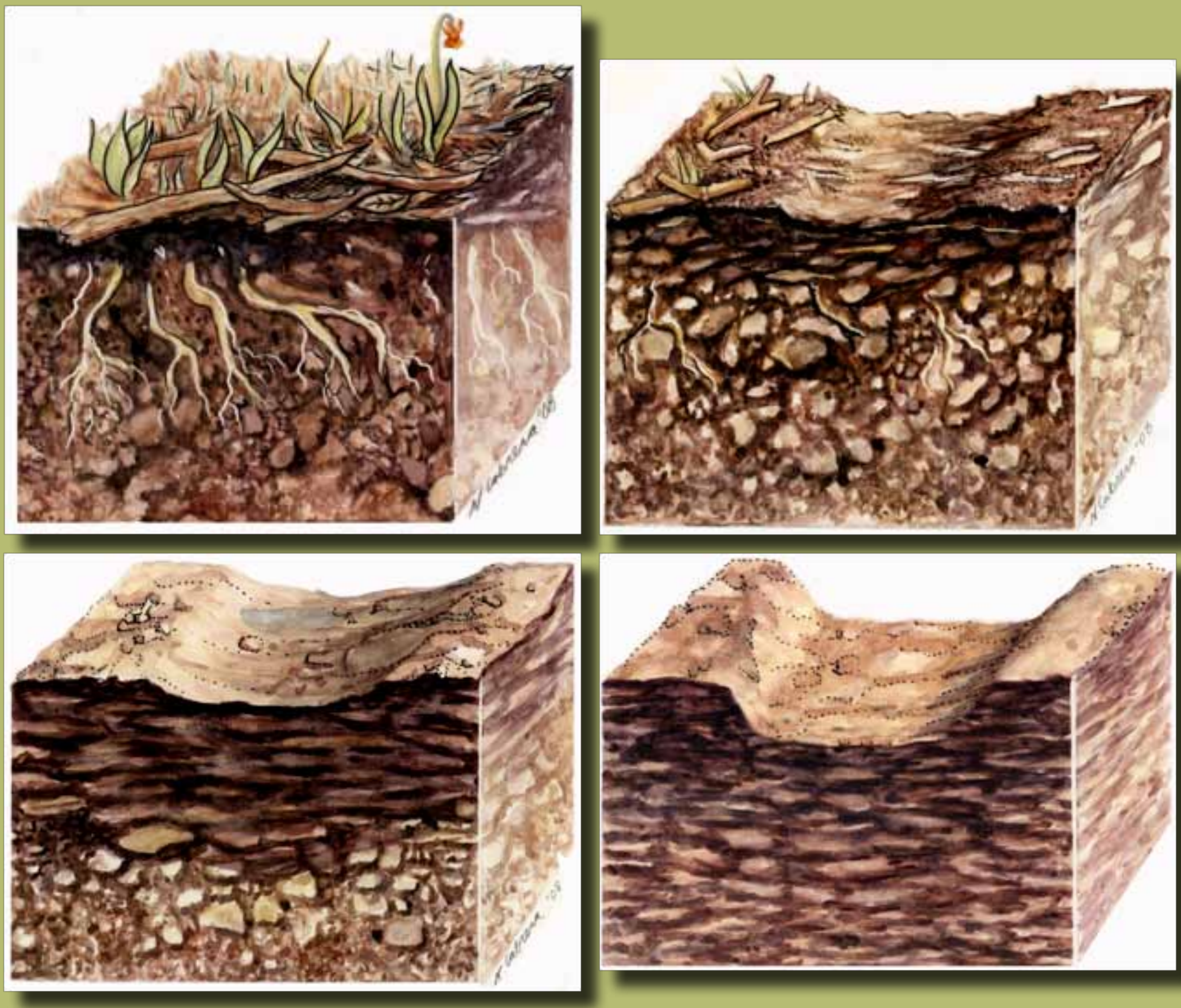
Scientific Background for Soil Monitoring on National Forests and Rangelands

Workshop Proceedings, April 29-30, 2008, Denver, Colorado



United States Department of Agriculture / Forest Service

Rocky Mountain Research Station

Proceedings RMRS-P-59

April 2010

Page-Dumroese, Deborah; Neary, Daniel; Trettin, Carl, tech. eds. 2010. **Scientific background for soil monitoring on National Forests and Rangelands: workshop proceedings**; April 29-30, 2008; Denver, CO. Proc. RMRS-P-59. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 126 p.

Abstract

This workshop was developed to determine the state-of-the-science for soil monitoring on National Forests and Rangelands. We asked international experts in the field of soil monitoring, soil monitoring indicators, and basic forest soil properties to describe the limits of our knowledge and the ongoing studies that are providing new information. This workshop and the proceedings are particularly important as National Forests wrestle with determining how (or if) to modify their existing soil quality standards and guidelines.

Compilers

Deborah Page-Dumroese, Research Soil Scientist, USDA Forest Service, Rocky Mountain Research Station, Moscow, ID.

Daniel Neary, Research Soil Scientist, USDA Forest Service, Rocky Mountain Research Station, Flagstaff, AZ.

Carl Trettin, Research Soil Scientist, USDA Forest Service, Southern Research Station, Cordesville, SC.

Front cover schematic: In: Napper, C.; Howes, S.; Page-Dumroese, D. (In process). Soil disturbance field guide. 0820 1815-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology Center.

Papers were edited to a uniform style; however, authors are responsible for content and accuracy of their papers.

You may order additional copies of this publication by sending your mailing information in label form through one of the following media. Please specify the publication title and series number.

Fort Collins Service Center

Telephone	(970) 498-1392
FAX	(970) 498-1122
E-mail	rschneider@fs.fed.us
Web site	http://www.fs.fed.us/rm/publications
Mailing address	Publications Distribution Rocky Mountain Research Station 240 West Prospect Road Fort Collins, CO 80526

Rocky Mountain Research Station
240 W. Prospect Road
Fort Collins, Colorado 80526

Scientific Background for Soil Monitoring on National Forests and Rangelands

Workshop Proceedings, April 29-30, 2008, Denver, Colorado

Preface

These proceedings are the result of interactions with Regional Soil Program Managers, Forest Soil Scientists, Regional Timber Sale Administrators, Research Soil Scientists and Silviculturists, University Professors, and the BC Ministry of Forest and Range Soil Scientists through the National Soil Quality Standards working group established by the Region 1 Regional Forester (Abigail Kimbell) in 2002. This group helped guide the development of a national Forest Soil Disturbance Monitoring Protocol, developed the idea for a picture guide to forest soil disturbance, and brought together leaders in soil quality and soil quality monitoring to establish the state-of-the-science documented in these proceedings. This documentation is meant to provide the information needed for revision of Regional Soil Quality Standards and Guidelines.

Contents

Soil Quality: Some Basic Considerations and Case Studies

Dale W. Johnson, Natural Resources and Environmental Science, University of Nevada, Reno, Reno, NV

Abstract—Some fundamental properties of soils that pertain to the concept of soil quality are discussed including a discussion of what can and cannot be changed with management. Case studies showing the effects of N-fixing vegetation and N-enrichment effects on invasive species are provided to illustrate the complications that may arise from applying one soil quality standard to all cases. Finally, the "nitrogen problem is discussed: nitrogen is the most frequently growth-limiting nutrient and yet it is also the nutrient that is often the most problematic to manage without causing deleterious effects on the availability of other nutrients and water quality.

Introduction

Soil quality is a concept that, in theory, all soil scientists should embrace. Concerns have been expressed, however, that the concept is too broad and encompassing to be meaningful, and that if soil quality indicators are applied, this must be done on a site-specific basis with specific management objectives in mind (Karlen and others 1997; Page-Dumroese and others 2000; Schoenholtz and others 2000). The first questions that come to mind for this author are who will define soil quality? Soil Scientists? Farmers? Water quality experts? Conservationists? Lawyers? What criteria or outcome will be used to set the criteria for soil quality? Plant growth? Water quality? The soils themselves? Will one definition fit all? Not likely. Will the various definitions conflict? Almost certainly.

Several excellent reviews of soil quality have already been published and the reader is referred to them for details on potential criteria as well as more philosophical aspects of the issue (*e.g.*, Karlen and others1997; Page-Dumroese and others 2000; Schoenholtz and others 2000). In this paper, I will only briefly review some basic soil properties with an eye to what we might be able to change by human intervention and what cannot be, and how (if at all) these changes can be translated into the concept of soil quality.

Some Basic Soil Concepts

Factors of Soil Formation

Jenny (1941) defined factors of soil formation as parent material, climate, topography, and biota, all of which are integrated over time:

$$\text{Soil} = \int f(\text{parent material, climate, biota, topography})$$

There have been elaborations of this model over the years since its inception, but for our purposes it will suffice. The factors of soil formation that we can and often do modify include biota, most usually by modifying vegetation, and with heavy equipment and great effort we can also modify topography. Vegetation effects on soils are very well documented, including nutrient depletion by uptake (species variation being a major factor here; Binkley and Menyailo 2005). Introducing nitrogen fixing species can greatly enhance soil C and N status, but also may cause soil acidification by producing excess nitrification (Van Miegroet and Cole 1984). Further aspects of the effects of too much N fixation and other inputs of N will be discussed later. We can also modify soil biota,

Table 1. An abbreviated description of the 12 soil orders according to the U.S. 12th Approximation.

Soil order	Description
Alfisols	Clay migration, moderately high % BS
Andisols	Volcanic parent material, high P fixation
Aridisols	Arid soils, high in salts and pH
Entisols	Not well-developed even after long periods (can occur anywhere)
Gelisols	Permafrost
Histosols	Soils.formed from organic matter (peats and mucks)
Inceptisols	Still forming, water is available for soil formation
Mollisols	Organic-rich A horizons, % BS usually > 50%
Oxisols	Highly-weathered (e.g., tropical rainforest)
Spodosols	Fe, Al, and organic matter transport, whitish E Horizon (e.g., boreal forest)
Ultisols	Clay transport like Alfisols, but much more acidic; higher temperature; often highly weathered (e.g., Southeastern United States)
Vertisols	Mixed soils; swelling clays, frost, etc. cause lower horizons to mix with upper horizons; often characterized by cracks

although with far less precision, by introducing mycorrhizae (*e.g.,* Hererra and others 1993; Trappe 1997), modifying the C:N ratio either by adding N or organic C, or adding nutrients via fertilization (Miller 1981). On the other hand, we cannot modify parent material (except perhaps with heavy equipment and great difficulty), climate, or time.

The factors of soil formation listed above lead to the development of soils as we see them, and many soil classification systems have been proposed (Buol and others 2003). In the U.S. 12th approximation, (USDA 1999), the highest level classification is the soil order (table 1). The U.S. system becomes very complex and specific from that point on, and a full description of it is well beyond the scope of this paper. The 12 soil orders have some inherent properties that affect properties commonly associated with their "quality." Some, such as Entisols and Inceptisols, can be so poorly developed because of their young age (the time factor) or parent material (for example, weathering-resistant and inherently nutrient poor quartz sand). Others, such as Mollisols and many Alfisols, can, for the same reasons, be quite rich in nutrients commonly associated with high "quality." Many of these soil orders (for example, Ultisols, Mollisols, Oxisols, Spodosols, and especially Aridisols and Gelisols) have a rather specific geographic distribution that is influenced mainly by climate whereas others (Andisols and to some degree Vertisols) are more strongly influenced by parent material. So arises the first question regarding soil quality: do we judge soil quality from a single standard, by lumping all 12 orders and the myriad subdivisions within them into one bucket and assessing their quality from an overall standard, (which some, because of their very nature, will of course never be able to achieve), or do we restrict our assessments of soil quality to within soil order, at a minimum, and perhaps even at a lower order of classification such as great group or even lower? If the latter, we may soon find, for example, that a high "quality" Mollisol is quite a different thing from a high "quality" Oxisol.

Soil Physical Properties

The soil physical properties commonly listed in basic soil texts (Brady and Weil 2008; Gardiner and Miller 2008; Singer and Munns 2006) include texture, structure, coarse (rock) fragments (which is that particle size >2 mm by convention), bulk density, and porosity. These basic physical properties lend the soil its properties associated with water, namely, field moisture capacity (FMC) (the maximum amount of water held in the soil after drainage, typically at tensions of –10 m to –33 kPa), permanent wilting percentage (PWP) (soil water content at which plants can no longer remove water from soil, usually defined at –1,500 kPa, but for desert plants can be as high at –6,000 kPa), available water capacity (FMC-PWP), and hydraulic conductivity. Water available to plants at any given time (plant available water, PAW) is in theory equal to the difference between soil moisture content at the time in question minus soil moisture content at PWP; thus, after gravitational drainage has occurred, PAW ≤ AWC (available water

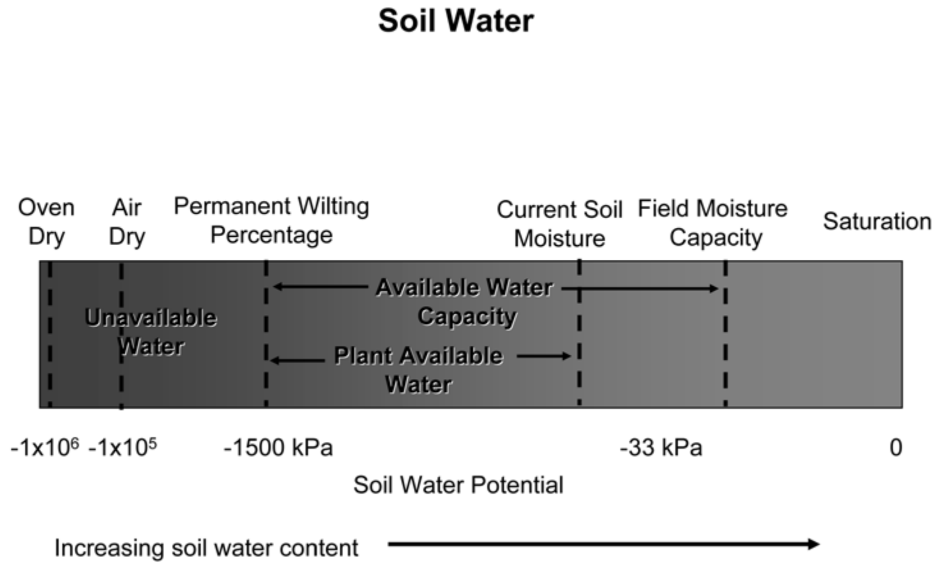


Figure 1. Schematic representation of soil water fractions.

content) (fig. 1). These soil water properties are a function of texture and structure as well as organic matter content, but this relationship is complex. The idealized (round) maximum pore size that will hold water at any given tension can be calculated from the capillary rise equation, and thus soil water properties are a function not only of total soil porosity (often calculated as 1 – bulk density/2.65 for mineral soils, assuming the density of the soil mineral fraction to be 2.65 g cm^{-2}) but also of pore size distribution, which in turn is a function of soil texture and soil structure (*e.g.,* aggregation). Thus, soils with high clay content and poor structure may have very high FMC, but will also likely have high PWP so that AWC is actually lower than soils with a loamy structure (fig. 2).

Soil structure and bulk density can both be changed by management and so can soil water properties. Soil texture cannot be changed. Adding organic matter to clay soils can improve aggregation, which in turn can lessen the problem with too many fine pores and high PWP. On the other hand, repeated disturbance leading to organic matter loss can have the opposite effect. Bulk density, total porosity, pore size distribution and, therefore, soil water properties can all be modified by management. Compaction reduces total porosity and usually creates more fine pores, perhaps increasing both FMC and PWP with variable effects on AWC. Compaction is usually seen as an undesirable effect, but, as shown by Gomez and others (1999), compaction can cause AWC and tree growth to go in either a positive or a negative direction. Specifically, Gomez and others (1999) found that compaction in clay textured soils caused the expected effect of reducing AWC, but in a sandy loam soil, compaction caused greater increases in FMC than in PWP, thus increasing AWC and tree growth. Thus, compaction can actually improve soil "quality."

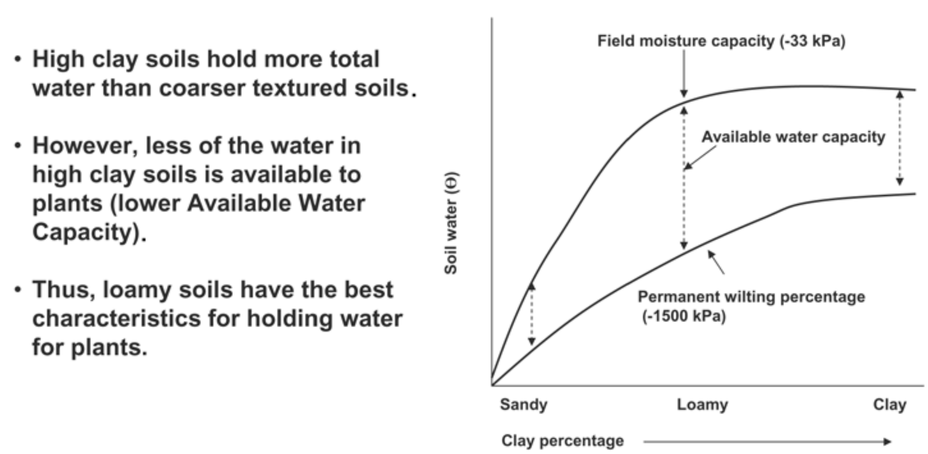


Figure 2. Schematic representation of available soil water with changing soil texture.

Soil Chemical Properties

Soil chemical properties commonly measured include total carbon, organic carbon, total nitrogen, C:N ratio (including organic carbon only), cation exchange capacity, exchangeable Ca^{2+}, K^+, Mg^{2+}, Na^+, Al^{n+}, base saturation, extractable NH_4^+ and NO_3^-, extractable ortho-P, extractable SO_4^{2-}, and extractable micronutrients. All of these parameters can be modified by management (*e.g.,* fertilization) and this is commonly done in agricultural and intensively managed forest soils. There are, however, problems with measurement of many of these soil chemical parameters. Total C and total N are easily measured with modern combustion equipment, but it must be borne in mind that these analyses include both organic and inorganic forms. In the case of C, this can be significant if carbonates are present, and typically they must be removed by acid pretreatment if proper C:N ratio calculations are to be made. Ammonium and NO_3^- (mineral N) analyses provide data on readily available N, analogous to "cash in the wallet"; but, like "cash in the wallet," they do not necessarily provide a good index of soil N status as they are ephemeral quantities and turn over rapidly in soils. (To carry the analogy a step further, it could well be that the millionaire carries little cash in his wallet.) It is the flux from organic to mineral N, not the standing pool of mineral N, that gives the best estimates of N availability (as cash flow gives a better estimate of wealth than cash in the wallet), and thus there are many methods proposed to measure "N mineralization"(Robertson and others 1999). Unfortunately, all of these methods have artifacts associated with them. All N mineralization methods not involving isotopes require that plant N uptake be prevented; thus, roots must either be removed or killed. In the former case, the process of root removal may create the "assart" effect, whereby soil disturbance increases N mineralization and in the latter case, N mineralization may be artificially augmented by inputs of mineral N from decaying roots. Or, alternatively, methods that eliminate roots also eliminate the possibility of rhizosphere-enhanced soil organic matter mineralization, thus underestimating real, in-situ N mineralization (*e.g.,* Hamilton and Day 2001). Isotope methods seek to avoid these problems (see reference for a full discussion), but are expensive and have artifacts of their own to deal with. In short, there is no reliable, standard, and relatively inexpensive method for measuring N availability in soils. In this author's opinion, organic C, organic N, and organic C:N ratio are the best compromises in terms of information provided compared to cost.

There are far fewer problems with exchangeable cations and cation exchange capacity (CEC) than there are for N, but care must be taken to be consistent with methods. Most agricultural labs in the United States use ammonium acetate for cation exchange capacity, which in theory buffers pH to 7. As noted by Sumner and Miller (1996), the continued use of this method is unfortunate because it grossly overestimates the CEC of acidic soils. The Ba-TEA method that raises pH to 8.3 causes an even greater inflation of CEC values in acid soils. While the pH in most agricultural soils is manipulated routinely, it often has a target value of 7. Seldom are forest soils at pH 7, and even more seldom do we attempt to bring them to pH 7; thus, many forest soils laboratories use the neutral salt method, (1 M NH_4Cl; Skinner and others 2001), which measures CEC at normal soil pH, or close to it, perhaps with some depression in pH due to the salt effect, where NH_4^+ displaces some exchangeable H^+ and Al^{3+} by mass action. In theory, either ammonium acetate or ammonium chloride will extract approximately the same amount of base cations, but ammonium acetate will measure a greater proportion of pH-dependent CEC, which will be an important factor in organic-rich surface horizons. Thus, the two methods could yield two different measures of base saturation for the same soil at the same time, leading the unsuspecting to believe that some change has occurred. This is illustrated schematically in figure 3, where a hypothetical soil is extracted by these two methods.

Extractable ortho-P methods yield results that are nearly as ephemeral as is the case for mineral N. We have found substantial seasonal variation in Bray-extractable P (weak solutions of HCl + NH_4F) (Johnson and Todd 1984; Johnson and others 1988) and also some inconsistent differences between Bray- and bicarbonate-extractable P (Johnson and others 1997; Susfalk 2000). Specifically, Bray extractions consistently yield greater values for P in soils derived from decomposed granite in our sites in the eastern Sierra

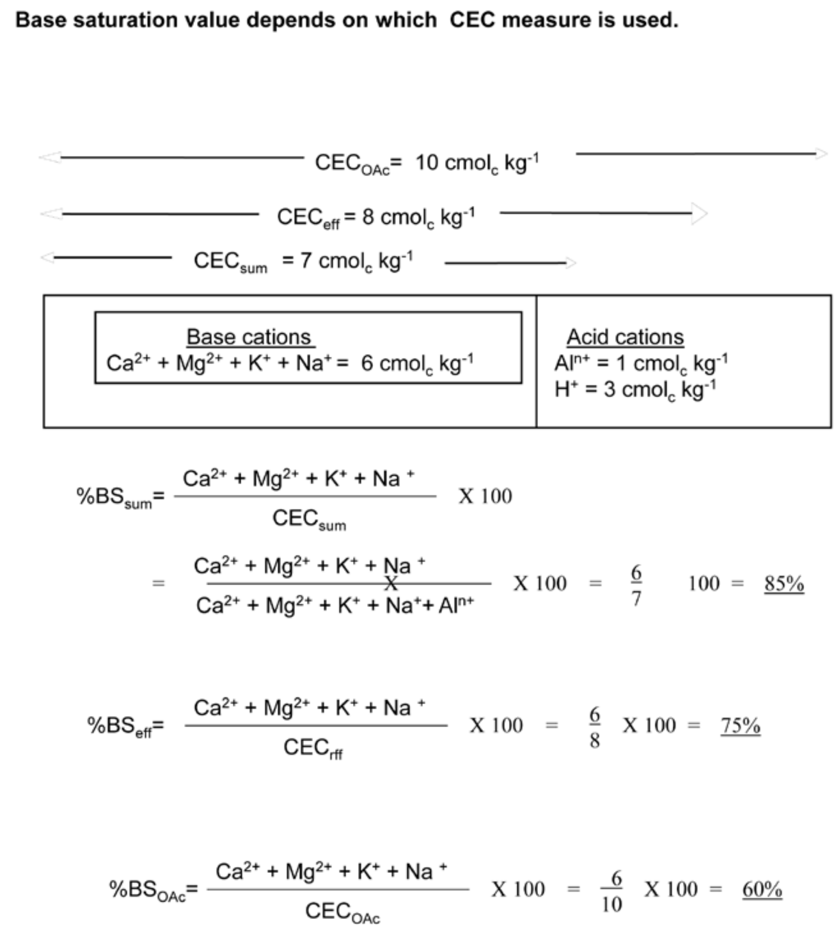


Figure 3. Example of how different methods for measuring cation exchange capacity can lead to misleading conclusions about base saturation.

Nevada mountains (Johnson and others 2005; Susfalk 2000) whereas bicarbonate extractions often yield greater values for P in soils derived from andesite (Susfalk 2000). Susfalk (2000) studied P in soils from this region in great depth and concluded that the andesite-derived soils had far greater buffering power for ortho-P than the soils derived from decomposed granite, causing the andesitic soils to both quickly adsorb added ortho-P and also to release greater quantities of ortho-P with repeated extractions. He concluded that "a one-point P extraction index (bicarbonate-P or Bray-P) was a poor indicator of extractable P in [the andesitic soils] because it was unable to account for buffering effects, and [also a poor indicator of extractable P in granitic soils] because they extracted non-labile forms of P that may not have been plant-available."

Far less work has been done on extractable sulfate, but it is well known that pH has a very strong influence on it (Singh 1984) and that soils enriched in sesquioxides and high amounts of pollutant sulfur inputs have the highest levels of soil sulfate (Johnson 1984).

Many of the micronutrients are especially sensitive to pH. Copper, zinc, and iron, in particular, become less available at higher pH as they begin to precipitate as hydroxides. Molybdenum and, to a lesser extent, boron (being in anionic form in soil solution) become more available at higher pH as they desorb from sesquioxides. Copper is strongly absorbed by organic matter and, therefore, can be deficient in high-OM soils.

Soil Biological Properties

We can, with relative ease, cause changes in vegetation, which will in turn cause changes in soil biological and chemical properties. For example, planting with N-fixers can greatly increase soil C and N status, but also can result in greater soil acidification (Johnson and Curtis 2001; Van Miegroet and Cole 1984). We can also, to a more limited degree, change soil microbiota by introducing mycorrhizal innoculum, fertilizers, or raising C:N ratio by adding woody materials or even sugar to tie up available N. One

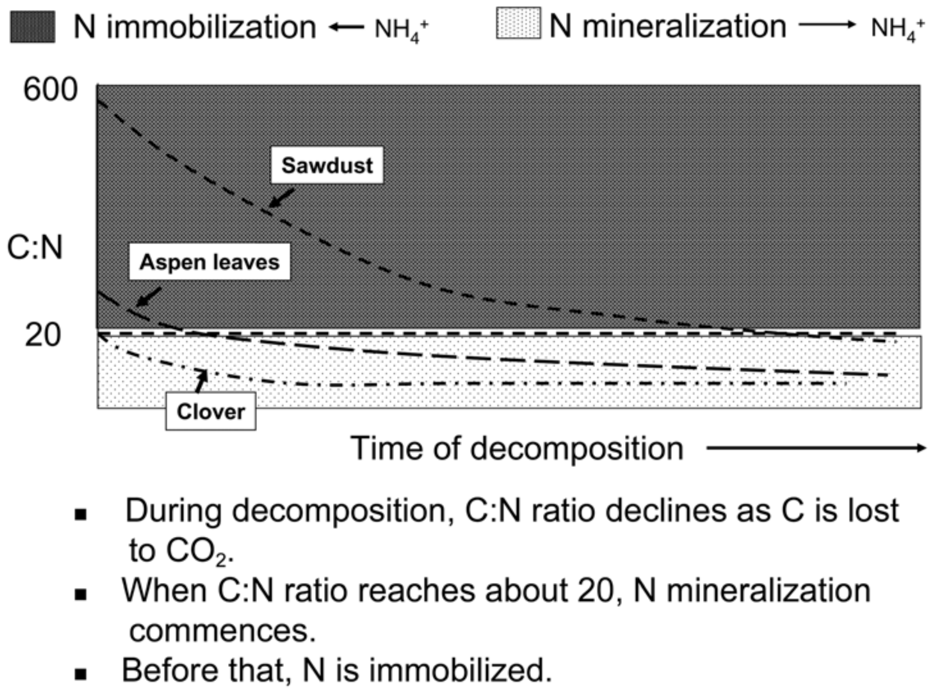


Figure 4. Schematic representation of the effects of soil C:N ratio on net N mineralization and immobilization.

of the easiest soil biological factors to change is that of nitrifying organisms: add available N, and they will increase their activity in most cases, probably quite quickly, and not entirely without negative consequences. We can also, with somewhat more effort, stimulate denitrifiers by creating anaerobic conditions and supplying organic substrates.

In the context of soil biology, it is perhaps germane to consider the results of long-term decomposition studies conducted by Berg and others (2003). Textbook knowledge says that adding material with high C:N ratios such as woody tissues will cause slower decomposition; also, available N immobilization as microbes, with their own C:N ratios of between 6 and 12 to 1, try to digest materials with C:N ratios an order of magnitude or more greater. In order to adjust the C:N ratios of the material they consume, they (1) release organic C as CO_2, and (2) import available N from soil pools. As a consequence, the C:N ratio of decomposing materials decreases during decomposition. As the material reaches a value of approximately 20:1, microbes begin releasing, instead of taking up, available N and, therefore, shift from the immobilization to the mineralization phase (fig. 4).

A significant complication to this textbook scenario was introduced by Berg and others (2003) with their concept of limit values. Their long-term (two-decade) decomposition studies showed that, indeed, materials with higher C:N ratios initially decomposed more slowly than those with lower C:N ratios. Over time, however, they found that materials with initially higher C:N ratios leveled off sooner, reaching a quasi-steady-state condition referred to as the limit value for remaining mass that was lower than that reached by materials with an initially lower C:N ratio. Thus, over the long term, organic C and N contents of materials with initially lower C:N ratios remained greater than those with initially higher C:N ratios—presumably this material is very humic and stable in nature, perhaps entering the stable soil organic matter pool. Thus, litter with initially greater “quality,” which is often indexed as litter with lower C:N ratio, certainly leads to short-term increases in decomposition and, therefore, initially lower initial C and N pools in the O horizon. Over the long run this higher quality litter also leads to greater soil organic C and N contents (fig. 5). This example illustrates how a soil quality parameter, such as available N, can change with time—even without any intervention by humans or disturbance—simply by the nature of decomposition and its interaction with C and N in decomposing material, as manifested in both its short- and long-term effects. This reversal of N availability and C sequestration over time would seem to make an assignment of a soil quality value a very elusive thing indeed.

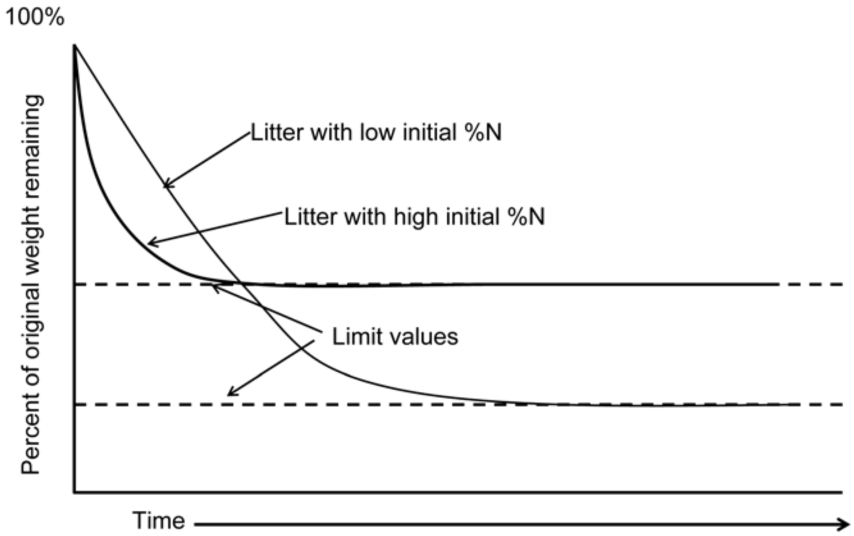


Figure 5. Schematic representation of the decomposition of litter with initially high vs. initially low C:N ratio (after Berg and others 2003).

Case Studies

So what constitutes a good quality soil? The Soil Science Society of America defined soil quality as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen and others 1997). The questions being asked in the following case studies are (1) are these goals mutually compatible? (2) are these goals always desirable? and finally, and most importantly, (3) does the very concept of soil quality add to or detract from the concept of soil fertility? It seems to this author that the problem with the concept of soil quality is that it implies a blanket value judgment on soils that one fears will be applied (perhaps legally) to all soils in all situations. We are more familiar with the concept of soil fertility, and while it also implies a value judgment it is more specific (is the soil good for plant growth?) and can more readily be quantified with standard soil analyses. When we speak of water quality, we generally refer to conditions of low fertility (oligotrophic) as being desirable and waters of high fertility (eutrophic) being "polluted" and undesirable. To some degree, the same judgments may well apply to soil quality in some circumstances. For example, an endangered species that is thrifty with nitrogen is being threatened by increasing competition from a nitrogen-loving invasive species as a result of increased nitrogen fertility due to pollutant inputs. And, of course, more fertile soils are in fact more likely to produce more fertile surface waters, thus creating an automatic conflict between the concepts of soil and water quality.

Case Study 1: The Effects of Red Alder on Soil Quality

Red alder (*Alnus rubra*) is a native N-fixing tree in the Pacific Northwest that occupies sites after disturbances such as fire, logging, erosion, etc. It has long been known that red alder improves soil N status and that subsequent stands of Douglas-fir (*Pseudotsuga menziesii*) greatly benefit from this (Binkley 2003). A little over two decades ago, however, Van Miegroet and Cole (1984) found that red alder simply cannot stop itself from fixing N even when no more N is needed by any biological entity in the ecosystem except nitrifying bacteria. Nitrification results in the creation of nitrate and acid, and when the nitrate is not taken up, the acid exchanges for base cations on the soil exchange complex, nitrate leaches and soil acidifies. There is also the suggestion that soil available P is tied up because of the excess N, but this is somewhat more controversial (Compton and others 1998; Giardina and others 1998). Furthermore, red alder apparently makes soil conditions less suitable for itself, and does not do well on sites formerly occupied by red alder (Van Miegroet and others 1992). Douglas-fir, on the other hand, is not bothered by the acidity or lower soil P status and thrives in the N-rich environment. How, then, does one define soil quality in this instance? The quality for red alder is poor, that for Douglas fir is good, and, while red alder occupies the site, water quality is degraded by high nitrate concentrations (which cease quickly after the red alder is cut down, apparently causing cessation of N fixation). Compton and others (2003) find that the degree of occupancy of red alder in watersheds was directly related to the concentrations of nitrate in streamwaters.

Case Study 2: The Effects of Snowbrush on Soil Fertility

Snowbrush (*Ceanothus velutinus*) is a major fire-adapted N-fixing species occurring on disturbed sites in the Sierra Nevada and southern Cascade mountains. The heat generated from fire is thought to be the major mechanism for seed germination (Gratkowski 1962). Nitrogen (N) fixation in snowbrush is associated with *Frankia* spp. actinomycetes, and reported fixation rates of up to 142 kg N ha^{-1} yr^{-1} (Binkley and others 1982; Youngberg and Wollum 1976). Snowbrush is generally intolerant to shade, but it has been observed to dominate a site for over 50 years following a wildfire by suppressing forest regeneration (Conrad and Radosevich 1982). Zavitkovski and Newton (1968) describe four stages to snowbrush growth following fire or disturbance: (1) growth with little or no accumulation of organic matter between the ages of 1 to 5 years; (2) rapid growth with increasing biomass, increase of N in biomass, and accumulation of organic matter between the ages of 5 to 10 years; (3) an equilibrium stage, which lasts between the ages of 10 to 15 or as long as 50 years; and (4) the final stage of decline and decomposition, usually due to the growth of a forest canopy shading the snowbrush out.

We have made several comparisons of soils beneath snowbrush and adjacent Jeffrey pine (*Pinus jeffreyi*) stands in Little Valley, Nevada, a site just east of Lake Tahoe (Johnson 1995; Johnson and others 2005). We have found that soils beneath snowbrush consistently have lower bulk density and higher total C and total N concentrations than in adjacent pine stands, as would be expected. Unlike the case with red alder, however, we have also found that there are no differences in extractable P concentrations in soils beneath snowbrush as compared to soils beneath pine, but snowbrush soils have consistently higher concentrations of exchangeable Ca^{2+}, K^{+}, and Mg^{2+} than in adjacent pine stands. The higher base cation status beneath snowbrush is consistent with the fact that we have found no evidence of elevated levels of NO_3^- leaching beneath snowbrush stands (Johnson 1995; Stein 2006).

Thus, it appears that snowbrush improves soil bulk density and nutrition—soil "quality"—in most measurable ways. Is this a desirable outcome? Purely from the perspective of soil "quality" it certainly is; however, because snowbrush does not "poison itself out" of a site like red alder apparently does, it can persist for many decades after fire and prevent reforestation. Thus, we have high quality soils but an undesirable vegetative cover to go with these high quality soils.

Case Study 3: Cheatgrass in the Great Basin

Cheatgrass (*Bromus tectorum*), an exotic annual grass, is rapidly expanding throughout the Great Basin. This highly competitive invader is resulting in the widespread deterioration of mid- to low-elevation sagebrush ecosystems and, more recently, salt desert ecosystems (Brooks and Pyke 1991). Cheatgrass has altered fire regimes in native ecosystems because it increases fine fuels, is highly flammable, and increases the rate of fire spread (Link and others 2006). In many parts of the region an annual grass-fire cycle now exists in which fire return intervals have decreased from about 60 to 110 years to as little as 3 to 5 years (Whisenant 1990). Recent field studies have shown the importance of available inorganic nitrogen in controlling cheatgrass establishment and growth (McLendon and Redente 1991; Young and others 1999). Experiments with sugaring soils to stimulate microbial competition for N, thus reducing mineral N supplies in soils have proven to severely limit cheatgrass growth and to favor native species by reducing competition (Young and others 1999).

An alternative approach to sugaring to tie up mineral N might be to reduce total N supplies and, therefore, mineral N supplies by repeated burning. It is well documented that nearly all N contained in organic material that is burned is volatilized and lost from the system, potentially causing long-term declines in ecosystem N capital unless the N is replaced by atmospheric deposition, N-fixation, or fertilization (Blair 1997; Neary and others 1999; Raison and others 1985). On the other hand, burning commonly causes short-term increases in soil ammonium levels because of the heat-induced denaturing of soil organic N (Neary and others 1999). The pulse of ammonium is often followed by a pulse of nitrate and nitrate leaching once nitrifying bacteria occupy the site again. The short-term pulse of ammonium after fire is thought to be one factor favoring nitrophilic cheatgrass after rangeland fire (Monaco and others 2003). Over the long-term, however, one would expect that repeated burning without replacement of lost N could cause reductions in soil mineral N levels, at least after the initial post-fire pulse has passed (Blair 1997; Johnson and Matchett 2001; Ojima and others 1994). This is attributed to both volatile losses of N and also to a form of progressive N deficiency, where N concentrations in vegetation decline over time in response to reduced soil N availability, causing inputs of detritus with lowering C:N ratios. The N deficiency is further exacerbated by increasing microbial competition for N in much the same manner as the short-term sugaring experiments described above (Blair 1997; Johnson and Matchett 2001; Ojima and others 1994). Although it has been shown that cheatgrass invasion can rapidly alter N cycling (Evans and others 2001), little is known about the effects of repeated fire on N availability in cheatgrass dominated rangelands. Our objective in this study is to explore the prospects for "burning out" cheatgrass with repeated fires designed to reduce total and available soil N and, consequently, cheatgrass growth and reproduction.

