil bulk density and soil macroporosity within different visual soil condition classes and interpretations of change based on R6 Soil Quality Standard thresholds.

Forest/Ranger District	**Visual Soil Disturb-ance Class**	**Soil Bulk Density (g/cc)**	**% Increase in Bulk Density**	**US FS Region 6 Bulk Density Threshold?**	**Soil Macro porosity (cm^3/cm^3)**	**% Decrease in Macro porosity**	**% Soil Macro porosity**	**US FS Region 6 Macro porosity Threshold?**
Mt Hood NF, Estacada RD	1	.48			.36		55	
	2	.77	**61**	**Exceeds**	.25	29	41	Below
	3	.88	**84**	**Exceeds**	.11	**69**	18	**Exceeds**
Umpqua NF, Cottage Grove RD	1	.60			.40		60	
	2	.91	**52**	**Exceeds**	.25	44	39	Below
	3	.80	**35**	**Exceeds**	.24	40	40	Below
Ochoco NF, Prineville RD (clay area)	1	1.18			.12		23	
	2	1.32	12	Below	.02	**86**		**Exceeds**
	3	1.28	9	Below	.05	**61**	**10**	**Exceeds**
Olympic NF, Quinault RD*	1	.54			.32		44	
	2	.59	8	Below	.16	50	21	N/A
	3	.55	3	Below	.20	38	26	N/A
Deschutes NF, Bend Ft Rock RD*	1	.75			.30		50	
	2	.76	2	Below	.22	27	37	N/A
	3	.86	16	Below	.23	22	41	N/A
Ochoco NF, Prineville RD (ash area)*	1	.99			.25		45	
	2	1.11	12	Below	.25	1	48	N/A
	3	1.05	6	Below	.21	17	38	N/A

*Volcanic ash/pumice soils have only a bulk density criterion for detrimental compaction as recognized in FS R6; however, macroporosity data for these soils are shown for comparison purposes.

Interpretation of soil conditions classes

Three of the five monitoring and soil sampling locations met the current FS R6 SQS by not exceeding detrimental soil conditions over more than 20 percent of the activity area while two of the monitoring locations did not (Table 5.6). Lower inherent soil resistance to compaction, indicated by a larger increase in soil bulk density and/or a loss of soil macroporosity, was important in the Mt Hood and Umpqua National Forest soils not meeting the FS R6 SQS. These soil measurements led to the decision to count both visual disturbance classes 2 and 3 toward the detrimental soil disturbance total. Soil-based indicator measurements for the Olympic and Deschutes National Forest soils indicated that none of the visual soil disturbance classes reflected detrimental soil compaction. These observations clearly demonstrate the need for soil-based indicators for compaction that better reflect which visual soil disturbance classes represent a detrimental condition and which do not.

Interpretation of soil-based indicators at the Ochoco site was complicated by the fact that there are two major soil types within the activity area. At the Ochoco site the clay textured non-andic soil exceeded the FS R6 SQS for detrimental compaction whereas the andic volcanic ash soil did not. Interpretations of this type of situation are not addressed in the current FS R6 SQS.

Finally, at the Olympic site soil visual soil condition class 3 was identified as detrimental based on observed soil puddling (Table 5.6). Although similar to compaction in its soil resource impacts, puddling is most likely to occur on soils with higher clay contents that also have high moisture levels during equipment operations.

Table 5.6 Visual soil condition classes observed on the five NF study sites, as related to the current FS R6 SQS.

Forest/Ranger District	**% Area by visual soil disturbance class**			**% Area of soils in detrimental condition due to soil compaction**	**% Area of detrimental soil condition due to puddling**	**Meets the current FS R6 SQS?**
	1	2	3			
Mt Hood NF, Estacada RD	65	25	10	35	0	No
Umpqua NF, Cottage Grove RD	76	10	14	24	0	No
Olympic NF, Quinault RD	65	17	18	0*	18**	Yes
Deschutes NF, Bend Ft Rock RD	77	9	15	0*	0	Yes
Ochoco NF, Prineville RD	84	8	8	16***	0	Yes

*Although the area extent of visual soil disturbance classes 2 and 3 exceed the FS R6 SQS of 20% maximum area, the soil-based indicator data did not show actual detrimental conditions.
**Although the area extent of visual disturbance class 3 did not exceed FS R6 SQS soil indices thresholds for detrimental soil compaction, this disturbance class did meet the definition of detrimental puddling (Table 2).
***The Ochoco NF, Prineville RD location had two different soils within the monitoring unit. The clay soil exceeded critical R6 SQS thresholds indicating a detrimental soil condition while the ash soil did not.

Summary

The FS soil disturbance monitoring protocol and Regional SQS are intended to maintain key soil functions, but the results from these diverse sites in Oregon and Washington indicate that the visual soil conditions commonly assessed do not consistently reflect actual measurements of detrimental soil conditions as defined within the FS R6 SQS. Although the visual identification of different soil condition classes and the quantification of those condition classes were straightforward, the interpretation of those soil conditions using the FS R6 SQS was not. For example, all of the non-ash/non-pumice soils exceeded the FS SQS criteria, indicating detrimental conditions in all the disturbance classes identified, whereas none of the ash or pumice soils showed detrimental soil conditions in any of the visual disturbance classes. Detrimental changes in measured physical soil indices were also not consistent within a given visual disturbance class. For example, in most cases a detrimental increase in soil bulk density was not associated with a detrimental reduction in macroporosity, and a detrimental change in macroporosity was not associated with a detrimental change in soil bulk density. These observations strongly suggest a need for further refinement of the FS SQS and assessment protocols to achieve better conformance with actual, important resource impacts that account for sensitivity and resiliency of various soil types to management disturbances. Part 3 of this Chapter will discuss in greater detail some important issues with the current R6 SQS, and develop some concepts and direction for their refinement.

Part 3: A review of key ecological processes, soil functions, and soil-based indicators used to assess soil changes from management

Forest soil types in the Pacific Northwest vary widely from medial, ashy or pumiceous, volcanic-influenced Andisols to fine-textured, skeletal soils spanning a variety of different taxonomies (USDA NRCS 2010). Forest types also range from highly productive rain forests near the coast to forests of marginal productivity in the interior east (Franklin and Dyrness 1988). Anticipated responses of these resources to disturbance can be expected to vary widely due to also the variety of soil types and climatic conditions across the region and this expectation has been validated in several studies (Page-Dumroese et al., 2000; Fleming, et al. 2006; Gomez, et al. 2002; Powers et al. 2005). Therefore, criteria used to evaluate important soil disturbances in these diverse ecosystems should reflect this variety of inherent soil and site differences.

Similarly, a description of visual soil disturbances such as depth of wheel track, evidence of topsoil removal, or fire severity can be interpreted differently depending upon soil, climate and other local conditions. Thus, there is also a need for soil-based indicators that can help interpret different visual soil disturbance classes.