The preceding discussion clearly shows that greater soil "quality"—specifically, better soil N status—favors one of the most destructive invasive species in the Great Basin. Reducing soil N availability (quality?) seems to be the best, albeit somewhat faint, hope of controlling this species.

The Nitrogen Problem

Nitrogen is unique among nutrients in many ways. Unlike P, K, Ca, and Mg, for example, N is rarely present in parent rock, and in the vast majority of cases is naturally introduced to the soil from the atmosphere by symbiotic and non-symbiotic fixation, atmospheric deposition, and lightning. The major inorganic forms of N in soils include both a cation (NH_4^+) that is strongly absorbed to soils and an anion (NO_3^-) that is very weakly absorbed to soils. Unlike most other macronutrients, however, inorganic forms of nitrogen do not persist in non-aridic soils for long. Nitrogen is the most frequently limiting nutrient in terrestrial ecosystems, and inorganic forms of N are rapidly taken up and depleted under N deficient conditions that are common in terrestrial ecosystems. When N is supplied in excess of biological demand, it does not accumulate to any significant degree on soil exchange sites or as precipitation. While the NH_4^+ form is strongly held on soil exchange sites, it does not persist for long in most soils, even when N supplies greatly exceed biological demand, before it is converted to NO_3^- during the nitrification process (which also produces H^+ - nitric acid). Nitrate so produced, if not taken up, is poorly adsorbed and will leach from soils, taking with it base cations and thus acidifying the soil. In contrast, additions of P, K, Ca, or Mg in excess of biological demands can result in large and prolonged accumulations of the ionic forms of these nutrients on exchange and adsorption sites.

Thus, N is a difficult nutrient to manage, which is unfortunate because it is the most often limiting nutrient. All nutrients (in fact all substances, including water) have regions of deficiency, sufficiency, and toxicity with increasing supplies (fig. 6). We can think of this classical curve not only in terms of plant response, but also environmental response. So, for example, while the sufficiency plateau for K, Ca, and Mg can be quite broad, as supplies of these nutrients exceed biological demands and accumulate on soil exchange or adsorption sites, the sufficiency plateau for N is very narrow, with little space between deficiency on the left and undesirable consequences such as excessive

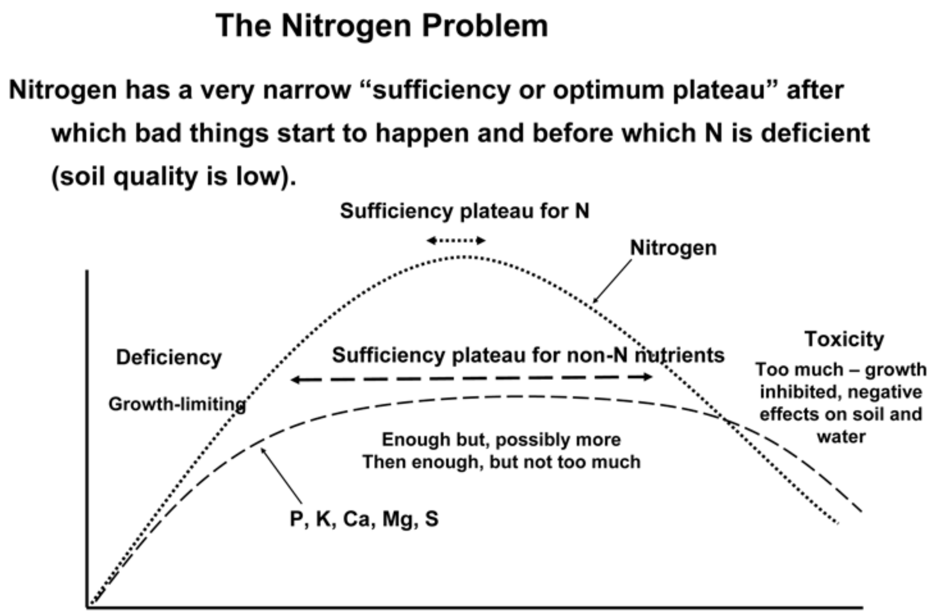


Figure 6. Schematic representation of deficiency-sufficiency-toxicity vs. nutrient supply curves for nitrogen and other nutrients.

nitrate leaching on the right. In the cases of K, Ca, and Mg, increases in leaching rates may occur without undue harm to water quality; in the case of P, leaching is nearly always minimized by various adsorption and precipitation processes in the soil and most P transport from the ecosystem is by erosion. For N, on the other hand, there is a very narrow sufficiency plateau for N between the deficiency region and the point quickly thereafter when excess N leaches from the system and degrades water quality. Thus, trying to manage for a high quality soil will necessarily require that it have good N status, but it is very difficult to achieve good N status without tipping over the edge into the toxicity region.

References

Berg, Bjorn A.; De Santo, V.; Rutigliano, F.A.; Fierro, A.; Ekbohm, G. 2003. Limit values for plant litter decomposing in two contrasting soils—influence of litter elemental composition. Acta Oecologia 24: 295-302.

Binkley, Dan. 2003. Seven decades of stand development in mixed and pure stands of conifers and nitrogen-fixing red alder. Can. J. For. Res. 33: 2274-2279.

Binkley, Dan; Cromack, K., Jr.; Fredriksen, R.L. 1982. Nitrogen accretion and availability in some snowbush ecosystems. Forest Sci. 28: 720-724.

Binkley, Dan; Menyailo, O., eds. 2005. Tree Species Effects on Soils: Implications for Global Change. NATO Science Series. Springer, Dordrecht.

Blair, John M. 1997. Fire, N availability, and plant response in grasslands: a test of the transient maxima hypothesis. Ecology 78: 2359-2368.

Brady, Nyle C.; Weil, R.R., eds. 2008. The Nature and Properties of Soils. Fourteenth Edition. Prentice Hall, Upper Saddle River, New Jersey. 965 p.

Brooks, M.L.; Pyke, D.A. 2001. Invasive plants and fire in the deserts of North America. Pages 1-14 in K.E.M. Galley, T.P. Wilson, eds. Proceedings of the Invasive Species Workshop: the Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: the First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 11, Tall Timbers Research Station, Tallahassee, Florida.

Buol, S.W.; Southard, R.J.; Graham, R.C.; McDaniel, P.A. 2003. Soil Genesis and Classification. Fifth Edition. Blackwell Publishing.

Compton, Jana E.; Cole, D.W. 1998. Phosphorus cycling and soil P fractions in Douglas-fir and red alder stands. For. Ecol. Manage. 110: 101-112.

Compton, Jana E.; Robbins Church, M.; Larned S.T.; Hogsett, W.E. 2003. Nitrogen export from forested watersheds in the Oregon Coast Range: the role of N2-fixing red alder. Ecosystems. 6: 773-785.

Conrad, Susan G.; Radosevich, S.R. 1982. Growth responses of white fir to decreased shading and root competition by montane chaparral shrubs. Forest Science. 28: 309-320.

Evans, R.D.; Rimer, R.; Sperry, L.; Belnap, J. 2001. Exotic plant invasion alters nitrogen dynamics in an arid grassland. Ecological Applications. 11: 1301-1310.

Gardiner, D.T.; Miller, R.W. 2008. Soils in our environment. Eleventh Edition. Pearson/Prentice Hall, Upper Saddle Hill, New Jersey. 600 p.

Giardina, Christian; Huffman, S.; Binkley, D.; Caldwell, B. 1995. Alders increase phosphorus supply in a Douglas-fir plantation. Can. J. For. Res. 25: 1652-1657.

Gomez, A.; R. Powers, R.F.; Singer, M.J.; Horwath, W.R. 2002. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Sci. Soc. Am. J. 66: 1334-1343.

Gratkowski, J.H. 1962. Heat as a factor in germination of seeds of *Ceanothus velutinus* var. *laevigatus* T. and G. Dissertation, Oregon State University, Corvallis.

Hamilton, E.W.; Frank, D.A. 2001. Can plants stimulate soil microbes and their own nutrient supply? Evidence from a grazing tolerant grass. Ecology. 82(9): 2397-2402.

Herrera, M.A.; Salamanca, C.P.; Barea, J.M. 1993. Inoculation of woody legumes with selected arbuscular mycorrhizal fungi and rhizobia to recover desertified Mediterranean ecosystems Appl. Environ. Microbiol. 59(1): 129-133.

Jenny, Hans. 1941. Factors of Soil Formation. A System of Quantitative Pedology. McGrawHill Book, New York.

Johnson, Dale W. 1984. Sulfur cycling in forests. Biogeochemistry. 1: 29-44.

Johnson, Dale W. 1995. Soil properties beneath *Ceanothus* and pine stand in the eastern Sierra Nevada. Soil Sci. Soc. Am. J. 59: 918-924.

Johnson, Dale W.; Curtis, P.S. 2001. Effects of forest management on soil carbon and nitrogen storage: Meta Analysis. For. Ecol. Manage. 140: 227-238.

Johnson, Dale W.; Todd, D.E. 1984. Effects of acid irrigation CO_2 evolution, extractable nitrogen, phosphorus and aluminum in a deciduous forest soil. Soil Sci. Soc. Am. J. 48: 664-666.

Johnson, Dale W.; Henderson, G.S.; Todd, D.E. 1988. Changes in nutrient distribution in forests and soils of Walker Branch Watershed, Tennessee, over an eleven-year period. Biogeochemistry. 5: 275-293.

Johnson, Dale W.; Murphy, J.D.; Susfalk, R.B.; Caldwell, T.G.; Miller, W.W.; Walker, R.F.; Powers, R.F. 2005. The effects of wildfire, salvage logging, and post-fire N fixation on the nutrient budgets of a Sierran forest. For Ecol. Manage. 220: 155-165.

Johnson, Dale W.; Susfalk, R.B.; Dahlgren, R.A. 1997. Nutrient fluxes in forests of the eastern Sierra Nevada Mountains, USA. Global Biogeochem. Cycles. 11: 673-681.

Johnson, L.D.; Matchett, J.R. 2001. Fire and grazing regulate belowground processes in tallgrass prairie. Ecology. 82: 3377-3389.

Karlen, D.L.; Mausbach, M.J.; Doran, J.W.; Cline, R.G.; Harris, R.F.; Schuman. G.E. 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61: 4-10.

Link, S.O.; Keeler, C.W.; Hill, R.W.; Hagen, E. 2006. *Bromus tectorum* cover mapping and fire risk. International Journal of Wildland Fire. 15: 113-119.

McLendon, T.; Redente, R.F. 1991. Nitrogen and phosphorus effects on secondary succession dynamics on a semi-arid sagebrush site. Ecology. 72: 2016-2024.

Miller, Hugh G. 1981. Forest fertilization: some guiding concepts. Forestry. 54: 157-167.

Monaco, T.A.; Johnson, D.A.; Norton, J.M.; Jones, T.A.; Connors, K.J.; Norton, J.B.; Redinbaugh, M.B. 2003. Contrasting responses of Intermountain West grasses to soil nitrogen. Journal of Range Management. 56: 289-290.

Neary, Daniel G.; Klopatek, C.C.; DeBano, L.F.; Ffolliot, P.F. 1999. Fire effects on belowground sustainability: a review and synthesis. For. Ecol. Manage. 122: 51-71.

Ojima, Dennis S.; Schimel, D.W.; Parton, W.J.; Owensby, D.W. 1994. Long- and short-term effects of fire on nitrogen cycling in a tallgrass prairie. Biogeochemistry. 24: 67-84.

Page-Dumroese, Deborah; Jurgensen, M.; Elliot, W.; Rice, T.; Nesser, J.; Collins, T.; Meurisse, R. 2000. Soil quality standards and guidelines for forest sustainability in northwestern North America. For. Ecol. Manage. 138: 445-462.

Raison, R. John; Khanna, P.K.; Woods, P.V. 1985. Mechanisms of element transfer to the atmosphere during vegetation fires. Can. J. For. Res. 15:132-140.

Robertson, G. Phillip; Wedin, D.; Groffman, P.M.; Blair, J.M.; Holland, E.A.; Nadelhoffer, K.J.; Harris, D. 1999. Soil carbon and nitrogen availability: nitrogen mineralization, nitrification, and soil respiration potentials. Pages 258-271 in G.P. Robertson, D.C. Coleman, C.S. Bledsoe, and P. Sollins, eds. Standard soil methods for long-term ecological research. Oxford University Press, New York. 462 p.

Schoenholtz, Stephen H.; Van Miegroet, H.; Burger, J.A. 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. For. Ecol. Manage. 138: 335-356.

Singer, Michael J.; Munns, D.N. 2006. Soils: An Introduction. Pearson/Prentice Hall, Upper Saddle Hill, New Jersey, USA. 466 p.

Singh, Ball R. 1984. Sulfate sorption by acid forest soils: 3. Desorption of sulfate from adsorbed surfaces as a function time, desorbing ion, pH and amount of adsorption, Soil Sci. 138: 189-197.

Skinner, Malcolm F.; Zabowski, D.; Harrison, R.; Lowe, A.; Xue, D. 2001. Measuring the cation exchange capacity of forest soils. Commun. Soil Sci. Plant Anal. 32: 1751-1764.

Stein, Chad M. 2006. Post-fire vegetation in Sierran forests: effects on nitrogen fixation, soil nitrogen availability, and water quality. MS thesis. University of Nevada, Reno.

Sumner, M.E.; Miller, W.P. 1996. Cation exchange capacity and exchange coefficients. Ch. 40. in: Sparks, D.W.; A.L. Page; P.A. Helmke; R.H. Loeppert;, P.N. Soltanpour; M.A. Tabatabai; C.T. Johnson; and M.E. Sumner. Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America, Madison, WI.

Susfalk, Richard B. 2000. Relationships of soil-extractable and plant-available phosphorus in forest soils of the eastern Sierra Nevada. MS thesis. University of Nevada, Reno. 227 p.

Trappe, James M. 1977. Selection of fungi for ectomycorrhizal inoculation in nurseries. Annual Review of Phytopathology. 15: 203-222.

Van Miegroet, Helga; Cole, D.W. 1984. The impact of nitrification on soil acidification and cation leaching in a red alder ecosystem. J. Environ. Qual. 13: 586-590.

Van Miegroet, Helga; Homann, P.S.; Cole, D.W. 1992. Soil nitrogen dynamics following harvesting and conversion of red alder and Douglas-fir stands. Soil Sci. Soc. of Am. J. 56: 1311-1318.

Whisenant, S.G. 1990. Changing fire frequencies on Idaho's Snake River Plains: ecological and management implications. in E.D. McArthur; E.M. Romney; S.D. Smith; P.T. Tueller, comps. Proceedings—Symposium on cheatgrass invasion, shrub die-off and other aspects of shrub biology and management. Gen. Tech. Rep. INT-276, Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Young, J.A.; Allen, F.A. 1996. Cheatgrass and range science: 1930-1950. J. Range Manage. 50: 530-535.

Young, James A.; Blank, R.R.; Clements, D.C. 1999. Nitrogen enrichment and immobilization influences on the dynamics of annual grass community. Pages 279-281 in David Eldridge; and David Freudenberger, eds. People and rangelands building the future. Proceedings of the VI International Rangeland Congress. Townsville, Queensland, Australia; July 19-23.

Youngberg, Chester T.; Wollum, A.G., II. 1976. Nitrogen accretion in developing *Ceanothus velutinus* stands. Soil Sci. Soc. Am. J. 40: 109-112.

Zavitkovski, J.; Newton, M. 1968. Ecological importance of snowbrush, *Ceanothus velutinus*, in the Oregon Cascades. Ecology. 49: 1134-1145.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Using Soil Quality Indicators for Monitoring Sustainable Forest Management

James A. Burger, Professor Emeritus of Forestry and Soil Science, Department of Forestry, Virginia Polytechnic Institute and State University, Blacksburg, VA

Garland Gray, Professor of Forestry and Soil Science, Department of Forestry, Virginia Polytechnic Institute and State University, Blacksburg, VA

D. Andrew Scott, Research Soil Scientist, Southern Research Station, USDA Forest Service, Pineville, LA

Abstract—Most private and public forest land owners and managers are compelled to manage their forests sustainably, which means management that is economically viable, environmentally sound, and socially acceptable. To meet this mandate, the USDA Forest Service protects the productivity of our nation's forest soils by monitoring and evaluating management activities to ensure they are both scientifically wise and socially responsive. The purpose of this paper is to review soil quality indicators and models for their possible use in soil management and evaluation programs. The Forest Service has taken a progressive stance on adapting their long-used soil quality monitoring program to take advantage of new science and technology. How forest soils function in terms of their stability, hydrology, and nutrient cycling is better understood, and indicators of these functions have been identified and tested for cause and effect relationships with tree growth and ecosystem health. Soil quality models are computer-based evaluation tools that quantify soil change and potential change in forest productivity due to management inputs or unintended detrimental disturbances. Soil quality models, when properly conceptualized, developed, and implemented, can provide a legally defensible monitoring and evaluation program based on firm scientific principles that produce unequivocal, credible results at minimum cost.

Introduction

Most private and public forest land owners are compelled to manage their forests sustainably. Sustainable forest management (SFM) is a 21st century management approach that has been branded by the forestry community in the United States and other parts of the world as a concept that provides the basis for site-specific management practices and guidelines. Sustainable forestry is economically viable, environmentally sound, and socially acceptable (Sample and others 2006).

Based on these SFM principles, groups of countries sharing similar forest resources developed criteria and indicators (C&Is) that measure and monitor sustainability (Montreal Process 1995). The C&Is serve as policy and management tools; they are neither management standards nor regulations. They provide a framework for determining the status of ecological, economic, and social conditions of forests, landowners and communities, and they provide the basis for SFM programs on private and public land (Roundtable on Sustainable Forests 2008). For example, Criterion 4, conservation and maintenance of soil and water resources, has two indicators pertaining to soil resources: (1) proportion of forest management activities that meet best management practices or other relevant legislation to protect soil resources; and (2) area and percent of forest land with significant soil degradation.

It remains the task of landowners or their representatives to develop and apply appropriate best management practices as called for by indicator #1, and to monitor the level of "significant soil degradation" referred to in indicator #2. Many private landowners have their forest operations certified by third-party entities against a set of standards (Rametsteiner and Simula 2002). Examples of certification programs include the Sustainable Forestry Initiative (SFI 2004), Forest Stewardship Council (FSC 1996), and the Canadian Standards Association (CSA 2003).

The U.S. National Forest System applies the Montreal Process C&Is through ecosystem management policies guided by federal law (the Multiple Use and Sustained Yield Act of 1960, The National Environmental Policy Act of 1969, the Forest and Rangeland Renewable Resources Planning Act of 1974, and the National Forest Management Act of 1976 [NFMA]). The NFMA requires that national forests be managed in a way that protects and maintains soil productivity (USDA Forest Service 1983). Section 2550.5 of the Forest Service Manual under soil management program (FSM 2009) defines soil productivity as "…the inherent capacity of the soil resource to support appropriate site-specific biological resource management objectives, which includes the growth of specified plants, plant communities, or a sequence of plant communities to support multiple land uses." The objective of the soil management program is to "maintain or improve soil quality on National Forest System lands to sustain ecological processes and function so that desired ecosystem services are provided in perpetuity." Soil quality management (FSM section 2551) is used to accomplish this objective by (1) using *adaptive management* (FSM 1905) to design and implement land management activities in a manner that achieves desired soil conditions to ensure that soil and water conservation practices are implemented and effective; (2) assessing the *current condition* of soil resources; and (3) *monitoring resource management activities and soil conditions* to ensure that soil and water conservation practices are implemented and effective (italics added for emphasis). Regional foresters, forest supervisors, district rangers, and soil scientists within each of the 10 Forest Service regions all play a role in achieving this objective. Soil quality monitoring programs are standardized in objectives and principles, but are region-specific to account for varying soils and ecosystems. The environmental and technical soundness of the soil quality monitoring program is important because it must withstand both scientific scrutiny and legal challenges. The Air, Water, and Soil Division and the research wing of the Forest Service periodically review the soil quality monitoring protocol to ensure that the standards and procedures are scientifically and technically up to date, and to ensure that the monitoring process is systematically achieved.

To help that review process, this paper provides an overview of soil quality principles and monitoring approaches that can be incorporated in an adaptive management process for achieving sustainable forest management.

Some Background

Adaptive Management

Various forest land management agencies and industries have developed processes for achieving SFM using logic models, reliable processes, and adaptive management. Several models are shown in figure 1. Each is conceptualized a little differently, but all contain the same basic elements: (1) an explicit or implied definition of SFM; (2) a knowledge database from which to develop management guidelines; (3) the guidelines or regulations from which best management practices are prescribed; (4) a process for monitoring compliance, effectiveness, and long-term efficacy; and (5) a research program that creates new knowledge for adaptive management.

As an example, we adapted and expanded the Heninger and others (1998) model with an SFM goal of maintaining forest and soil productivity after stand replacement harvesting (fig. 2), one of the key provisions of the "environmentally sound" component of SFM. The first step in the process after establishing or assuming a cause-and-effect relationship between harvesting disturbance and soil quality is to use existing data and knowledge (everything we know) from a "strategic database" to develop management "guidelines" that would prevent detrimental effects. All involved in applying the guidelines are trained. The guidelines, as applied in the forest, are the "best management practices" (BMPs), which are written policy guidelines that describe the manner in which specific forest operations or management activities will be conducted. They are

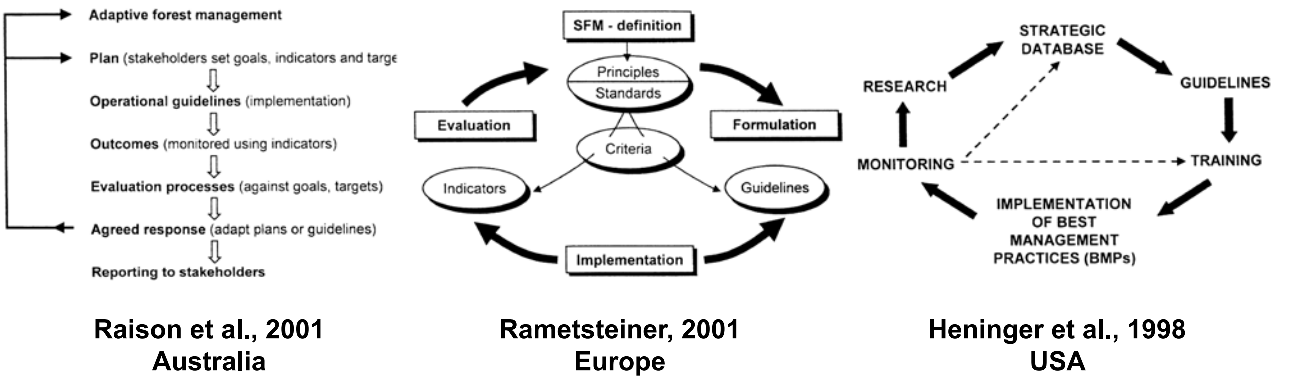


Figure 1. Examples of adaptive management models used for achieving sustainable forest management.

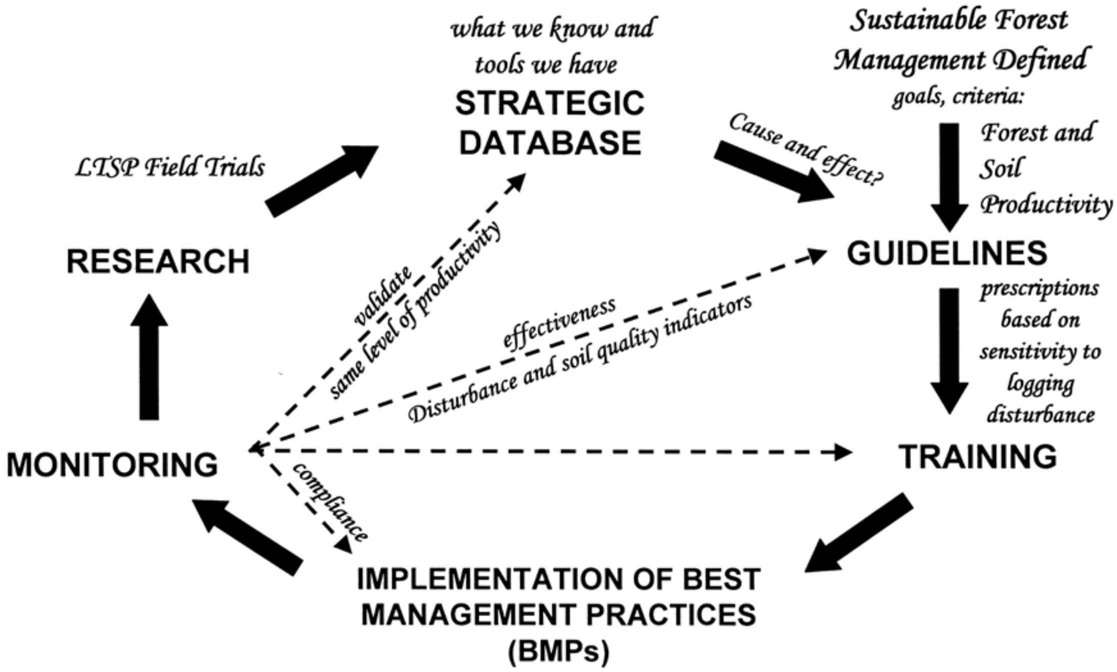


Figure 2. Components of an adaptive management model.

based on accomplishing the management objective in a cost-effective manner while maintaining or improving soil and forest productivity, and are subject to change as science and practice show ways for improvement.

Monitoring BMPs Used for Sustainable Forest Management

The next step is to determine if the BMPs are working as intended. Forest practices should be monitored for BMP compliance, a short-term indication of effectiveness of the BMPs, and long-term validation of SFM (Avers 1990) as defined by policy (*e.g.*, same growth potential and forest composition). Compliance monitoring simply ensures implementation of the BMPs. Effectiveness monitoring uses visual and measured soil disturbance indicators (DIs) and measured soil quality indicators (SQIs) to make a judgment of the efficacy of the BMPs, and whether they are likely to maintain soil and hydrologic function based on our cumulative research and knowledge. Because maintaining forest productivity and other services through time is the sustainability goal, long-term monitoring to determine if the forest is functioning the way it did before disturbance is validation that the BMPs are working as intended. When DIs and SQIs are properly chosen and calibrated, judgments on effectiveness of the BMPs can be made within weeks or months and guidelines can be modified as needed to improve forest practices. Because forests are long-lived, it may take years or decades to finally validate SFM. If monitoring shows that we need better guidelines, BMPs, or SQIs, targeted research should be conducted to expand our knowledge in the strategic database to further adapt our management to meet SFM goals. This adaptive management model, or some variant, can be applied to all managed forests, regardless of ownership, to achieve SFM required by law or compelled by forest certification processes.

For the purpose of this paper, we will assume that a primary SFM goal is maintaining soil and hydrologic function (Montreal Process Criterion #4) so that forest productivity (rate of biomass production per unit time and area) is not impaired. To accomplish this goal, BMPs are used by most public and private forest land owners, and BMP compliance (i.e., were the prescribed practices implemented?) is easily monitored. However, monitoring and demonstrating BMP effectiveness is challenging because forest managers must establish with certainty in a short period (*e.g.*, within 1 yr after completion of the operation) that forest operations in an activity area have not impaired soil and hydrologic function. The assumption is that pre- and post-disturbance soil and hydrologic function can be determined and compared. If they are the same, the BMPs were effective, and post-operation forest productivity and other forest services should be the same. This is the basis of the SFI and FSC standards and the USDA Forest Service soil management program (FSM 2009). However, the relationship between the measures of soil and hydrologic function and forest productivity must eventually be validated with long-term trials so that the standards and BMPs can be modified if needed (adaptive management process) (fig. 2).

The assumption that soil productivity, and by extension forest productivity, can be monitored, measured, and judged based on its combined attributes (properties and processes) is important because it provides a tool for land managers to meet forest sustainability standards established by law or policy (*e.g.*, U.S. National Environmental Policy Act of 1969). Because trees are long-lived, management impacts on productivity—positive or negative—may take decades to discern. Therefore, changes in soil and hydrologic properties and processes that can be measured immediately after a disturbance can serve as surrogates or proxies for change in soil and forest productivity as long as they are based on science and legally defensible. The change in soil properties and processes that results in an improved or degraded soil condition is a measure of soil quality.

Soil Quality Concepts and Principles

Soil Productivity Versus Soil Quality

Soil productivity is usually defined as a soil's ability to produce biomass or some harvestable crop. If not modified, soil has a natural or inherent productive potential based on its genesis and setting in the landscape. Some soils are naturally more productive than others, but not necessarily more valuable in terms of the role they play in their natural setting. For example, an Aridisol supporting a pinion-juniper forest in New Mexico is less productive than an Andisol supporting a mixed conifer forest in California, but each soil is providing ecosystem services commensurate with its development and setting. Within a given forest ecosystem, some soils are naturally more productive than others. This difference in soil productivity is reflected in a measure of forest site index or volume production after a given amount of time. Soil quality has been defined as its ability to provide services important to people. It is useful as a measure of the extent to which a managed soil is improved or degraded from its natural state or some other selected reference condition. Soil is complex; it has many physical, chemical, and biological properties that define its natural state and determine its productivity. Disturbances or management inputs usually change multiple properties at once. To evaluate soil change or soil quality, all or most of the important properties that were affected by the disturbance must be measured.

Agriculture scientists define soil quality as its ability to function (Larson and Pierce 1994) in a way that sustains biological productivity, environmental quality, and plant, animal, and human health and habitation (Doran and Parkin 1994; SSSA 1995). It is not a new concept. It was used by Storie (1933) 75 years ago to rate agricultural value of California soils. More recently, Warkentin and Fletcher (1977) recommended its use for monitoring the effects of intensive agriculture on soils. Karlen, and others (2003) reviewed its development and use in agriculture, and Burger and Kelting (1999) showed how one might use soil quality models to assess the impacts of intensive forest management.

Soil quality is analogous to the concepts of air and water quality where judgments are made concerning their fitness to breathe and drink based on selected, measurable standards. However, extending the air and water quality concepts to soil is less intuitive and more complex because we do not ingest soil directly. Its "fitness" is judged based on habitation and growth of plants and animals that are in turn ingested by humans; therefore, it is once removed from our personal experience. Soil also has multiple functions beyond food production: carbon sequestration, waste processing, and water regulation, among others. Furthermore, soil quality can change at different rates. Change can be slow and cumulative over time, and it can change in both negative and positive directions due to management. Finally, there is no "pure" (as in pure air or pure water) soil baseline against which to make judgments; there are many different soil types in nature each of which has its own natural condition. Nonetheless, the analogy with air and water holds in the sense that soil quality can be used to make judgments about the impacts of management, both negative and positive, against predetermined conditions or standards.

Soil Services, Functions, and Indicators

In order to use soil quality as a uniformly applied monitoring tool, there must be some agreement on its definition and use as a concept and monitoring tool. Similar to the concept of sustainable forestry, it is a work in progress. As a starting point, it is helpful to conceptualize soil in terms of "what it does for us" (services), "how it does it" (functions), "its character or attributes" (properties and processes), and "how we monitor and measure its performance or change in the level of services provided" (indicators).

Forest productivity, carbon sequestration, and a regulated hydrologic cycle are examples of soil services, sometimes called management goals (Andrews and others 2004) (table 1). Some soil services are more important than others in a given forest ecosystem. Therefore, forest managers should judge soil quality in terms of how management affects the most important services that soils provide. Soil services may not be completely complementary with respect to soil quality; one soil service may, in fact, reduce soil quality for another service. For example, longleaf pine ecosystems are managed primarily for biodiversity, not productivity. Longleaf pine as a species can be used effectively in production-based silvicultural systems, but generally speaking the interest in longleaf pine as opposed to other southern pines is the biodiversity value the entire ecosystem provides. However, the longleaf pine ecosystem thrives on disturbance, and in fact, the ecosystem loses much of its biodiversity value without disturbance. These disturbances clearly have the potential to alter soil quality, but the alterations may be positive or negative depending on the soil service. If the service managed for is biodiversity, repeated burning or other disturbances required for the main soil service increase the potential risk for surface erosion (reduction of soil quality for water quality protection), and nutrient loss (reduction of soil quality for soil productivity), but increase soil quality for a multitude of herbaceous plants that require not only the open conditions that burning provides, but also the specific soil conditions that allow them to compete with more nutrient-demanding plants. In other words, the best soils for the highest biodiversity in the longleaf pine ecosystem may not be the best soils for tree growth, and they may not be as capable of protecting water quality or sequestering carbon.

Using forest productivity as an example of a desired service, the soil functions to provide this service in several ways: (1) it remains stable and intact as a medium for root growth and habitat for soil animals; (2) it accepts, holds, and supplies water; (3) it

Table 1—Examples of soil services, functions, properties, processes, and indicators useful for monitoring sustainable forest management.

Soil services	Soil function	Soil properties and processes	Soil indicators	
			Disturbance	Soil quality
	Soil stability: Intact medium to promote root growth and provide habitat for soil animals	Horizonation Depth Strength Water content	Mass movement Erosion Ground cover	Soil horizon depth Strength Soil loss (t/ac) Aggregate uniformity SOM
Forest productivity	**Soil hydrology:** (accept, hold, and supply water, and drain properly for optimum gas exchange)	Texture Structure Porosity Infiltration Conductivity Water storage Gas exchange	Soil compaction Rutting Puddling Impeded drainage Surface runoff	θ vol. between 1/3 bar and 15 bar Soil structure Soil consistence Macroporosity Redox potential O_2 level
Regulated hydrologic cycle Regulated carbon balance Waste bioremediation	**Nutrient cycling:** (sequester, hold, and cycle organic matter and nutrients and promote biological activity)	SOM content Nutrient content pH CEC Decomposition Mineralization N fixation Acidification Leaching	CWD amount and distribution Litter displacement Severe burn Organic matter loss Acid deposition Accelerated nutrient leaching	C content Active organic matter Effective CEC Extractable nutrients N mineralization Microbial biomass Biopores Fecal deposits Soil respiration

promotes optimum gas exchange; (4) it sequesters, holds, and cycles organic matter and nutrients; and (5) it promotes biological activity (Doran and Parkin 1994; Burger and Kelting 1999; Andrews and others 2004). In the context of forest soils and forestry operations, these functions might be consolidated to soil stability, soil hydrology, and nutrient cycling (table 1). If a soil is protected from erosion, mass wasting, and displacement, it is stable and can provide a medium for plant growth. If it is protected from compaction, rutting, and puddling, it can function hydrologically, that is, water can infiltrate the soil, be stored, and be released for uptake by plants, and the soil will have the right proportion of macro- and micropore space so that it can drain properly. In forest soils, nutrient supply and biological activity are intimately tied to organic matter and nutrient cycling processes, including rates of input, decomposition and mineralization, storage, and release or uptake. Protection of these processes from soil surface disturbances, displacement of soil organic matter layers, and severe burns should maintain function in a given soil of a certain ecosystem. Of course, soil function is ecosystem-specific and must be assessed in the context of desired ecological condition. For example, soils in tupelo-cypress, longleaf pine, pinion-juniper, and black spruce ecosystems have the same functional elements, but each ecosystem will have different levels of soil properties and processes considered "normal."

Examples of the soil properties and processes, sometimes called soil attributes (Nortcliff 2002), associated with the first function (soil stability) are horizonation, strength, depth, and water content (table 1). Some soil properties and processes cannot be measured directly or efficiently; therefore, DIs, SQIs, measurable surrogates, or proxies of soil function must be used. Indicators may be a soil condition, property, or process such as soil compaction, soil strength, or water infiltration, or a combination of several soil properties such as soil tilth (soil tilth combines a measure of bulk density, strength, aggregate uniformity, soil organic matter, and plasticity index [Singh and others 1990]). Soil DIs or SQIs may be determined visually, or via measurement by laboratory or field testing (table 1).

Regardless of their simplicity or complexity, ideal indicators should (1) have a baseline against which to compare change; (2) provide a sensitive and timely measure of a soil's ability to function within a given ecosystem; (3) be applicable over large areas; (4) be capable of providing a continuous assessment; (5) be inexpensive and easy to use, collect, and calculate; (6) discriminate between natural changes and those induced by management; (7) have a cause-and-effect connection with forest productivity; and (8) be responsive to corrective measures (Burger and Kelting 1999).

These indicator characteristics are mostly obvious and intuitive, but two common monitoring pitfalls are using indicators too broadly, and not having a cause-and-effect relationship with the soil service or management goal. The ideal indicator would be applicable over large areas, but in reality indicators and their relative importance are quite soil- and site-specific.

Perhaps the most serious monitoring pitfall is using indicators with no cause-and-effect relationship with the soil service (*e.g.*, soil productivity) (Powers and others 1998; Miller and others, in preparation). Many forest disturbances, both natural and human-induced, are totally benign. In fact, the health and productivity of some forest ecosystems require disturbance (*e.g.*, ground fire, litter layer disturbance by animals). A detrimental disturbance in one forest ecosystem may be a beneficial process in another. Furthermore, disturbances are often soil- and species-specific (Page-Dumroese and others 2000; Powers and others 2005; Kranabetter and others 2006). Indicators of detrimental disturbance must be applied carefully, and they should have known correlations with forest productivity or some other service or management goal. All indicators will not have all eight features listed above, which is why several may be needed to adequately measure BMP effectiveness.

Different Indicators Needed for Different Soils

Soil services (what soils do for us) and soil functions (how they do it) are fairly universal. However, soil types and their properties and processes (attributes) vary greatly, which requires site-specific selection of indicators for monitoring the most important soil functions for a given soil type and disturbance activity. Furthermore, some soils are more resistant to impact than others; a given impact may be detrimental to one soil and have no effect on another. This is illustrated in the example in figure 3: Soil quality is shown as a function of a soil's ability to hold, supply, and cycle organic matter and nutrients (nutrient cycling) on the y axis, and the ability to accept, hold, and supply water, air and heat (air/water balance) on the x axis (Burger 1997); both are important forest soil functions identified by several researchers (Powers and others 1998; Burger and Kelting 1998). Soil quality generally increases as organic matter and nutrients are conserved, and soil quality increases as the air/water ratio is balanced. Soil specificity is shown in several general ways:

- Alfisols (*e.g.*, Soil A) are more likely to be detrimentally impacted by changes in air/water balance than changes in fertility, while the opposite is true for Entisols (*e.g.*, Soil B). Alfisols are usually better buffered than Entisols against nutrient removals, while Entisols usually have a coarser texture and resist compaction and loss of macropore space. Ultisols and Inceptisols are likely to be more equally impacted by changes in both soil functions, but are better buffered against extreme changes in air/water balance and nutrient cycling, respectively, for the Alfisols and Entisols.
- The risk of a detrimental impact varies within a soil order. For example, a low-quality Entisol (well-drained marine sand, Soil C) is more likely to be detrimentally impacted by organic matter and nutrient removal (Brendemuehl 1967) than a high-quality Entisol (alluvial flood plain soil, Soil B) (Aust and others 1997), which is illustrated in figure 3 by convergence of a possible response surface toward higher soil quality.
- Soil compaction and organic matter removal may be good indicators for air/water balance and nutrient cycling, respectively, for most soils, but their relative importance (weight) would be different for different soils. Soil compaction would be more detrimental to most Alfisols than organic matter removal, and organic matter removal would be more detrimental to most Entisols than compaction. Therefore, a uniform, one-size-fits-all soil quality monitoring program would not be applicable across all soils and forest sites. This was illustrated in a study by Page-Dumroese and others (2000) who evaluated the effectiveness of applying uniform soil quality standards

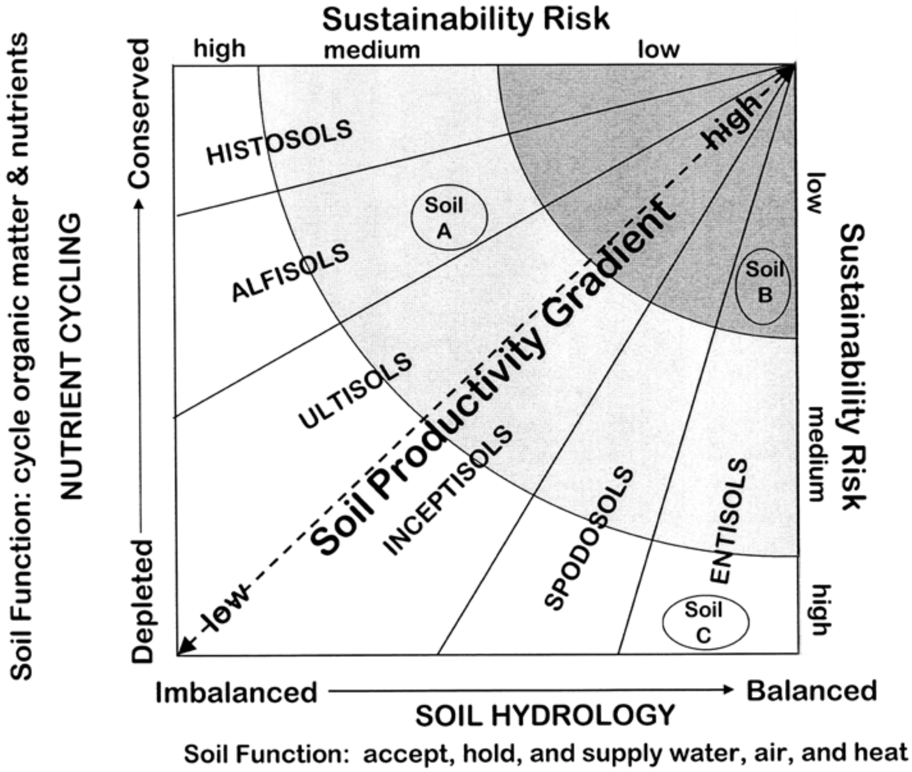


Figure 3. Soil quality response surface defined by soil nutrient cycling and hydrology (after Burger 1997).

to disturbances caused by forest operations over diverse forest landscapes in the Pacific Northwest. They concluded that application of selected USDA Forest Service standards (USDA Forest Service 1991) did not provide a comparative accounting of detrimental change in soil quality for the sites measured, and that some level of soil and site specificity needs to be incorporated in monitoring protocols.

USDA Forest Service Soil Monitoring and Research Programs

Soil Quality Monitoring

The USDA Forest Service has a well-established soil quality monitoring program that has been in place for several decades (USDA Forest Service 1991; Powers and others 1998). The program is a process by which data are collected to determine if soil management objectives have been achieved. It is meant to assist land managers in making better decisions on how to maintain or improve long-term soil productivity. The program and its evolution were described by Powers and others (1998) and by Page-Dumroese and others (2000). A fundamental assumption is that forest operations cause soil disturbances at some critical level that interfere with soil function (soil stability, soil hydrology, and nutrient cycling), which in turn have a detrimental effect on soil and forest productivity. A second assumption is that measures of one or more soil disturbances can be used to judge whether an operation had a detrimental impact on productivity, provided the disturbance, or a combination of disturbances, exceeded a predetermined threshold (usually 15 percent of the pre-disturbance condition) on more than 15 percent of the activity area. Disturbance and SQIs used by Forest Service Regions as reported in supplements to FSH 2509.18 are shown in table 2. Regions 1, 2, 4, 6, 8, and 9 use DIs for monitoring sustainable management, while Regions 3 and 5 use SQIs representing soil functions (table 2). The use of different sets of indicators and different approaches suggest a degree of region-specific application of the soil quality monitoring process; however, standardization of approach to the extent feasible would be advantageous for withstanding public and legal scrutiny.

Table 2—Detrimental soil disturbances or soil functions monitored by Forest Service Region (R1 through R10) and those listed in the Soil Management Handbook (USDA Forest Service 1991).

	Region and effective date									
	R1 1999	R2 1992	R3 1999	R4 2003	R5 1995	R6 1998	R8 2003	R9 2005	R10 1992	HB 1991
Disturbance:										
Compaction	X	X		X		X	X	X	X	X
Rutting	X					X	X	X	X	
Displacement									X	X
Severely burned	X	X		X		X		X	X	X
Surface erosion	X					X	X	X	X	X
Organic matter loss	X			X		X	X	X		
Mass movement	X					X		X	X	
Puddling		X		X				X	X	X
Ground cover				X				X	X	
Altered wetness									X	
Functions:										
Stability			X							
Hydrology			X		X					
Nutrient cycling			X							
Soil productivity					X					
Buffering capacity					X					

According to Powers and others (1998), the soil quality standards are meant as early warning thresholds of impaired soil conditions. When threshold standards for detrimental disturbance are exceeded, a 15 percent decline in productivity is assumed. Threshold standards are based on scientific findings or best professional judgment, but there is little or no documented evidence of any connection between disturbance thresholds and productivity. When critical data are lacking, it is prudent to err on the conservative side to ensure that productivity is not impaired; on the other hand, unreasonably strict standards having no basis in fact can limit forest use opportunities and tie up human resources in unnecessary litigation.

Following an assessment of soil disturbance in forests of the Interior Columbia Basin, Miller and others (in preparation) suggest that current soil quality methodology is inadequate, and they make a case for a more rigorous approach underpinned by research findings and sound scientific interpretations. Their finding was based on 15 soil monitoring projects after logging in which they visually classified disturbance and took bulk density samples along transects. They concluded that (1) different applications of a visual assessment protocol by different people led to different conclusions as to whether a logging operation is judged detrimental; (2) visual versus measured estimates of bulk density showed that visual estimates are unreliable; (3) the effect of equipment tracks and surface soil displacement is often over estimated, which overstates detrimental impacts of logging operations; (4) because current interpretations of detrimental disturbance are seldom justified by scientific investigations (*e.g.*, the assumption that a 15 percent increase in bulk density reduces tree growth on all soils is not supported by research), classification of soil disturbance should be for descriptive purposes only; (5) given broad variation in soils and climate among national forests, using the same standards for defining detrimental disturbance as it affects tree growth is not reasonable; and (6) current soil disturbance interpretations are based on experience and opinions of local specialists that are seldom documented or peer-reviewed. To overcome these limitations, they recommend a formal process for selecting activity areas for monitoring, and a revised set of descriptive disturbance and SQIs that account for both severity and extent of disturbance. For making judgments on impaired productivity, they recommend using risk-rating models based on research findings and collective expert opinion that account for specific site factors, potential vegetation, and forestry activity. Risk rating can then be used for site-specific prescriptions allocated to high-risk sites.

Synthesis of LTSP Research Findings

If the critique of the Forest Service's soil quality monitoring program by Miller and his co-workers has merit, the adaptive management model (fig. 2) suggests that the way to improve effectiveness monitoring is to adjust DIs and SQIs using current research findings. The North American long-term soil productivity study (LTSP) (Powers and others 1990) was installed, in part, to validate or improve SQIs used for short-term judgments of sustainable forest management. The study addressed organic matter removal and compaction DIs each at three levels: stem-only harvest, whole-tree harvest, and whole-tree harvest plus litter layer removal; and none, moderate, and high levels of compaction, respectively. Although still a relatively young project after only 15 years, preliminary results have been reported that suggest several ways in which the selection and interpretation of USFS DIs and SQIs might be reconsidered or adjusted.

Powers and others (2005) reported findings from the first 10 years of study for a range of LTSP study sites in CA, ID, LA, MI, MS, and NC. Several other key papers reported site-specific responses to the LTSP treatments at different locations. Key findings include the following:

- Soil organic matter across all sites was generally unaffected by complete removal of surface organic matter (stem-only versus whole-tree plus litter removal). Based on composite results, it appears that carbon inputs to mineral soil horizons are due primarily to root decomposition, while carbon mineralized in the surface Oi and Oe layers efflux as CO_2.
- For four contrasting CA sites, whole-tree plus litter removal caused substantial declines in soil C and N concentrations and mineralizable N. In a later report for the NC and LA loblolly pine LTSP plots (age 10 data), Sanchez and others (2006) reported no organic matter removal effects on tree growth. Heavy compaction resulted in a slight increase in stand volume on LA plots and a slight decrease in growth on NC plots. Organic matter removal had little effect on soil N but significantly reduced extractable P. This effect on P was also reported by Scott and others (2004) for LA plots at age 5.
- Composite data for all sites indicated no general decline in productivity with organic matter removal, which is consistent with the observation by Blake and Ruark (1992) that effects of organic matter removal is confounded by an array of influences both positive and negative. One exception was that aspen biomass on the MI plots was significantly less on plots where trees and litter were removed due to vigorous sprouting and dieback of root suckers. Another was on some inherently P-deficient soils in LA and MS, which showed substantial declines due to whole-tree harvesting at age 10 (Scott and Dean 2006).
- Severe soil compaction increased D_b an average of 18 percent in the 10- to 20-cm soil layer, but little compaction occurred if initial D_b was >1.4 Mg m^{-3}. Composite data for all sites showed that severe compaction had little or no effect on standing biomass; however, biomass on sandy sites increased by 40 percent while that on clayey sites decreased by half. This textural influence was clearly demonstrated across three CA LTSP sites (Gomez and others 2002). The authors reported growth responses to compaction by mixed conifers that decreased, remained the same, and increased for a clay, loam, and sandy loam, respectively. The soil series, in the same order, were Challenge (Typic Palexerults), Cohasset (Ultic Haploxeralfs), and Chaix (Typic Dystroxerepts). The different impacts of compaction among soils (negative, benign, positive) were attributed to changes in strength, pore space distribution (which changed available water holding capacity), and an interaction between these factors.

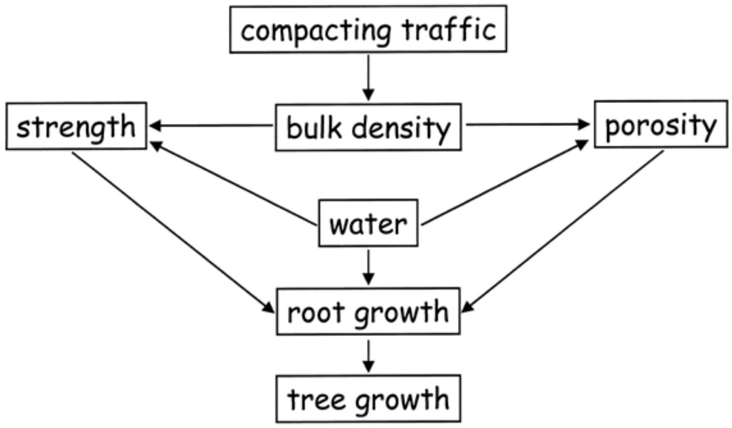


Figure 4. Root and tree growth as a function of soil compaction effects on bulk density, soil strength, porosity, and water content (after Greacen and Sands 1980).

This finding corroborates the Greacen and Sands (1980) model showing that strength and porosity are the static physical properties most directly affecting the tree (fig. 4). The clay soil suffered the greatest increase in soil strength and the greatest loss in porosity with no increase in available water holding capacity (AWHC) resulting in decreased tree growth on compacted plots. Although the loam soil had a strength exceeding 3 MPa below 10 cm, its AWHC increased significantly, which resulted in a negative/positive tradeoff and a net result of no change in tree response. Compaction increased strength of the sandy loam soil, but AWHC increased at all depths of the measured profile, resulting in a net positive change in growth.

Implications of LTSP Research Findings for Soil Quality Monitoring

Collectively, the LTSP research results have the following implications for the Forest Service's soil quality monitoring protocol:

- The age-10 LTSP data clearly demonstrate site- and soil-specific responses to disturbance, which further explains the inconsistent conclusions provided by soil disturbance monitoring when applied across different sites (Page-Dumroese and others 2000) or when applied by different people (Miller and others, in preparation). Currently used detrimental DIs are all good in principle, but they need to be selectively applied and weighted by importance in different regions and within regions.
- The effect of organic matter removal (*e.g.*, whole-tree plus litter) from the surface of a forest site is clearly site-specific (sucker sprouting in aspen; P depletion in Gulf Coast loblolly pine; N depletion in CA mixed conifers). The LTSP data show that much higher levels of removal are needed to affect a detrimental response than are currently set as regional standards on most sites, yet some highly sensitive sites may be impaired by removals currently allowed. Organic matter is a master variable in the sense that it plays multiple roles in forest ecosystems. In addition to N and P cycling and natural regeneration demonstrated in the LTSP trials, it is habitat for myriad animals, protects mineral soil from erosion, buffers temperature and water extremes in the surface mineral soil, and is an energy source for plants and animals. Some of these functions are more important than others on a given site, but, in any case, those that play a clear role in productivity should be monitored. In addition to the DI (area and degree of organic matter displacement), one or more soil/site quality indicators (N mineralization, sucker sprouting, etc.) should be used to make judgments about SFM.
- Soil compaction is an important and useful DI, but it is clear from the LTSP data that it is not always detrimental; in fact, it clearly enhances soil productivity in some cases. In other cases, forest productivity may be improved while soil productivity is unchanged. Stagg and Scott (2006) found that planted loblolly pine growth was increased by compaction through reducing understory competition. Planted tree growth on plots with herbicide applications to control competition showed little response to

compaction. This finding reinforces the principle that many types of disturbance in ecosystems are beneficial and sometimes necessary for normal ecosystem function (for example, fire, windthrow, and deposition of sediment by natural processes); human influences often enforce these positive processes. Therefore, simple visual indicators of compaction are inadequate for judging detrimental disturbance (Aust and others 1998; Steber and others 2007). A measure of bulk density, the one commonly measured SQI in Forest Service monitoring protocols, will often lead to erroneous conclusions because detrimental effects of compaction can occur in clayey soils with less than a 15 percent change, and beneficial effects can occur in sandy soils with an even greater change. Better indicators of compaction are soil strength and the ratio between macro- and micro-porosity as shown by the conceptual model by Greacen and Sands (1980) (fig. 4). Compaction increases D_b, but the impact of the D_b change on strength and pore space distribution are the real drivers of root growth and productivity (fig. 4), and D_b change is not always a reliable surrogate for these soil properties. Attempts have been made to determine root-growth limiting D_b for forests (Daddow and Warrington 1983), but rules of thumb from these attempts have not been successfully applied to forests.

More Known About Soil Response to Disturbance Than Reflected in Current Monitoring Protocols

The old cliché "more research is needed" certainly applies to our quest for a better understanding of site-specific forest response to disturbances for achieving SFM. However, we maintain that more is known about soil disturbance processes and effects than is currently reflected in Forest Service SQM protocols. For example, a 15 percent increase in D_b is used by most Forest Service regions as an indication of detrimental disturbance. The empirical findings by Gomez and others (2002) clearly show that this indicator will lead to erroneous conclusions on many sites and strongly suggests that we need to move beyond a blanket approach of using visually estimated or measured D_b. Gomez and others (2002) showed that soil strength and pore space distribution were better SQIs than D_b, as conceptualized by Greacan and Sands (1980) decades ago. Furthermore, we understand the basis for this model given decades of research on the interactions among factors in the model. Recent work by Siegel-Issem and others (2005) contrasting data from California and Missouri LTSP sites demonstrates our understanding of compaction effects that can be extrapolated to many soils across regions. A brief summary of selected bits of their results are presented to make the point that a synthesis of knowledge can be used to improve SQM.

The California soil was a Cohasset coarse sandy loam (Haploxeralf) (fig. 5A) from the Tahoe National Forest similar to the one Gomez and others (2002) studied, but with a sandy loam texture. Its parent material is an andesitic mudflow and the dominant vegetation is mixed conifers. The Missouri soil was a Clarksville silt loam (Paleudult) (fig. 5B) from the Carr Creek State Forest. Its parent material is a sandstone residuum and the dominant vegetation is oak-hickory with a component of shortleaf pine. Given the contrasting particle size distributions and different levels of organic matter, the soils reacted very differently to compaction. The MO soil reached proctor level D_b (maximum possible under controlled conditions) at 1.53 Mg kg^{-3} compared to 1.25 Mg kg^{-3} for the CA soil. As D_b increased and volumetric water content (θ) decreased, soil strength increased. For the CA coarse sandy loam, above D_b 1.00 Mg kg^{-1} and below 35 percent θ, soil strength approached or exceeded 2MPa, the strength that becomes root-limiting. Below 1.00 Mg kg^{-1}, D_b had virtually no effect on soil strength at any θ (fig. 5C). By contrast, soil strength of the MO silt loam did not reach the 2MPa threshold until D_b exceeded 1.5 Mg kg^{-1}, which was nearly the proctor limit (fig. 5D).

The total and available water holding capacity (AWHC) of the CA soil increased significantly with increasing D_b (fig. 6A), but there was little change in the AWHC of the MO soil (fig. 6B). Increasing D_b dramatically reduces the non-capillary or macropore space in most soils. When macropore space drops below 10 percent, roots of upland species become hypoxic due to inadequate gas exchange rates (Grable and Siemer 1968).

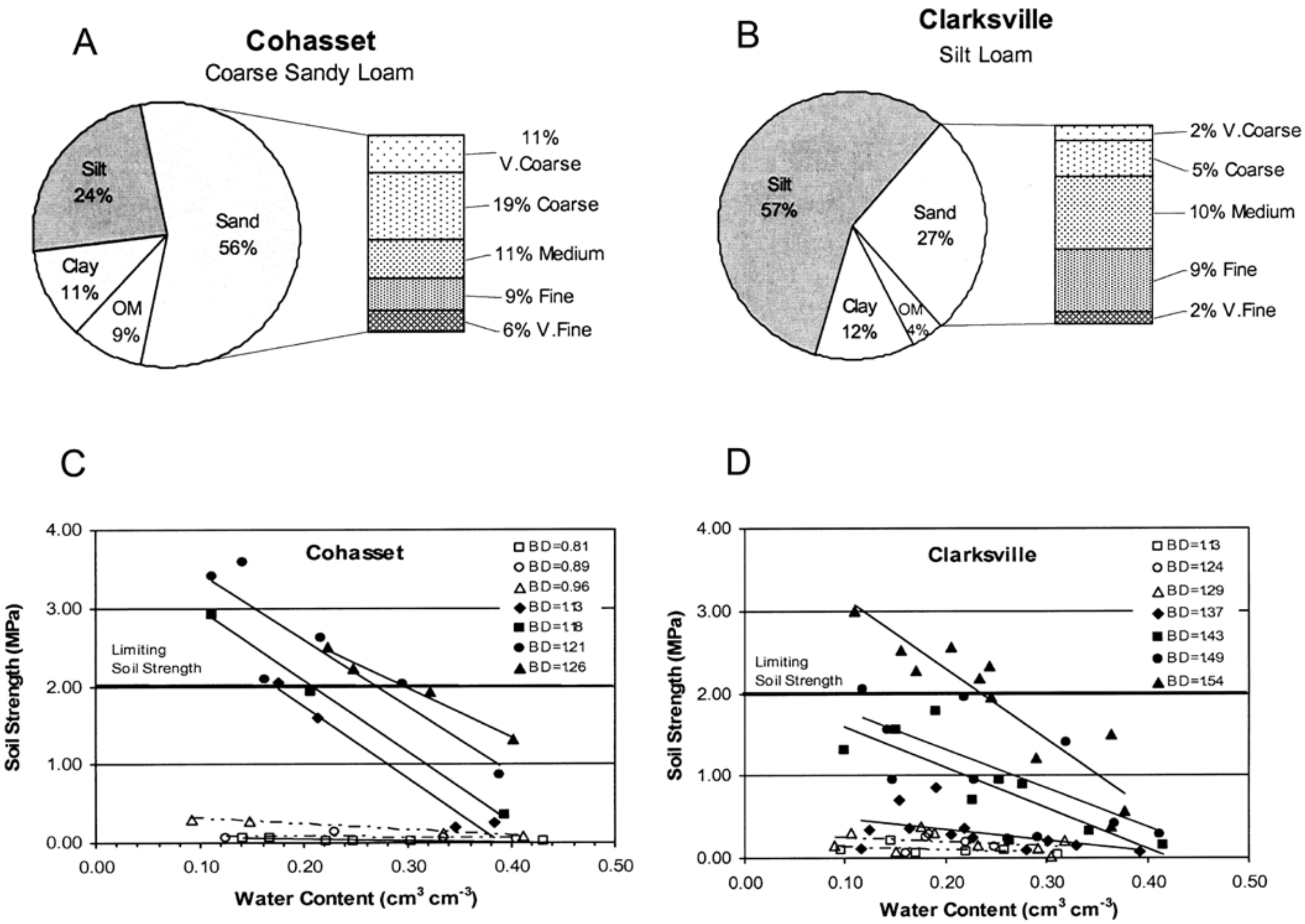


Figure 5. Particle size distribution of a Clarksville and Cohasset soil series from MO and CA LTSP study sites, respectively (from Siegel-Issem and others 2005).

This is illustrated in figure 6D for shortleaf pine in the MO soil. Root length density followed a classic bell-shaped response for upland species in loam soils, decreasing from optimum water content as the soil became both drier and wetter due to inadequate available water on the dry end and inadequate aeration on the wet end of the soil water gradient (da Silva and others 1994). As D_b increases, the range in soil water content within which roots can grow narrows, which in turn causes a decrease in root length density. The trees growing in the CA soil suffered from increased strength on the dry end of the θ gradient, but not at all on the wet end of the θ gradient, despite reduced aeration porosity (fig. 6C).

These soil and tree responses to compaction under controlled lab conditions corroborate the field results reported by Gomez and others (2002). Soil texture and organic matter content influence the extent to which a soil can be compacted and the relative influence of strength versus pore size distribution. The degree and influence of compaction are predictable based on texture and organic matter content and thus could be used to adjust the importance of D_b change relative to other DIs. Furthermore, soil strength and pore space distribution could be used as soil texture-specific SQIs in lieu of estimated or measured D_b. Clearly, we know enough about soil physical processes to create a combined basic/empirical mathematical model to estimate and make definitive judgments of detrimental compaction, rutting, and puddling impacts on productivity. The same could probably be said for organic matter displacement and loss, and good models already exist for soil erosion prediction and risk assessment (Laflen and others 1997). A similar argument was made by Miller and others (in preparation) based on their firsthand experience with the limitations of current SQM protocols. Modeled soil disturbance processes that address the stability, hydrology, and nutrient cycling functions

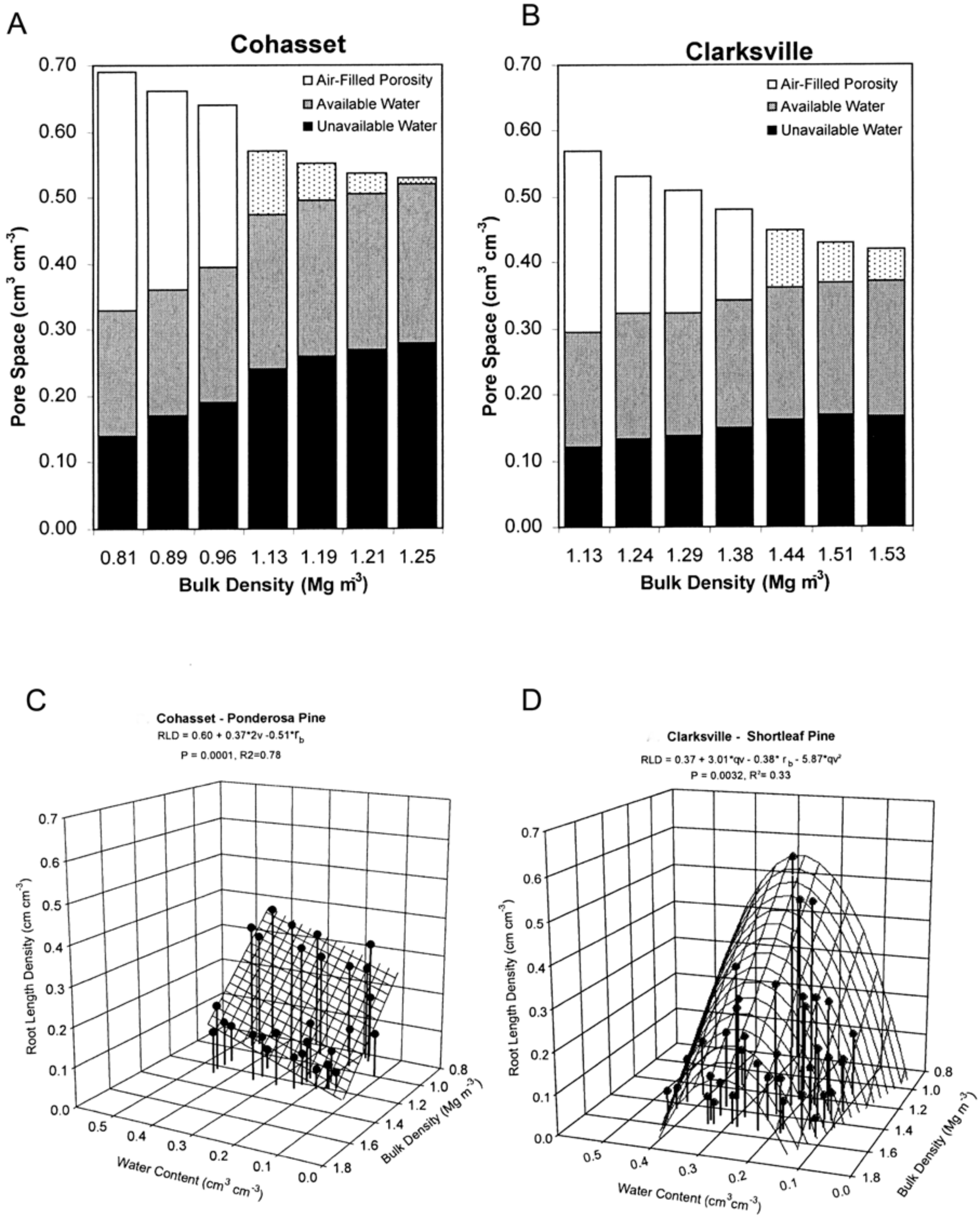


Figure 6. Pore space distribution and root length density of shortleaf pine seedlings and ponderosa pine seedlings grown on Clarksville and Cohasset soils, respectively, as a function of soil bulk density and volumetric water content (Siegel-Issem and others 2005).

of soils need to be combined in a single, workable, cost-effective protocol that can be continuously updated as new findings warrant.

Modeling Soil Quality

An Approach for Modeling Soil Quality

A number of efforts have been made to model soil quality (Doran and Parkin 1994; Carter and others 1997), quantitatively score soil quality for use as a performance standard (Larson and Pierce 1994; Andrews and others 2004), and extrapolate soil quality classes or risk assessments to an activity area (Halvorson and others 1996; Wendroth and others 1997; Kelting and others 1999). Most of these efforts have been made on agricultural landscapes, and extensive reviews of these topics are covered in several publications (Doran and Parkin 1994; Doran and Jones 1996; Gregorich and Carter 1997; Lal 1999). Several compilations have also been made for forest landscapes (Ramakrishna and Davidson 1998; Raison and others 2001).

This approach is conceptualized in figure 7. Forest practices can degrade or improve soil quality compared to a pre-disturbance or reference condition (solid circle in diagram). Often, positive and negative effects occur simultaneously. Degrading processes include soil displacement or erosion, water logging, compaction, organic matter loss, nutrient depletion, and acidification, among others. Soil improvement can include enhanced fertility, better tilth, increased available water holding capacity, better drainage of excess water, organic matter addition, and liming. Intensive industrial forest operations may impose a combination of these effects with a net result of better, same, or worse soil quality. Extensive forest operations that only include harvesting during wet weather could have a net negative effect on soil quality due to soil compaction and water logging. Soil quality is the ability of the soil to function by storing and releasing water to plants, cycling nutrient elements, buffering organisms from temperature extremes, decomposing organic debris, etc. As mentioned above, they can be categorized as soil stability, hydrology, and nutrient cycling functions (table 1). These soil functions can be monitored and measured using soil properties or processes (depicted by letters A through G in fig. 7), or by using DIs or SQIs that serve as surrogates for properties and processes (table 1). Forest operations may improve some properties (arc of wedges exceeding the pre-disturbance or reference condition), and they may degrade others (arc of wedges less than the reference condition) (fig. 7). The net effect of the disturbance on soil quality may be the same (sum of the area of the wedges equal to the area of the reference condition), or the net effect may be better or worse than the reference condition. Some soil properties may be more important to forest productivity than others (greater angle, thus area, of some wedges compared to others), but seldom is one "all" important or even dominantly important. However, if Liebig's principle of "most limiting" factor applied, one could select and monitor the function most affected (*e.g.*, function A) as it is degraded most from the reference condition and is below the standard or allowable limit (dashed circle). In most cases, all properties (A through G) contribute to soil quality in interactive ways, and those interactions are often complex and unknown. A better judgment of soil quality change would entail a composite, weighted score of all soil functions (sum of the area of the wedges compared to the area of the allowable condition).

Forest Service Regions 3 and 5 use this general approach as reported in supplements to 2509.18 (USDA Forest Service 1991). Region 3 (R3) defines soil function in terms of stability, hydrology, and nutrient cycling and uses a combination of DIs and SQIs as indicators of those functions to classify soil condition as satisfactory, impaired, or unsatisfactory. Given our previous discussion of the limitations of arbitrarily (meaning no evidence of cause and effect) applying visual DIs, we suggest that the R3 approach is the most comprehensive and sophisticated. Lacking are justifications for indicator selection, site-specific weighting, and relationships with vegetative productivity, and a scoring mechanism to show that combined indicators will result in a specified amount of productivity decline over a specified areal extent. Nonetheless, the approach is conceptually based with logical linkages among soil function, properties, and indicators, and it includes a risk assessment within three categories.

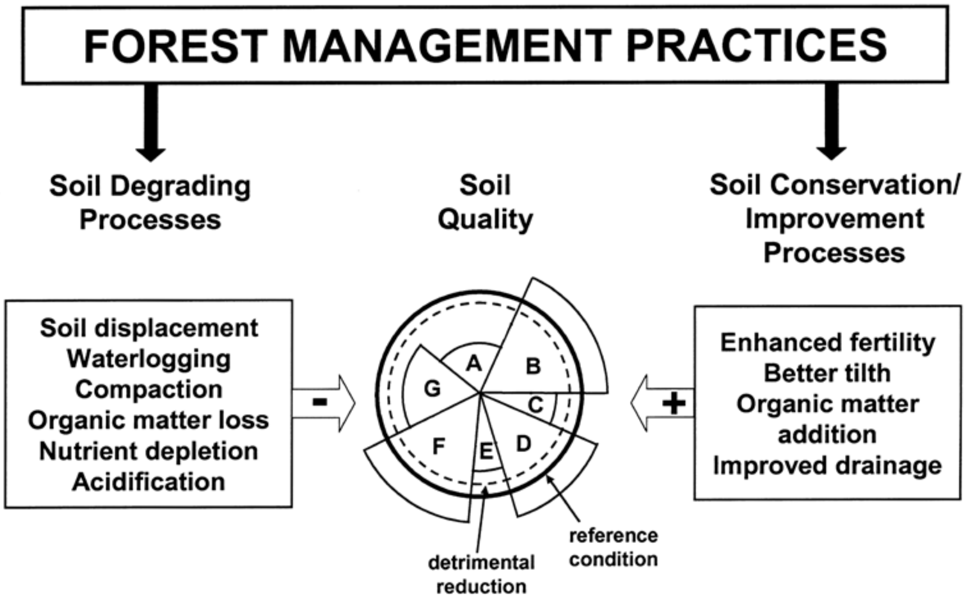


Figure 7. Conceptualization of the effects of forest management practices on soil quality.

Steps for Building a Soil Quality Model

A common approach to soil quality monitoring is to (1) select key disturbance or soil quality indicators representing soil function, (2) develop sufficiency relationships between soil services and the indicators, and (3) weight and combine sufficiency levels for all indicators in additive or multiplicative models based on their importance and vertical and spatial extent in an activity area.

Step 1: Select Key Soil Quality Indicators—Two good review papers on indicator selection for forest soils are by Schoenholtz and others (2000) and Moffat (2003). Both reviews provide lists of physical, chemical, and biological indicators with a rationale for their potential use. Ultimately, selection of indicators for a given forest type and land region must be done by scientists and practitioners with expert knowledge of specific forest ecosystems, forestry operations, and forest response to disturbances. However, in addition to local expertise, there is a large body of research literature on soil/site effects on growth and yield for forest ecosystems for every region of the country. This research has been ongoing for nearly a century as foresters have striven to understand fundamental relationships underpinning productivity.

Carmean (1975) did an early review of this literature, and Pritchett and Fisher (1987) did a follow-up review listing the number of reports in which a given soil property was found to be a determinant of growth and yield. For example, for western conifers the key soil properties and the number of times reported were effective soil depth (20), available water (8), surface soil texture (8), soil fertility (4), subsoil texture (3), and stone content (4). For southern pines the key soil properties and number of times reported were subsoil depth and consistency (23), surface soil depth (21), surface and internal drainage (19), depth to least permeable horizon (14), depth to mottling (13), subsoil imbibitional water value (8), N, P, or K content, and surface organic content (3). Moffat (2003) also has a short literature synthesis on soil/site growth and yield relationships in his review. These reviews demonstrate that there is a huge knowledge base on which to draw for first approximation soil quality models.

Step 2: Developing Soil Quality Sufficiency Curves—Central to soil quality models are sufficiency curves, which are cause-and-effect relationships between a soil service such as forest productivity and a soil indicator. For forest productivity, sufficiency of a given soil indicator is often based on its ability to support root growth. The assumption is that if a soil indicator is sufficient for root growth, it will be sufficient for tree growth. Sufficiency for each soil indicator is scaled from 0 to 1, where a value of 0 is totally root-growth limiting and a value of 1 has no limitations for root growth. Sufficiency relationships can be developed based on the literature, designed

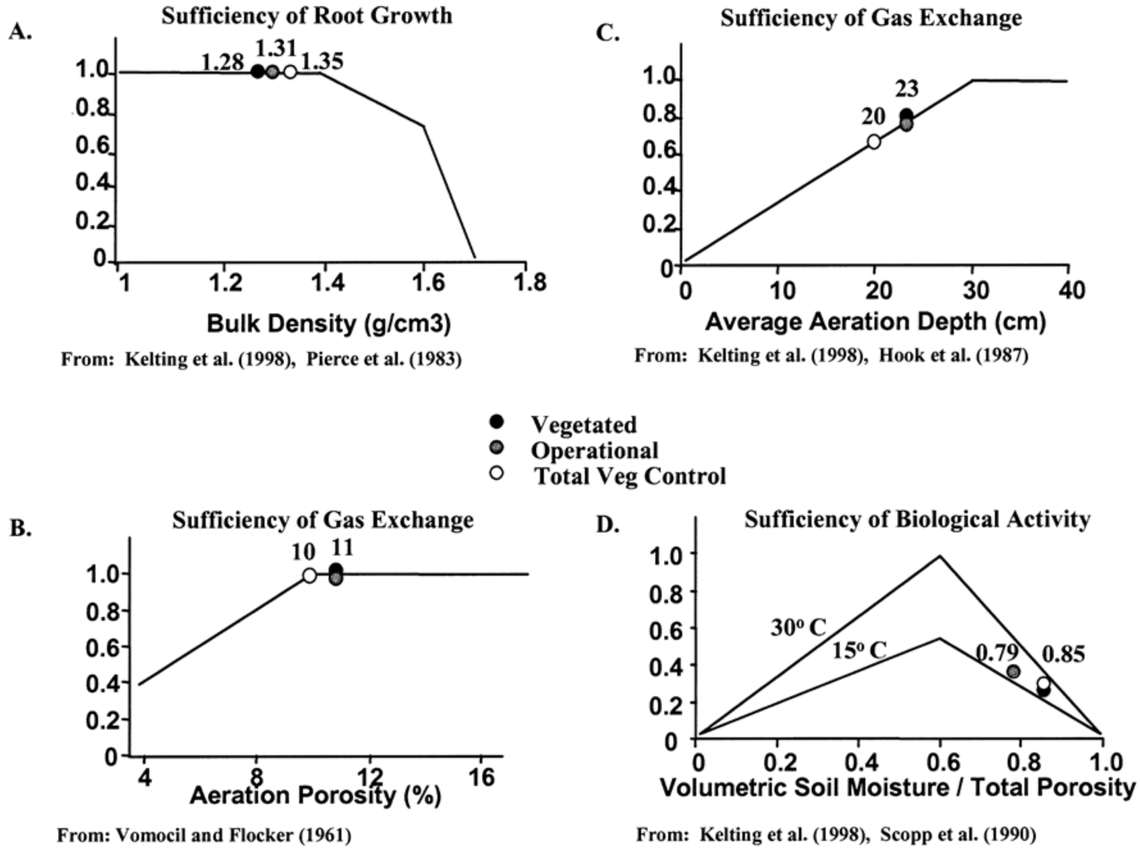


Figure 8. Sufficiency curves for vegetation treatment effect on (A) the soil rooting environment, (B and C) aeration, and (D) soil biological activity.

experiments, or professional experience and judgment. For example, Kelting and others (1999) developed sufficiency relationships for loblolly pine response to soil conditions on poorly drained soils. The curves were based on a combination of compiled literature and research. Lister and others (2004) used these relationships to judge the effect of different levels of ground cover vegetation on soil quality recovery after wet-weather logging (fig. 8).