Some important questions that can be addressed with measurements of soil-based indicators include:

1. What are the anticipated effects of soil disturbances on key soil functions?
2. Which soil types are more or less resistant to change in response to management activities or other major influences?
3. Which soil types are expected to recover in a relatively short period of time and which are not?
4. Which soil-based indicators are appropriate for assessing a given soil disturbance and which are not?
5. What are the important management implications of these findings, e.g. equipment operability on different soil types under different conditions, and what are the soil restoration opportunities?

To illustrate how such questions can be addressed, selected soil based indicators were measured for the six different soil types at the five R6 study sites and results interpreted based on the soil measurements. The intent is to (1) demonstrate the importance of measuring soil-based indicators to better understand and interpret visual soil condition classes, (2) illustrate the importance of recognizing how different soils respond to disturbances in terms of resistance and resilience to change, and (3) demonstrate different ways of interpreting results based on soil type and climate.

Refinements of Interpretations of Soil-based Indicators: Soil Bulk Density, Total Soil Porosity, and Soil Macroporosity

Soil compaction resulting from equipment operations is a commonly cited physical soil disturbance resulting from forest management. When soils become compacted there is an alteration of basic soil properties such as soil density, total pore volume, pore size distribution, macroporosity continuity and soil strength (Greacen and Sands, 1980). Soil bulk density, total soil porosity, and soil pore size distribution are all strongly influenced by the aggregation of soil particles as well as soil texture (Scott, 2000). When soils compact bulk density typically increases. Soil compaction can also result in a decrease in total soil porosity, a decrease in macroporosity, and an increase in mesopores and micropores (Scott, 2000).

Functional relevance

Higher soil bulk densities have been correlated with reduced growth of tree roots, with some variability amoung species (Daddow and Warrington, 1983; Minore et al., 1969). A decrease in total soil porosity, decrease in macroporosity, and an increase in mesopores and micropores can affect the soil air-water balance (Siegel-Issem et al., 2005; Startsev and McNabb, 2009) and in some cases reduce infiltration capacity and increase runoff (Startsev and McNabb, 2000).

Methods of measurement

Soil bulk density is defined as the mass per unit volume of the soil and represents the ratio of the mass of solids to the total volume of the soil (Soil Survey Staff, 1996). Determinations of soil bulk density for the purposes of measuring soil compaction are commonly made by drying and weighing a soil sample of known volume that has been sampled so as to preserve its natural structure (Blake and Hartge, 1986). Changes in soil bulk density can be determined with a minimum of sampling equipment and such measurements have been used extensively by researchers to estimate changes in soil functions related to soil porosity and soil strength. With common measurement methods, changes in soil bulk density provide convenient means for comparing soil monitoring results amomg different study areas.

Total soil porosity can be determined from a measurement of dry soil bulk density and a measurement of soil particle density (Blake and Hartge, 1986). The mathematical relationship between these parameters is:

$$f = 1 - \rho_b/\rho_p$$

where f is the total porosity (m^3/m^3), ρ_b is the soil bulk density (kg/m^3), and ρ_p is the soil particle density (kg/m^3) (Scott, 2000). Using a calculated change in total soil porosity to estimate important changes in soil macroporosity, however, can be problematic. The reason is that when soils compact there is both a loss of total soil porosity and a shift in soil pore size distribution and the degree of change in these two soil parameters is not consistent between soil types (Chapter 4).

The modified water desorption procedure, described in Chapter 4, addresses this issue by providing a practical alternative for assessing important changes in pore size distribution resulting from forest management. The method does not require more elaborate and costly laboratory equipment and therefore can be used in field offices where only a minimum of facilities are available. Once soil macroporosity and soil bulk density have been measured for an individual soil type, a correlation can then be established to reasonably predict soil porosity changes from future measurements of bulk density of similar soils.

Different patterns of reductions in total soil porosity and shifts in soil pore sizes resulting from soil compaction on the five R6 study sites are illustrated in Figures 5.2, 5.3, 5.4, and 5.5. The figures show both a loss of total soil porosity occurring when soils are compacted and a rearrangement of soil pore sizes resulting from the reduction in aeration porosity (macropores). The results also illustrate the variation by soil type in both total soil porosity losses and the shifts in pore size distribution when compaction occurs.

Management interpretations

The Mt Hood and Umpqua NF soils include Inceptisol and Alfisol soil orders supporting western hemlock (*Tsuga heterophylla*) and Douglas-fir (*Pseudotsuga menziesii*) forest types respectively. These are some of the more productive forest types in the Pacific Northwest Region, due in part to the large amount of precipitation as indicated by their udic soil moisture regimes. Compaction of these soils resulted in both a reduction in total porosity and a shift in pore size distribution (Figure 5.2). Excessive loss of soil macroporosity due to compaction is expected to negatively affect soil infiltration and aeration in these moist climates, and thus macroporosity changes in these soil types is likley to be an important soil-based indicator for key soil changes resulting from disturbance. However, high seasonal moisture and high site productivity could improve the rate of recovery of these soils.

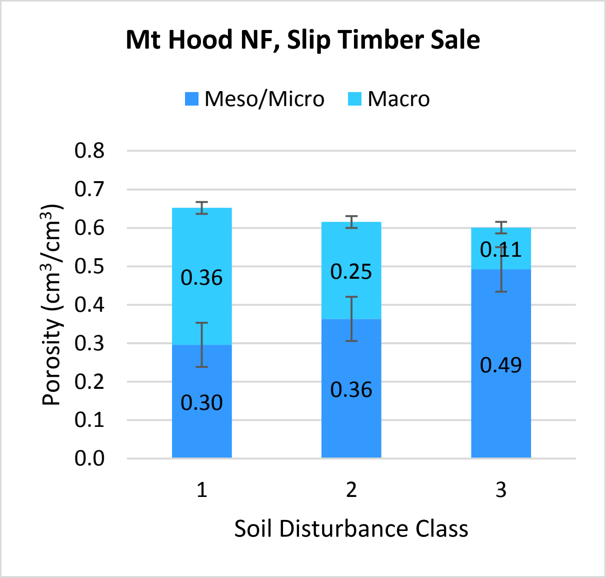
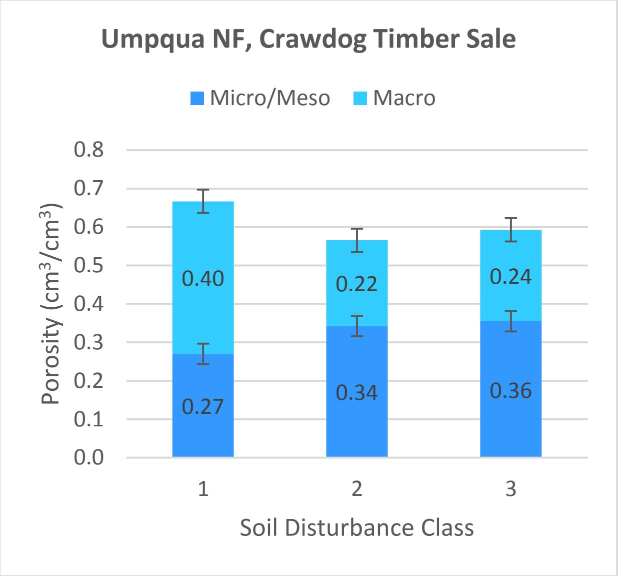


Figure 5.2 Soil pore size distribution as related to soil disturbance level for the Mt Hood and Umpqua NF study sites (Error bars represent one standard error).