Furthermore, most of this work was regression-based, so sufficiency curves are often reported or can be constructed from reported data. Lacking past research of this type, soil scientists can develop their own soil/site growth and yield relationships for specific forests or land types. The results accumulating from LTSP studies that have been targeted for this purpose are even better.

Step 3: Combining and Weighting Indicators in a Soil Quality Model—After indicators are selected and their sufficiency curves established, they can be incorporated in a model for an overall index of soil quality (Gale and others 1991). Eq. (1) is a soil-quality model developed by Kelting and others (1999) and Lister and others (2004) for loblolly pine on an affiliate LTSP site on Mead-Westvaco property in the lower coastal plain of SC. The soils were predominantly poorly drained Argent loam (Ochraqualf) and Santee loam (Argiaquoll) subject to compaction, rutting, and puddling when tree stands are harvested under wet conditions. The model provides an index of the net effect of harvesting disturbance using key soil quality indicators that are disturbed by wet-weather logging and influence tree growth predictably:

$$SQ = \sum_{i=1}^{area} \left[(D_b \times wt) + (P_a \times wt) + (AD \times wt) + (\Theta / P_t \times wt)\right] \times WF_{area} \quad (1)$$

where SQ is the overall soil quality index (0 to 1), D_b the sufficiency for bulk density, P_a the sufficiency for aeration porosity, AD the sufficiency for aeration depth, Θ/P_t the

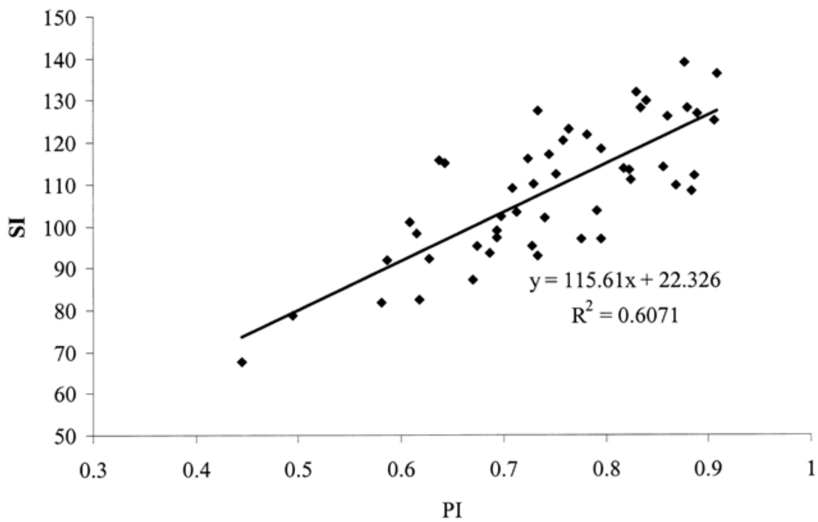


Figure 9. Relationship between site index (tree height at age 50) of white pine and a productivity index (soil quality) calculated from literature-based sufficiency curves for pH, soluble salts, soil density, slope, coarse fragment content, and aspect. Site index and soil measurements were for 52 reclaimed mined sites in the Appalachian region of Virginia and West Virginia.

sufficiency for biological activity, wt the relative weight or standardized coefficient for each indicator, WF_{area} the weighting factor for the extent of the overall activity area impacted, and area is each subsection of the overall activity area surveyed.

Jones and others (2005) developed a soil quality model to judge suitability of land reclaimed to forest after mining disturbance. Their work demonstrates all steps in the development of a soil quality modeling approach and might be used as a template for similar efforts. Previous soil/site regression studies suggested that the major mine soil growth limiting factors were soil density, P deficiency, toxic levels of soluble salts, extremes in pH, soil texture, coarse fragment content (Torbert and others 1988a, b; Torbert and others 1990; Andrews and others 1998; Rodrigue and Burger 2004). Using these reported relationships between tree growth and mine soil properties, Jones and co-workers developed sufficiency curves for mine soil properties that were consistently related to growth in these regression studies, and then used the following general soil quality model as a first approximation:

$$SQI = (pH \times texture \times density \times CF)^{1/4} \times depth \qquad (2)$$

where SQI = site quality index; pH = sufficiency of pH; texture = sufficiency of texture; density = sufficiency of soil density; CF = sufficiency of coarse fragments; and depth = sufficiency of rooting depth (equivalent to WF in Eq. 1). To test the performance of the model, a SQI was calculated for each of 52 reclaimed sites planted with white pine. Tree height and age were used to determine site index (SI), and soils were sampled for pH, texture, density, CF, and depth. SQI values were calculated using Equation 2 and regressed with white pine SI. SI was significantly linearly related to SQI (calculated from Eq. 2) with an R^2 value of 0.63 (fig. 9), showing that this general SQI model could be used with acceptable accuracy to predict forest productivity based on mine soil properties; that is, it could be used as a performance standard to determine if post-mining productivity equaled pre-mining productivity as required by law.

The SQI model (Eq. 2) assumes that all soil variables are equally important, which is unlikely. Jones and co-workers refined the model to make it locally specific. They regressed measured SI with measured soil properties from the 52 study sites. Standardized coefficients were calculated and used to develop relative importance factors for weighting the soil variables in the final site-specific model:

$$SQI_{ss} = (pH \times IF) + (texture \times IF) + (density \times IF) + (depth \times IF) \qquad (3)$$

where SQIss = site-specific SQI; pH = sufficiency of pH; texture = sufficiency of texture; density = sufficiency of soil density; depth = sufficiency of rooting depth; and IF = importance factor for each soil property (table 3). This weighted, additive, site-specific model improved the fit with measured SI somewhat with an R^2 of 0.68 (fig. 10). This model can and should be further validated with additional field testing. It, along

Table 3—Standardized coefficients, importance factors, and significance values for the independent variables used in the final model (Equation 4).

Variable	Standardized coefficient	Importance factor	*p*-value
Density	–0.54789	0.44	<0.0001
Rooting depth	0.34989	0.28	0.0004
Texture	–0.25135	0.20	0.0039
pH	–0.10393	0.08	0.2167

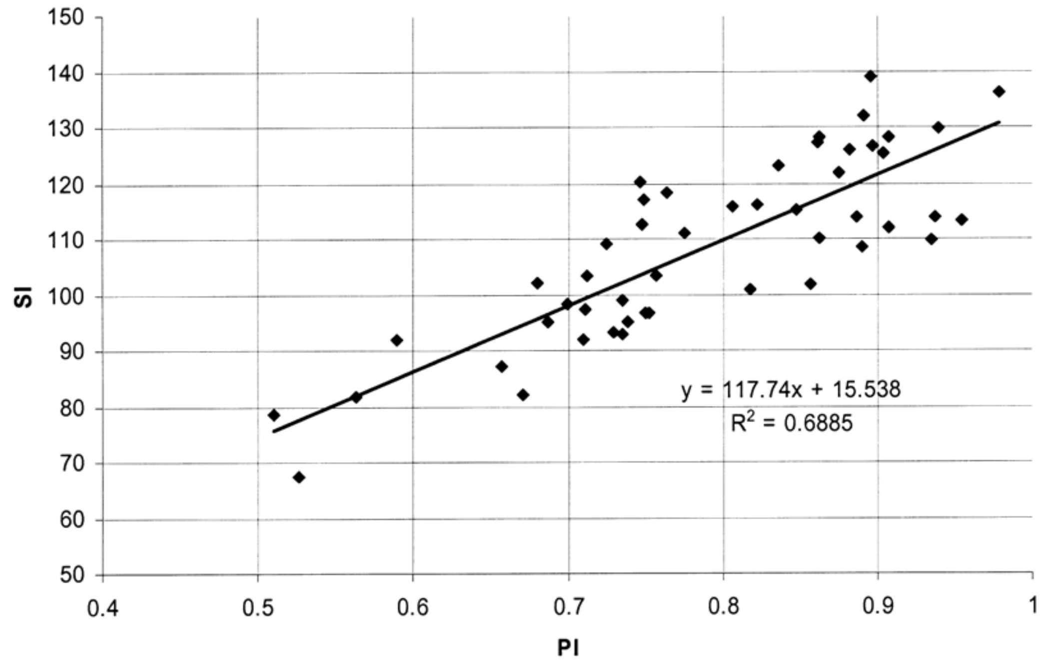


Figure 10. Relationship between site index (tree height at age 50) of white pine and a productivity index (soil quality) calculated from literature-based sufficiency curves for pH, soil density, soil depth, and soil texture. Sufficiency values for the four soil properties were weighted based on their relative contribution to white pine site index. Soil measurements were for 52 reclaimed mined sites in the Appalachian region of Virginia and West Virginia.

with similar earlier work (Torbert and others 1994; Burger and others 1994, 2002), is currently being advocated for use as a mechanism to judge post-mining forest productivity in the Appalachian region.

Site quality models as outlined above can easily be applied to different sections of an activity area by calculating SQIs by section (*e.g.*, percent of area compacted) and weighting indices by areal extent. The model, sufficiency calculations, weighting by importance, and weighting by areal extent can all be part of a SQI algorithm programmed in field computers. Immediately after field and laboratory sampling data are entered, an area based SQI can be generated.

This work by Jones and others (2005) shows that a first approximation general SQ model can be developed based on a compilation and synthesis of research results for a given area, and that further refinement can improve its specificity. Using this model within current operational and regulatory frameworks is entirely feasible. General models that incorporate the known productivity determinants could be made for general forest types across Forest Service regions and made more region- and site-specific with local data on sufficiency curves for specific forest types and plant species.

Classifying and Mapping Risk of Soil Impairment Across Landscapes

Once armed with a good soil quality monitoring protocol, another consideration is applying monitoring effort proportional to risk of soil impairment due to natural or human-caused disturbances. Some soils and sites are relatively more resistant than others to the same disturbance impacts, and some soils and sites rebound to pre-disturbance conditions faster than others. GIS-based risk assessments at a landscape, watershed, or national forest scale would be helpful for allocated monitoring resources and prescribing appropriate management practices.

Elias and Burger (in preparation) recently developed acid deposition (AD) resistance maps for the Monongahela National Forest in West Virginia to help target monitoring efforts cost effectively. Increasing soil acidification, base leaching, and soil Al toxicity may adversely impact forest productivity. Stand volume in about one-third of 91 Forest Inventory and Analysis (FIA) plots recently (10-yr period between 1989-2000) declined periodic annual increment (PAI) of by up to 9.5 $m^3ha^{-1}yr^{-1}$, while another one-third was less than 3 $m^3ha^{-1}yr^{-1}$ growth (Elias and others 2009), which is less than expected growth. Incremental growth was not correlated with site index, but was strongly correlated with Ca/Al molar ratio, effective base saturation, and other indicators of acidification. Given the broad range in periodic annual increment (PAI) and the diverse terrain and soil parent materials that range from acid sandstones to limestone, a GIS-based acid deposition resistance index was modeled to help direct monitoring efforts.

Elias and Burger (in preparation) created AD resistance relationships for parent material, slope, aspect, elevation, soil mineralogy, depth, texture, and rock fragments based on published relationships and expert knowledge to encompass the range of each factor found on the Monongahela National Forest (MNF) (table 4). All soil and site factors were tied to existing MNF GIS layers. At each FIA plot location, values for each site factor were determined using 30 by 30 m U.S. Geologic Survey Digital Elevation Models (USGS DEM), SSURGO, and MNF maps (table 4). A resistance index ($RI_{general}$) was then calculated for each FIA plot using the following model:

$$RI_{general} = [.2\text{ (parent material score)} + .2\text{(aspect score)} + .2\text{(elevation score)} + .2\text{(soil depth score)} + .2\text{(texture score)}]^2 \quad (4)$$

PAI was significantly correlated with $RI_{general}$ indicating that the combined soil/site factors were associated with forest productivity and that the modeling approach had merit. A site-specific AD resistance model (RI_{MNF}) was then developed by weighting

Table 4—Range of site factors used to create a Resistance Index for the Monongahela National Forest in West Virginia.

Factor	Range of characteristics and resistance:				
	0				1
Parent material‡	Acidic				Calcareous
Slope	Resistance = $-0.00005x^2 + 0.0055x*2.7$				
Aspect	235 – 286	197 – 234/ 285 – 325	145 – 196/ 326 – 15	107 – 144/ 16 – 55	56 – 106
Elevation	Resistance = $-0.0005* e^{0.005x} + 1$				
Mineralogy	Siliceous				Mixed
Depth	Resistance = $1.3* e^{-55/(x + 0.0001)}$				
Rock fragments	Resistance = $-0.0175* e^{0.045x} + 1.015$				
Texture	Resistance = $-0.001x^2 + 0.06x$				

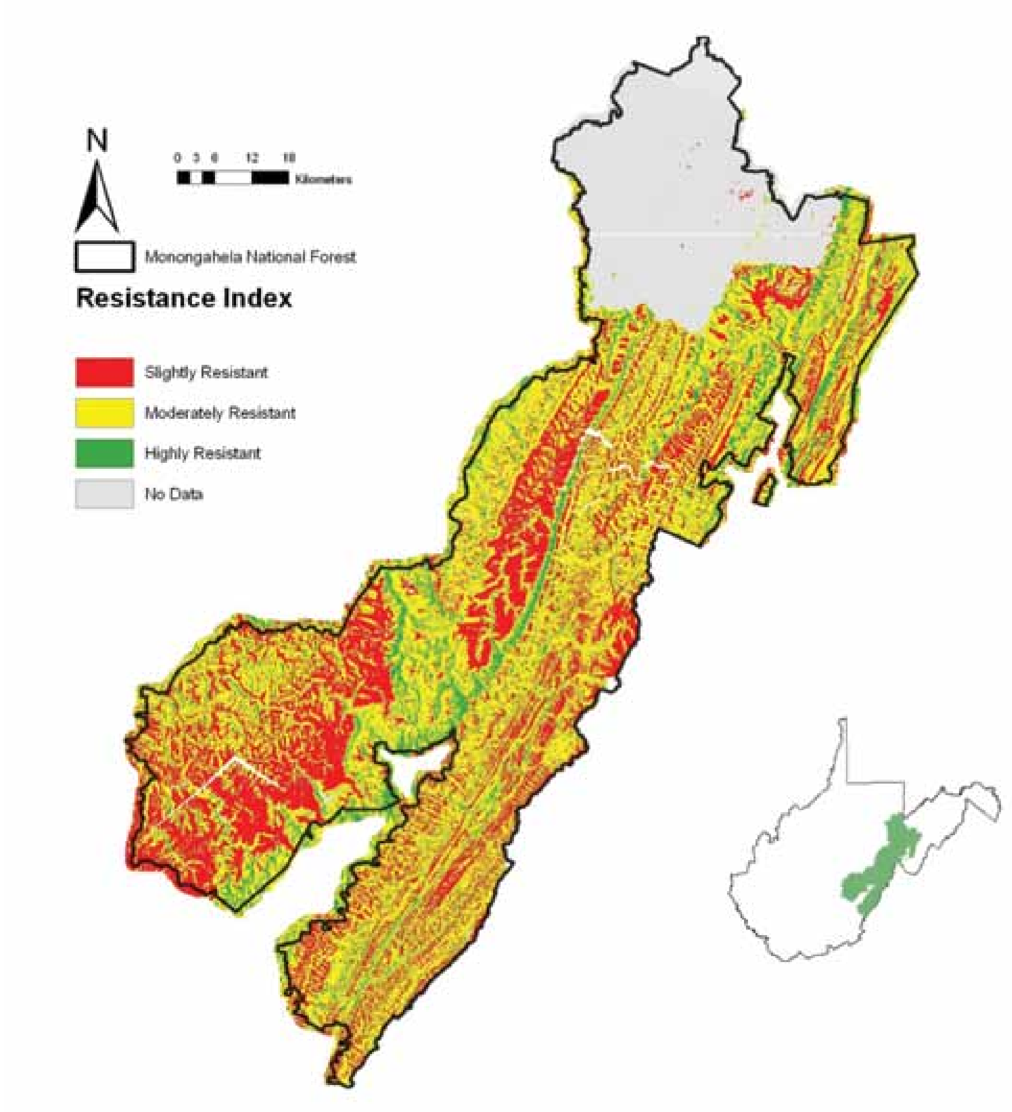


Figure 11. Map of resistance to acidification on the Monongahela National Forest.

the influence of each site factor to reflect current forest conditions as measured on MNF FIA plots.

The relationship between RI_{MNF} and significant indicators (pH, EBS, Ca/Al ratio, Al content) were used to create RI classes (slightly, moderately, and highly resistant). Class breaks were made at indicator levels associated with forest response in similar ecosystems (Cronan and Grigal 1995; Fenn and others 1998). A resistance index based on the classes of weighted site and soil factors (RI_{MNF}) was mapped across the Monongahela National Forest (fig. 11). Across the MNF, 14 percent of the land area was mapped as highly resistance to acidification ($RI_{MNF} \geq 0.7$), 57 percent was mapped as moderately resistant ($0.7 > RI_{MNF} > 0.45$), and 29 percent was mapped as slightly resistant ($RI_{MNF} \leq 0.45$).

This work by Elias (2008) demonstrates the use of soil quality monitoring principles for assessing risk of soil quality change across a forest. Correlation between forest growth and disturbance (PAI and AD) was established; criteria and indicators were selected based on a synthesis of previous research; the indicators were tested and those correlated with growth were selected; and a gradient of sensitivity (RI) to AD was developed and mapped based on available GIS layers. A systematic monitoring protocol using these soil quality indicators can now be directed to the least resistant sites, but soil-specific soil quality standards still need to be established for triggering mitigative and preventive management practices.

Incorporating Adaptive Management and Soil Quality Models Into the Forest Service Soil Management Program

Stewards of the public's forests are compelled to manage in a way that is economically viable, environmentally sound, and socially acceptable; this is called sustainable forest management (SFM). The Montreal Process is a multi-national initiative providing policy and management tools for achieving SFM. The United States is a Montreal Process signatory and the U.S. Forest Service represents the United States on its various committees. The organization establishes criteria and indicators for monitoring the status and health of temperate forests (Montreal Process 1995). Criterion #4 calls for monitoring the level of significant soil degradation. Various monitoring methods have been proposed and tried throughout the world with varying degrees of success, but the general approach of using indicators to measure change in soil function due to forest management disturbances is central to all.

The USDA Forest Service has a long-established soil quality monitoring program (USDA Forest Service 1991) with a goal of "developing a legally defensible monitoring and evaluation program based on firm scientific principles that produces unequivocal, credible results at minimum cost." Attaining this goal is a work in progress, as it is for all land management agencies, private landowners, and third-party certification entities. Due to recent legal challenges associated with management activities within the National Forest System, the Forest Service is especially compelled to review and update its soil management program.

The current objectives of the Forest Service Soil Management program as recently amended in the Forest Service Manual (FSM 2500-2009-1) are good and should meet the spirit and letter of the authorities that govern Forest Service management, but the policies and program approach for achieving the objectives fall short of getting the job done. The current approach is essentially one of inventorying the soil resource, classifying and describing its current condition, and monitoring its condition after management activities using disturbance indicators with threshold levels that, if exceeded, indicate that the soil has been impaired. This approach has limitations: (1) it is a passive and reactive approach; (2) it requires the use of disturbance indicators that have little or no science-based cause-and-effect relationship with ecological processes and function; (3) it uses the same disturbance indicators (one size fits all) across a gradient of highly variable soils and forest ecosystem, which is not workable; and (4) experience shows that different people applying current methods on the same site produce different results and assessments. Increasingly, elements of the public are challenging this approach as being inadequate for protecting soil quality and forest productivity.

We believe a broader, proactive, adaptive management approach that would (1) explicitly define best management practices for use on NFS lands, (2) monitor their implementation and effectiveness using science-based soil quality models, and (3) continually incorporate research results into the adaptive management process via established mechanisms would better serve the soil management program and achieve the overall goal of SFM. The use of adaptive management is now policy according to the recently revised Forest Service Manual (Section 2551.02). The overall approach, objective, policy, and even the general ecological processes and functions being sustained could be common across the NFS. However, the soil and ecosystem services, the indicators of change, and soil quality models, and the interpretations of the models regarding risk and judgments of impairment and mitigation need to be region-, forest-, and soil-specific as needed, although much overlap is possible and desirable.

Using similar adaptive management approaches across Forest Service Regions, to the extent possible, would provide better credibility with the public, and it would be more efficient to share techniques, models, and protocols. Choices for the hierarchical components of adaptive management would best follow biological, not jurisdictional boundaries. In order to develop guidelines for BMPs and evaluate soil quality, the soil services in question must first be selected. These would most likely be selected at large biological and jurisdictional scales. For example, the NFS would likely choose soil productivity, protection of water quality, biodiversity, and ability to sequester or buffer C and pollutants as major soil services that differ in relative importance at smaller scales. Within each soil service, soil functions can generally be set at broad biological spatial scales, because the fundamental functions that allow soils to provide services are not specific to biological systems. To protect soil and ecosystem function, management guidelines applied as BMPs could be developed inter-regionally in many cases. Some management practices are site- and forest-specific, while others can be broadly applied across Forest Service regions.

The attributes and indicators that provide the details of soil quality modeling, however, cannot cross biological boundaries as well as they can cross jurisdictional boundaries. Sufficiency curves for a given indicator are generally forest-type specific. For example, sufficiency curves for soil productivity of upland oak-dominated forests are likely to be similar in Tennessee or Wisconsin, even though these forests are located in two separate Forest Service regions. Similarly, ponderosa pine likely has more in common with loblolly pine than with redwood. In some cases, different forest types might have more in common with respect to soil indicator sufficiency responses than site types within a forest type. Coastal Douglas-fir may respond to soil indicators more similarly to redwood than to Douglas-fir in the Rocky Mountains. The best first approximation would likely be to adapt Bailey's (1995) ecoregions for development of SQMs.

In many cases, SQMs might be developed at the province or section level, while in other cases land type association might be more appropriate. While this would require increased regional cooperation, and in some cases more local involvement, it would reduce duplicative efforts where provinces or land type associations crossed regional boundaries, and it could increase the reliability and appropriateness of an SQM. The relative importance of specific land type associations or the relative management intensity within land types would help to prioritize the scale at which SQMs would need to be developed. SQMs might be able to be developed at the province level for provinces that have few management activities or for which certain services are of less importance, while heavily managed or critical areas might require SQMs at land type association levels to ensure their effectiveness.

Compared to current use of disturbance indicators with ill-defined "impairment" thresholds, soil quality models have the potential to improve monitoring and evaluation protocols when based on the following: (1) a clear management goal is defined (*e.g.*, maintain soil and function for long-term forest productivity); (2) soil function (stability, hydrology, nutrient cycling) is monitored and evaluated using site-specific indicators based on a synthesis of research and expert opinion; (3) indicators, both disturbance and soil quality, are correlated with productivity; (4) disturbance and soil quality indicators can be uniformly used and applied by trained technicians; (5) measures of disturbance and soil quality can be weighted based on importance and areal extent and combined into a single index that is correlated with tree growth or some other measure of productivity; (6) performance standards (some score or level of the combined indicators) can be established based on pre-disturbance conditions.

Powers and others (1998) stress that SQM protocols must be operationally feasible and cost effective, and they and others (Fox 2000) have criticized soil quality models as too complicated and too costly for routine monitoring. We believe this criticism is based on a misunderstanding of effort and cost of developing the models and protocol versus applying them. The models and protocols are developed by soil scientists as relatively simple and straightforward decision-support computer programs. Soil technicians apply the field protocols and enter data for computation. We believe the extent and quality of our current research database and our ability to select good, cost-effective indicators has been underestimated. The general literature, combined with up-to-date results from LTSP trials, could serve as a source for a refined soil quality monitoring protocol. For example, several soil properties recently shown to be correlated with both disturbance and tree growth are pore size distribution, strength, extractable P, and mineralizable N. Sampling for all these properties, except strength, is no more complicated than taking a soil core sample for bulk density, and strength is measured directly in the field using a penetrometer. Testing for density, pore size distribution, N, and P are routine tests that can be done locally or via contract.

In any case, implementation protocols for Soil Quality Management policy (FSM Section 2551.03) need to be reviewed and revised to be legally defensible. For years, soil quality managers have used disturbance and soil productivity indicators in the same way that air and water quality indicators are used, yet soil quality indicators do not perform properly alone or apart from a more comprehensive soil quality assessment. Similarly, reporting monitoring results without putting them in proper context within an adaptive management program (FSM 2009: 2551.03) will likely be inefficient or counterproductive.

Soil quality cannot be defined by individual indicator threshold values the way indicators for air and water quality can be. Water quality, for example, can be defined based on whether values for temperature, oxygenation, sediment load, and various chemicals are within some defined tolerance level. Tolerance levels are easily set because the effects have been directly observed in either humans or other animals. In soils, indicators work indirectly in concert with other indicators. Soil quality indicators show the sufficiency of a combination of soil properties and processes to function toward providing a service. Sufficiency is based on a reference level (*e.g.*, pre-harvest soil condition) specific for a given soil in a given forest ecosystem.

Critics of the soil quality modeling approach for assessing soils worry about a lack of threshold values for soil quality indicators beyond which a soil is "impaired"; however, currently used threshold values for individual indicators are usually not appropriate for judging impairment because they do not have actual cause-effect relationships with soil functions. There is little or no science for establishing threshold levels for soils. By contrast, the basic science needed to create and develop first-approximation sufficiency curves for most soil functions is widely available. Sufficiency curves can be improved with additional research and monitoring over time, but the basic structure of each curve can be developed today with our current understanding of soil functions.

Soil quality models created with a set of well-selected indicators and associated sufficiency curves do not provide threshold levels. SQMs provide a scaled "score" that indicates the direction and magnitude of change in the ability of a soil to function to provide a particular service. For example, Kelting and others (1999) developed a soil quality model that used bulk density, aeration porosity, and nitrogen mineralization (indicators) to evaluate sufficiency for root growth and biological activity (soil functions). They used the SQM to evaluate the impact of wet-weather harvesting (management action) on intensively managed loblolly pine growth (soil service) in the lower coastal plain of South Carolina. The SQM was scaled to actual loblolly pine growth on these sites. The SQM could be generally adapted to most southern pine forests with imperfect drainage, but the score would need to be scaled to be site- and species-specific (*e.g.*, naturally managed longleaf pine on the flatwoods of central Louisiana).

Soil quality models also have the ability to provide much more information about soil services other than soil productivity. Because of forest management's agronomic-based background and focus on producing timber, soil scientists and forest managers have focused on soil productivity (measured as wood production: $m^3\ ha^{-1}\ yr^{-1}$). However, across the National Forest System, other soil services such as water quality protection, wildlife habitat, and carbon, nutrient and pollutant sequestration and processing are vitally important. These services are even more difficult to measure directly, and threshold values for individual indicators are probably even less useful. However, sufficiency curves and SQMs can be created for the soil functions that provide these services (Scott and others 2006), and they can be continually improved through targeted research and monitoring.

The final key to developing soil quality models is to recognize their proper place within an adaptive management program. As mentioned above, soil quality models do not provide threshold standards for individual indicators that can be applied across sites, forests and regions; they provide relative values for overall sufficiency or ability to provide a soil service that changes in response to management. Threshold values can be set for the overall change in soil quality, but not individual indicators. Because of this, soil quality models (and their indicators) do not function well as broad spatial scale monitoring tools. Rather, they work best as tools to help evaluate management impacts at the site level. They provide the ability to evaluate BMP effectiveness within adaptive management frameworks.

In summary, we believe there is ample opportunity given our current knowledge and technical skills to improve soil management in the context of adaptive management programs. Action and change are needed in order to meet the goal of legally defensible, science-based soil management that produces "unequivocal and credible results." Required is a commitment by regional foresters and soil specialists to accept the challenge of developing sophisticated, computer-based soil quality models as part of the monitoring process. Also required is a commitment by Forest Service soil scientists to be part of the adaptive management process by providing input for the selection of soil quality indicators, development of sufficiency curves, and construction of the actual SQMs. The process of discovering "how the forest works" (creating knowledge) may be more enticing to soil scientists than applying knowledge for protecting it; but we would argue that the outcome of applying existing knowledge for a good adaptive management for the NFS is equally important and rewarding.

References

Andrews, Jeffrey A.; Johnson, J.E.; Torbert, J.L.; Burger, J.A.; Kelting, D.L. 1998. Minesoil and site properties associated with early height growth of eastern white pine. Journal of Environmental Quality 27:192-199.

Andrews, Susan S.; Karlen, D.L.; Cambardella, C.A. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Science Society of America Journal 68:1945-1962.

Aust, W. Michael; Burger, J.A.; Carter, E.A; Preston, D.P.; Patterson, S.C. 1998. Visually determined soil disturbance classes used as indices of forest harvesting disturbance. Southern Journal of Applied Forestry 22:245-250.

Aust, W. Michael; Schoenholtz, S.H.; Zaebst, T.W.; Szabo, B.A. 1997. Recovery status of a tupelo-cypress wetland seven years after disturbance—Silvicultural implications. Forest Ecology and Management 90:161-169.

Avers, Peter E. 1990. Standards and guidelines: What they are and how they are used. p. 52-53. In: Schwitzer, D.L.; McNaughton, M.J. (eds.). Proceedings, National Workshop on Monitoring Forest Plan Implementation. U.S. Department of Agriculture, Forest Service, Land Management Planning. Washington, DC.

Bailey, Robert.G. 1995. Description of the ecoregions of the United States. 2nd ed. Misc. Pub. No. 1391. U.S. Department of Agriculture, Forest Service. Washington, DC.

Blake, John I.; Ruark, G.A. 1992. Soil organic matter as a measure of forest productivity: some critical questions. p. 28-40. In: Proceedings of the Soil Quality Standards Symposium. Soil Science Society of America Meeting; San Antonio, TX; 21-27 October 1990. WO-WSA-2. U.S. Department of Agriculture, Forest Service, Watershed and Air Management Staff. Washington, DC.

Brendemuehl, Ray H. 1967. Loss of topsoil slows slash pine seedling growth in Florida sandhills. Res. Note S0-53. U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. New Orleans, LA.

Burger, James A. 1997. Conceptual framework for monitoring the impacts of intensive forest management on sustainable forestry. p. 147-156. In: Hakkila, P.; Heino, M.; E. Puranen; E. (eds.). Forest Management for Bioenergy. Res. Pap. 640.The Finnish Forest Research Institute, Vantaa Research Centre.

Burger, James A.; Johnson, J.E.; Andrews, J.A.; Torbert, J.L. 1994. Measuring mine soil productivity for forests. p. 48-56. In: Proceedings, International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Vol. 3. Pittsburgh, PA; April 24-29, 1994. Special Publication SP06C-94. U.S. Department of the Interior, Bureau of Mines.

Burger, James A.; Kelting, D.L. 1999. Using soil quality indicators to assess forest stand management. p. 17-52. In: Adams, M.B.; Ramakrishna, K.; Davidson, E.A. (eds.). The Contribution of Soil Science to the Development of and Implementation of Criteria and Indicators of Sustainable Forest Management. Special Publication 53. Soil Science Society of America. Madison, WI.

Burger, James A.; Kelting, D.L. 1999. Using SQIs to assess forest stand management. Forest Ecology and Management 122:155-166.

Burger, James A.; Mitchem, D.O.; Scott, D.A. 2002. Field assessment of mine site quality for establishing hardwoods in the Appalachians. p. 226-240. In: Barnhisel, R.; Collins, M. (eds). Proceedings, American Society of Mining and Reclamation 19th Annual National Conference and International Affiliation of Land Reclamation 6th International Conference; Lexington, KY; June 9-13, 2002.

Carmean, William H. 1975. Forest site quality evaluation in the United States. Advances in Agronomy 27:209-269.

Carter, Martin R.; Gregorich, E.G.; Anderson, D.W.; Doran, J.W.; Janzen, H.H.; Pierce, F.J. 1997. Concepts of soil quality and their significance. p. 1-19. In: Gregorich, E.G.; Carter, M.R. (eds.). Soil Quality for Crop Production and Ecosystem Health. Elsevier, New York.

Cronan, Christopher S.; Grigal, D.F. 1995. Use of calcium/aluminum ratio as indicators of stress in forest ecosystems. Journal of Environmental Quality 24:209-226.

Canadian Standards Association (CSA). 2003. Sustainable Forest Management: Requirements and Guidelines. Canadian Standards Association. CAN/CSA-Z80902.

Daddow, Richard; Warrington, G. 1983. Growth-limiting soil bulk densities as influenced by soil texture. WSDG report—WSDG-TN-00005. U.S. Department of Agriculture, Forest Service. Fort Collins, CO. 17 p.

da Silva, Alvaro.P.; Kay, B.D.; Perfect, E. 1994. Characterization of the least limiting water range of soils. Soil Science Society of America Journal 58:1775-1781.

Doran, John W.; Jones, A.J., eds. 1996. Methods for Assessing Soil Quality. SSSA Special Pub. No. 49. Soil Science Society of America Inc. Madison, WI. 410 p.

Doran, John W.; Parkin, T.B. 1994. Defining and assessing soil quality. p. 3-21. In: Doran, J.W.; Coleman, D.C.; Bezedick, D.F.; Stewart, B.A. (eds.). Defining Soil Quality for a Sustainable Environment. Special Publication No. 35. American Society of Agronomy. Madison, WI.

Elias, Patricia E. 2008. Acid deposition effects on soil chemistry and forest growth on the Monongahela National Forest. Master of Science Thesis, Virginia Polytechnic Institute and State University. Blacksburg, VA. 157 p.

Elias, Patricia E.; Burger, J.A.; Adams, M.B. 2009. Acid deposition effects on forest composition and growth on the Monongahela National Forest, West Virginia. Forest Ecology and Management. 258:2175-2182.

Elias, Patricia E.; Burger, J.A. (In preparation). Adaptive management for maintaining productivity on acidified sites on the Monongahela National Forest. Northern Journal of Applied Forestry.

Fenn, Mark E.; Poth, M.A.; Aber, J.D.; Baron, J.S.; Bormann, B.T.; Johnson, D.W.; Lemly, A.D.; McNulty, S.G.; Ryan, D.F.; Stottlemyer, R. 1998. Nitrogen excess in North American ecosystems: Predisposing factors, ecosystem responses, and management strategies. Ecological Applications 8:706-733.

Forest Service Manual (FSM). 2009. Soil Management. Forest Service Manual Chapter 2550—Amendment No. 2500-2009-1. U.S. Department of Agriculture, Forest Service. Washington, DC.

Forest Stewardship Council (FSC). 1996. FSC International Standard: FSC principles and criteria for forest stewardship. FSC-STD-01-001, v. 4-0. Forest Stewardship Council, A.C., Bonn, Germany.

Fox, Thomas R. 2000. Sustained productivity in intensively managed forest plantations. Forest Ecology and Management 138:187-202.

Gale, Margaret R.; Grigal, D.F.; Harding, R.B. 1991. Soil productivity index: Predictions of site quality for white spruce plantations. Soil Science Society of America Journal 55(6):1701-1708.

Gomez, G. Armando; Powers, R.F.; Singer, M.J.; Horwath, W.R. 2002. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Science Society of America Journal 66:1334-1343.

Greacen, Emmett L.; Sands, R. 1980. Compaction of forest soils: A review. Australian Journal of Soil Research 18:163-189.

Gregorich, Edward G.; Carter, M.R. 1997. Soil Quality for Crop Production and Ecosystem Health. Elsevier, New York. 448 p.

Grable, Albert R.; Siemer, E.G. 1968. Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potentials, and elongation of corn roots. Soil Science Society of America Proceedings 32:180-186.

Halvorson, Jonathan J.; Smith, J.L.; Papendick, R.I. 1996. Integration of multiple soil parameters to evaluate soil quality: A field example. Biology and Fertilization of Soils 21:207-214.

Heninger, Ronald L.; Terry, T.A.; Dobkowski, A.; Scott, W. 1998. Managing for sustainable site productivity: Weyerhaeuser's forestry perspective. Biomass and Bioenergy 13:255-267.

Jones, Andrew T.; Galbraith, J.M.; Burger, J.A. 2005. Development of a forest site quality classification model for mine soils in the Appalachian coalfield region. p. 523-539. In: Barnhisel, R.I. (ed.). Proceedings, 22nd Meeting, American Society for Mining and Reclamation. June 18-24, 2005, Breckenridge, CO. ASMR, 3234 Montavesta Rd. Lexington, KY.

Karlen, Douglas L.; Ditzler, C.A.; Andrews, S.S. 2003. Soil quality: Why and how? Geoderma 114:145-156.

Kelting, Daniel L.; Burger, J.A.; Patterson, S.C.; Aust, W.M.; Miwa, M.; Trettin, C.C. 1999. Soil indicators to assess sustainable forest management—A southern pine example. Forest Ecology and Management 122:157-168.

Kranabetter, J. Marty; Sanborn, P.; Chapman, B.K.; Dube, S. 2006. The contrasting response to soil disturbance between lodgepole pine and hybrid white spruce in subboreal forests. Soil Science Society of America Journal 70:1591-1599.

Laflen, John M.; Elliot, W.J.; Flanagan, D.C.; Meyer, C.R.; Nearing, M.A.; Soil, J. 1997. WEPP-predicting water erosion using a process-based model. Journal of Soil Water Conservation 52:96-102.

Lal, Rattan (ed.). 1999. Soil Quality and Erosion. CRC Press, New York. 329 p.

Larson, William E.; Pierce, F.J. 1994. The dynamics of soil quality as a measure of sustainable management. p. 37-51. In: Doran, J.W.; Coleman, D.C.; Bezedick, D.F.; Stewart, B.A. (eds.) Defining soil quality for a sustainable environment. Special Publication No. 35, American Society of Agronomy. Madison, WI.

Lister, Tonya W.; Burger, J.A.; Patterson, S.C. 2004. Role of vegetation in mitigating soil quality impacted by forest harvesting. Soil Science Society of America Journal 68:263-271.

Miller, Richard E.; McIver, J.D.; Howes, S.W.; Gaeuman, W.B. (In preparation). Assessment of soil disturbance in forests of the Interior Columbia Basin: A critique and suggestions for change. PNW-GTR-000. U.S. Department of Agriculture, Forest Service.

Moffat, Andy J. 2003. Indicators of soil quality for UK forestry. Forestry 76:547-564.

Montreal Process. 1995. Criteria and indicators for the conservation and sustainable management of temporal and boreal forests. Canadian Forest Service, Catalogue Fo42 238/1995E. Canadian Forest Service, Hull, Quebec.

Nortcliff, Stephen. 2002. Standardization of soil quality attributes. Agriculture, Ecosystems and Environment 88:161-168.

Page-Dumroese, Deborah; Jurgensen, M.; Elliot, W.; Rice, T.; Nesser, J.; Collins, T.; Meurisse, R. 2000. Soil quality standards and guidelines for forest sustainability in northwestern North America. Forest Ecology and Management 138:445-462.

Powers, Robert F.; Alban, D.H.; Miller, R.E.; Tiarks, A.E.; Wells, C.G.; Avers, P.E.; Cline, R.G.; Fitzgerald, R.O.; Loftus, Jr., N.S. 1990. Sustaining site productivity in North American forests: problems and prospects. p. 49-79. In: Gessel, S.P.; Lacate, D.S.; Weetman, G.F.; Powers, R.F. (eds.). Proceedings of the Seventh North American Forest Soils Conference on Sustained Productivity of Forest Soils. Faculty of Forestry, University of British Columbia. Vancouver, BC.

Powers, Robert F.; Scott, D.A.; Sanchez, F.G.; Voldseth, R.A.; Page-Dumroese, D.; Eliott, J.D.; Stone, D.M. 2005. The North American long-term soil productivity experiment. Findings from the first decade of research. Forest Ecology and Management 220:17-30.

Powers, Robert F.; Tiarks, A.E.; Boyle, J.R. 1998. Assessing soil quality: Practicable standards for sustainable forest productivity in the United States. p. 53-80. In: Davidson, E.A.; Adams, M.B.; Ramakrishna, K. (eds.), The Contribution of Soil Science to the Development and Implementation of Criteria and Indicators of Sustainable Forest Management. Special Publication 53. Soil Science Society of America. Madison, WI.

Pritchett, William L.; Fisher, R.F. 1987. Properties and Management of Forest Soils (3rd ed.). John Wiley and Sons, Inc. New York. 489 p.

Raison, R. John; Brown, A.G.; Flinn, D.W. (eds.). 2001. Criteria and Indicators for Sustainable Forest Management. CABI Publishing. New York.

Ramakrishna, Kilaparti; Davidson, E.A. 1998. Intergovernmental negotiations on criteria and indicators for the management, conservation, and sustainable development of forests: What role for forest scientists? p. 1-16. In: Davidson, E.A.; Adams, M.B.; Ramakrishna, K. (eds.), The Contribution of Soil Science to the Development and Implementation of Criteria and Indicators of Sustainable Forest Management. Special Publication 53. Soil Science Society of America. Madison, WI.

Rametsteiner, Ewald; Simula, M. 2002. Forest certification—an instrument to promote sustainable forest management. Journal of Environmental Management 67:87-98.

Rodrigue, Jason A.; Burger, J.A. 2004. Forest soil productivity of mined land in the midwestern and eastern coalfield regions. Soil Science Society of America Journal 68(3):833-844.

Roundtable on Sustainable Forests. (http://www.sustainableforests.net/docs/2008/200802_TN_National_Workshop/4-Draft_Sustainable_Forests_Act_071204.pdf)

Sample, V. Alaric; Kavanough, S.L.; Snieckus, M.M. (eds.). 2006. Advancing Sustainable Forest Management in the United States. Pinchot Institute for Conservation. Washington, DC.

Sanchez, Felipe G.; Scott, D.A.; Ludovici, K.H. 2006. Negligible effects of severe organic matter removal and soil compaction on loblolly pine growth over 10 years. Forest Ecology and Management 227:145-154.

Schoenholtz, Stephen H.; Van Miegroet, H.; Burger, J.A. 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. Forest Ecology and Management 138:335-357.

Scott, D. Andrew; Dean, T. 2006. Energy trade-offs between intensive biomass utilization, site productivity loss, and ameliorative treatments in loblolly pine plantations. Biomass and Bioenergy 30:1001-1010.

Scott, D. Andrew; Burger, J.A.; Crane, B.S. 2006. Expanding site productivity research to sustain non-timber forest functions. Forest Ecology and Management 227:185-192.

Scott, D. Andrew; Tiarks, A.E.; Sanchez, F.G.; Elliott-Smith, M.; Stagg, R. 2004. Forest soil productivity on the southern long-term soil productivity sites at age 5. p. 372–377.In: Connor, K.F. (ed.), Proceedings of the 12th Biennial Southern Silvicultural Research Conference. Gen. Tech Rep. SRS-71. U.S. Department of Agriculture, Forest Service, Southern Research Station. Asheville, NC.

Siegel-Issem, Cristina M.; Burger, J.A.; Powers, R.F.; Ponder, F.; Patterson, S.C. 2005. Seedling root growth as a function of soil density and water content. Soil Science Society of America Journal 69:215-226.

Singh, Kamal K.; Colvin, T.S.; Erbach, D.C.; Mughal, A.Q. 1992. Tilth index: An approach to quantifying soil tilth. Transactions of the American Society of Agricultural Engineering 35:1777-1785.

SMCRA. Congress of the United States. 1993. Surface Mining Control and Reclamation Act of 1977. Committee on Natural Resources. 103rd Congress. U.S. Government Printing Office, ISBN 0-16-040007-4, Washington, DC.

Soil Science Society of America (SSSA). 1995. Statement on soil quality. Agronomy News, June, 1995.

Stagg, Richard H.; Scott, D.A. 2006. Understory growth and composition resulting from soil disturbances on the long-term soil productivity study sites in Mississippi. p. 52-56. In: Connor, K.F. (ed.) Proceedings of the 13th Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS-92. U.S. Department of Agriculture, Forest Service, Southern Research Station. Asheville, NC.

Steber, Aaron; Brooks, K.; Perry, C.H.; Kolka, R. 2007. Surface compaction estimates and soil sensitivity in aspen stands of the Great Lakes States. Northern Journal of Applied Forestry 24:276-281.

Storie, R. Earl. 1933. An index for rating the agricultural value of soils. Bull. No. 556. California Agriculture Experiment Station.

Sustainable Forestry Initiative (SFI). 2004. Sustainable Forestry Initiative 2005-2009 Standard. Sustainable Forestry Initiative, Inc., Arlington, VA.

Torbert, John L.; Burger, J.A.; Daniels, W.L. 1988a. Minesoil factors influencing the productivity of new forests on reclaimed surface mines in southwestern Virginia. p. 63-67. In: Proceedings, Conference on Mine Drainage and Surface Mine Reclamation. Vol. II: Mine reclamation, abandoned mine lands and policy issues; Pittsburgh, PA; April. 19-21, 1988. Information Circular 9184. U.S. Department of the Interior, Bureau of Mines.

Torbert, John L.; Burger, J.A.; Daniels, W.L. 1990. Pine growth variation associated with overburden rock type on a reclaimed surface mine in Virginia. Journal of Environmental Quality 19:88-92.

Torbert, John L.; Burger, J.A.; Johnson, J.E.; Andrews, J.A. 1994. Indices for indirect estimates of productivity of tree crops. Final Report, OSM Cooperative Agreement GR996511. College of Forestry and Wildlife Resources, Virginia Polytechnic Institute and State University, Blacksburg.

Torbert, John L.; Tuladhar, A.R.; Burger, J.A.; Bell, J.C. 1988b. Minesoil property effects on the height of ten-year-old white pine. Journal of Environmental Quality 17:189-192.

USDA Forest Service. 1983. The principal laws relating to Forest Service activities. p. 591. In: Agriculture Handbook 453. U.S. Department of Agriculture, Forest Service. Washington, DC.

USDA Forest Service. 1991. Soil Management Handbook, Soil Quality Monitoring. FSH 2509.18 Chapter 2. WO Amendment 2509.18-91-1. Effective 9/3/91. U.S. Department of Agriculture, Forest Service. Washington, DC.

Warkentin, Benno P.; Fletcher, H.F. 1977. Soil quality for intensive agriculture. p. 594-598. In: Proceedings, International Seminar on Soil Environment and Fertilizer Management. National Institute of Agricultural Science. Tokyo, Japan.

Wendroth, Ole; Reynolds, W.D.; Vieira, S.R.; Reichardt, K.; Wirth, S. 1997. Statistical approaches to the analysis of soil quality data. p. 247-276. In: Gregorich, E.G.; Carter, M.R. (eds.). Soil Quality for Crop Production and Ecosystem Health. Elsevier, New York.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

The North-American Long-Term Soil Productivity Study: Concepts and Literature

Deborah S. Page-Dumroese, USDA Forest Service, Rocky Mountain Research Station, Moscow, ID

Abstract—The resiliency of forest sites after a pulse disturbance is one of the key questions mandated by the National Forest Management Act (NFMA) of 1976. This Act mandated that we maintain the productive capacity of federally managed stands. The original USDA Forest Service soil quality standards were based largely on professional judgment. The North American Long-Term Soil Productivity (LTSP) study was founded to provide a scientific basis for validating or proposing changes to the current standards. Research on the 100 field installations centers around how two key properties, site organic matter and soil porosity, affect a forest's long-term productivity capacity. Results from these installations are listed in a bibliography.

Introduction

The Long-Term Soil Productivity (LTSP) program began in 1989 as a "grass roots" effort that quickly grew to a national program within the USDA Forest Service (Powers 2006). LTSP was founded to examine the long-term consequences of soil disturbance on fundamental forest productivity. Today more than 100 installations and affiliated sites comprise the world's largest coordinated research network.

Background

The National Forest Management Act (NFMA) of 1976 specified that the "Secretary of Agriculture shall limit the sale of timber from each National Forest to a quantity equal to or less than the quantity which can be removed from such forest annually in perpetuity on a sustained-yield basis." This landmark land-ethics statement mandated that the USDA Forest Service conduct research, monitoring, and assessments to evaluate management effects and to manage for sustained-yield in perpetuity in a manner that protects all resources and values. NFMA led to the development, by National Forest Systems, of their soil quality standards. The standards that evolved were based on professional judgment and were meant to act as an early warning rather than absolute limits (Cline and others 2006). Forest managers expressed a desire for simplicity and nationally consistent metrics, although many authorities have since pointed out that single parameters, values, or measurement methods are not appropriate in all cases (Page-Dumroese and others 2006). Therefore, the LTSP study is critical to development of more site-specific soil quality standards, guidelines, or prescriptions.

Development of useful indicators of soil quality will continue to be tied to the intensive investigations by the LTSP program and its many collaborators. Results from this research can lead to the development of indicators of best management practices. These indicators of sustainable forestry should be (1) scientifically sound, (2) operationally practical, (3) socially responsible and credible, (4) standard methodology for measurement, (5) easily interpretable, (6) integrated, (7) linked to silvicultural prescriptions, (8) easily measured and cost effective.

There are five key findings from the LTSP installations that have direct impact on forest management and soil quality: (1) soil organic matter is the link between most management systems and sustainable site productivity (*e.g.*, maintain the forest floor during management activities), (2) nutrient deficiencies can be corrected, (3) soil texture is the key variable affecting soil organic matter and site productivity, (4) return of crop residues enhances soil organic matter and site productivity, and (5) productive cropping systems have environmental benefits (Cline and others 2006).

All the collaborators with the LTSP study share a commitment to practice ethical stewardship and sustainable forest management. All collaborators agree that achieving sustainable forest operations is an iterative process and that altering existing soil quality standards is one step in developing best management practices and the indicators for monitoring.

LTSP References

Alban, D. H.; Host, G. E.; Elioff, J. D.; Shadis, D. 1994. Soil and vegetation response to soil compaction and forest floor removal after aspen harvesting. Res. Pap. NC-315. USDA Forest Service, St. Paul, MN. 8 p.

Alban, D. H.; Tiarks, A. E.; Powers, R. F.; Page-Dumroese, D. S.; Ponder, F., Jr.; Buford, M. A. 1993. Forest management impacts on long-term productivity-early results form a U.S. research program. IEA New Brunswick meeting, May 17, 1993. Abstract and paper published as symposium proceedings.

Amaranthus, M. P.; Page-Dumroese, D. S.; Harvey, A.; Cazares, E.; Bednar, L. F. 1996. Soil compaction and organic matter affect conifer seedling nonmycorrhizal and ectomycorrhizal root tip abundance and diversity. PNW-RP-494, USDA Forest Service Pacific Northwest Research Station, Portland, OR. 12 p.

Archibald, D. J.; Wiltshire, W. B.; Morris, D. M.; Batchelor, B. 1997. Forest management guidelines for the protection of the physical environment. Version 1.0. Ontario Government, Ministry of Natural Resources. MNR #51032. Queen's Printer, Toronto. 47 p. http://www.mnr.gov.on.ca/MNR_E000531.pdf.

Arencena, J. M. 2000. Cations in solutions form forest soil subjected to forest floor removal and compaction treatments. For. Ecol. Manage. 133: 71-80.

Ares, A.; Terry, T.; Harrison, R. B.; Piatek, K.; Flaming, F.; Licata, C.; Strahm, B.; Meade, R.; Miller, R.; Devine, W.; Peter, P.; Petersen, K.; Anderson, H.; Harrington, T. 2006. Achieving long-term site productivity in the Pacific Northwest: Research-driven strategic databases to guide best management practices. In: Proceedings: IUFRO 4.04.02 Forest Plantation Meeting: Sustainable Forest Management with Fast Growing Plantations. October 10-13, 2006, Charleston, SC.

Ares, A.; Terry, T. A.; Harrington, C. A.; Devine, W. D.; Peter, D.; Bailey, J. D. 2007. Biomass removal, soil compaction, and vegetation control effects on five-year growth of Douglas-fir in Coastal Washington. For. Sci. 53(5): 600-610.

Ares, A.; Terry, T. A.; Piatek, K. B.; Harrison, R. B.; Miller, R. E.; Flaming, B.; Licata, C.; Strahm, B.; Harrington, C. A.; Meade, R.; Anderson, H. W.; Brodie, L. C.; Kraft, J. M. 2007. The Fall River Long-term Site Productivity study in coastal Washington: site characteristics, experimental design, and biomass, carbon and nitrogen stores before and after harvest. Gen. Tech. Rep. PNW-GTR-691. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. 85 p.

Ares, A.; Terry, T. A.; Piatek, K. B.; Harrison, R. B.; Harrington, C. A.; Meade, R.; Leon, R.; Miller, R. E.; Flaming, B. L.; Licata, C. W.; Petersen, K.; Strahm, B. D.; Anderson, H. W.; Brodie, L. C.; Kraft, J. M. 2007. Pre- and post-harvest stores of carbon and nitrogen in a highly reproductive forest site subjected to increasing biomass removals in coastal Washington. Weyerhaeuser Company Technical Note. 15 p.

Ares, A.; Terry, T. A.; Miller, R. E.; Anderson, H. W.; Flaming, B. L. 2005. Forest harvesting effects on soil physical properties and Douglas-fir growth on a Coastal Washington site. Soil Sci. Soc. Am. J. 69: 1822-1832.

Arocena, J. M.; Sanborn, P. 1999. Mineralogy and genesis of selected soils and their implications for forest management in central and northeastern British Columbia. Can. J. Soil Sci. 79: 571-592.

Arvonio, A. 2000. The effects of various timber harvesting treatments on soil bacteria populations in black spruce ecosystems. Thesis. Lakehead University, Thunder Bay, ON.

Atzet, T.; Powers, R. F.; McNabb, D. H.; Amaranthus, M. P.; Gross, E. R. 1989. Maintaining long-term forest productivity in southwest Oregon and northern California. P. 185-201. In: Perry, D. A.; Meurisse, R.; Thomas, B.; Miller, R.; Boyle, J.; Means, J.; Perry, C. R.; Powers, R. F., (eds.). Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Timber Press, Inc. Portland, OR.

Aust, W. M.; Blinn, C. R. 2004. Forestry best management practices for timber harvesting and site preparation in the eastern United States—an overview of water quality and productivity research during the past 20 years. Water, Air, and Soil Pollution 4: 5-36.

Aust, W. M.; Burger, J. A.; Carter, E. C.; Preston, D. P.; Patterson, S. C. 1998. Visually determined soil disturbance classes used as indices of forest harvesting disturbance. South. J. Appl. For. 22: 245-250.

Aust, W. M.; Berger, J. A.; McKee, W. H.; Scheerer, G. A.; Tippett, M. D. 1998. Bedding and fertilization ameliorate effects of designated wet-weather skid trails after four years for loblolly pine plantations. South. J. Appl. For. 22: 222-225.

Axelrood, P. E.; Chow, M. L.; Arnold, C. S.; Lu, K.; McDermott, J. M.; Davies, J. 2002. Cultivation-dependant characterization of bacterial diversity from British Columbia forest soils subjected to disturbance. Can. J. Microbiol. 48: 643-654.

Axelrood, P. E.; Chow, M. L.; Radomski, C. C.; McDermott, J. M.; Davies, J. 2002. Molecular characterization of bacterial diversity from British Columbia forest soils subjected to disturbance. Can. J. Microbiol. 48: 655-674.

Battigelli, J. P.; Spence, J. R.; Langor, D. W.; Berch, S. M. 2004. Short-term impact of forest soil compaction and organic matter removal on soil mesofauna density and oribatid mite density. Can. J. For. Res. 34:1136-1149.

Battigelli, J.; Berch, S. 2002. Soil fauna in the sub-boreal spruce (SBS) installations of the long-term soil productivity (LTSP) study of central British Columbia: One-year results for soil mesofauna and macrofauna. British Columbia Ministry of Forests. LTSPS Research Note 05. 6 p. http://www.for.gov.bc.ca/hfd/pubs/Docs/Ltsps/Rrn005.pdf

Bhatti, J. S.; Foster, N. W.; Oja, T.; Moayeri, M. H.; Arp, P. A. 1998. Modeling potentially sustainable biomass productivity in jack pine forest stands. Can. J. Soil Sci. 78: 105-113.

Bhatti, J. S.; Foster, N. W.; Arp, P. A. 1997. Evaluating the sustainability of forest production when jack pine stems and logging residues are used for energy production. P. 9-13. In: Richardson, J. (ed.). Proceedings, bioenergy and boreal forest management workshop, 23 Sept. 1997, Timmins, Ontario. International Energy Agency Task XII: Biomass Production, Harvesting and Supply Forest Management Activity. Canadian Forest Service, Ottawa, ON.

Bliss, C. M.; Scott, D. A.; Dean, T. 2006. Soil nutrient dynamics in response to forest floor manipulations across a site quality gradient. Agronomy Abstracts. P. 927. In: International meeting of the American Society of Agronomy, Nov. 12-16, 2006, Indianapolis, IN. American Society of Agronomy, Madison, WI.

Boyle, J. R.; Powers, R. F. (Eds.) 2001. Forest soils and ecosystem sustainability. Elsevier, Amsterdam, The Netherlands. 462 p.

Bruins, A. 1997. Comparing the effects of decomposition bag pore size on fine root decomposition: Microbial access versus root material retention. B. Sc. F. Thesis. Lakehead University, Thunder Bay, ON.

Buckley, D. S.; Zasada, J. C.; Trappeiner, J. C., II; Stone, D. M. 1997. Plant morphological characteristics as a tool in monitoring response to silvicultural activities. P. 37-41. In: Communicating the role of silviculture in managing the national forests: Proceedings of the National Silviculture Workshop; 19-22 May, 1997; Warren, PA. Gen. Tech. Rep. NE-238. USDA Forest Service Northeastern Forest Experiment Station, Radnor, PA.

Buford, M. A.; Ragus, J. F.; Tiarks, A. E. 1995. Long-term soil productivity research in the South. Asheville, NC. USDA Forest Service Southern Region and Southern Research. [not paged]. Leaflet.

Burger, J. A. 2002. Soil and long-term site productivity values. P. 165-189. In: Richardson, J. et al. (eds.) Bioenergy from sustainable forestry: Guiding principles and practice. Kleuwer, Boston, MA.

Burger, J. A.; Scott, D. A. 2001. Soil interpretations for sustainable forest management in the Southeastern United States. P. 65-72. In: Boruvka, L. (ed.) Soil Science—Past, Present, and Future. Proceedings of the Joint Meeting of the Czech Society of Soil Science, and the Soil Science of America. Sept. 16-20, 2001. Prague, Czech Republic.

Burger, J. A.; Kelting, D. L. 1999. Using soil quality indicators to assess forest stand management. For. Ecol. Manage. 122: 155-166.

Burger, J. A.; Kelting, D. L. 1998. Soil quality monitoring for assessing sustainable forest managment. P. 17-52. In: Adams, M. B.; Ramakrishna, K.; Davidson, E. A. (Eds.) Criteria and indicators of soil quality for sustainable forest productivity. Spec. Publ. 53, Soil Sci. Soc. Am., Madison, WI.

Burger, J. A. 1997. Conceptual framework for monitoring the impacts of intensive forest management on sustainable forestry. P. 147-156. In: Hakkila, P. (Ed.) Forest management for bioenergy. The Finnish Forest Research Institute.

Burger, M. A. 1994. A wetland trafficability hazard index based on the soil physical properties and site hydrology evaluations. M. S. Thesis. 139 p. Virginia Polytechnic and State University, Blacksburg, VA

Burger, J. A.; Powers, R. F. 1991. Field designs for testing hypotheses in long-term site productivity studies. P. 79-105. In: Dyck, W. J.; Mees, C. A. (eds.) Long-term Field Trials to Assess Environmental Impacts of Harvesting. IEA/BE T6/A6 Rep. No. 5. FRI Bull. No. 161. Forest Res. Inst., Rotorua, New Zealand.

Busse, M.; Beattie, S. E.; Powers, R. F.; Sanchez, F. G.; Tiarks, A. E. 2006. Microbial community responses in forest mineral soil to compaction, organic matter removal and vegetation control. Canadian Journal of Forest Research 36: 577-588.

Busse, M.; Riegel, G.; Johnson, W. 2006. Long-term effects of prescribed fire and thinning in central Oregon ponderosa pine forests. In: Proceedings, third international fire ecology and management congress, Nov. 13-17, 2006, San Diego, CA.

Busse, M. D.; Riegel, G. M. 2005. Managing Ponderosa pine forests in central Oregon: who will speak for the soil? P. 109-122. In: Ritchie, M. W.; Maguire, D. A.; Youngblood, A. (Eds.) Proceedings, symposium on ponderosa: issues, trends and management, Oct. 81-21, Klamath Falls, OR. Gen. Tech. Rep. PSW-GTR-198. Pacific Southwest Research Station, USDA Forest Service, Albany, CA.

Busse, M. D.; Fiddler, G. O.; Ratcliff, A. W. 2004. Ectomycorrhizal formation in herbicide-treated soils of differing clay and organic matter content. Water, Air, and Soil Pollution 152: 23-34.

Busse, M.; Fiddler, G.; Gillette, N. 2003. Are herbicides detrimental to ectomycorrhizae? P. 46-53. In: Cooper, S. L. (comp.) Proceedings, 24th Ann. Forest Vegetation Management Conference, Jan. 14-16, 2003; Redding, CA. Univ. California Coop. Exten., Redding, CA.

Busse, M. D.; Rappaport, N. G.; Powers, R. F. 2001. Hexazinone effects on soil viota and processes: initial findings. P. 66-72. In: Cooper, S. L. (comp.) proceedings, 22nd Annual forest vegetation management Conference. University of California Cooperative Extension, Redding, CA.

Busse, M. D.; Ratcliff, A. W.; Shestak, C. J.; Powers, R. F. 2001. Glyphosate toxicity of the effects of long-term vegetation control on soil microbial communities. Soil Biology and Biochemistry 33: 1777-1789.

Busse, M. D.; Cochran, P. H.; Barrett, J. W. 1996. Changes in ponderosa pine site productivity following removal of understory vegetation. Soil Sci. Soc. Am. J. 60: 1614-1621.

Butnor, J. R.; Johnsen, K. H.; Sanchez, F. G. 2006. Whole-tree and forest floor removal from loblolly pine plantation have no effect on forest floor CO_2 efflux 10 years after harvest. For. Ecol. Manage. 277: 89-95.

Carter, E. A.; Aust, W. M.; Burger, J. A. 1998. Soil strength, volumetric content, and soil roughness characteristics of a bedded wet pine flat. P. 401-405. In: Proceedings, Ninth Biennial southern Silvicultural Research Conference. Clemson, SC. February 25-27, 1997. USDA Forest Service, Asheville, NC.

Carter, M.; Tiarks, A.; Buford, M.; Farrish, K.; Cooksey, T.; Foster, D.; Hill, G.; Zhou, M.; Dean, T.; Newbold, R.; Williams, R. 1996. Nutrient budgets for the seventeen locations of the LTSP and MPEQ studies in *Pinus taeda*. P. 71. In: Proceedings of the 14th North American forest biology workshop. Forest management impact on ecosystem processes. 1996 June 16-20. Quebec City, Canada: Universite Laval.

Choi, W.-J.; Chang, S. X.; Curran, M. P.; Ro, H.-M.; Kamaluddin, M.; Zwiazek, J. J. 2005. Foliar $\delta^{13}C$ and $\delta^{15}N$ response of lodge pole pine and Douglas-fir seedlings to soil compaction and forest floor removal. Forest Science 51(6): 546-555.

Chow, M. L.; Radomski, C. C.; McDermott, J. M.; Davies, J.; Axelrood, P. E. 2002. Molecular characterization of vacterial diversity in Lodgepole pine (*Pinus contorta*) rhizoshpere soils from British Columbia forest soils differing in disturbance and geographic source. FEMS Microbiology Ecology 42: 347-357.

Craigg, T. L. 2006. Evaluation of methods used to assess changes in forest soil quality. MS Thesis. 304 p. University of California, Davis, CA.

Conlin, T. S. S.; van den Driessche, R. 2000. Response of soil CO_2 and O_2 concentrations to forest soil compaction at the long-term soil productivity sites in central British Columbia. Can. J. Soil Sci. 80: 625-632.

Curran, M. P.; Heninger, R. L.; Maynard, D. G.; Powers, R. F. 2005. Harvesting effects on soils, tree growth, and long-term productivity. P. 3-15. In: Harrington, C. A.; Schoenholtz, S. H. (Tech. ed.). Productivity of western forests: a forest products focus. Gen. Tech. Rep. PNW-GTR-642. USDA Forest Service Pacific Northwest Research Station, Portland, OR.

Curran, M. P.; Maynard, D. G.; Heninger, R. L.; Terry, T. A.; Howes, S. W.; Stone, D. M.; Niemann, T.; Miller, R. E.; Powers, R. F. 2005. An adaptive management process for forest soil conservation. Forestry Chron. 81(5):717-722.

Curran, M. P.; Miller, R. E.; Howes, S. W.; Maynard, D. G.; Terry, T. A.; Heninger, R. L; Niemann, T.; van Rees, K.; Powers, R. F.; Schoenholtz, S. H. 2005. Progress towards more uniform assessment and reporting of soil disturbance for operations, research and sustainability protocols. For. Ecol. Manage. 220: 17-30.

Dean, T.; Scott, A.; Newbold, R. 2005. An application of hierarchy theory to long-term sustainability. P. 349-350. In: Peterson, C. E.; Magurie, D. A. (Eds.) Balancing ecosystem values: innovative experiments for sustainable forestry. Gen. Tech. Rep. PNW-GTR-635. USDA Forest Service Pacific Northwest Research Station, Portland, OR.

Devine, W. D.; Harrington, C. A. 2006. Effects of vegetation control and organic matter removal on soil water content in a young Douglas-fir plantation. Res. Pap. PNW-RP-568. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 28 p.

Devine, W. D.; Harrington, C. A. 2007. Influence of harvest residues and vegetation on microsite soil and air temperatures in a young conifer plantation. Agricultural and Forest Meteorology 145: 125-138.

Devine, W. D.; Harrington, C. A.; Terry, T. A. 2005. Volumetric soil water content in 4- and 50-year-old Douglas-fir [*Pseudostuga menziesii* (Mir.) Franco] stand. P. 161-164. In: Harrington, C. A.; Schoenholtz, S. H., (eds.). Proceedings: Productivity of western forests: a forest product focus. Kamilchie, WA. Sept. 20-24. Gen. Tech. Rep. PNW-GTR-642. USDA Forest Service Pacific Northwest Research Station, Portland, OR.

Duarte, N. 2001. Nitrogen form and availability measured with ion exchange resin in a loblolly pine stand on the Coastal Plain of North Carolina. Thesis. 110 p. North Carolina State, University, Raleigh, NC.

Duckert, D. R.; Morris, D. M.; Duego, D.; Duckett, S.; McPherson, S. (In press). Developing site disturbance standards in Ontario: Linking science to forest policy within an adaptive management framework. Canadian Journal of Soil Science.

Duckert, D. R.; Morris, D. M. 2001. Impacts of harvest intensity on long-term site productivity on black spruce ecosystems: An Establishment Report. CNFER Tech. Rep. TR-008. Ontario Ministry Natural Resources.

Eaton, R.; Spaine, P.; Sanchez, F. G. 2006. Harvest intensity and understory control impacts on loblolly pine fusiform rust incidence. P. 61-64. In: Proceedings of the 13th biennial southern silvicultural research conference. Feb. 28-March 4. Memphis, TN. Gen. Tech. Rep. SRS-GTR-92. USDA Forest Service Southern Forest Research Station, Asheville, NC.

Eaton, R.; Smith, W.; Ludovici, K. (In press). Growth response of dominant and co-dominant loblolly pines to organic matter removal, soil compaction, and competition control. Preceedings of the 14th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-GTR. USDA Forest Service Southern Forest Research Station, Asheville, NC.

Eaton, R. J. 1996. Effects of organic matter removal soil compaction, and competition control on collembola populations in a *Pinus taeda* plantation. Thesis. 112 p. North Carolina State University, Raleigh, NC.

Eisenbies, M. H. 2006. Long-term timber productivity research on intensively managed pine forests on the South. P. 139-153. In: Ireland, L. C.; Camp, A. E.; Brissette, J. C.; Donohew, Z. R. (eds). Long-term silvicultural and ecological studies: results for science and management. GISF Res. Pap. 005. Yale University, New Haven, CT.

Eisenbies, M. H.; Burger, J. A.; Aust, W. M.; Patterson, S. C.; Fox, T. R. 2006. Assessing change in soil-site productivity of intensively managed loblolly pine plantations. Soil Sci. Soc. Am. J. 70: 130-140.

Eisenbies, M. H.; Burger, J. A.; Aust, W. M.; Patterson, S. C. 2005. Soil physical disturbance and logging residue effects on changes in soil productivity in five-year-old loblolly pine plantations. Soil Sci. Soc. Am. J. 69: 1833-1843.

Eisenbies, M. H.; Burger, J. A.; Aust, W. M.; Patterson, S. C. (In press). Changes in site productivity and the recovery of soil properties following wet- and dry-weather harvesting disturbances in the Atlantic coastal plain at stand age 10. Canadian Journal of Forest Research.

Eisenbies, M. H. 2004. Loblolly pine and soil-site responses to harvesting disturbance and site preparation at stand closure. Dissertation. Virginia Polytechnic and State University, Blacksburg, VA.

Eisenbies, M. H.; Burger, J. A.; Aust, W. M.; Patterson, S. C. 2004. Loblolly pine response to wet-weather harvesting on wet flats after 5 years. Water, Air, and Soil Pollution 4:217-233.

Eisenbies, M. H.; Burger, J. A.; Xu, Y. J.; Patterson, S. C. 2002. Distribution of slash and litter after wet and dry site harvesting of loblolly pine plantations. P. 510-514. In: Outcalt, K. W. (Ed.) Proceedings of the eleventh biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-48. USDA Forest Service Southern Forest Research Station, Asheville, NC.

Elliot, J. A.; Morris, D. M.; Kantor, J. L. 1993. Studying successional pathways in forest communities: An annotated bibliography. For. Res. Info. Pap. No. 110. Ontario Ministry of Natural Resources.

Elliot, W. J.; Page-Dumroese, D.; Robichaud, P. 1999. The effects of forest management on erosion and soil productivity. P. 195-209. In: Lal, R. (Ed.). Soil quality and soil erosion. Chapter 12. CRC Press.

Flaming, B. L. 2001. Effects of harvest intensity and organic matter removal on nitrogen availability and leaching at a high productivity coastal Douglas-fir site. Thesis. University of Washington, Seattle, WA.

Fleming, R. L.; Laporte, M. F.; Hogan, G. D.; Hazlett, P. W. 2006. Effects of harvesting and soil disturbance on soil CO_2 efflux from a jack pine forest. Can. J. For. Res. 36: 589-600.

Fleming, R. L.; Powers, R. F.; Foster, N. W.; Kranabetter, J. M.; Scott, D. A.; Ponder, Jr., F.; Berch, S.; Chapman, W.; Kabzems, R. D.; Ludovici, K.; Morris, D. M.; Page-Dumroese, D. S.; Sanborn, P. T.; Sanchez, F. G.; Stone, D. M.; Tiarks, A. E. 2006. Effects of organic matter removal, soil compaction, and vegetation control on 5-year seedling performance: a regional comparison of long-term soil productivity sites. Can. J. For. Res. 36: 529-550.

Fleming, R. L.; Foster, N. W.; Jeglum, J. K.; Hazlett, P. W. 1999. Soil compaction and sustainable productivity on coarse-textured jack pine sites. P. 72-81. In: Lowe, A. T.; Smith, C. T. (Comp.). Developing systems for integrating bioenergy into environmentally sustainable forestry. Workshop proceedings of the International Energy Agency Bioenergy Agreement Task 18, 7-11 1998. Nokia, Finland.

Foster, N. W.; Morrison, I. K. 2002. Carbon sequestration by a jack pine stand following urea application. For. Ecol. Manage. 169: 45-52.

Foster, N. W.; Bhatti, J. S.; Arp, P. A. 1997. Long-term site productivity research for developing and validating computer models that contribute to scientifically based codes of practice. P. 203-212. In: Hakkila, P.; Heino, M.; Puranen, E. (Eds.) Forest management and bioenergy, Proceedings of the International Energy Agency Task XII, 9-10 Sept. 1996, Jyvaskyla, Finland, Finnish Forest Research Institute, Vantaa Research Centre, Res. Pap. 640.

Foster, N. W. 1996. Sustainability of nutrient supply to short-rotation jack pine forests for energy. P. 99-106. In: Karau, J., (eds.). Proceedings of the Canadian energy plantation workshop. 2-4 May 1995. Gananoque, Ontario.

Foster, N. W.; Morrison, I. K.; Hazlett, P. W.; Hogan, G. D. 1995. Carbon and nitrogen cycling within mid- and late-rotation jack pine. P. 355-375. In: McFee, W. W.; Kelly, J. M., (eds.). Carbon forms and functions in forest soils. Soil Science Society of America, Inc., Madison, WI.

Foster, N. W.; Morrison, I. K. M.; Hazlett, P. W.; Hogan, G. D.; Salerno, M. I. 1994. Changes in nutrient procurement with age and site productivity in jack pine forest. NZ J. For. Sci. 24: 169-182.

Foster, N. W.; Morrison, I. K. 1989. Effects of site preparation and full tree logging on nutrient cycling. P. 28-46. In: Corbett, P. M. (Compiler). Aspects of site preparation: biology and practice. Ontario Ministry of Natural Resources, Northwestern Ontario Forest Technology Development Unit, Thunder Bay, Ontario. Technical Workshop Report #2.

Gale, M. R.; Powers, R. F.; Boyle, J. R., (eds.). 2005. Forest Soils Research: Theory, Reality, and its Role in Technology Transfer. Elsevier, Amsterdam. 331 p.

Gomez, A.; Power, R. F.; Singer, M. J.; Horwath, W. R. 2002. Soil compaction effects on water status of ponderosa pine assessed through 13C/12C composition. Tree Physiol. 22: 459-467.

Gomez, A.; Power, R. F.; Singer, M. J.; Horwath, W. R. 2002. Soil compaction effects of growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Sci. Soc. Am. J. 66: 1334-1343.

Gomez, A.; Power, R. F.; Singer, M. J.; Horwath, W. R. 2002. N uptake and N status in ponderosa pine as affected by soil compaction and forest floor removal. Plant and Soil 242: 263-275.

Gomez, A.; Horwath, W. R.; Singer, M. J.; Powers, R. F. 1999. Water and nutrient stress in ponderosa pine as a result of soil compaction. Agronomy Abstracts. P. 310. In: International meeting, American Society of Agronomy, Oct. 31-Nov. 4, 1999, Salt Lake City, UT. American Society of Agronomy, Madison, WI.

Gomez, A.; Singer, M. J.; Powers, R. F.; Horwath, W. R. 1998. Effects of soil compaction and forest floor removal on tree growth in California forest. Agronomy Abstracts. P. 303. In: International meeting, American Society of Agronomy, Oct. 18-22, 1998, Baltimore, MD. American Society of Agronomy, Madison, WI.

Gomez-Guerrero, A. 2000. Soil compaction and forest floor removal effects on the initial growth of ponderosa pine in Sierra Nevada forests. Dissertation. University of California, Davis, CA.

Gordon, A. M.; Morris, D. M.; Gordon, A. G. 2001. Ecological considerations in forest regeneration and management. P. 63-90. In: Wagner, R. G.; Columbo, S. J., (eds.). Regenerating the Canadian forest: principles and practice for Ontario. Fitzhenry & Whiteside, Toronto.

Gordon, A. G.; Morris, D. M.; Balakrishnan, N. 1993. Impacts of various levels of biomass removals on the structure, function, and productivity of black spruce ecosystems: Research protocols. Ont. Min. Nat. Res., For. Res. Info. Paper No. 109. Lakehead University, Thunder Bay, Ontario.

Gressel, N. 1996. Linkages between phosphorus and carbon cycling in forest soils. Dissertation. University of California, Berkeley, CA.

Gressel, N.; McColl, J. G.; Preston, C. M.; Newman, R. H.; Powers, R. F. 1996. Linkage between phosphorus transformations and carbon decomposition in a forest soil. Biogeochemistry 33: 97-123.

Gressel, N.; McColl, J. G.; McGrath, A. E.; Powers, R. F. 1995. Spectroscopy of aqueous extracts of forest litter. I: Suitability of methods. Soil Sci. Soc. Am. J. 59: 1715-1723.

Gressel, N.; McColl, J. G.; Powers, R. F. 1995. Carbon decomposition and phosphorus transformations in coniferous forests. Agronomy Abstracts. P. 308. In: International meeting, American Society of Agronomy, Oct. 29-Nov. 3, 1995, St. Louis, MO. American Society of Agronomy, Madison, WI.

Gressel, N.; McColl, J. G.; Powers, R. F.; McGrath, A. E. 1995. Spectroscopy of aqueous extracts of forest litter. II: Effects of management practices. Soil Sci. Soc. Am. J. 59: 1723-1731.