Figure 5.2 continued



The Olympic NF soils include Andisols in the Udands sub-order, indicating a highly weathered soil in a humid climate. These soils have a perudic soil moisture regime in climates where precipitation exceeds evapotranspiration in all months of normal years and moisture tension rarely reaches 100 kPa in the upper portions of the soil profile (i.e. the “soil moisture control section” defined in USDA NRCS, 2010). These soils support highly productive western hemlock (*Tsuga heterophylla*) forest types. The Olympic NF soils showed large soil macroporosity losses due to a shift in soil pore size distribution following compaction (Figure 5.3). With the very moist conditions in these forests, losses in macroporosity are expected to have a negative effect on soil infiltration and drainage as well as soil aeration. Thus, macroporosity changes in these soil types is expected to be an important soil-based indicator of significant soil changes resulting from disturbance although this expectation requires further validation with extended measurements. Like the Mt Hood and Umpqua Forest soils, however, high site productivity could promote recovery rates in these locations.

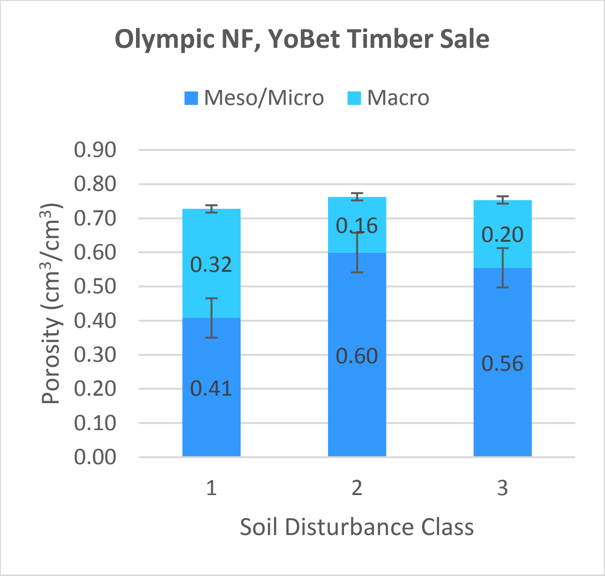


Figure 5.3 Soil pore size distribution as related to soil disturbance level for the Olympic NF study site (Error bars represent one standard error).

The Deschutes NF soils include Andisols supporting ponderosa pine (*Pinus ponderosa*) forest types. Like the volcanic ash-derived Andisols on the Ochoco NF, these soils show inherently large levels of soil macroporosity and little change as a result of compaction (Figure 5.4). And similar to the Ochoco Andisols, these soils appear to be very resistant to changes in porosity resulting from disturbance.

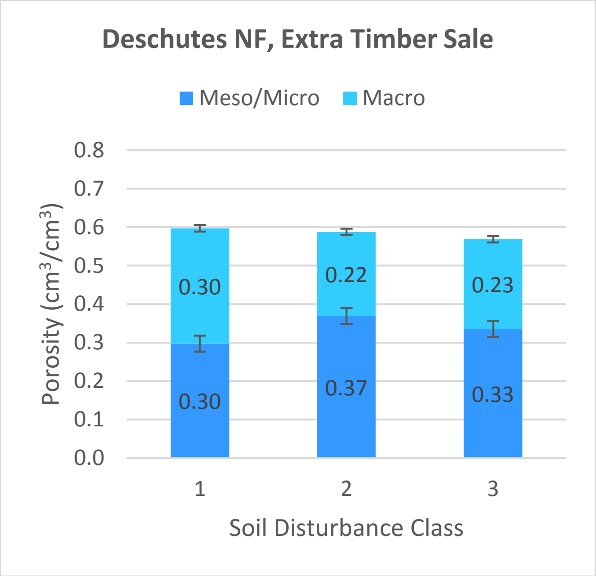
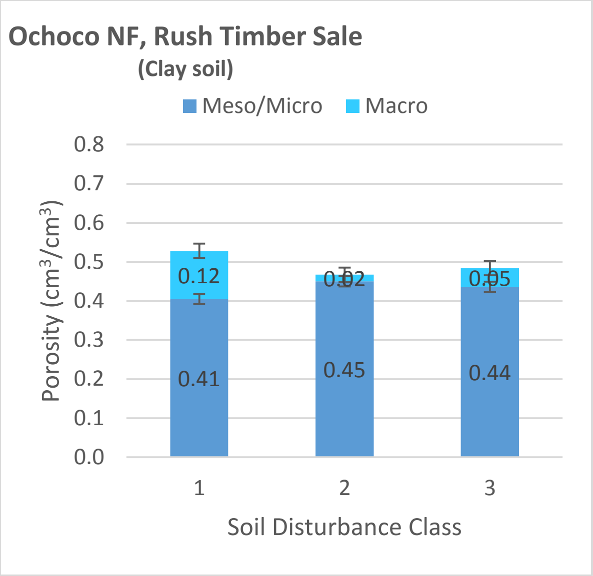


Figure 5.4 Soil pore size distribution as related to soil disturbance level for the Deschutes NF study sites (Error bars represent one standard error).

The Ochoco NF study site is located within a soil map unit complex containing two soil types in different soil orders (Mollosols and Andisols), both supporting Douglas-fir forest types. The high clay content of the Mollisol soil, as indicated by its fine, smectitic taxonomic family classification (USDA NRCS, 2010), appears to be associated with an inherently low macroporosity, and compaction has reduced macroporosity to critically low levels (USDA Forest Service, 1998) in compacted disturbance classes (Figure 5.5). However, recovery in these soils could be enhanced and somewhat rapid due to the ameliorating effects of the shrink-swell properties of the smectitic clays. If additional measurements show that soil macroporosity changes are short term, macroporosity assessments may be a less important soil-based indicator for making assessments of sites with soils in the fine, smectitic family. In contrast, the volcanic ash soils show inherently large levels of soil macroporosity and little change as a result of compaction, making these soils very resistant to changes in porosity from disturbance. Due to naturally high soil macroporosity and high resistance of the Andisol soils to compaction, soil macroporosity does not appear to be an important soil-based indicator for evaluations of areas with such soils.



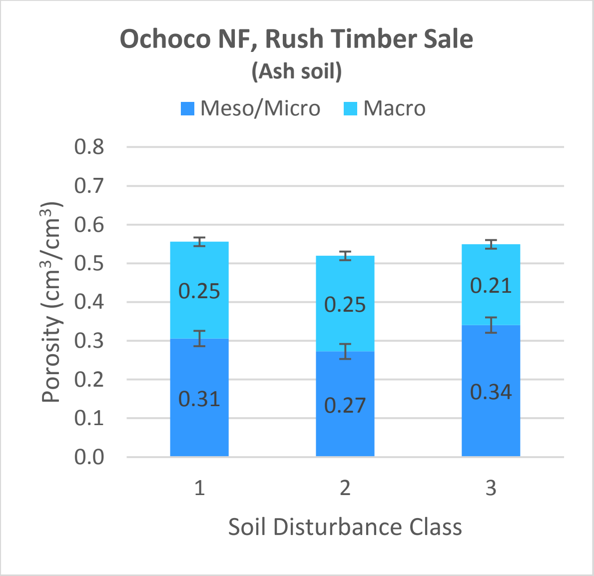


Figure 5.5 Soil pore size distribution as related to soil disturbance level for the Ochoco NF study site (clay soil) (Error bars represent one standard error).

Soil-based indicators not currently included in FS R6 SQS

In a review of the assessment of soil quality, Powers et al. (1998) noted that by itself, a single variable such as soil bulk density, has limited biological relevance. These authors suggested that rather than searching for a single indicator of soil quality (e.g., soil bulk density, soil base saturation, or soil organic matter) a broader and more integrative approach should be taken that reflects dominant processes that are important to management. Recommendations included soil resistance measured using (i) a recording soil penetrometer as a physical index that integrates soil density, structure, and moisture content, (ii) mineralizable soil nitrogen as a nutritional index that integrates organic matter quality, content, and microbial activity, and (iii) soil faunal activity as a biological index that integrates the activity of soil organisms. To date, none of these soil-based indicators have been included in the FS R6 SQS. I chose to further investigate the use of soil resistance and mineralizable soil nitrogen at the five monitoring sites.

A soil-based indicator of soil strength

Soil strength describes the soil hardness or the resistance of the soil to deformation (Scott 2000). When soils become compacted the soil strength typically increases. Soil characteristics that affect soil strength include particle size distribution and shape, clay mineralogy, amorphous oxide content, and organic matter content (Gerard 1965; Byrd and Cassel, 1980; Stitt et al., 1982). Within a soil type, changes in soil water content, bulk density, and structure can affect soil strength (Scott 2000). In general soil strength decreases as the water content of the soil increases and increases as soil bulk density increases; however, this is not always the case. A soil-based indicator of soil strength is not currently included in the FS R6 SQS (USDA Forest Service 1998).

Functional relevance

Root elongation rates and the penetration resistance that roots experience are, at least in part, related to the penetration resistance of the soil. Increases in soil bulk density due to disturbances have also been correlated with reduced growth of tree roots (Daddow and Warrington, 1983; Minore et al., 1969). Greacen et al. (1968) founded that critical thresholds of penetrometer resistance at which root elongation stopped were in the 0.8 to 5.0 MPa range. Zou et al. (2001) found that, at a constant soil matric potential and an air-filled soil porosity > 0.20 cm^3/cm^3, root elongation in radiata pine seedlings decreased exponentially as soil resistance increased.

It has been suggested that some soil functions may be best evaluated in the context of the interaction between several soil-based indicators. For example, research has led to the recognition that the effects of physical soil disturbances such as compaction on key soil functions is a result of complex interactions between a number of physical soil attributes. This led to the development of the concepts of non-limiting water range (Letey 1985) and later the least limiting water range (da Silva et al., 1994; Zou et al., 2000; Siegel-Issem et al., 2005) with critical limits for soil water contents associated with field capacity (-0.01 MPa), wilting point (-1.5 MPa), air-filled porosity (10%), and soil resistance (2.0 MPa). Soil-based indicators of changes in soil porosity address a portion of the least-limiting water range concept. A measure of soil resistance provides the remaining information.

Methods of measurement

Pushing a soil probe or a spade into the soil can be used to detect increases in soil strength resulting from compaction. The current FS R6 SQS rely on a measured change in soil bulk density as the soil-based indicator to predict important increases in soil strength that may be plant root limiting. This assessment, however, can be further refined through the use of the recording soil penetrometer, which is capable of measuring, at predetermined intervals, the force required to push a probe into the ground (Kees 2005; Lowery and Morrison Jr., 2002; Miller et al., 2001).

Management interpretations

Some increases in soil resistance from management disturbance were noted in the Mt Hood Inceptisols and the Umpqua Alfisols (Figure 5.6). These management-induced increases in soil resistance are approaching root limiting levels (Greacen and Sands, 1980; Zou et al., 2001; Siegel-Issem et al., 2005) in both visual soil disturbance classes 2 and 3. Levels of soil resistance are not expected to change much over the growing season due to udic soil moisture regimes in which the local soil moisture control section is not dry for no more than 90 cumulative days in normal years (USDA NRCS 2010).