Gressel, N.; McColl, J. G.; Preston, C. M.; Powers, R. F. 1994. Phosphorus and carbon linkage in forest soils: an NMR study. Agronomy Abstracts. P. 376. In: International meeting, American Society of Agronomy, Nov. 13-18, 1994, Seattle, WA. American Society of Agronomy, Madison, WI.

Haeussler, S.; Kabzems, R. 2005. Aspen plant community response to organic matter removal and soil compaction. Can. J. For. Res. 35: 2030-2044.

Haeussler, S.; Bedford, L.; Leduc, A.; Bergeron, Y.; Kranabetter, J. M. 2002. Silvicultural disturbance severity and plan communities of the southern Canadian boreal forests. Silva Fennica 36: 307-327.

Harms, W.; Aust, W. M.; Burger, J. A. 1998. Wet Flatwoods. Chapter 9. P. 421-444. In: Conner, W.; Messina, M., (eds.). Southern Forested Wetlands Ecology and Management. CRC Press-Lewis Publishers.

Harvey, A. E.; Page-Dumroese, D. S.; Jurgensen, M. F.; Graham, R. T.; Tonn, J. R. 1997. Site preparation alters soil distribution of roots and ectomycorrhizae on outplanted western white pine and Douglas-fir. Plant and Soil 188: 107-117.

Harrington, C. A.; Terry, T. A.; Harrison, R. B. 2005. Fall River Long-term Site Productivity Study. P. 169-172. In: Harrington, C. H.; Schoenholtz, S. H. (Eds). Proceedings: Productivity of western forests: A forest products focus. Overview of study areas on field trips. Sept. 20-24, Kamilchie, WA. Gen. Tech. Rep. PNW-GTR-42. USDA Forest Service Pacific Northwest Research Station, Portland, OR.

Hassett, J. E.; Zak, D. R. 2005. Aspen harvest intensity decreases microbial biomass, extracellular enzyme activity and soil nitrogen cycling. Soil Sci. Soc. Am. J. 69: 227-235.

Hayes, J. P.; Schoenholtz, S. H.; Hartley, M. J.; Murphy, G.; Powers, R. F.; Berg, D.; Radosevich, S. R. 2005. Environmental consequences of intensively managed forest plantations in the Pacific Northwest. Journal of Forestry 103(2): 83-87.

Hazlett, P. W.; Foster, N. W.; Morrison, I. K.; Yin, X. 1996. Impact of varying N and S deposition on nutrient cycling in jack pine ecosystems. P. 83-95. In: Cox, R.; Percy, K.; Jensen, K.; Simpson, C., (eds.). Air pollution and multiple stress. Proceedings of the 16th IUFRO international meeting for specialists in air pollution effects on forest ecosystems. Sept. 7-9, 1994. Fredericton, New Brunswick.

Hoepting, M. K. 2006. Carbon and nitrogen dynamics associated with post-wildfire stand development of boreal mixed conifer ecosystems: applications of data in model validation and refinement. Thesis. Lakehead University, Thunder Bay, Ontario.

Hoepting, M. K. 2000. Use of the CENTURY model to predict the effects of climate change on a black spruce forest in northwestern Ontario. Thesis. Lakehead University, Thunder Bay, Ontario.

Holcomb, R. W. 1996. The Long-Term Soil Productivity Study in British Columbia. Canadian Forest Service and British Columbia Ministry of Forests. FRDA report 256. 23p. http://www.for.gov.bc.ca/hfd/pubs/docs/Frr/Frr256.pdf

Hope, G. 2006. Establishment of Long-term Soil Productivity Studies on Acidic Soils in the Interior Douglas-fir Zone. British Columbia Ministry of Forests. LTSPS Research Note 08. 4 p.

Hudnall, W. H.; Tiarks, A. E.; Waddell, W. C.; Patterson, W. B. 1995. Soil water relationships within the long-term forest management plots, USFS, Louisiana. P. 85-89. In: Selim, H. M.; Brown, W. H., (eds.). Proceedings, conference on environmental issues at the LSU Agricultural Center. July 24-25, 1995. Louisiana State University, Baton Rouge, LA.

Hunt, S. L.; Gordon, A. M.; Morris, D. M. 2005. Aspects of ecological development in managed stands of jack pine and black spruce in northern Ontario: Understory vegetation and nutrient relations. For. Chron. 81: 61-72.

Hunt, S. 2003. Carbon dynamics in jack pine and black spruce plantations: relationship to stand age and site quality. Dissertation. University of Guelph, Guelph, Ontario.

Hunt, S. L.; Gordon, A. M.; Morris, D. M.; Marek, G. T. 2003. Understory vegetation in northern Ontario jack pine and black spruce plantations: 20-year successional changes. Can. J. For. Res. 33: 1791-1803.

Jeglum, J. K.; Kershaw, H. M.; Morris, D. M.; Cameron, D. A. 2003. Best forestry practices: a guide for the boreal forest of Ontario. Cat. # Fo124-1/2003E. Great Lakes Forestry Centre, Canadian Forest Service, Sault Ste. Marie, Ontario. 110 p.

Johnsen, K. H.; Teskey, B.; Samuelson, L.; Butnor, J.; Sanchez, F.; Sampson, D.; Maier, C.; McKeand, S. 2003. Carbon sequestration in loblolly pine plantations: methods, limitations and research needs for estimating storage pools. P. 373-381. In: Johnsen, K.; Rauscher, H. M.; Hubbard, W. G., (eds.). Southern Forest Science Conference Proceedings. November 26-28. Atlanta, GA.

Johnsen, K. H.; Wear, D.; Oren, R.; Teskey, R. O.; Sanchez, F.; Will, R.; Butnor, J.; Markewitz, D.; Richter, D.; Rials, T.; Allen, H. L.; Seiler, J.; Ellsworth, D.; Maier, C.; Katul, G.; Dougherty, P. M. 2001. Carbon sequestration via southern pine forestry. J. For. 99(4): 14-21.

Jordan, D.; Ponder, F., Jr.; Hubbard, V. C. 2003. Effects of soil compaction, forest litter and nitrogen fertilizer on two oak species and microbial activity. Appl. Soil Ecol. 23: 33-41.

Jordan, D.; Hubbard, V. C.; Ponder, F., Jr.; Berry, E. C. 2000. The influence of soil compaction and the removal of organic matter on two native earthworms and soil properties in an oak-hickory forest. Biol. Fertil. Soils 31: 323-328.

Jordan, D.; Hubbard, V. C.; Ponder, F., Jr.; Berry, E. C. 1999. Effect of soil compaction and organic matter removal on two earthworm populations and some soil properties in a hardwood forest. Pedobiologia 43: 802-807.

Jordan, D.; Li, F.; Ponder, F., Jr.; Berry, E. C.; Hubbard, V. C.; Kim, K. Y. 1999. The effects of forest practices on earthworm population and soil microbial biomass in a hardwood forest in Missouri. Appl. Soil Ecol. 13: 31-38.

Jurgensen, M.; Page-Dumroese, D.; Laks, P.; Collins, A.; Reed, D.; Crawford, D. 2003. Chemical, physical and biological factors affecting wood decomposition in forest soils. In: 34th Annual international research group on wood preservation-section 2: test methodology and assessment. Published proceedings IRG/WP 03-03-20281.

Jurgensen, M.; Laks, P.; Reed, D.; Collins, A.; Page-Dumroese, D.; Crawford, Douglas. 2004. Chemical, physical and biological factors affecting wood decomposition in forest soils. IRG documents 2003: IRG 35, 6-10 June 2004, Ljubljana, Slovenia. Stockholm, Sweden: IRG Scretariat. 2004: 14 p.

Kabzems, T.; Haeussler, S. 2005. Soil properties, aspen, and white spruce responses 5 years after organic matter removal and compaction. Can. J. For. Res. 35: 2045-2055.

Kabzems, R. 2002. Aspen and white spruce responses to organic matter removal and soil compaction in the BWBS long-term soil productivity study. British Columbia Ministry of Forests. LTSPS Research Note 06. http://www.for.gov.bc.ca/hfd/pubs/Docs/Ltsps/Rrn006.pdf.

Kabzems, R. 2000. Fourth year responses of aspen and white spruce; the BWBS Long-Term Soil Productivity Study. British Columbia Ministry of Forests, LTSPS Research Note 02. 4 p. http://www.for.gov.bc.ca/hfd/pubs/Docs/Ltsps/Rrn002.pdf.

Kabzems, R. 2000. Fourth-year plant community responses: the BWBS long-term soil productivity study. British Columbia Ministry of Forests, LTSPS Research Note 03. 4 p. http://www.for.gov.bc.ca/hfd/pubs/Docs/Ltsps/Rrn003.pdf.

Kamaluddin, M.; Chang, S. X.; Curran, M. P.; Zwiazek, J. J. 2005. Soil compaction and forest floor removal affect early growth and physiology of lodge pole pine and Douglas-fir in British Columbia. For. Sci. 51: 513-521.

Kelting, D. L.; Burger, J. A.; Patterson, S. C. 2000. Early loblolly pine growth response to charges in the soil environment. NZ J. For. Sci. 30: 206-244.

Kelting, D. L. 1999. Timber harvesting and site preparation effects on soil quality for loblolly pine growing on the lower coastal plain of South Carolina. Dissertation. 197 p. Virginia Polytechnic and State University, Blacksburg, VA.

Kelting, D. L.; Burger, J. A.; Patterson, S. C.; Aust, W. M.; Miwa, M. 1999. Soil quality assessment in domesticated forests: a southern pine example. For. Ecol. Manage. 122: 167-185.

Kershaw, H. M.; Jeglum, J. K.; Morris, D. M. 1996. Long-term productivity of boreal forest ecosystems. II. Survey of expert opinion on the impact of forestry practices in boreal forest ecosystems. NODA/NFP Tech. Rep. TR-23. Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie, Ontario. 21 p.

Klos, R. J. 2001. Effects of varying climate regimes on respiration and net primary production in a black spruce ecosystem using CENTURY. Thesis. Lakehead University, Thunder Bay, Ontario.

Kranabetter, J. M.; Sanborn, P.; Chapman, B. K.; Dube, S. 2006. The contrasting response to soil disturbance between lodgepole pine and hybrid white spruce in subboreal forests. Soil Sci. Soc. Am. J. 70: 1591-1599.

Kranabetter, J. M.; Chapman, B. K. 2004. An analysis of litter nitrogen dynamics using artificial soils across a gradient of forest soil disturbances. Can. J. Soil Sci. 84: 159-167.

Kranabetter, J. M.; Sanborn, P. 2003. Short-term effects of forest soil compaction and site organic matter removal on mineralizable soil nitrogen in Central British Columbia. British Columbia Ministry of Forests. LTSPS Research Note 07. 6 p. http://www.for.gov.bc.ca/hfd/pubs/Docs/Ltsps/Rrn007.pdf.

Kranabetter, J. M. 1999. Second year response of plant communities; the SBS Long-term Soil Productivity Study. British Columbia Ministry of Forests, LTSPS Research Note 01. 4 p. http://www.for.gov.bc.ca/hfd/pubs/Docs/Ltsps/Rrn001.pdf.

Kranabetter, J. M.; Chapman, B. K. 1999. Effects of forest soil compaction and organic matter removal on leaf litter decomposition in central British Columbia. Can. J. Soil Sci. 79: 543-550.

Laiho, R.; Sanchez, F.; Tiarks, A.; Doughtery, P.; Trettin, C. 2003. Impacts of intensive forestry on early rotation trends in site carbon pools in the southeastern U.S. For. Ecol. Manage. 174: 177-189.

Lankford, G. K. 1995. Effects of soil compaction and harvest removals on vegetation and soils in a loblolly pine plantation. Thesis. 82 p. North Carolina State University, Raleigh, NC.

Leblanc, J.-D.; Fleming, R. L.; Foster, N. W.; Hazlett, P. W.; Weldon, T. P.; Cameron, D. A. 2004. Effects of logging method, scarification and vegetation control on jack pine plantation establishment. Forest Research Partnership. Report 021. http://forestrresearch.ca/product_catalogue/reports.htm.

Li, Q.; Allen, H. L.; Wilson, C. A. 2003. Nitrogen mineralization dynamics following the establishment of a loblolly pine plantation. Can. J. For. Res. 33: 364-374.

Li, F. 1996. Earthworm activity affected by organic matter removal soil compaction in a central hardwood forest. Thesis. University of Missouri, Columbia.

Licata, C. W. 2004. Nitrogen mineralization in a coastal Washington Douglas-fir plantation under two levels of logging slash and coarse woody debris retention. Thesis. University of Washington, Seattle, WA.

Lister, T. W.; Burger, J. A.; Patterson, S. C. 2004. Role of vegetation in mitigating soil quality impacted by forest harvesting. Soil Sci. Soc. Am. J. 68: 263-271.

Lister, T. W. 1999. Forest harvesting disturbance and site preparation effects on soil processes and vegetation in a young pine plantation. Thesis. 104 p. Virginia Polytechnic and State University, Blacksburg, VA.

Luckai, N. 2004. Effects of stand age, disturbance type and harvest intensity on soil microbial biomass in (*Picea mariana* (Mill.) B.S.P.) ecosystems in northwestern Ontario. Dissertation. University of Guelph, Guelph, Ontario.

Ludovici, K. 2008. Compacting Coastal Plain soils changes midrotation loblolly pine allometry by reducing root biomass. Can. J. For. Res. 38: 2169-2176.

Lynham, T. J.; Alexander, M. E.; Morris, D. M.; Kantor, J. L. 2002. Ecological effects of forest fires in the boreal and Great Lakes- St. Lawrence forest regions of Ontario: A partially annotated bibliography. Info. Rep. GLC-X-6. Natural Resources Canada. Canadian Forest Service, Sault Ste. Marie, Ontario.

Mariani, L.; Chang, S. X.; Kabzems, R. 2006. Effects of tree harvesting, forest floor removal and compaction on soil microbial biomass, microbial respiration, and N availability in a boreal aspen forest in British Columbia. Soil Biology & Biochemistry 38: 1734-1744.

Maynard, D. G.; Curran, M. P. 2007. Bulk density measurements in forest soils. Chapter 66, p. 863-869 in M. R. Carter and E. G. Gregorich, editors. Soil sampling and methods of analysis (2nd edition). CRC Press, Taylor and Francis Group, Boca Raton, FL.

Mellin, T. C. 1995. The effects of intensive forest management practices on the communities of loblolly pine plantations in North Carolina. Thesis. 71 p. North Carolina State University, Raleigh, NC.

Metsaranta, J. 1999. Use of the CENTURY model to assess long-term forest management impacts on forest productivity and nitrogen dynamics in a northwestern Ontario black spruce forest. Thesis. Lakehead University, Thunder Bay, Ontario.

Mitchell, B. 1998. Applying the CENTURY model to forest ecosystems: Calibration and sensitivity analysis. Thesis. Lakehead University, Thunder Bay, Ontario.

Miwa, M.; Aust, W. M.; Burger, J. A.; Patterson, S. C.; Carter, E. C. 2004. Wet weather timber harvesting and site preparation effects on coastal plain sites: a review. South. J. Appl. For. 28: 137-151.

Miwa, M. 1999. Physical and hydrologic response of wet flats to timber harvest disturbance. Dissertation. 250 p. Virginia Polytechnic and State University, Blacksburg, VA.

Miwa, M.; Aust, W. M.; Burger, J. A.; Patterson, S. C. 1998. Characterization of disturbed forest soils in the lower coastal plain of South Carolina. P. 379-385. In: Outcalt, K. W. (Ed.). Proceedings, ninth biennial southern silvicultural research conference. Feb. 25-27. Clemson, SC. USDA Forest Service Southern Forest Research Station, Asheville, NC.

Morris. D. M. 2009. Changes in DOC and DON fluxes in response to harvest intensity of black spruce-dominated forest ecosystems in northwestern Ontario. Canadian Journal of Soil Science. 89: 67-79.

Morris, D. M.; Mackereth, R. W.; Duckert, D. R.; Hoepting, M. K. (In review). The Influence of soil rutting severity on regeneration potential and seedling performance for black spruce-dominated forest ecosystems in northwestern Ontario. Canadian Journal of Soil Science.

Morris, D. M. 2004. Elemental storage and cycling in boreal mixedwoods. Ontario Ministry Natural Resources, Boreal Mixedwood Notes, No. 29.

Morris, D. M.; Gorgon, A. G.; Gordon, A. M. 2003. Patterns of canopy interception and throughfall along topographic sequence for black spruce dominated forest ecosystems in northwestern Ontario. Can. J. For. Res. 33: 1046-1060.

Morris, D. M. 2000. Biogeochemical cycling of macroelements in black spruce (*Picea mariana* (Mill.) B.S.P.) ecosystems: quantifying precipitation and litterfall fluxes. Dissertation. University of Guelph, Guelph, Ontario.

Morris, D. M.; Ducket, D. R. 1999. Studying the impacts of harvest intensity on site productivity of Ontario's black spruce ecosystems. For. Chron. 75: 439-445.

Morrison, I. K. 2003. Decomposition and element release from confined jack pine needle litter on and in the feathermoss. Can. J. For. Res. 33: 16-22.

Morrison, I. K; Foster, N. W.; Hazlett, P. W. 1993. Carbon reserves, carbon cycling, and harvest effects in three mature forest types in Canada. NZ J. For. Sci. 23: 403-412.

Morrison, I. K.; Foster, N. W. 1990. On fertilizing semimature jack pine stands in the boreal forest of central Canada. P. 416-431. In: Gressel, S. P.; et al. Sustained productivity of forest soils. Proc. 7th North American forest soils conference. 24-28 July 1988, Vancouver, BC. Faculty of Forestry, University of British Columbia, Vancouver, BC.

Mungoven, M. J. 1996. Compaction effects on physical properties of three forest soils in the upper Great Lakes region. Thesis. 78 p. University of Wisconsin, Madison.

Page-Dumroese, D.; Jurgensen, M.; Elliot, W.; Rice, T.; Nesser, J.; Collins, T.; Meurisse, R. 2000. Soil quality standards and guidelines for forest sustainability in northwestern North America. For. Ecol. Manage. 138: 445-462.

Page-Dumroese, D. S. 1993. Susceptibility of volcanic ash soils to compaction in northern Idaho. INT-RN-409. USDA Forest Service, Intermountain Research Station, Ogden, UT. 5 p.

Page-Dumroese, D. S.; Harvey, A. E.; Jurgensen, M. F.; Amaranthus, M. P. 1996. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. Can. J. Soil Sci. 78: 29-34.

Page-Dumroese, D. S.; Jurgensen, M. F.; Harvey, A. E. 1994. Relationships among woody residues, soil organic matter, and ectomycorrhizae in the cedar hamlock ecosystem. P. 85-91. In: Baumgartner, D. (Ed.). Interior cedar-hamlock-white pine forests: ecology and management. March 2-4, 1993. Spokane, WA. Washington State University, Pullman.

Page-Dumroese, D. S.; Jurgensen, M. F.; Harvey, A. E. 2003. Fire and fire-suppression impacts on forest soil carbon. P. 201-210. In: Kimble, J. M.; Heath, L. S.; Birdsey, R. A.; Lal, R., (eds.). The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. Chapter 13. CRC Press.

Page-Dumroese, D. S.; Jurgensen, M. F.; Harvey, A. E.; Graham, R. T.; Tonn, J. R. 1997. Soil change and tree seedling response associated with site preparation in northern Idaho. West. J. Appl. For. 12: 81-88.

Page-Dumroese, D. S.; Jurgensen, M. F.; Tiarks, A. E.; Ponder, F., Jr.; Sanchez, F. G.; Fleming, R. L.; Kranabetter, J. M.; Powers, R. F.; Stone, D. M.; Elioff, J. D.; Scott, D. A. 2006. Soil physical property changes at the North American long-term soil productivity sites: 1 and 5 years after compaction. Can. J. For. Res. 36: 551-564.

Parker, R. T.; Maguire, D. A.; Marshall, D. D.; Cochran, P. 2007. Ponderosa pine growth response to soil strength in the volcanic ash soils of central Oregon. West. J. Appl. For. 22: 134-141.

Paz, L. W. 2001. Soil-water characteristics and hydrologic implications following forest soil disturbance: The relative influence of organic residue and soil compaction on permeability and moisture capacity- a study on Cohasset soil in the Sierra Nevada mixed conifer zone. Ph.D. dissertation. University of California, Berkeley, CA.

Petersen, K. 2005. The effects of vegetation control on the early growth of Douglas-fir at a high quality site in coastal Washington. Thesis. University of Washington, Seattle, WA.

Ponder, F., Jr. 2005. Effects of soil compaction and biomass removal on soil CO_2 efflux in a Missouri forest. Commun. Soil Science and Plant Analysis 36: 1301-1311.

Ponder, F., Jr. 2004. Soil compaction affects growth of young shortleaf pine following litter removal and week control in the Missouri Ozarks. P. 225-264. In: Proceedings, 14th central hardwood forest conference; 2004 March 16-19; Wooster, OH. Gen. Tech. Rep. NE-316. U. S. Department of Agriculture, Forest Service, North Central Research Station, Newton Square, PA.

Ponder, F., Jr. 2003. Effect of site treatment on soil temperature and oak and pine growth and nutrient concentrations. P. 213-222. In: Van Sambeek, J. W.; Dawson, J. O.; Ponder, F., Jr.: Loewenstien, E. F.; Fralish, J. S. (Eds.) Proceedings, 13th central hardwood forest conference; 2002 April 1-3; Urvana. Gen. Tech. Rep. NC-234. USDA Forest Service, North Central Research Station, St. Paul, MN.

Ponder, F., Jr.; Tardos, M. 2002. Phospholipid fatty acids in forest soil four years after organic matter removal and soil compaction. Appl. Soil Ecol. 19: 173-182.

Ponder, F., Jr.; Li, F.; Jordan, D. Berry, E. C. 2000. Assessing the impact of *Diplocardia ornate* on physical and chemical properties of compacted forest soil in microcosms. Biol. Fertil. Soil 32: 166-172.

Ponder, F., Jr.; Alley, D. E.; Jordan, D.; Swartz, M. E.; Hubbard, V. C. 1999. Impacts of harvest intensity and soil disturbance on early tree growth and earthworm populations in a Missouri Ozark Forest. P. 121-127. In: Stringer, J. W.; Loftis, D. L. (Eds.) Proceedings 12th central hardwood forest conference: 1999 February 28- March 2: Lexington, KY. Gen. Tech. Rep. SRS-24. USDA Forest Service Southern Forest Research Station, Ashville, NC.

Ponder, F., Jr. 1997. Initiation long-term soil productivity research in Missouri. P. 370-378. In: Brookshire, B. L.; Shifley, S. R., (Eds.). Proceedings of the Missouri Ozark forest ecosystem project symposium: An experimental approach to landscape research: 1997 June 3-5: St. Louis, MO. Gen. Tech. Rep. NC-193. USDA Forest Service North Central Forest Experiment Station, St. Paul, MN.

Ponder, F., Jr.; Alley, D. E. 1997. Soil sampler for rocky soils. Res. Note NC-371. USDA Forest Service North Central Forest Experimental Station, St. Paul, MN. 5 p.

Ponder, F. Jr.; Mikkelson, N. M. 1995. Characteristics of a long-term forest soil productivity site in Missouri. P. 272-281. In: Proceedings, 10th central hardwood forest conference, Morgantown, WV. March 5-8, 1995.

Powers, R. F. 2006. Long-term soil productivity: genesis of the concept and principles behind the program. Can. J. For. 36(3): 516-528.

Powers, R. F.; Scott, D. A.; Sanchez, F. G.; Voldseth, R. A.; Page-Dumroese, D. S.; Elioff, J. D.; Stone, D. M. 2005. The North American long-term soil productivity experiment: findings from the first decade of research. For. Ecol. Manage. 220(1-3): 31-50.

Powers, R. F.; Sanchez, F. G.; Scott, D. A.; Page-Dumroese, D. 2004. The North American long-term soil productivity experiment: coast-to-coast findings from the first decade. P. 191-206. In: Shepperd, W. D.; Eskew, L. G., (comps.). Silviculture in special places: Proceedings of the national silviculture workshop; 2003 September 8-11; Granby, CO. Proceedings RMRS-P-34. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO.

Powers, R. F. 2002. Effects of soil disturbance on fundamental, sustainable productivity of managed forests. P. 63-82. In: Verner, J., (comp.). The Kings River Sustainable Ecosystem Project. USDA Forest Service. Gen. Tech. Rep. PSW-GTR-183. Pacific Southwest Research Station, Albany, CA.

Powers, R. F. 2001. Assessing potential sustainable wood yield. Chapter 5. P. 105-128. In: Evans, Julian (ed.) The forests handbook. Blackwell Science, Oxford, UK.

Powers, R. F.; Hauxwell, D. L; Nakamura, G. O., (eds.). 2000. Forest soils biology and forest management. USDA Forest Service Gen. Tech. Rep. PSW-GTR-178. Pacific Southwest Research Station, Albany, CA. 113 p.

Powers, R. F. 1999. If you build it, will they come? Survival skills for silvicultural studies. Forestry Chron. 75: 367-373.

Powers, R. F. 1999. On the sustainability productivity of planted forests. New Forests 17: 253-306.

Powers, R. F.; Alves, T. M.; Spear, T. H. 1999. Soil compaction: can it be mitigated? Reporting a work in progress. P. 47-56. In: Proceedings, 20th annual forest vegetation management conference, Redding, CA.

Powers, R. F.; Aune, P. S. 1998. Communicating silviculture: values and benefits for the new millennium. P. 3-9. In: Communication the role of silviculture in managing the national forests. Gen. Tech. Rep. NE-238. USDA Forest Service Northeastern Forest Experiment Station. Randor, PA.

Powers, R. F.; Tiarks, A. E.; Boyle, J. R. 1998. Assessing soil quality: practicable standards for sustainable forest productivity in the United States. P. 53-80. In: Adams, M. B.; Ramakrishna, K.; Davidson, E. A., (eds.). Criteria and indicators of soil quality for sustainable forest productivity. Spec. Publ. 53, Soil Sci. Soc. Am., Madison, WI.

Powers, R. F.; Fiddle, G. O. 1997. The North American long-term soil productivity study: progress through the first 5 years. P. 88-102. In: Proceedings, 18th Annual Forest Vegetation Conference, Redding, CA.

Powers, R. F.; Morrison, I. K. 1996. Soil and sustainable forest productivity: a preamble. Soil Sci. Soc. Am. J. 60: 1613.

Powers, R. F.; Tiarks, A. E.; Burger, J. A.; Carter, M. C. 1996. Sustaining the productivity of planted forests. P. 97-134. In: Carter, M. C. (Ed.). Proceedings, 35th forestry symposium: Growing trees in a greener world: Industrial forestry in the 21st century. School of Forestry, Wildlife and Fisheries, Louisiana State University, Baton Rouge, LA.

Powers, R. F.; Avers, P. E. 1995. Sustaining forest productivity through soil quality standards: a coordinated U.S. effort. P. 147-190. In: Abboud, S. A.; McGill, W. B., (eds.). Environmental soil science: anthropogenic chemicals and soil quality criteria. Can. Soc. Soil Sci. Brandon, Manitoba.

Powers, R. F.; Tiarks, A. E.; Boyle, J. R. 1995. Soil properties as indicators of soil quality and forest health: a critique. Agron. Abstr. P. 312. In: International meeting, American Society of Agronomy, Oct. 29-Nov. 3, 1995, St. Louis, MO. American Society of Agronomy, Madison, WI.

Powers, R. F.; Tiarks, A. E.; Buford, M. A. 1995. Influence of site disturbance on fundamental productivity and soil processes in pine plantations of the U.S.: the "LTSP experiment." P. 68-70. In: Gaskin, R. E.; Zabkiewicz, J. A., (comp.) Proceedings, 2nd International Conference on Forest Vegetation Management; 20-24 March, 1995: Rotorua, New Zealand. FRI Bull. 192. Forest Res. Inst., Rotorua, New Zealand.

Powers, R. F.; Mead, D. J.; Burger, M. W.; Ritchie, M. W. 1994. Designing long-term site productivity experiments. P. 247-286. In: Dyck, W. J.; Cole, D. W.; Comerford, N. B., (eds.). Impacts of forest harvesting on long-term site productivity. Chapman & Hill, London.

Powers, R. F. 1992. Are we maintaining the productivity of forest lands? Establishing guidelines through a network of long-term studies. P. 240-248. In: Pacific Rim forestry—bridging the world. Proceedings, 1991 annual convention, Society of American Foresters. August 1991, San Francisco, CA. Society of American Foresters, Bethesda, MD.

Powers, R. F. 1992. Soil as a controlling factor in forest health and sustainability. P. 6-8. In: Proceedings, 40th anniversary meeting, California Forest Pest Council. Sacramento, CA. November 1991. Forest Pest Council, San Francisco, CA.

Powers, R. F. 1991. Are we maintaining productivity of forest lands? Establishing guidelines through a network of long-term studies. P. 70-81. In: Harvey, A. E.; Neuenschwander, L. F. (comps.). Proceedings, symposium on management and productivity of western-montane forest soils. Boise, ID. April 1990. Gen. Tech. Rep. INT-280. USDA Forest Service Intermountain Research Station, Ogden, UT.

Powers, R. F. 1991. Do timber management operations degrade long-term productivity? A research and national forest systems cooperative study. P. 101-115. In: Proceedings, national silviculture workshop. Petersburg, AK. July 1989. USDA Forest Service, Timber Management, Washington, DC.

Powers, R. F. 1990. Are we maintaining productivity of forest lands? Establishing guidelines through a cooperative national program. P. 98-112. In: Schwitzer, D. L.; MacNaughton, M. J., (comps.). Proceedings, national workshop on monitoring Forest Plan implementation. Minneapolis, MN. May 1990. USDA Forest Service Land Management Planning, Washington, DC.

Powers, R. F. 1990. Designed stress experiments to evaluate the impacts of management practices on long-term site productivity. P. 39-40. In: Proceedings, forestry and the world around us. 1989 Western forestry conference. December 1989, Sacramento, CA. Western Forestry & Conservation Assoc. Portland, OR.

Powers, R. F. 1990. Forest soils research to meet changing future needs. P. 91. In: Abstracts, 1990 annual meeting of the American Association for the Advancement of Science, New Orleans, LA.

Powers, R. F. 1990. The soil as a fundamental resource. P. 4-5. In: Powers, R. F., (ed.). Sustaining site productivity of forest lands. A user's guide to good soil management. Publ. 21481. Division of Agriculture and Natural Recourses, University of California, Oakland, CA.

Powers, R. F. 1990. Sustaining site productivity on forestlands: A user's guide to good soil management. Publ. 21481. Division of Agriculture and Natural Resources. University of California, Oakland, CA. 30 p.

Powers, R. F.; Alban, D. H.; Miller, R. E.; Tiarks, A. E.; Wells, C. G.; Avers, P. E.; Cline, R. G.; Fitzgerald, R. O.; Loftus, N. S., Jr. 1990. Sustaining site productivity in North America: problems and prospects. P. 49-79. In: Gressel, S. P.; Lacate, D. S.; Weetman, G. F.; Powers, R. F., (eds.). Sustained productivity of forest soils. Proceedings, 7th North American forest soils conference. July 1988, Vancouver, BC. Faculty of Forestry, University of British Columbia, Vancouver, BC.

Powers, R. F.; Alban, D. H.; Ruark, G. A.; Tiarks, A. E. 1990. A soils research approach to evaluating management impacts on long-term productivity. P. 127-145. In: Dyck, W. J.; Mees, C. J., (eds.). Impacts of intensive harvesting on forest site productivity. IEA/BE T6/A6 Rep. No. 2. FRI Bull. No. 159. Forest Research Institute, Rotorua, New Zealand.

Powers, R. F. 1989. Maintaining long-term forest productivity in the Pacific Northwest: defining the issues. P. 3-16. In: Perry, D. A.; Meurisse, R.; Thomas, B.; Miller, R.; Boyle, J.; Means, J.; Perry, C. R.; Powers, R. F., (eds.) Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Timber Press, Inc. Portland, OR.

Powers, R. F.; Goudey, C.; Ragus, J.; Tiarks, A.; Alban, D.; Ruark, G. 1989. A proposed national study: Evaluating timber management impact on long-term soil productivity: a Research and National Forests Systems cooperative study. P. 121-138. In: Proceedings, 1989 National soil and water monitoring workshop. March 1989, Sacramento, CA. WO-WSA-1. USDA Forest Service, Washington, DC.

Preston, D. P. 1996. Harvesting effects on the hydrology of wet pine flats. Thesis. 126 p. Virginia Polytechnic and State University, Blacksburg, VA.

Ratcliff, A. W.; Busse, M. D.; Shestak, C. J. 2006. Changes in microbial community structure following herbicide (glyphosate) additions to forest soils. Applied Soil Ecology 34: 114-124.

Risch, A.; Jurgensen, M. F.; Page-Dumroese, D. S.; Schutz, M. 2004. Above- and below- ground carbon and nutrient pools during succession following land use change in subalpine ecosystems of the Central European Alps. In: Risch, A. C., (ed.). Above- and below-ground patterns and processes following land use change in subalpine conifer forests of the Central European Alps. Thesis No. 15368, ETH Zurich, Switzerland.

Roberts, S.; Harrington, C.; Terry, T. 2005. Harvest residue and competing vegetation affect soil moisture, soil temperature, N availability, and Douglas-fir growth. Forest Ecology Manage. 205: 333-350.

Ross, J. 2007. The effects of harvest intensity on regeneration potential and black spruce seedling performance on black spruce-dominated ecosites: 10th year results. Thesis. Lakehead University, Thunder Bay, Ontario.

Sampson, M. T. 2007. Saving the soil. Lessons from the long-term soil productivity experiment. Science Perspectives (summer 2007). Pacific Southwest Research Station, USDA Forest Service, Berkeley, CA. 5 p.

Sanborn, P.; Kranabetter, M.; Chapman, B. 2000. Nutrient removals in woody biomass: preliminary estimates from the sub-boreal spruce long-term soil productivity study. British Columbia Ministry of Forests. LTSPS Research Note 04. 6 p. http://www.for.gov.bc.ca/hfd/pubs/Docs/Ltsps/Rrn004.pdf

Sanchez, F. G.; Scott, D. A.; Ludovici, K. H. 2006. Negligible effects of severe organic matter removal and soil compaction on loblolly pine growth over 10 years. For. Ecol. Manage. 227: 145-154.

Sanchez. F. G.; Tiarks, A. E.; Kranabetter, J. M.; Page-Dumroese, D. S.; Powers, R. F.; Sanborn, P. T.; Chapman, W. K. 2006. Effects of organic matter removal and soil compaction on fifth-year mineral soil carbon and nitrogen contents for sites across the United States and Canada. Can. J. For. Res. 36: 565-576.

Scheerer, G. A. 1994. Site preparation effectiveness in the amelioration of compaction and rutting damage on wetland sites of the South Carolina lower coastal plain. M.S. Thesis. 132 p. Virginia Polytechnic and State University, Blacksburg, VA.

Scott, D. A.; Novosad, J.; Goldsmith, G. (In press). Long-term soil productivity of western Gulf loblolly pine plantations. In: M. Furniss, (ed.). Proc. Advancing the Fundamentals of Science Conference. Gen. Tech. Rep. PNW-GTR-USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Scott, D. A.; Dean, T. J. 2006. Energy trade-offs between intensive biomass utilization, site productivity loss, and ameliorative treatments in loblolly pine plantations. Biomass and Bioenergy 30: 1001-1010.

Scott, D. A.; Burger, J. A.; Crane, B. S. 2006. Expanding site productivity research to sustain non-timber forest functions. For. Ecol. Manage. 227: 185-192.

Scott, D. A.; Stagg, R. H.; Smith, M. A., Jr. 2006. A non-destructive method for quantifying small-diameter woody biomass in southern pine forests. P. 358. In: Connor, K. F., (ed.). Proc. of the 13th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-GTR-92. USDA Forest Service Southern Research Station, Asheville, NC.

Scott, D. A.; Sanchez, F. G. 2005. Long-term soil productivity of southern coastal plain pine forests. Agron. Abstr. 288-3 (CD). International meeting of the American Society of Agronomy, Nov. 6-10, 2005, Salt Lake City, UT. American Society of Agronomy, Madison, WI.

Scott, D. A.; Tiarks, A. E.; Sanchez, F. G.; Elliott-Smith, M. L.; Stagg, R. H. 2004. Forest soil productivity on the long-term soil productivity sites at age 5. P. 372-377. In: Connor, K. F., (ed.). Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-71. USDA Forest Service Southern Forest Research Station, Asheville, NC.

Scott, D. A. 2003. Soil Recovery from compaction with and without residue retention and weed control in loblolly pine stands. Agronomy Abstracts. International meeting of the American Society of Agronomy, Nov. 1-6, 2003, Denver, CO. American Society of Agronomy, Madison, WI.

Shea, R. W. 1993. Effects of prescribed fire and silviculture activities on fuel mass and nitrogen redistribution in *Pinus ponderosa* ecosystems of central Oregon. Thesis. 132 p. Oregon State University, Corvallis, OR.

Shestak, C. J.; Busse, M. D. 2005. Compaction alters physical but not biological indices of soil health. Soil Sci. Soc. Am. J. 69: 236-246.

Siegel, C. M. (In progress). Validation of root growth models for compacted forest soils. Dissertation. Virginia Polytechnic and State University, Blacksburg, VA.

Siegel, C. M.; Burger, J. A.; Powers, R. F. 1998. Root growth opportunity as a function of soil strength and moisture for several forest soils and tree species. Agronomy Abstracts. P. 301. In: International meeting of the American Society of Agronomy, Oct. 18-22, 1998, Baltimore, MD. American Society of Agronomy, Madison, WI.

Siegel, C. M.; Powers, R. F.; Spear, T. H. 1994. Compaction and weed competition affect soil strength, moisture availability and growth of young conifers on contrasting soils. Agronomy

Abstracts. P. 381. In: International Meeting of the American Society of Agronomy, Nov. 13-18, 1994. Seattle, WA. American Society of Agronomy, Madison, WI.

Siegel-Issem, C. M.; Burger, J. A.; Powers, R. F.; Ponder, F.; Patterson, S. C. 2005. Seedling root growth as a function of soil density and water content. Soil Sci. Soc. Am. J. 69: 215-226

Strahm, B. D.; Harrison, R. B. 2007. Mineral and organic matter controls on the sorption of macronutrient anions in variable-charge soils. Soil Sci. Soc. Am. J. 71: 1926-1933.

Siegel-Issem, C. M.; Scott, D. A.; Burger, J. A. 2004. Spatial heterogeneity of soil strength, bulk density and tree volume response in compacted loblolly pine plantations. Agronomy Abstracts. P. 400. In: International Meeting of the American Society of Agronomy, Oct. 31- Nov. 4, 2004. Seattle, WA. American Society of Agronomy, Madison, WI.

Siegel-Issem, C. M. 2002. Forest Productivity as a function of root growth opportunity. Thesis. 148 p. Virginia Polytechnic and State University, Blacksburg, VA.

Skokun, N. 2003. Influence of harvest intensity on soil properties, and early seedling performance for upland, shallow, Dystric Brunisols in northwestern Ontario. Thesis. Lakeland University, Thunder Bay, ON.

Solomon, S. C. 1993. Effects of compaction removal of forest floor litter on soil physical properties. Thesis. 63 p. North Carolina Agricultural and Technical State University, Greensboro, NC.

Stagg, R. H.; Scott, D. A. 2006. Understory growth and composition resulting from soil disturbances on the long-term soil productivity study sites in Mississippi. P. 52-56. In: Connor, K. F., (ed.). Proc. Of the 13th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-GTR-92. USDA Forest Service Southern Research Station, Asheville, NC.

Stone, D. M. 2002. Lake states aspen productivity following soil compaction and organic matter removal. P. 59-67. In: Parker, S.; Hummel, S. S., (eds.). Beyond 2001: A silvicultural odyssey to sustaining terrestrial and aquatic ecosystems. Proceedings, national silviculture workshop, May 2001; Hood River, OR. Gen. Tech. Rep. PNW-GTR-546. USDA Forest Service Pacific Northwest Research Station, Portland, OR.

Stone, D. M. 2002. Logging options to minimize soil disturbance in the northern Lake States. North. J. Appl. For. 19(3): 115-121.

Stone, D. M. 2002. Reserve tree method produces abundant aspen regeneration and increases early growth. P.68-73. In: Parker, S.; Hummel, S. S., (eds.). Beyond 2001: A silvicultural odyssey to sustaining terrestrial and aquatic ecosystems. Proceedings, national silviculture workshop, May 2001; Hood River, OR. Gen. Tech. Rep. PNW-GTR-546. USDA Forest Service Pacific Northwest Research Station, Portland, OR.

Stone, D. M.; Kabzems, R. 2002. Aspen development on similar soils in Minnesota and British Columbia after compaction and forest floor removal. For. Chron. 78: 886-891.

Stone, D. M. 2001. Sustaining aspen productivity in the Lake States. P.47-59. In: Symposium proceedings, sustaining aspen in western landscapes: Symposium; 13-15 June 2000; Grand Junction, CO. RMRS-P-18. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO.

Stone, D. M.; Elioff, J. D.; Potter, D. V.; Peterson, D. B.; Wagner, R. 2001. Restoration of aspen-dominated ecosystems in the Lake States. P. 137-143. In: Symposium proceedings, sustaining aspen in western landscapes; 13-15 June 2000; Grand Junction, CO. RMRS-P-18. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO.

Stone, D. M.; Elioff, J. D. 2000. Soil disturbance and aspen regeneration on clay soils: three case histories. For. Chron. 76(5): 747-752.

Stone, D. M. 1999. Snow damage in young aspen. In: Great lakes, great forests; Proceedings of the Society of American Foresters 1998 national convention, 19-23 September, 1998, Traverse City, MI. Publ. SAF 99-01. Society of American Foresters, Bathesda, MD.

Stone, D. M.; Gates, J. A.; Elioff, J. D. 1999. Are we maintaining aspen productivity on sand soils? P. 177-184. In: ZumBahlen, B.; Ek, A. R., (comps.). Improving forest productivity for timber- a key to sustainability. proceedings of conference; 1-3 December, 1998; Duluth, MN; Department of Forest Resources, University of Minnesota, St. Paul, MN.

Stone, D. M.; Elioff, J. D. 1998. Soil properties and aspen development five years after compaction and forest floor removal. Can. J. Soil Sci. 78: 51-58.

Stone, D. M. 1997. A decision tree to evaluate silvicultural alternatives for mature aspen in the northern Lake States. North. J. Appl. For. 14(2): 95-98.

Stone, D. M.; Strand, J. C. 1997. Monitoring the Mighty Duck Timber Sale: a national forest-conservation organization- research partnership. P. 186-189. In: Communicating the role of silviculture in managing the National Forests. Proceedings, national silviculture workshop, 1997 May 19-22; Warren, PA. Gen. Tech. Rep. NE-238. USDA Forest Service Northeastern Forest Experiment Station, Radnor, PA.

Stone, D. M.; Robl, J. L. 1996. construction and performance of rugged ceramic cup soil water samplers. Soil Sci. Soc. Am. J. 60(2): 417-420. Tenhagen, M. D.; Jeglum, J. K.; Ran, S.; Foster, N. W. 1996. Effects of a range of biomass removals on long-term productivity of jack pine ecosystems: Establishment report. Inf. Rep. O-X-454. Canadian Forest Service, Sault Ste. Marie, On.

Strahm, B. D. 2006. Abiotic retention mechanisms of organic and macronutrient anions in variable-charge soils. Ph.D. Dissertation. University of Washington, Seattle, WA.

Strahm, B. D.; Harrison, R. B. 2006. Nitrate sorption in a variable-charge forest soil of the Pacific Northwest. Soil Sci. 171: 313-321.

Strahm, B. D.; Harrison, R. B.; Flaming, B. L.; Terry, T. A.; Licata, C. W.; Petersen, K. S. 2005. Factors affecting nitrogen mobility: Organic matter retention and variable-charge soils. P. 165. In: Harrington, C. A.; Schoenholtz, S. H., (eds.). Productivity of western forests: A forest products focus. Gen. Tech. Rep. PNW-GTR-642. USDA Forest Service Pacific Northwest Research Station, Portland, OR.

Strahm, B. D.; Harrison, R. B.; Flaming, B. L.; Terry, T. A.; Licata, C. W.; Petersen, K. S. 2005. Soil solution nitrogen concentrations and leaching rates as influenced by organic matter retention on a highly productive Douglas-fir site. For. Ecol. Manage. 218: 74-88.

Swartz, P. 1997. Determining replacement times and rotation ages based on nutrient status for a range of black spruce ecosystems in northwestern Ontario. Thesis. Lakehead University, Thunder Bay, Ontario.

Swearingen, K. A. 1999. Competitive relations for soil water in an experiment of soil compaction and organic residues in a young ponderosa pine-mixed shrub community. Thesis. Oregon State University, Corvallis, OR.

Sword, M. A.; Tiarks, A. E. 2002. Local soils information needed to define the root zone in process models on the Gulf Coastal Plain. Gen. Tech. Rep. SRS-058. USDA Forest Service Southern Forest Research Station, Asheville, NC.

Tan, X.; Chang, S. X.; Kabzems, R. 2008. Soil compaction and forest floor removal reduced microbial biomass and enzyme activities in a boreal aspen forest soil. Biol. Fertil. Soils 44: 471-479.

Tan, X.; Chang, S. X.; Kabzems, R. 2005. Effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest long-term soil productivity study. For. Ecol. Manage. 217: 158-170.

Taylor, M. E.; Kershaw, H. M.; Morris, D. M.; Jeglum, J. K. 1995. Long term productivity of boreal forest ecosystems. I: An annotated bibliography. N ODA Note No. 8. Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie, ON.

Terry, T. A.; Harrington, C. A.; Harrison, R. B. 2001. Fall River long-term site productivity study: study objectives, descriptions of treatments, and experimental design. Long-term Site Productivity Paper #01-1/ March 2001. Weyerhaeuser Company Forestry Research Technical Note. 10 p.

Tiarks, A.; Smith-Elliott, M.; Stagg, R. 2000. Loblolly pine (*Pinus taeda*) plantations in the subtropical southeastern United States. P. 101-103. In: Nabiar, E. K. S.; Tiarks, A. E.; Cossalter, C.; Ranger, J., (eds.). Site management and productivity in tropical plantation forests. December 7-11, 1999, Kerala, India. Center for International Forestry Research, Bogar, Indonesia.

Tiarks, A.; Klepzig, K.; Sanchez, F.; Lih, M.; Powell, J.; Buford, M. 1999. Roles of coarse woody debris in the loblolly pine ecosystem. P. 238-242. In: Haywood, J. D., (ed.). Proceedings tenth biennial southern silviculture research conference. February 16-18, Shreveport, LA. Gen. Tech. Rep. SRS-30. USDA Forest Service Southern Forest Research Station, Asheville, NC.

Tiarks, A. E. 1999. Nutrient management in pine forests. P. 1-6. In: Proceedings for the fifteenth annual ARK-LA-TEX forestry forum, March 9, 1999, Shreveport, LA.

Tiarks, A. E.; Buford, M. A.; Powers, R. F.; Ragus, J. F.; Page- Dumroese, D. S.; Ponder, F., Jr.; Stone, D. M. 1997. North American Long-term soil productivity research program. P. 140-147. In: Communicating the role of silviculture in managing the National Forests. Proceedings, national silviculture workshop, 1997 May 19-22; Warren, PA. Gen. Tech. Rep. NE-238. Radnor, PA. USDA Forest Service Northeastern Forest Experiment Station, Radnor, PA.

Tiarks, A. E.; Hudnall, W. H.; Ragus, J. F.; Patterson, W. B. 1995. Effect of pine plantation harvesting and soil compaction on soil water and temperature regimes in a semitropical environmental. P. 65-78. In: Schulte, A.; Ruhiyat, D., (eds.). Proceedings, International Congress on soils of tropical forest ecosystems, 3rd conference on forest soils. (ISSS-AISS-IBG), Volume 3, Soil and Water Relationships; Oct. 29-Nov. 3, 1995. Samarinda, Indonesia. Mulawarman University Press, Samarinda, Indonesia.

Tiarks, A. E.; Hudnall, W. H.; Patterson, W. B. 1994. Soil compaction effects on forest management, productivity and soil water. P. 108-109. In: Proceedings, 15th World Congress of Soil Science. July 10-16, 1994, Acapulco, Mexico. International Society of Soil Science and Mexican Society of Soil Science, Acapulco, Mexico.

Tiarks, A. E.; Powers, R. F.; Alban, D. H.; Ruark, G. A.; Page-Dumroese, D. S. 1993. USFS long-term soil productivity national research project: a USFS cooperative research program. P. 236-241. In: Kimble, John, (ed.). Utilization of soil survey information for sustainable land use. Proceedings of the eight international soil management workshop. Portland, OR. May 1993. USDA Soil Conservation Serv., Lincoln, NB.

Tiarks, A. E.; Kimble, M. S.; Elliot-Smith, M. L. 1991. The first location of a national, long-term forest soil productivity study: methods of compaction and residue removal. P. 431-442. In: Coleman, S. S.; Neary, D. G., (eds.). Proceedings, 6th biennial southern silvicultural research conference, Oct. 30- Nov. 1, 1990, Memphis, TN. Gen. Tech. Rep. SE-70, Volume 1. USDA Forest Service Southern Forest Research Station, Asheville, NC.

Tippett, M. D. 1992. Impacts of timber harvesting on soil physical properties in wetlands. Thesis. 165 p. Virginia Polytechnic and State University, Blacksburg, VA.

Tiveau, D. 2000. Secondary vegetation succession on jack pine (*Pinus banksiana*) cutovers in northeastern Ontario, Canada. Thesis. 18 p. Swedish University of Agricultural Science, Uppsala.

Troncoso, G. E. 1997. Effect of compaction and organic residues on soil moisture and temperature regimes during the growing season in Sierra Nevada, California. Thesis. Oregon State University, Corvallis, OR.

Vance, E. D.; Terry, T. A.; Harrison, R. B.; Harrington, C. A.; Strahm, B. D.; Ares, A. 2006. The Fall River long-term soil productivity study: Linking processes to operations in Pacific Northwest Douglas-fir. West. For. 51: 12-15.

Van Cleve, K.; Powers, R. F. 1995. Soil Carbon, soil formation and ecosystem development. Chap. 9. P. 155-200. In: McFee, W. W.; Kelly, J. M., (eds.). Carbon forms and functions in forest soils. Soil Sci. Soc. Am., Madison, WI.

Waddell, W. C. 1997. The aquic conditions of seasonally wet forest soils. Thesis. 189 p. Louisiana State University and Agricultural and Mechanical College, Baton Rouge, LA.

Waldrop, M. P.; McColl, J. G.; Powers, R. F. 2003. Effects of forest postharvest management practices on enzyme activities in decomposing litter. Soil Sci. Soc. Am. J. 67: 1250-1256.

Walkinshaw, C. H.; Tiarks, A. E. 1998. Effects of soil compaction and organic matter removal on morphology of secondary roots of loblolly pine. P. 418-421. In: Waldrop, T. A., (ed.). Proceedings of the ninth biennial southern silvicultural research conference; 1997 February 25; Clemson, SC. Gen. Tech. Rep. SRS-20. USDA Forest Service Southern Research Station, Asheville, NC.

Warren, C. 2002. The evaluation of soil rutting severity along a topographic sequence for black spruce-dominated forest ecosystems in northwestern Ontario: A seedling bioassay approach. Thesis. Lakehead University, Thunder Bay, ON.

Wilson, C. A. 1994. The effects of compaction and organic matter removal on nitrogen mineralization in a coastal plain soil of North Carolina. Thesis. 31 p. North Carolina State University, Raleigh, NC.

Wrigley, A. 2007. Changes in soil nutrient status and seedling performance in response to harvest intensity on upland, shallow site types in northwestern Ontario: 10th year results. Thesis. Lakehead University, Thunder Bay, ON.

Xu, Y. J.; Burger, J. A.; Aust, W. M.; Patterson, S. C.; Miwa, M.; Preston, D. P. 2002. Changes in surface water table depth and soil physical properties after harvest and establishment of loblolly pine in Atlantic Coastal Plain wetlands of South Carolina. Soil Till. Res. 63: 109-121

Xu, Y. J.; Burger, J. A.; Aust, W. M.; Patterson, S. C. 1999. Recovery of hydroperiod after timber harvesting in a forested wetland. P. 282-287. In: Proceedings, Tenth Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS-30. USDA Forest Service Southern Forest Research Station, Asheville, NC.

Xu, Y. J.; Burger, J. A.; Aust, W. M.; Patterson, S. C. 1999. Responses of surface hydrology and early loblolly pine growth to soil disturbance and site preparation in a Lower Coastal Plain wetland. NZ J. For. Sci. 30: 250-265.

Young, D. H.; Powers, R. F.; Rust, B. L. 2004. Monitoring impacts of ground-based thinning on soil quality in a late-seral reserve. Agronomy Abstracts. 5101 (CD of Abstracts. In: Proceedings, international meeting of the American Society of Agronomy, Oct. 31- Nov. 4, 2004. Seattle, WA. American Society of Agronomy, Madison, WI.

Youngblood, A.; Everett, R.; Busse, M. 1994. Building National Forest System-research partnerships for ecosystem management of east-side Oregon and Washington forests. P. 207-214. In: Foley, L. H., (tech. coord.). Silviculture: From the cradle of forestry to ecosystem managment. USDA Forest Service Gen. Tec. Rep. SE-88. USDA Forest Service Southern Forest Experiment Station, Asheville, NC.

Zhang, J.; Oliver, W. W.; Busse, M. D. 2006. Growth and development of ponderosa pine on sites of contrasting productivities: relative importance of stand density and shrub competition effects. Can. J. For. Res. 36: 2426-2438.

Zhu, Z.; Foster, N. W.; Arp, P. A.; Meng, F.; Bourque, C. P.-A. 2004. A test of the application of the model ForNBM in a northeastern Ontario Jack Pine (*Pinus banksiana* Lamb) stand. For. Ecol. Manage. 193: 385-397.

Zhu, Z.; Arp, P. A.; Meng, F.; Bourque, C. P.-A.; Foster, N. W. 2003. A forest nutrient cycling and biomass model (ForNBM) based on year-round, monthly weather conditions, Part I: Assumption, structure and processing. Ecol. Model. 169: 347-360.

Zhu, Z.; Arp, P. A.; Meng, F.; Bourque, C. P.-A.; Foster, N. W. 2003. A forest nutrient cycling and biomass model (ForNBM) based on year-round, monthly weather conditions, Part II: Calibration, verification, and application. Ecol. Model. 170: 13-17.

Soil Quality Monitoring: Examples of Existing Protocols

Daniel G. Neary, Research Soil Scientist, Rocky Mountain Research Station, USDA Forest Service, Flagstaff, AZ

Carl C. Trettin, Research Soil Scientist, Southern Research Station, USDA Forest Service, Charleston, SC

Deborah Page-Dumroese, Research Soil Scientist, Mountain Research Station, USDA Forest Service, Moscow, ID

Abstract—Many forestry and agricultural agencies and organizations worldwide have developed soil monitoring and quality standards and guidelines to ensure future sustainability of land management. These soil monitoring standards are typically developed in response to international initiatives such as the Montreal Process, the Helsinki Ministerial Conference, or in support of Best Management Practices program development and Code of Forest Practices regulations. This paper describes international (Australia, New Zealand, Canada, and the European Union) and U.S. efforts and perspectives on soil quality monitoring, and offers suggestions on how to use the existing USDA Forest Service standards and modify them for future relevance.

Introduction

International Approaches

The 1990 Helsinki Ministerial Conference began the process for developing management guidelines and criteria to ensure conservation and sustainable management of forests in Europe and elsewhere (Helsinki 1994). In 1993, the United Nations convened an international seminar in Montreal, Canada, on the sustainable development of temperate and boreal forests. This conference led Canada and nine other nations to form the Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forest. This working group soon became known as the "Montreal Process." The Montreal Process was a parallel, but independent, initiative to the Helsinki Process that developed similar criteria (Anon. 1995). Criterion 5 of the six Helsinki Process criteria is to maintain and develop the role of forests in water supply and protection against erosion. Criterion 4 of the Montreal Process is to conserve and maintain soil and water resources. The latter Criterion includes the conservation of soil and water resources and the protective and productive functions of forests. Since the chemical, physical and biological characteristics of aquatic systems are excellent indicators of the condition and sustainability of the lands around them (Breckenridge and others 1995), key conditions of soil and water resources were selected as indicators of sustainability.

The original Montreal Process countries met in Santiago, Chile, in 1995 to endorse a statement of commitment, known as the "Santiago Declaration," along with a comprehensive set of seven criteria and 67 indicators for the conservation and sustainable management of temperate and boreal forests. This new set of criteria and indicators added to the growing body of type-specific measurement and assessment systems already underway through the Helsinki Process in Europe and elsewhere. Eight out of 67 indicators selected in the Montreal Process and endorsed by the nations that drafted the

Santiago Declaration in 1995 pertain to Criterion 4. Following are those indicators that specifically concern soil impacts:

(18) Area and percent of forest land with significant soil erosion;

(19) Area and percent of forest land managed primarily for protective functions, *e.g.*, watersheds, flood protection, avalanche protection, riparian zones;

(20) Percent of stream kilometers in forested catchments in which stream flow and timing has significantly deviated from the historic range of variation;

(21) Area and percent of forest land with significantly diminished soil organic matter and/or changes in other soil chemical properties;

(22) Area and percent of forest land with significant compaction or change in soil physical properties resulting from human activities;

(24) Percent of water bodies in forest areas (*e.g.*, stream kilometers, lake hectares) with significant variation from the historic range of variability in pH, dissolved oxygen, levels of chemicals (electrical conductivity), sedimentation or temperature change.

The Montreal Process criteria are distinguished from those developed by other sustainability efforts in that they recognize a fundamental connection between forests and people. The criteria function on the assumption that a nation cannot achieve forest sustainability without the support and understanding of its public. The criteria and indicators provide a common understanding and implicit definition of sustainable forest management. They are to be considered tools for assessing trends in forest conditions, and they provide a framework for describing, monitoring, and evaluating progress toward sustainability. An important consideration is that the Criteria and Indicators should not be confused as performance standards for certifying management or products.

Criteria are envisioned as a national-scale consensus of public values. They are meant to communicate an overview of what participating countries want to see in the conditions of their forests. Indicators provide the means for assessing forest conditions and for tracking trends. The Indicators are intended to be flexible components of resource monitoring protocols that can be adjusted to provide the most accurate assessment of environmental, economic, and social trends.

Sustainability is the stewardship goal of forestry, but a more specific definition of its goals and attributes is often complex and open to considerable interpretation (Moir and Mowrer 1995). Many ecologists have attempted to answer the "what," "what level," "for whom," "biological or economic," and "how long" questions of sustainability. Allen and Hoekstra (1994) discussed the emergence of the concept of sustainability and the difficulty in defining it. They clearly pointed out that there is no absolute definition of sustainability, and that it must be viewed within the context of human conceptual frameworks and societal decisions on the type of ecosystem to be sustained and the spatial and temporal scales over which attainment of sustainability is to be judged. Sustainability is also defined in terms of society's needs, the experiential frame of reference of ecosystem managers, and the ecological models that are used to predict future conditions for natural resources. However, our ability to predict future ecosystem conditions is confounded by the uncertainties of increasing encounters with extreme events, poorly understood ecological processes and linkages, surprises by the law of unintended consequences, the development of critical thresholds, and chaotic system behavior. Another approach to the definition of sustainability is to define the conditions that warn of or mark ecosystem deterioration into unsustainability (Moir and Mowrer 1995). Although the goals of the Montreal Process and Santiago Declaration are to ensure management of forest lands for sustainability, the Criteria and Indicators are in essence warning flags to obtain the attention of land managers before ecosystems decline into unsustainability.

Soil compaction, erosion, and organic matter losses are the chief factors that affect decline of ecosystem productivity (Burger 2002; Powers and others 1990). These factors can alter ecosystem carbon allocation and storage, nutrient content and availability, water storage and flux, rhizosphere processes, and insect and disease dynamics. The chief disturbances that affect these three factors are wildfire, insect and disease outbreaks, climate extremes, vegetation management (wood harvesting and stand tending activities, grazing, prescribed fire, chemical weed control, and manual removal of plant species), and recreation (foot traffic and vehicles) (Hart and Hart 1993). Management activities that eliminate natural disturbances (*e.g.*, fire suppression, insect control) or alter ecosystem properties can also affect ecosystem sustainability.

Why Soil Monitoring?

Soil quality monitoring was developed as a means of evaluating the effects of management or harvesting practices on soil functions that affect site productivity (Doran and Jones 1996). Specific reasons might include elevating general awareness of soil condition, education, evaluating specific practices, problem solving, and comparing the effects of alternative management practices and techniques. A number of soil physical, biological, and chemical parameters, which have linkages to soil productivity, have been proposed as forming the minimum data set for screening the condition, quality, and health of soils (Doran and others 1998). Evaluation of soil conditions develops a time-trend analysis that can then be used to assess the sustainability of land management practices.

Soil monitoring developed as a natural outcome from the Helsinki and Montreal Process efforts on sustainability. Codes of Forest Practice, which then were developed, sought to incorporate Best Management Practices and soil monitoring into up-front operations planning rather than post-operation environmental assessment. The approach to soil monitoring varies by country and consists of combinations of self-assessment, independent agency monitoring or combinations of the two approaches. Since soils are vital resources for both natural ecosystems and human endeavors, and they are not easily restored, monitoring of soil conditions and trends is viewed as a necessary activity to maintain their functions and quality (Morvan and others 2007).

In Ireland, the Code of Best Forest Practices has a focus on achieving sustainable forest production by implementing safe and environmentally sound forest harvesting practices. A component of that effort involves routine soil monitoring to verify that acceptable practices are followed and that they do not adversely affect the soil resource (Ireland Forest Service 2000).

The U.S. Forest Service direction on protecting the soil resource is detailed in its Forest Service Manual 2554, Soil Quality Monitoring. The Agency's stated purpose in soil monitoring is to (1) meet direction in the National Forest Management Act of 1976 and other legal mandates, (2) ensure management of National Forest lands under ecosystem management principles without permanently degrading land productivity, and (3) maintain or improve soil quality (O'Neill and others 2005; U.S. Forest Service 2009).

In Australia, State Forestry Practices Codes have been established to provide legally enforceable guidelines and standards to ensure reasonable protection of the natural resources such as soils (Grove 2007). Soil monitoring takes the form of self-monitoring by forestry agencies and companies as well as selected audits by the State Forest Practices Authorities. The belief in soil and other monitoring by the Forestry Consultative Committee is that it will improve forestry operations as well as ensure long-term sustainability.

Curran and others (2005) discussed requirements for sustainable management of forests in Canada and elsewhere. They noted that maintenance of the biological, chemical, and physical properties and processes of soils was crucial for long-term sustainability. A key component for improving the understanding of site productivity and predicting the consequences of forest disturbances and practices was a reliable soil monitoring system.

Concepts and Basis for Monitoring

Characteristics

Soil monitoring must be both logistically effective and scientifically sound in order to achieve the objectives of land management agencies and regulatory authorities. Lovett and others (2007) discussed the important characteristics of monitoring programs in their treatise "*The Seven Habits of Highly Effective Monitoring*." They recommended that effective monitoring programs should

- be designed around clear and compelling questions;
- include review, feedback, and adaptation components;
- choose measurements carefully and consider future uses;
- have systems to maintain data quality and consistency;
- incorporate plans for long-term data accessibility;
- have internal checks and controls to ensure careful examination, interpretation, and delivery of the monitoring data; and
- incorporate an integrated research and development program or strong linkages to other existing research programs.

Another important characteristic of an effective soil monitoring program is a statistically sound protocol for location selection and sampling procedure design. Soil monitoring can be conducted separate from other monitoring programs or within existing programs such as the U.S. Forest Service's FIA Program (O'Neill and others 2005).

Location and Design

The location and design of soil quality monitoring projects are discussed in more detail by Doran and Jones (1996). Sampling locations and designs vary widely depending on the country, state, or province conducting the monitoring. Basic designs fall into the categories of simple random sampling, stratified random sampling, and systematic sampling (Elzinga and others 2001). Examples include random sampling on line transects, random sampling on Cartesian coordinate grids (fig. 1), stratified sampling of stand components (*e.g.*, old-growth, pole stands, sapling clusters, clearings, coarse woody debris piles). Systematic sampling would include evenly spaced sample points on grids established on the monitoring area. This analysis does not compare and contrast soil monitoring location and design techniques. The purpose of this effort is to examine the basic approaches used in a selected number of locations in the world.

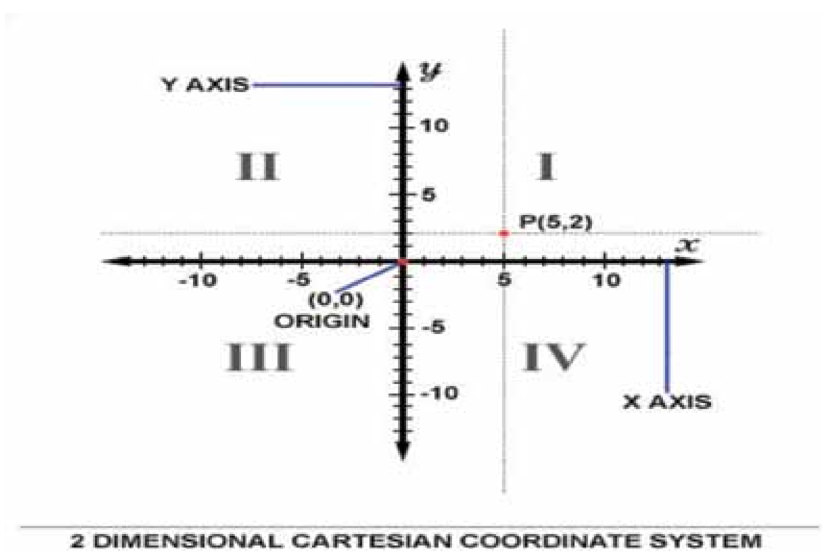


Figure 1. Cartesian coordinate sampling system (adapted from Johnson and Curtis 2001).

Existing Approaches

A number of soil monitoring approaches and systems have been implemented worldwide with mostly similar objectives but sometimes different perspectives. Specifically, the approaches of New Zealand, Australia, Canada, the European Union, and the new Forest Soil Disturbance Monitoring Protocol developed for use within the U.S. Forest Service will be examined.

New Zealand

Forest Code of Practice—New Zealand's 27 million ha of land consists of pasture and arable land (52 percent), native forests (23 percent), and plantation forests (5 percent). The remaining 20 percent is mountains, water, and urban areas. Planting of exotic species plantation forests began in the 1920s. These forests now account for 19 percent of New Zealand's forests but they produce 99 percent of the country's wood requirements. A Forest Code of Practice was established in 1990 (Vaughan and others 1993). The New Zealand Government passed the Resource Management Act of 1991 (RMA) to promote sustainable management of natural resources. The RMA is an effects-based resource law that focuses on land management activities that cause adverse environmental effects. The Forest Code of Practice sets out guidelines to maintain and protect forest values such as soils, water, scenery, recreation, cultural sites, site productivity, and off-site impacts. The Code focuses on both planning and operations to achieve sustainable forest management.

The key components of the planning process in the Code, before any operations are conducted, are (1) identifying important site values, (2) identifying operations that could have significant impact, (3) selecting low impact techniques and methods, (4) establishing protocols to check on compliance to the Code and obtaining approvals, and (5) monitoring actual performance during and after operations. Inputs to the planning come from both external and internal sources (fig. 2). Monitoring then uses an operations database, a rating system, checklists, an operations self appraisal, and finally a compliance check with District and Regional rules.

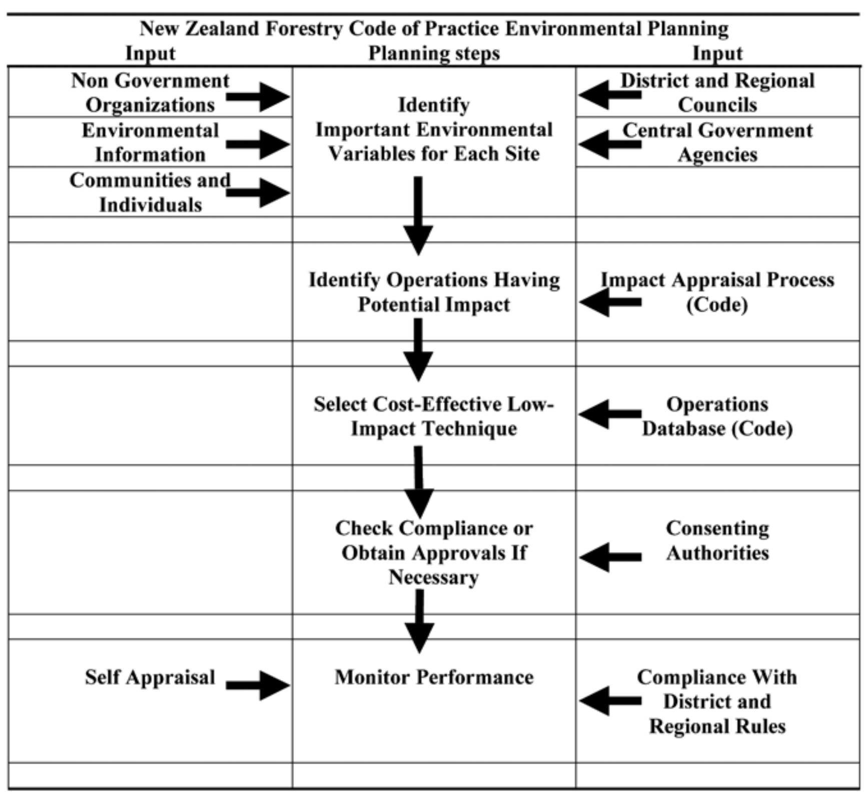


Figure 2. New Zealand Forestry Code of Practice environmental planning flow chart (adapted from Vaughan and others 1993).

Table 1—New Zealand Forest Code of Practice monitoring rating system and symbols (adapted from Vaughan and others 1993).

New Zealand Forestry Code of Practice monitoring rating system

Time	Risk	Impact	Symbols
Short-term	Minor	Minimal	
Long-term	Minor	Low	+/-
Short-term	Major	Intermediate	++/--
Long-term	Major	High	+++/---

Table 2—Example planning checklist for a Wairarapa, New Zealand, woodlot (adapted from Vaughan and others 1993).

Operation	Water quality	Wetland areas	Slope stability	Erosion	Water supply
			Identified environmental values		
			Access		
Roading	-	•	- - -	- -	- -
			Land preparation		
Herbicides	- -	•	•	•	- -
Oversowing	+ +	•	+	+	•
Tracking	- -	•	- - -	- -	- -
Grazing	- -	- - -	- - -	- - -	- -
			Establishment		
Planting	+	•	+ + +	+ + +	+ +
Releasing	•	•	• •	•	- -
Grazing	- - -	- - -	- - -	- - -	- -
Fertilizing	- -	•	+	+	- -
			Tending		
Pruning	+	•	•	+ +	•
Waste thin	+ +	+	+ + +	+ + +	•
			Protection		
Animal control	•	•	•	•	- -
Roads	- -	•	- -	- -	-
Weed control	- -	- -	•	•	•
			Harvesting		
Roading	- - -	• •	- - -	- - -	- - -
Landings	- - -	•			•
Felling	•	+ +	+ +	•	•
Processing	+ +	•	•	•	•
Extraction	- - -	- -	- -	- - -	- -
Stream cross	- -	-	-	- -	•
Transportation	•	•	-	-	•

The rating system utilizes a four-level risk rating system involving both short- and long-term impacts, minor or major risks, and categories of minimal, low, intermediate, or high (table 1). Symbols that correspond to each are then used on the planning forms. An example checklist from a Wairarapa woodlot near Wellington is shown in table 2 (Vaughan and others 1993). Forest managers are then required to develop mitigation plans based on the pre-harvest assessment. The Forest Code of Practice database provides detailed information on identifying risks and planning mitigation measures. Activities that can potentially have a significant impact on the environment require planning review and consent by District or Regional Councils. Post-operational self-monitoring and regular, periodic monitoring and maintenance are required to achieve the desired outcome of maintaining sustainable management of forest lands.

National Soil Quality Survey—New Zealand conducted a national-scale soil quality monitoring program between 1995 and 2001 at 222 sites in five regions of New Zealand (12 soil orders and 9 land-use categories) (Sparling and Schipper 1998, 2002). Land uses in the survey included arable cropping, mixed cropping, pasture, grassland, plantation forests, and native forest. Sampling of the topsoil (0–10 cm) was done and the properties measured were total carbon (C) and nitrogen (N), potentially mineralizable N, pH, Olsen phosphorus (P), cation exchange capacity, bulk density, total porosity, macroporosity, and total available and readily available water. Seven of these soil parameters (total C, total N, mineralizable N, pH, Olsen P, bulk density, and macroporosity) explained 87 percent of the total variability. Some of the issues that arose during the soil quality sampling were minimum data set, how to stratify, level of precision, cost, centralized data and sample management, re-sampling for trends, and sampling strategy. Important recommendations that came out of the survey were that (1) a precision of 10 percent was impractical due to cost, (2) a precision of 25 percent was more realistic, (3) central storage of data and samples was essential to success of this type of survey, (4) re-sampling needs to be over a 3- to 10-year time period with some being done every year, and (5) current financial constraints prohibit random sampling.

Following are the key findings from the New Zealand Soil Quality Survey:

- Soil Order had a strong effect on the results.
- Land use accounted for only 21 percent of total C variability.
- There was no evidence of acidification under exotic tree species.
- Changes in soil quality between land uses can be detected.
- Biochemical and total C indices are more sensitive to land management differences than physical parameters.
- Soil quality of mature pine plantations before and after logging were similar to native forests or low-productivity pasture.
- Many research needs were identified to make a national-scale soil quality survey a viable management tool.
- Changes in soil quality characteristics can be detected, but there is a general lack of a scientific framework to define acceptable and unacceptable ranges of soil quality parameters.

Australia

Australian Forestry—The total area of native forest reported in the latest *Australia's State of the Forests Report* (National Forest Inventory 2008) is estimated at 162.7 million ha, which is about 21 percent of Australia's land area. Some 75 percent of native forest estate was on public land, and the remainder was private land or unresolved tenure. About 70 percent of Australia's native forests were privately managed. Australia's plantation estate continues to expand, reaching 1.8 million ha in December 2006, an increase of 78,000 ha (4.5 percent) over the prior year 2005. The proportion of hardwood species has increased to 44 percent of the total, with softwood species making up the remainder. About 95 percent of the softwood plantations are *Pinus radiata* and other introduced pines. *P. radiata* is grown on a 30 to 40 year rotation and supplies about 50 percent of the domestic wood demand. Nearly all of the hardwood plantations are native eucalypts, including Tasmanian blue gum (*Eucalyptus globulus*), shining gum (*E. nitens*) and flooded gum (*E. grandis*).

A diverse range of ownership arrangements exists in the Australian plantation industry, including a variety of joint venture and annuity schemes between public and private parties. For several years, most investments in new plantations have been by the private sector. The proportion of public and private plantations was equal (46 percent) in 1999; however, privately owned plantations now account for 59 percent, far exceeding public plantations at 36 percent. This difference is especially pronounced for hardwood plantations, about 86 percent of which are privately owned compared with 36 percent of softwood plantations.

Australian Codes of Forest Practice—In Australia, Codes of Forest Practice are State-based and tied to sustainable yield. Except in Tasmania and Victoria, the Codes are applicable to only public lands. There are 14 State and territory Codes that began development in 1978. They all put an emphasis on quantitative performance standards

Table 3—Topics addressed in four Australian Codes of Forest Practice (adapted from McCormack 1996). Soils-related ones are in *italics.*

Tasmania	New South Wales	Victoria	Western Australia
Design & Planning	Design & Planning	Design & Planning	Design & Planning
	Tree Marking		Tree Marking
	Tree Felling		Tree Felling
Log Skidding/Tracks	*Log Skidding/Tracks*	*Log Skidding/Tracks*	*Log Skidding/Tracks*
Log Landings	*Log Landings*	*Log Landings*	*Log Landings*
Wet Weather	*Wet Weather*		
Water Quality		*Water Quality*	*Water Quality*
Slope Limitations		*Slope Limitations*	
Landscape Values		Landscape Values	Landscape Values
Wildlife habitat		Wildlife habitat	Wildlife habitat
	Fire		Fire
Plant Diversity			Plant Diversity
		Site Rehabilitation	
		Fuel Dumps	
	Licensing		
Cultural Resources			
Geomorphology			
		Crop Trees	

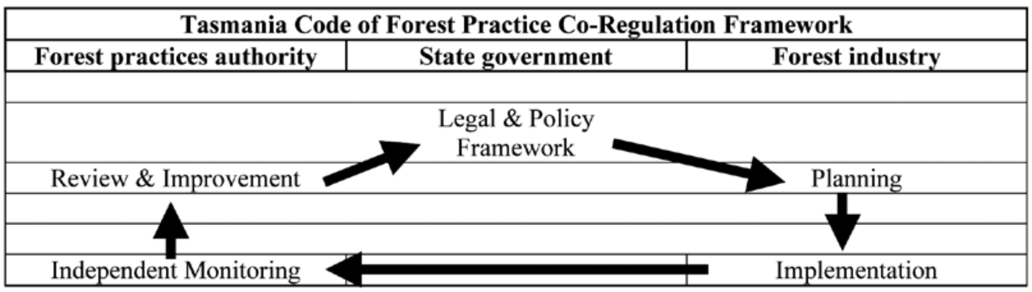


Figure 3. Tasmania adaptive management framework (Code of Forest Practice 1985).

that are keyed into sustainable timber yield and timber harvest planning (McCormack 1996). Old growth and rain forests were the critical issues that lead to these Codes. While soils and soil quality are not directly mentioned as major concerns (table 3), they are inherent in a number of the topics of concern to Australian Codes of Forest Practice.