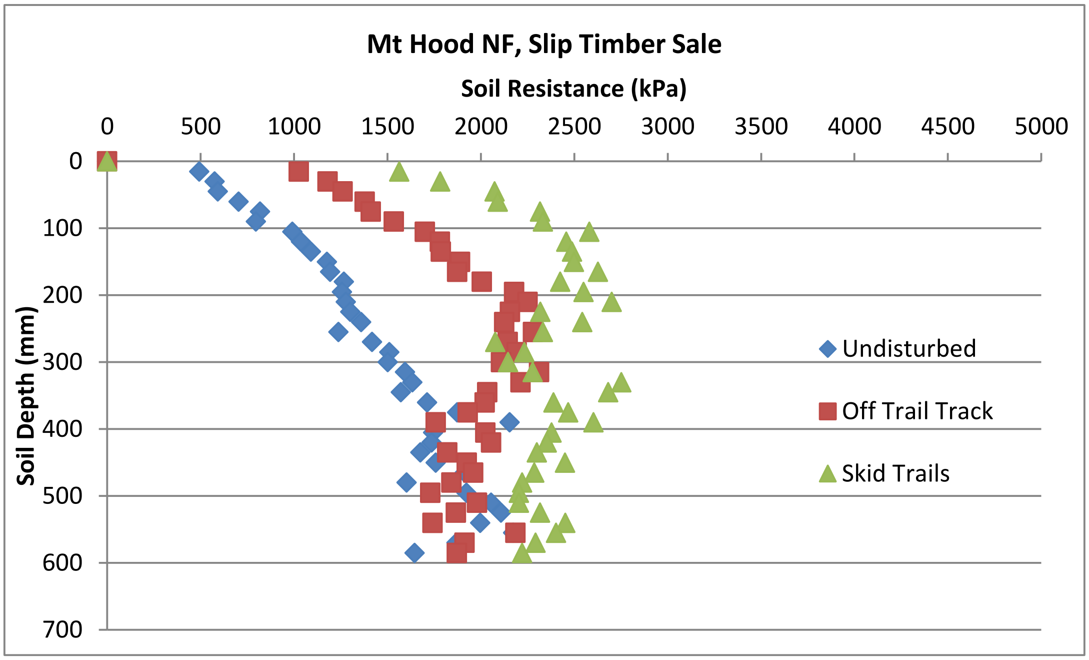
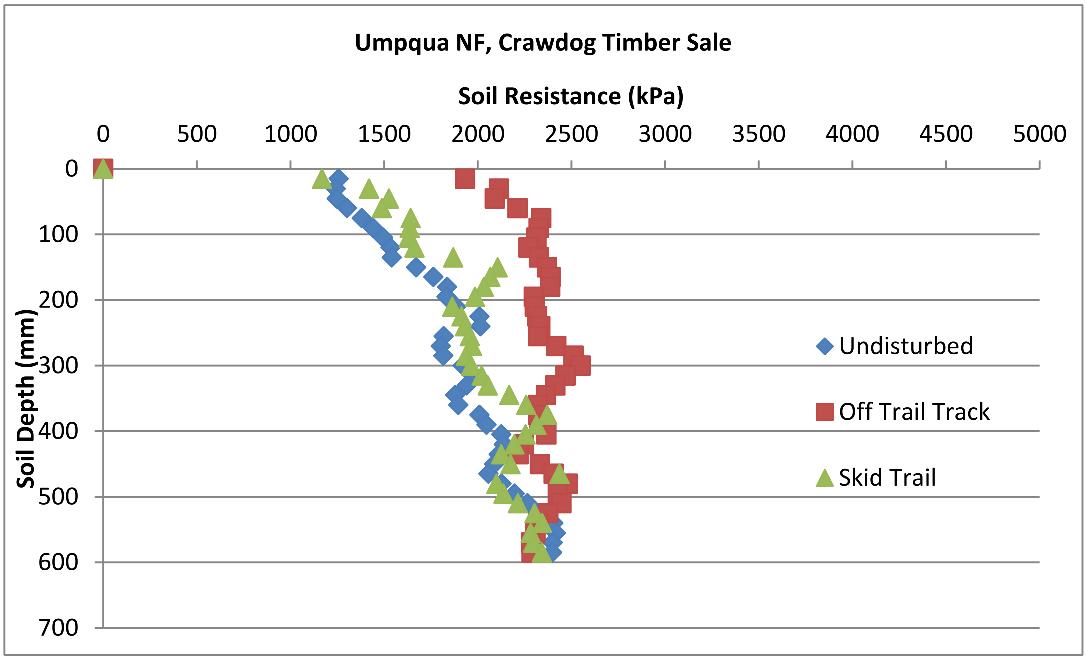


Figure 5.6 Soil resistance levels at 0 – 600 mm depth as related to visual soil disturbance class for the Mt Hood and Umpqua NF locations.

Figure 5.6 continued



Soil resistance in the Andisols at the Olympic location and the Mollisols and Andisols at the Ochoco location changed very little as a result of management disturbance (Figure 5.7). Thus, root limiting levels of soil resistance seems less of a concern in these soils. However, soil resistance is expected to increase seasonally in the xeric soil moisture regime at the Ochoco location, as soils dry out over the summer months. Such an increase is expected for all soil disturbance classes. The low penetration resistance of these soils when moist would also be associated with low bearing strength for ground-based equipment operations, and such operations on these soils when moist would be more likley to result in excessive soil disturbance. Thus, project design criteria for ground-based harvest should include operations monitoring and restrictions when these soils become too wet, to avoid excessive disturbance.

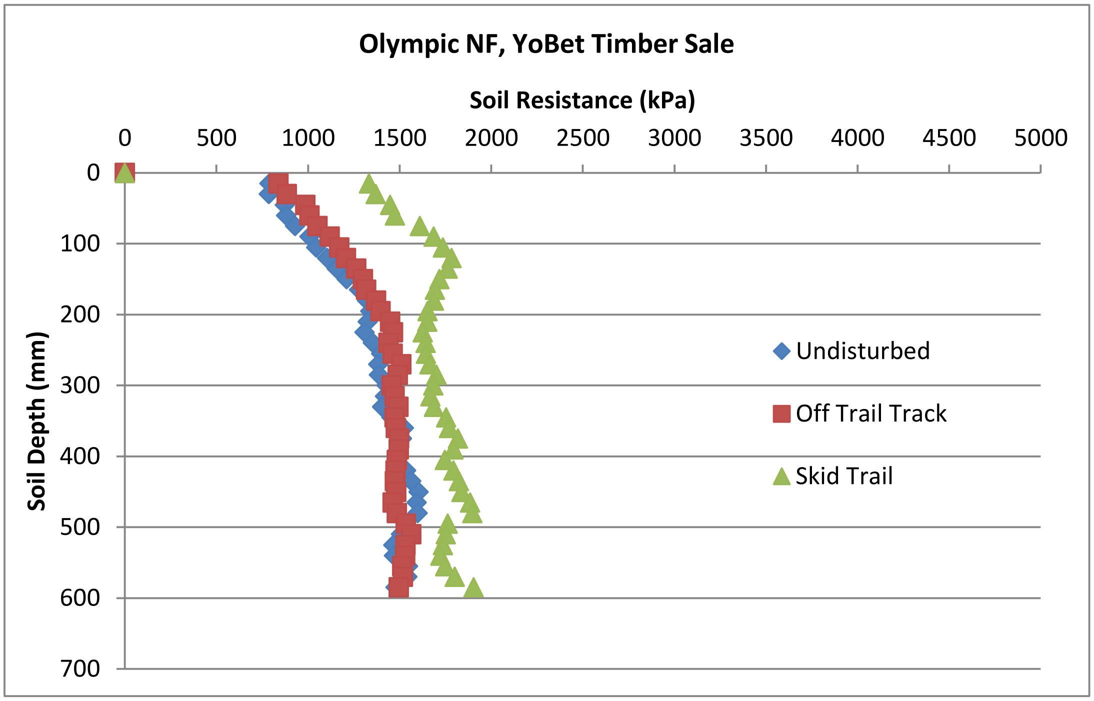
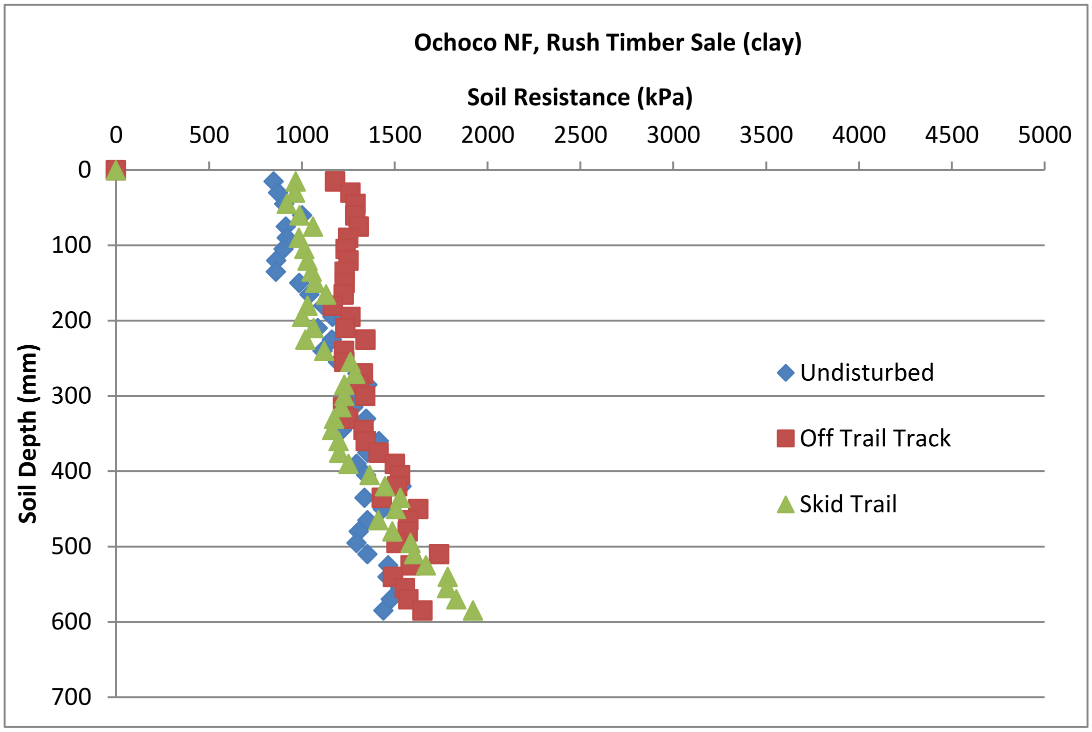
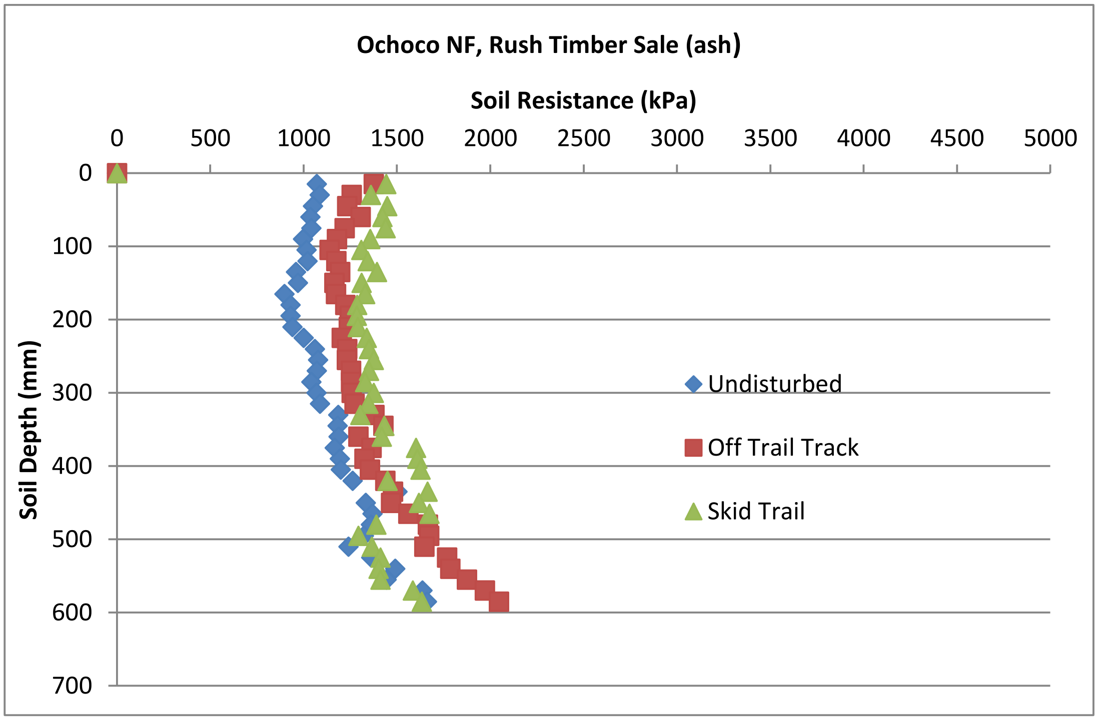


Figure 5.7 Soil resistance levels at 0 – 600 mm depth as related to soil disturbance class for the Olympic and Ochoco NF study locations.

Figure 5.7 continued





The Deschutes Andisols showed large increases in soil resistance following soil compaction. Increases in soil resistance levels in the Andisols soils on the Deschutes NF differ greatly from that of the Andisols soils of the Ochoco (Figures 5.8), even though both soils have very similar soil taxonimic classifications (Table 5.1). Both soils have been identified as being derived from Mazama ash and pumice deposits and are assumed to be of a similar geologic age. Both soils have also been exposed to a similar climate since their deposition. The Deschutes deposits are closer to the source of the eruption which, depending on historic wind speeds, etc., may have affected particle sizes of the volcanic deposits.

Unlike other soils in this study, the Deschutes Andisols showed a large increase in soil resistance even though sampling was done in early May when soils were near field capacity. As a positive result, the high soil resistance provides high bearing strength for ground-based equipment operations even when soils are moist to wet without causing excessive soil disturbance.

The level of soil resistance observed in this Andisol is expected to be root limiting in compacted skid trails (Parker et al., 2006; Greacen and Sands, 1980; Zou et al., 2001; Siegel-Issem et al., 2005). Past experience has shown these soils do respond well to subsoiling to reduce soil resistance levels following compaction (Craigg, 2000).

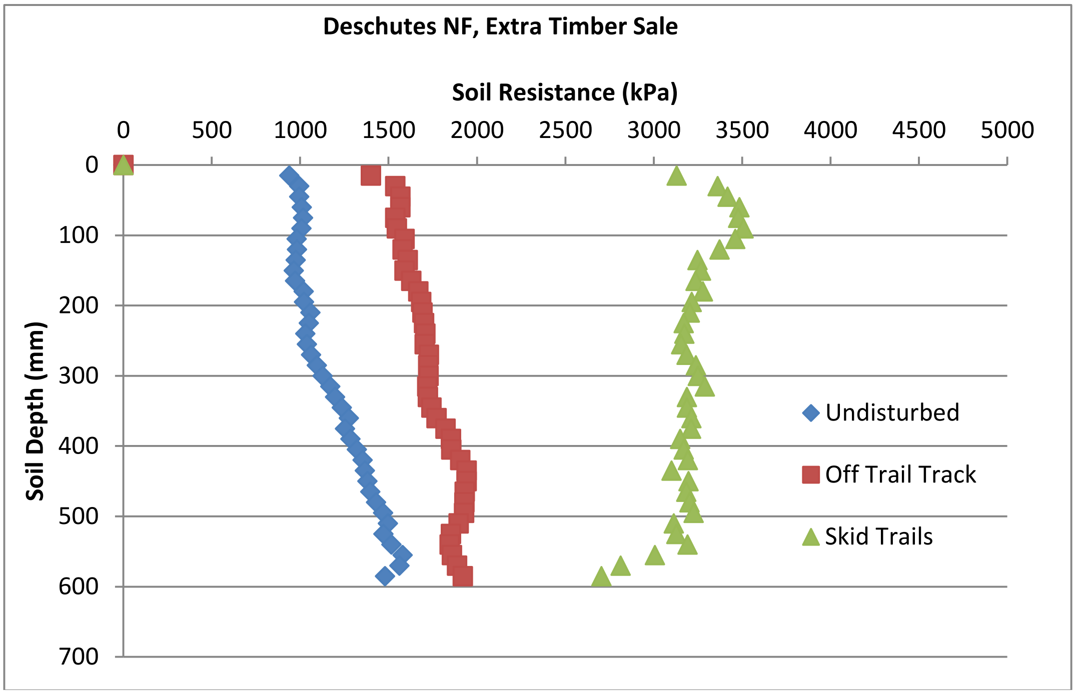


Figure 5.8 Soil resistance levels as related to soil disturbance level for the Deschutes NF study location.

A soil-based indicator of mineralizable soil nitrogen

In the current FS R6 SQS, evaluations of the effects of removal of above ground organic matter and/or the removal of mineral surface soil through displacement, soil puddling, surface erosion, and surface burn intensities are all made using a defined range of visual soil disturbance categories (USDA Forest Service 1998). While this provides a method of identifying when and where a defined degree of disturbance has occurred, it provides little quantifiable information about the functional significance of these types of disturbances. The real usefulness of this information lies not in a visual estimate of the degree of a given disturbance but rather in clarifying the relationship between visual soil disturbance categories and measured soil-based indicators that reflect key site functions.

Functional relevance

Soil disturbances such as displacement, soil puddling, surface erosion, and burning can have important effects on soil organic matter and in turn the soil's capacity to supply nutrients and other resources. Soil organic matter (SOM) typically constitutes only a small percentage of the mineral soil, yet it has a profound influence on soil functions. SOM occurs in a wide variety of forms within the mineral soil including the light fraction, microbial biomass, water-soluble organics, and stabilized organic matter in the form of humus, which have varying effects on the chemical, biological and physical soil properties that influence soil function (Stevenson 1994). Like SOM, the capacity of the soil to supply plant-available nitrogen (N) has also been recognized as an important indicator of soil quality (Powers 1980; Duxbury and Nkambule, 1994). Thus, a practical application of measurements or indices of soil N availability is through their potential usefulness in validation and calibration of visual soil disturbance classes.

Methods of measurement

A number of different biological and chemical methods have been suggested as a soil-based indicator of available N (Drinkwater et al., 1996; Powers 1980; Waring and Bremner, 1964). Two biological methods used to analyze available N include aerobic and anaerobic incubation procedures (Drinkwater et al., 1996). While the aerobic incubation method can produce optimal conditions for microbial mineralization of N, these soil conditions can be difficult to maintain throughout the incubation and accumulation of mineralized N can negatively affect microbial activity, which requires frequent leaching to avoid the buildup of nutrient salts. Waring and Bremner (1964) proposed an anaerobic incubation method as a simpler alternative to the aerobic method. This procedure can be completed in 7 to 14 days, and unlike the aerobic method, the water-logged conditions of the anaerobic incubation avoid the need to maintain optimal soil moisture and aeration conditions. The anaerobic conditions also prevent nitrification from occurring, thus only NH_4-N needs to be measured.

Management interpretations

A variety of soil A horizon depths and concentrations of mineralizable soil nitrogen in the study site soils are displayed in Table 5.7. The more productive west side Mt Hood, Umpqua, and Olympic Forest sites show higher mineralizable soil nitrogen concentrations compared to the eastside Deschutes and Ochoco Forests, thus indicating higher resistance and resilience to disturbance in the west side forests. The shallow A horizon depth of the volcanic ash derived Deschutes and Ochoco Forest soils also are notable and similarly indicate lower resistance and resilience in these forest soils.

Table 5.7 Depth of soil profile A horizon and concentration of mineralizable soil nitrogen (N) in the A horizon of the study site soils.

Forest/Ranger District	Soil A horizon depth (cm)	Mineralizable N (ppm)
Mt Hood NF, Estacada RD	15	83.2
Umpqua NF, Cottage Grove RD	15	61.1
Olympic NF, Quinault RD	13	98.1
Deschutes NF, Bend Ft Rock RD	8	11.7
Ochoco NF, Prineville RD (clay soil)	18	54.0
Ochoco NF, Prineville RD (ash soil)	8	48.1

Indices of soil N availability can be applied to two different types of disturbance classes: (i) disturbances that result in an immediate change in the soil nutrient status, and (ii) disturbances that change the soil nutrient status over time. For example, a soil disturbance that results in an immediate change in the soil's nutrient status or supplying capacity is the physical removal of surface mineral soil. This could be a result of mechanical disturbance or accelerated soil erosion. In this case comparisons can be immediately made by sampling in an undisturbed and disturbed area. This would be similar to the application of physical soil indices such as soil bulk density and soil macroporosity for determining levels of soil compaction.

Examples of management disturbances that may result in changes in soil nutrient status over time include the removal of above ground biomass from a site through repeated mechanical removal or burning. Unlike the physical removal of mineral soil that results in immediate change, changes in the soil’s nutrient status with repeated treatments can occur slowly. In this case, one would need to recognize that the changes in the soil may not be immediate. Therefore the soil index would need to be applied in areas that have had adequate time to reflect a change due to a given or repeated disturbance. The FS Long Term Soil Productivity studies have treatments of varying levels of organic matter removal and extended monitoring to help address these questions about soil changes over time (Powers 1991). Information gained from these studies could be used together with shorter observations to make inferences about future effects of management activities.

Conclusions

The FS SQS were first developed in response to the Multiple Use Sustained Yield Act of 1960 to provide direction for the management of National Forest lands in such a way that it would not result in “the permanent impairment of the productivity of the land,” as the law requires. The FS SQS for Region 6 emphasize both observable and measurable soil characteristics that field personnel can use to monitor effectiveness of activities in meeting soil management objectives (USDA Forest Service, 1998). Since their inception the FS SQS have greatly increased the awareness of the need to evaluate important soil disturbances that can result from forest management activities. However, FS standards and guidelines also are to be based on current knowledge and experience and thus are expected to be periodically updated and revised as new information becomes available.

The National Soil Disturbance Monitoring Protocol (NSDMP) (Page-Dumroese et al., 2009) was reviewed in Part 1 of this chapter. While the current protocol provides a statistically based, systematic method for determining area extent of different visual soil disturbances (Reeves et al., 2013; Howes 2006; Page-Dumroese et al., 2009), the call as to which visual soil disturbance classes reflect an important alteration in key soil functions is still left up to those doing the monitoring. Soil-based indices provide a quantifiable measure and link between visual soil disturbance classes and soil changes that actually have significant effects on important soil functions. However, because evaluation of these indices and their relationships with visual assessments is neither required nor consistently conducted for locally common soil types and operations, a protocol for such evaluations could be an important addition and update to the NSDMP. The data presented and discussed in this chapter support such a revision.

Key findings from the evaluation of current FS SQS in Part 2 of this chapter indicated that soil disturbance classes, as defined in the current FS R6 SQS, did not consistently indicate a detrimental soil condition. The data help confirm the importance of actual measurements of soil-based indicators to determine when a visual soil disturbance class represents a detrimental soil condition. In addition, measured changes in soil-based indicators (i.e. bulk density and porosity) that reflected detrimental changes in soil functions were not consistent within a given visual soil disturbance class. For example, in most cases a detrimental increase in soil bulk density was not associated with a detrimental reduction in macroporosity, and a detrimental change in macroporosity was not associated with a detrimental change in soil bulk density.

Further investigation of soil-based indicators in Part 3 of this chapter indicated that measures of soil bulk density can be used to estimate changes in total soil porosity resulting from disturbance. However, bulk density does not provide a good estimate of macroporosity shifts because different soils vary in the degree of changes in pore size distribution that result from disturbances. These observations strongly suggest a need for further refinement of the FS R6 SQS and the interpretations of soil-based indicators that account for varying sensitivity and resiliency of different soil types to management activities. Field data further suggest that specific soil indices and critical limits should be identified and validated for different soil types and different soil functions.

A strategic soil data base, compiled and stratified by soil taxonomic classes known to influence management in different ways, could provide an accessible and valuable reference to provide more effective answers to questions about the various effects of different soil disturbances. The classification system used in soil taxonomy in the U.S. identifies important soil characteristics and environmental factors such as climate, soil depth, texture, horizon structure, and mineralogy that affect the ways that different soils function. This systematic integration of site information provides opportunities to use soil taxonomy to better understand a soil's inherent capacity to perform different soil functions and the soil's anticipated response to disturbance. Those same soil characteristics and environmental factors used to classify soils can be used to group soils for various management strategies based upon important soil disturbances and differences in resistance and resilience to change.

For example, the loss of soil macroporosity resulting from compaction has the potential to cause negative effects on soil infiltration, drainage, and aeration. The Andisols soils derived from volcanic ash soil parent materials were found to have inherently high macroporosity and to be resistant to the loss of macroporosity when they were disturbed. Other soils in the study were more sensitive to loss of macroporosity when disturbed. The Mollisols soils with high clay content had low inherent soil macroporosity and were sensitive to loss of macroporosity when disturbed, but are also expected to be resilient due to the ameliorating effects of their shrink swell clays. Similar grouping of different soils could be made for other soil-based indices such as soil strength and mineralizable soil nitrogen.

Groupings based on specific soil taxonomy criteria could also be useful for the interpretation of the effects of soil disturbances on key soil functions. For example, the effect of reduced macroporosity resulting from compaction on soil infiltration, drainage, and aeration would be expected to greater in soils having a udic soil moisture regime compared to those having a xeric soil moisture regime.

Finally, to be fully meaningful, operational soil monitoring results also need to reflect important response variables such as changes in long-term productivity or hydrologic function, such as significantly increased runoff. Therefore, continued validation of soil disturbance responses through ongoing field monitoring and further research are a critical part of the process (Powers et al., 2005; Scott et al., 2014; Ares et al.. 2005; Miller et al., 1996; Wagenbrenner et al., 2015).

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Chapter 6 : Concluding Comments

Although I well understood the broad importance of soils information in forest resource management, the data, concepts and experience that were developed through this Ph.D. work have provided me with a much greater understanding and appreciation for the value of soils information in forestry including many new and different opportunities for effectively integrating soils information in forest planning and management. While both inherent and dynamic soil interpretations are comparably important for informing resource planning, in recent years, monitoring and interpretations of dynamic soil quality have become a dominant focus in many forest planning efforts. On public lands this has resulted largely from concerns about compliance with federal laws such as the National Environmental Policy Act (NEPA) and the National Forest Management Act (NFMA), which require evaluation of the environmental effects of management activities and maintenance of soil and other resources. In addition to public lands, forest industry also has emphasized dynamic soil quality assessments on their lands through their efforts in developing operational guidelines to maintain the productive capacity of their soils to achieve sustainable forest productivity. Although very important in sustainable forest management, the strong emphasis on concerns about dynamic soil quality in both research and management appears to have come at the expense of other studies and applications of soils knowledge and information.

The need to assess dynamic soil quality and limit soil impacts resulting from forest management cannot be ignored, but its dominance in forest decisions in recent decades has also led to a diminished awareness of the broader value of soils information in forest planning and management decisions. It is my hope that this work will help resource managers think about the soil resource in ways that they may not have considered in the past. Substantial resources have been expended to create comprehensive inventories and extensive mapping of forest soils, yet as a soil scientist with well over two decades of professional experience I believe that many planning and management decisions continue to be made with limited consideration of soil data and the refined land management interpretations that soils information can provide.

Assessments of soil disturbances are, and will continue to be, a very important part of forest resource management. The FS SQS help to ensure that soils are adequately protected during forest operations and are a credit to those who help develop and validate standards and guidelines. These standards and guidelines as well as the methods used to make assessments of soil disturbances have been valuable in generally limiting negative impacts. Agency policy states that the SQS should continue to be updated as additional information and soil research becomes available, and I believe that the data collected and discussed in this work has presented a strong case for such an updated in Region 6.