Tasmanian Code of Forest Practice—The Tasmania Forest Practices Act 1985 was the first Australian Code of Forest Practice (McCormack 1996; Tasmanian Forestry Commission 1993). It deals with a number of issues that relate to soils and soil quality (table 3). First and foremost, the Tasmania Code focuses on proper designing and planning prior to tree harvesting. The Code is administered by the Forest Practices Authority (FPA) but is a co-regulatory adaptive management process in nature (fig. 3). The first level of monitoring is provided by each forest owner, with random independent monitoring conducted by the FPA through Forest Practices Officers (FPO). The FPOs have regulatory powers and can insist on remedial work being done through court actions and fines. However, the main emphasis of FPOs is placed on education and demonstration of Best Management Practices rather than regulatory enforcement.

The Tasmanian FPA employs specialists in forestry, soil science, botany, zoology, geology, hydrology, and archeology whose research and monitoring supports the Code of Forest Practice. The FPA trains and provides advice to forest industry personnel and also conducts the independent audits of forest industry operations (fig. 3).

Canada

Canada has 404 million ha of forested land, accounting for 10 percent of the world's forests and 30 percent of the boreal forests (Natural Resources Canada 2009). Less than 1 percent of Canada's forests are harvested each year, and all Public forests must be successfully regenerated by natural (50 percent) or planting and direct-seeding techniques.

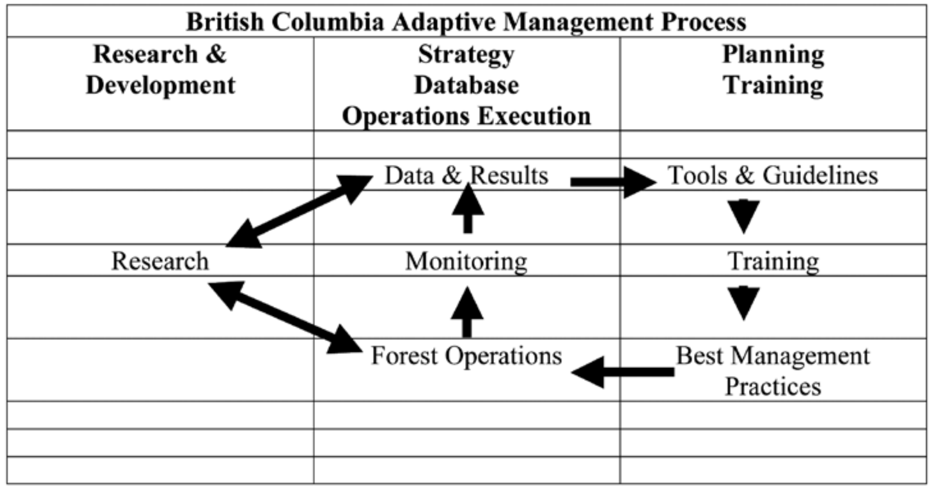


Figure 4. British Columbia soil monitoring adaptive management process (adapted from Curran 2007).

About 36 percent of the country's forests have been certified as being sustainably managed by globally recognized certification standards. Codes of Forest Practice are in place in Nova Scotia, Ontario, and British Columbia. Canada's forest laws and regulations are considered to be among the strictest in the world.

British Columbia has led Canada in developing procedures to ensure forest sustainability. The "Forest Practices Code of British Columbia" of 1996 established the legal framework for monitoring soil disturbances caused by forest operations. It has since been augmented by the "Forest and Range Practices Act of 2002." The Province has an iterative adaptive-management process that provides constant feedback to forest operations and research to improve Best Management Practices and operations planning and execution (fig. 4).

The Soil Conservation Guidebook (British Columbia Ministry of Forests 2001) provides an overview of post-harvest monitoring inspection procedures, the current requirements, and definitions for Soil Conservation Surveys; it also provides instructions on how to conduct surveys. Silvicultural prescriptions define the maximum percent of the net area to be reforested that may be occupied by disturbed soils and the extent to which that area of disturbance can be temporarily exceeded. The operations site plans identify sensitive soils and spell out the maximum percentage of the total harvest area that can be permanent access roads, temporary roads and skid trails, and roadside work areas. Visual Soil Conservation Survey reports are required to verify that prescription limits were not exceeded. If they are, then a formal survey is required. The Surveys focus on disturbance to soil caused by roads and skid trails and the amount of forest floor displacement or damage. In order to "standardize" what can be recognized as soil disturbance by equipment operators, contractors, inspectors, the public, or research scientists, a set of representative visual examples is provided (figs. 5a,b).

A transect survey is installed if a formal Soil Conservation Survey is warranted. Methods are specified in the Soil Conservation Guidebook (British Columbia Ministry of Forests 2001). This type of survey is usually completed as soon as possible after the operations disturbance and it requires site familiarity. The survey transects are documented in case follow-up measurements are needed (fig. 6)

European Union

Forests cover 160 million ha within the European Union, or about 42 percent of the 27-member Union. Six countries account for two-thirds of the forest area with Sweden and Finland alone accounting for 30 percent of the total forest area (Eurostat 2009). Official protocols exist in most member States of the European Union (EU) for soil monitoring (Morvan and others 2007); however, there is a lot of variation in the methodologies used and the intensity of sampling. The EU Monitoring Network has been active for 20 years using a 50 by 50 km grid with variable re-measurement periods. Parts of the

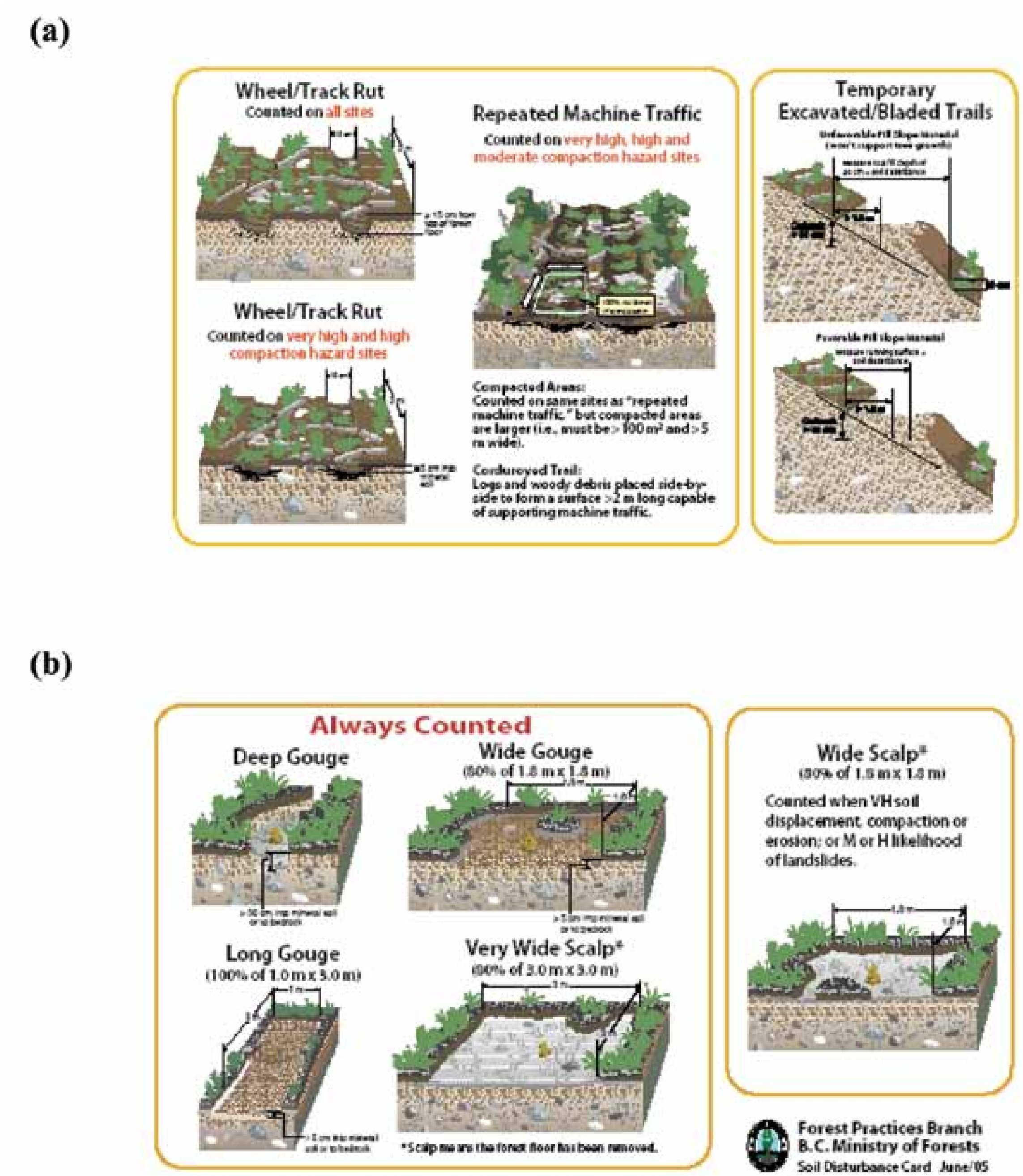


Figure 5. British Columbia Forest Practices Branch, Ministry of Forests visual soil disturbance indicator cards for (a) wheel ruts, machine traffic, and bladed trails; and (b) gouges and scalps (from Curran and others 2005 and British Columbia Ministry of Forests 2001).

EU Network contain dense established sampling grids (*e.g.*, United Kingdom, Ireland, Austria, Denmark) while in other areas the network is still sparse (*e.g.*, Spain, Italy, Greece) (fig. 7). About 90 percent of the EU soils and the land cover classes have at least one monitoring site. However, the density of soil monitoring sites within the European Soil Database units is highly variable. Some units (7 percent) do not have any monitoring sites. Pasture lands have the highest density of soil monitoring sites, but arable land and forests, while slightly less, are comparable in density. A grid of 16 by 16 km has been established for forest soils (ICP 2004).

The key soil parameters being monitored in the EU include erosion risk, compaction risk, the presence of peat, heavy metals, desertification, and presence of livestock. Other indicators being measured are texture, pH, organic matter, bulk density, cations,

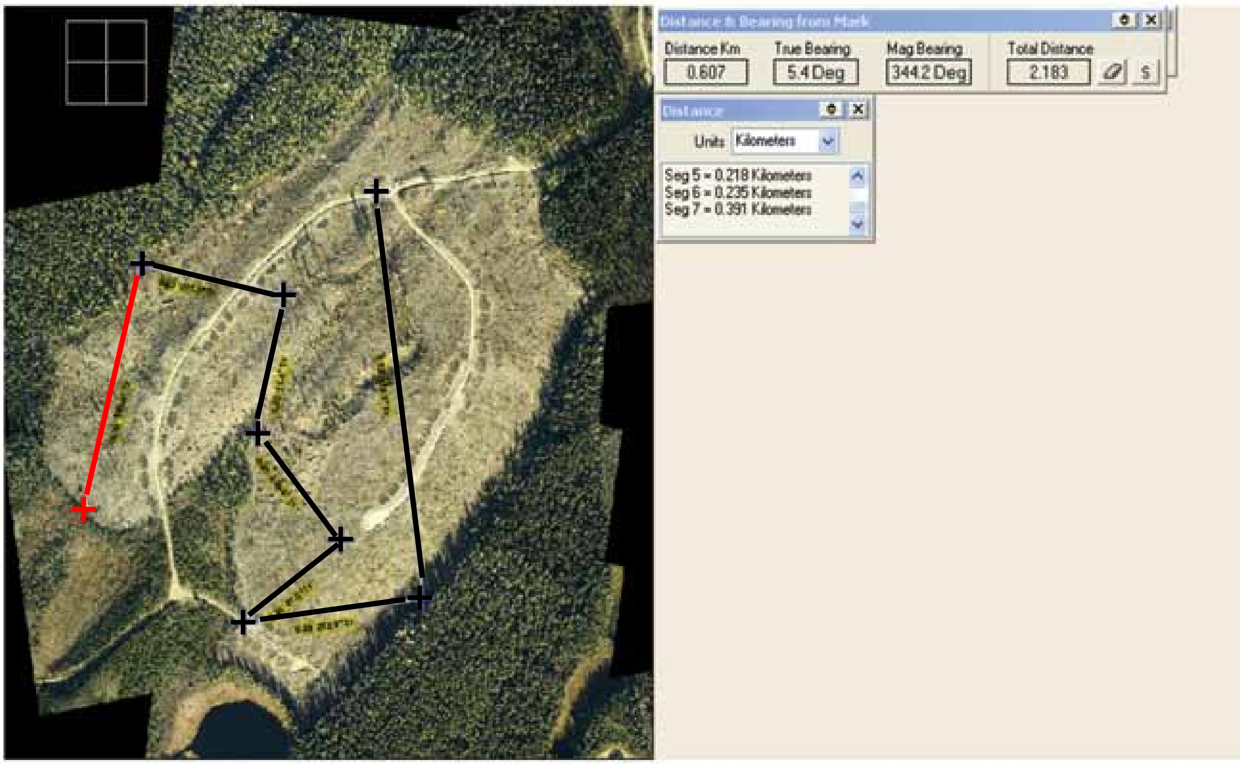


Figure 6. Example of a British Columbia formal soil conservation survey site documentation.

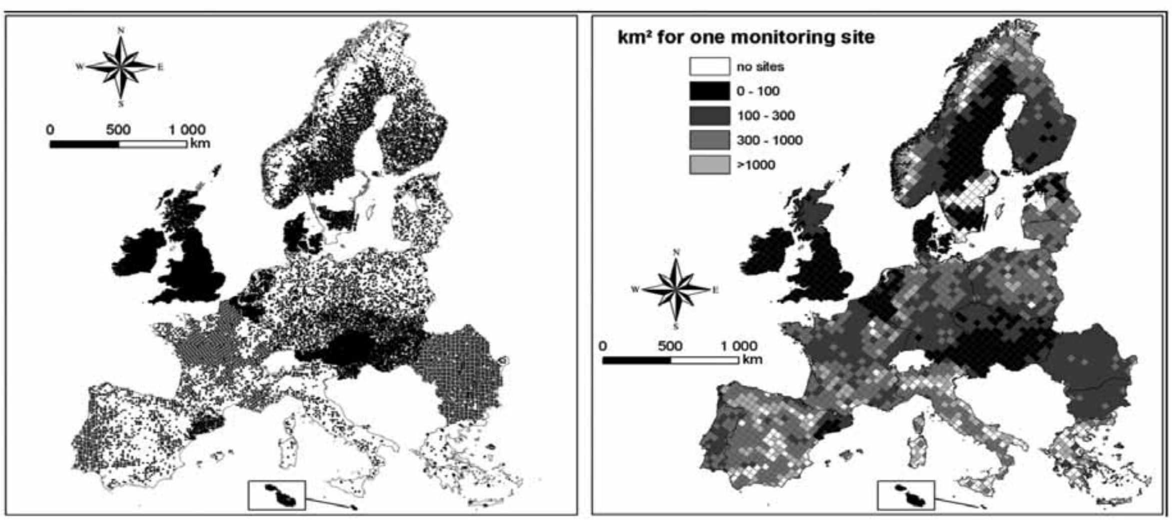


Figure 7. European Union soil monitoring network, GIS repartition (right) and actual density (left) in km^2 for one monitoring site in the 50 by 50 km Cooperative Program for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) grid of the soil monitoring sites in Europe (Moran and others 2007).

and earthworm activity (Morvan and others 2007). The EU Soil Monitoring Network is simply an inventory system, does not have any interaction with land management entities, and does not have any regulatory power. Soil Network needs include adding 4,100 sites in the lower density part of the network and standardizing sampling and analytical methods. Of the countries with mandated soil monitoring (table 4), Sweden requires measurements of soil physical conditions, coarse woody debris, and soil chemistry. Ireland requires measurements of soil condition, soil fertility, erosion, and other

Table 4—European Union countries with conventional forestry and forest bioenergy monitoring standards and requirements.

Country	Harvest code of forest practices	Bioenergy guidelines	Monitoring Required	Monitoring Type	Monitoring Soil
Denmark	Yes	No	No	None	No
Netherlands	Yes	No	Yes	Operations	No
Finland	Yes	Yes	Yes	Operations	No
Sweden	Yes	Yes	Yes	Multiple	Yes
Germany	Yes	Yes	Yes	Inventory	No
Ireland	Yes	No	Yes	Operations	Yes
United Kingdom	Yes	Yes	No	None	No

Table 5—Ireland forest soil monitoring impacts assessment, example from County Roscommon (adapted from Forest Service 2000).

Ireland Code of Best Forest Practice Soil Impact Assessment

County	Roscommon
Site	Coillte 529
Operation	Whole-tree harvesting
Timeframe	Long-term

Value	Impact factor	Severity VH	Severity H	Severity M	Severity L	Mitigation action
Soil	Fertility		X			NPK fertilizer
	Condition				X	None
	Erosion				X	None
	Other					

parameters as needed. Although the United Kingdom does not require soil monitoring at the present time, changes of Codes of Forest Practice will mandate this activity in the future (Hall 2008, personal communication).

Ireland—Over 70 percent of Ireland's 636,164 ha of forests are owned by the Irish Forestry Board (Coillte Teoranta). Soil monitoring in Ireland is contained within the country's Code of Best Forest Practice and is based on EU and National laws (Ireland Forest Service 2000). Like a number of other countries, the Irish Code is focused on planning, monitoring, and adaptive management rather than regulatory punitive actions. Monitoring is performed to evaluate the performance of the Ireland Code of Best Forest Practice as well as the skills of individual forest harvesting operators. It consists of a self-evaluation impact appraisal by the individual operators and an external assessment by the Irish Forestry Board.

The Ireland impact appraisal evaluates environmental, economic, and social impacts of forestry operations. The focus is on assessing potential impacts in terms of their level, likely consequence, importance, and length of time that the impacts will occur. Potential impacts are evaluated descriptively or on a "points" system on the basis of four subjective severity levels (very high, high, moderate, and low), and follow-up mitigation actions are then planned (table 5). Soil fertility was evaluated at being at high risk because of the soil type and the whole-tree harvesting planned for the cut block. So the mitigation technique prescribed for this stand was the addition of a nitrogen-phosphorus-potassium fertilizer. The other potential soil impacts were evaluated as being low so no mitigations were planned.

United States

Natural Resources Conservation Service and the Agricultural Research Service—Both the Natural Resources Conservation Service (NRCS) and the Agricultural Research Service (ARS) conduct research and development activities related to soil

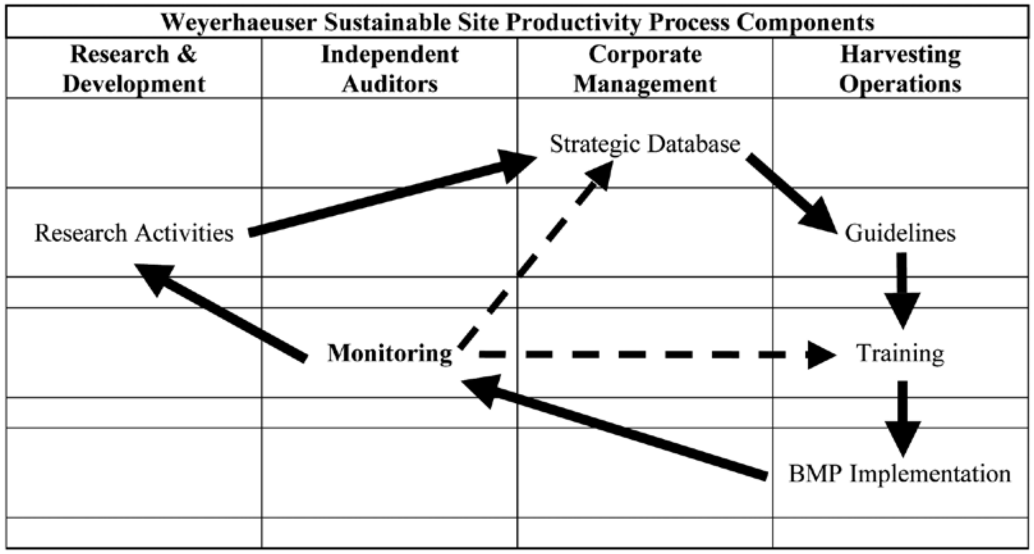


Figure 8. Weyerhaeuser sustainable site productivity process components (adapted from Heninger and others 1998).

quality and soil monitoring (Doran and Jones 1996; Doran and Parkin 1994; Doran and others 1998; Karlen and others 1997; USDA NRCS 2001). Additional information can be found at http://www.ars.usda.gov/main/site_main.htm?modecode=36-25-15-10 and http://www.usda.gov/sqi/. The ARS has also developed and standardized methods for monitoring grassland, shrubland, and savanna ecosystems (Herrick 2005a, b). These manuals deal with vegetation, soil, hydrologic, and geomorphic monitoring methods

U.S. Forest Service: Forest Inventory and Analysis—The U.S. Forest Service conducts soil monitoring as part of its Forest Inventory and Analysis (FIA) Program. Soil monitoring conducted by the FIA is discussed in detail in the following chapter by Amacher and Perry (Amacher and Perry 2010) and by O'Neill and others (2005a,b).

Weyerhaeuser—The Weyerhaeuser Company is committed to soil productivity by using a two-step strategy (Heninger and others 1997, 2002). First, Company operations use equipment and operations practices that are appropriate to the soil, topography, and weather to minimize erosion and harmful soil disturbance. Secondly, Weyerhaeuser employs forestry practices and technology to retain organic matter and soil nutrients on site. The components of the process to achieve sustainability are shown in figure 8 (Heninger 1997) and include (1) a research database; (2) common goals and standards leading to management guidelines; (3) education, training and teaming; (4) selection and use of Best Management Practices (BMPs); (5) independent monitoring of performance and compliance with BMPs; and (6) continuous feedback to the operations side of the organization, and implementation of adaptive experimentation where warranted. Guidelines and BMPs have been developed to minimize detrimental soil disturbance as indicated in figure 9. The key components of this system are the strategic database on soil disturbance impacts, the classification system described in figure 9, a soil operability risk rating system, and a close working relationship between the Research and Development and Operations units to develop BMPs. A key component of this process is monitoring soil impacts of operational practices by independent contractors to assess performance against specified standards. The monitoring provides feedback and information to the corporate soils database, Research and Development, and Operations training programs to continuously improve BMPs to meet Weyerhaeuser's sustainable site productivity strategy (fig. 8).

United States: Forest Soil Disturbance Monitoring Protocol

Background—At the end of the 20th Century, about 33 percent of the U.S. land area or 302 million ha was forest land, 71 percent of the area that was forested in the latter part of the 17th Century (Smith and others 2001). The U.S. Forest Service (USFS) manages around 59 million ha in the National Forest System (NFS) including 39 million

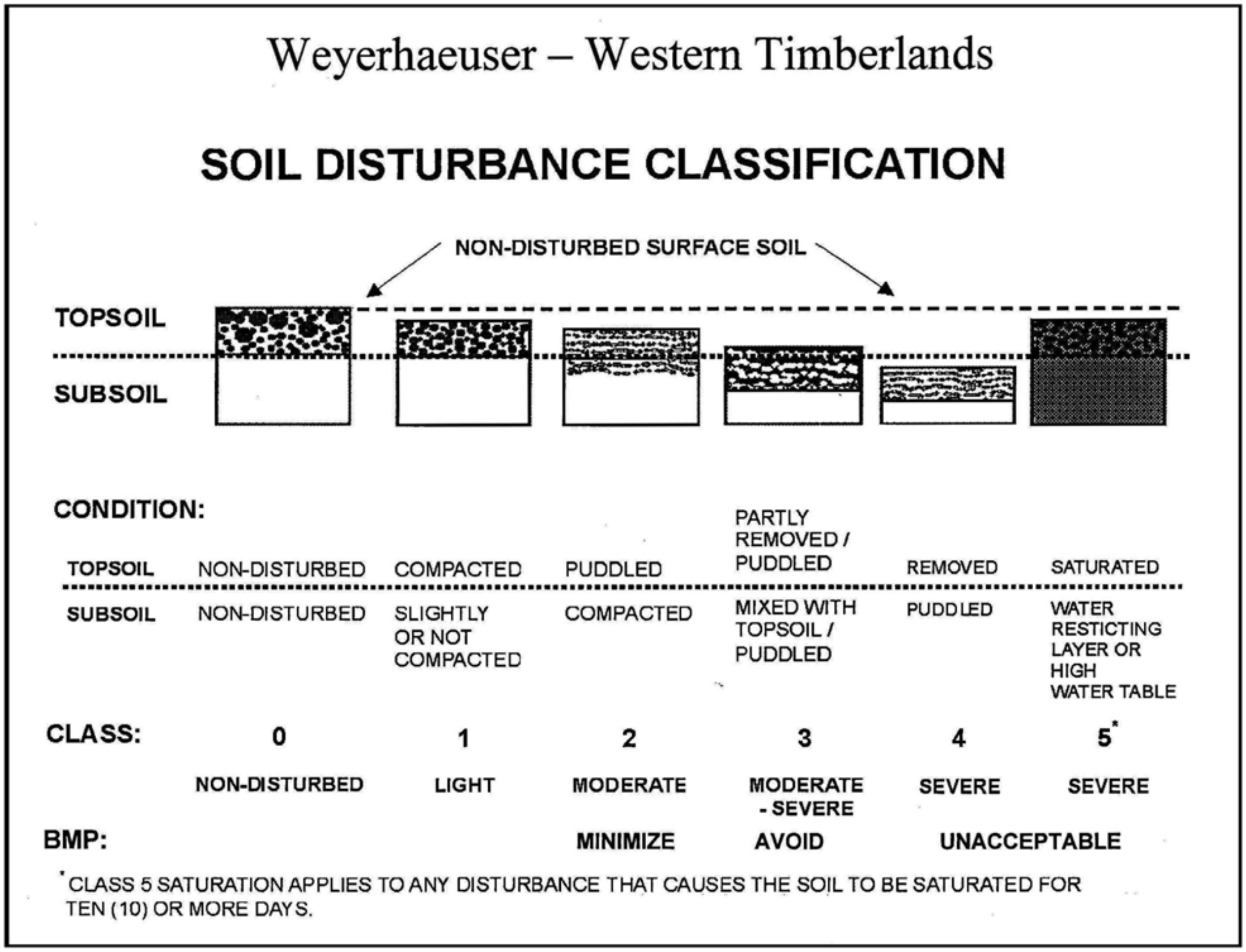


Figure 9. Weyerhaeuser soil disturbance classification system for Western Timberlands (adapted from Heninger and others 1997 and Curran and others 2007).

ha that are classified as capable of producing 1.4 m^3 ha^{-1} yr^{-1} of industrial wood and not legally reserved from timber harvest. Four Acts of Congress important to the issue of resource sustainability, and the soil resource in particular, provide enabling legislation for NFS lands (U.S. Forest Service 1993): (1) The Organic Administration Act of 1897, (2) The Multiple-Use Sustained-Yield Act of 1960, (3) The Forest and Rangeland Renewable Resources Planning Act of 1974 and amendments, and (4) The National Forest Management Act of 1976 (Cline and others 2006; U.S. Forest Service 1993). This legislation sets forth three points that support the need for a long-term soil monitoring program. First, land management should not produce substantial and permanent impairment of site productivity. Second, trees should be harvested only where soil, slope, or other watershed conditions will not be irreversibly damaged. Lastly, tree cutting should occur in a manner that ensures protection of soil, watershed, fish, wildlife, recreation and esthetic resources, and the regeneration of the tree resource. The essence of these key statements of land ethics is a legislative mandate that the USFS conduct research, monitoring, and other assessments to evaluate management effects and to manage for sustained site productivity in a manner that assures protection of all resources and values. The monitoring provisions caused considerable concern among field soil scientists in the NFS with regard to determining baseline soil productivity and what parameters might be used to measure management effectiveness in maintaining soil productivity (Cline and others 2006).

USFS Regions were directed to develop soil quality standards based on Agency guidelines in Forest Service Handbook (FSH) 2509.18: Soil Quality Monitoring. In Chapter 2 of FSH 2509.18, the soil quality monitoring program is spelled out as a systematic process in which data are collected to determine if soil management objectives of maintaining long-term soil productivity and development of operational standards are achieved. It was clearly the policy of the USFS to

- design and implement Best Management Practices,
- maintain or improve long-term site productivity,
- plan and conduct soil quality monitoring,
- evaluate the results of management actions, and
- recommend mitigation measures for measured soil changes.

Responsibilities were delegated to Regional Foresters, Forest Supervisors, District Rangers, and Soil Scientists to develop the soil quality monitoring program. Soil Scientists were specifically given the charge to conduct and supervise effectiveness and validation monitoring, to report management results and recommend changes in actions, and to coordinate validation monitoring with research units. However resources and time were not provided to adequately achieve these directions.

Chapter 2 of FSH 2509.18 went on further to list some “example” soil quality standards. These included increase in bulk density >15 percent, reduction in porosity >10 percent, forest floor removal along with 25 mm (1 inch) of mineral soil, macropore space reduction >50 percent, and erosion losses exceeding 2.2 to 4.4 Mg ha^{-1} (1-2 tons ac^{-1} yr^{-1}). A footnote on a table that listed these “standards” indicated that these were examples only and not intended to be actual soil quality standards; regional soil scientists were charged with that task. Chapter 2 in FSH 2509.18 also discussed topics such as establish threshold values causing significant changes, allowable area extent of disturbance, monitoring projects and plans, sample size and variability, sample design, data collection, and data analysis

The net result for USFS was that Washington Office guidance in FSH 2509.18 was carried forward and detrimental soil disturbance on greater than 15 percent of an activity area was selected as the soil quality standard for many of the Forest Service Regions.

Detrimental soil disturbance was defined as compaction >15 percent, rutting, soil displacement, severely burned areas, surface erosion, and soil mass movement. In essence, an “example” in FSH 2509.18 became the Region 1 “standard” and every other Region went its own way on setting standards. Region 1 issued a Manual supplement to describe its soil monitoring program (U.S. Forest Service 1999). However, it did not take long for problems to develop. There was inconsistent use of the standard with regard to soil type, soil properties, and across jurisdictional (Regional) boundaries. None of the Regional standards were really validated in cooperation with USFS Research and Development, except for the Long-Term Site Productivity Study (Powers and others 2005). Eventually, the original soil monitoring program was challenged in Federal District Court in Montana. This situation led to the development of the new Region1 Soil Monitoring Protocol prototype, and it soon became a National Forest soil monitoring protocol, because it describes a consistent approach and common language for soil monitoring within forested ecosystems.

New Soil Monitoring Protocol—A reliable monitoring protocol has been identified as a critical component of any adaptive management process for forest and rangeland soil conservation programs (Curran and others 2005). Uniform and unambiguous definitions of soil disturbance categories must also relate forest productivity and hydrologic function (Curran and others 2007). A soil monitoring protocol must incorporate a statistically rigorous sampling procedure and firm definitions of visually observable soil disturbance categories

The Protocol, first developed by USFS Region 1 and the Rocky Mountain Research Station, incorporates soil quality monitoring efforts pioneered in the Pacific Northwest (Region 6) (Howes and others 1983). The Protocol is a multi-faceted approach to the soil disturbance and forest sustainability issue (fig.10). The Protocol uses visual soil disturbance classes (Howes and others 1983; Page-Dumroese and others 2006), and a standard inventory, monitoring, and assessment tool. It employs common terminology and has an accessible database. The visual disturbance considerations are soil resilience, degree of disturbance, duration, distribution, and location in relation to other resources.

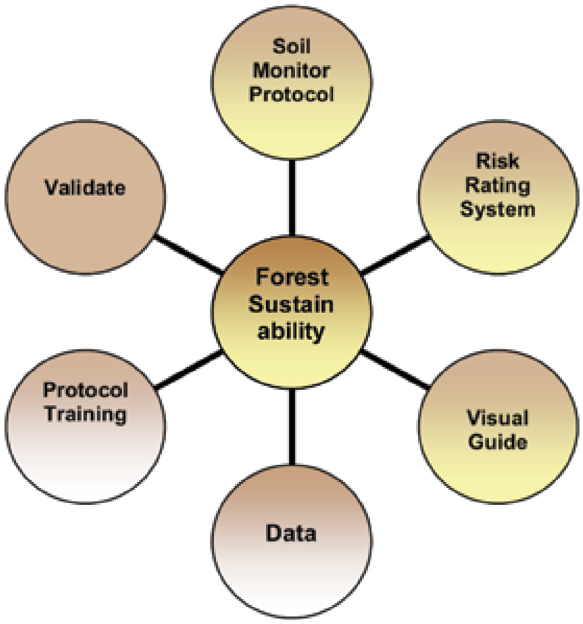


Figure 10. USFS Region 1 Soil Monitoring Protocol multi-faceted approach to forest site productivity.

Table 6—Forest Soil Disturbance Monitoring Protocol pre-harvest soil disturbance class definitions (Page-Dumroese and others 2009a, b).

Class 0—Undisturbed natural state

Soil surface:
- No evidence of past equipment operation.
- No depressions or wheel tracks evident.
- Forest floor layers present and intact.
- No soil displacement evident.

Class 1—Low soil disturbance

Soil surface:
- Faint wheel tracks or slight depressions evident and are <15 cm deep.
- Forest floor layers present and intact.
- Soil surface has not been displaced and shows minimal mixing with subsoil.
- Some evidence of burning impacts include a mosaic of charred and intact forest floor layers to partially consumed surface OM with blackened surface soil. Root crowns and surface roots of grasses are not consumed.

Class 2—Moderate disturbance

Soil surface:
- Wheel tracks or depressions are >15 cm deep.
- Forest floor layers partially intact or missing.
- Surface soil partially intact and may be mixed with subsoil.
- Burning consumed forest floor, root crowns, and surface roots of grasses. Surface soil is blackened.

Class 3—High disturbance

Soil surface:
- Wheel tracks and depressions highly evident with depth being >30 cm deep.
- Forest floor layers are missing.
- Evidence of topsoil removal, gouging, and piling.
- Soil displacement has removed the *majority* of the surface soil. Surface soil may be mixed with subsoil. Subsoil partially or totally exposed.
- Burning consumed the forest floor, root crowns and surface roots of grasses. Evidence of severely burned soils (mineral soil red in color).

Descriptions of the disturbance classes pre- and post-harvest are listed in tables 6 and 7. Full details of the Forest Soil Disturbance Monitoring Protocol can be found in Volume I and Volume II of the technical guides (Page-Dumroese and others 2009a, b).

In order to reduce monitoring variability, a visual guide of soil disturbance is being developed by the U.S. Forest Service's San Dimas Technology and Development Center with a draft title of *Soil Disturbance Field Guide* (Napper and others, 2009). The guide

Table 7—Forest Soil Disturbance Monitoring Protocol post-harvest/burn disturbance class definitions (Page-Dumroese and others 2009a, b).

Class 0—Undisturbed natural state

Soil surface:

- No evidence of past equipment operation.
- No depressions or wheel tracks evident.
- Forest floor layers present and intact.
- No soil displacement evident.

Class 1—Low soil disturbance

Soil surface:

- Faint wheel tracks or slight depressions evident and are <15 cm deep.
- Forest floor layers present and intact.
- Soil surface has not been displaced and shows minimal mixing with subsoil.
- Some evidence of burning impacts include a mosaic of charred and intact forest floor layers to partially consumed surface OM with blackened surface soil. Root crowns and surface roots of grasses are not consumed.

Soil resistance to penetration with tile spade or probe:

- Resistance of surface soils may be slightly greater than observed under natural conditions. Concentrated in the top 0-10 cm.

Observations of soil physical conditions:

- Change in soil structure from crumb or granular structure to massive or platy structure, restricted to the surface 0-10 cm.

Class 2—Moderate disturbance

Soil surface:

- Wheel tracks or depressions are >15 cm deep.
- Forest floor layers partially intact or missing.
- Surface soil partially intact and may be mixed with subsoil.
- Burning consumed forest floor, root crowns, and surface roots of grasses. Surface soil is blackened.

Soil resistance to penetration with tile spade or probe:

- Increased resistance is present throughout top 10-30 cm of soil.

Observation of soil physical condition:

- Change in soil structure from crumb or granular structure to massive or platy structure, restricted to the surface 10-30 cm.
- Platy structure is generally continuous
- Large roots may penetrate the platy structure, but fine and medium roots may not.

Class 3—High disturbance

Soil surface:

- Wheel tracks and depressions highly evident with depth being >30 cm deep.
- Forest floor layers are missing.
- Evidence of topsoil removal, gouging, and piling.
- Soil displacement has removed the *majority* of the surface soil. Surface soil may be mixed with subsoil. Subsoil partially or totally exposed.
- Burning consumed the forest floor, root crowns and surface roots of grasses. Evidence of severely burned soils (mineral soil red in color).

Soil resistance to penetration with tile spade or probe:

- Increased resistance is deep into the soil profile (> 30 cm)

Observations of soil physical conditions:

- Change in soil structure from granular structure to massive or platy structure extends beyond the top 30 cm.
- Platy structure is continuous.
- Roots do not penetrate the platy structure.

displays the same four classes of disturbance (none, low, moderate, and high) described in the Forest Soil Disturbance Monitoring Protocol across a range of forest ecosystems in the United States. It is meant for use as a guide to train field crews, a means to provide a high level of consistency, and a focal point for discussions to improve communication among professionals interested in assessing soil disturbance. Two examples for a class 2, low soil disturbance, are shown in figure 11 for lodgepole pine and ponderosa pine.

A standardized data sheet is part of the protocol to ensure that the same data are collected on each site (SoLo 2008). The form header contains basic site data, location, and general sampling details (table 8). The remainder of the table contains the specific soil descriptive and disturbance information (table 9). This protocol takes the first steps in describing how forest management alters soil surface conditions from a pre-harvest condition. Local specialists are charged with defining how those alterations might affect

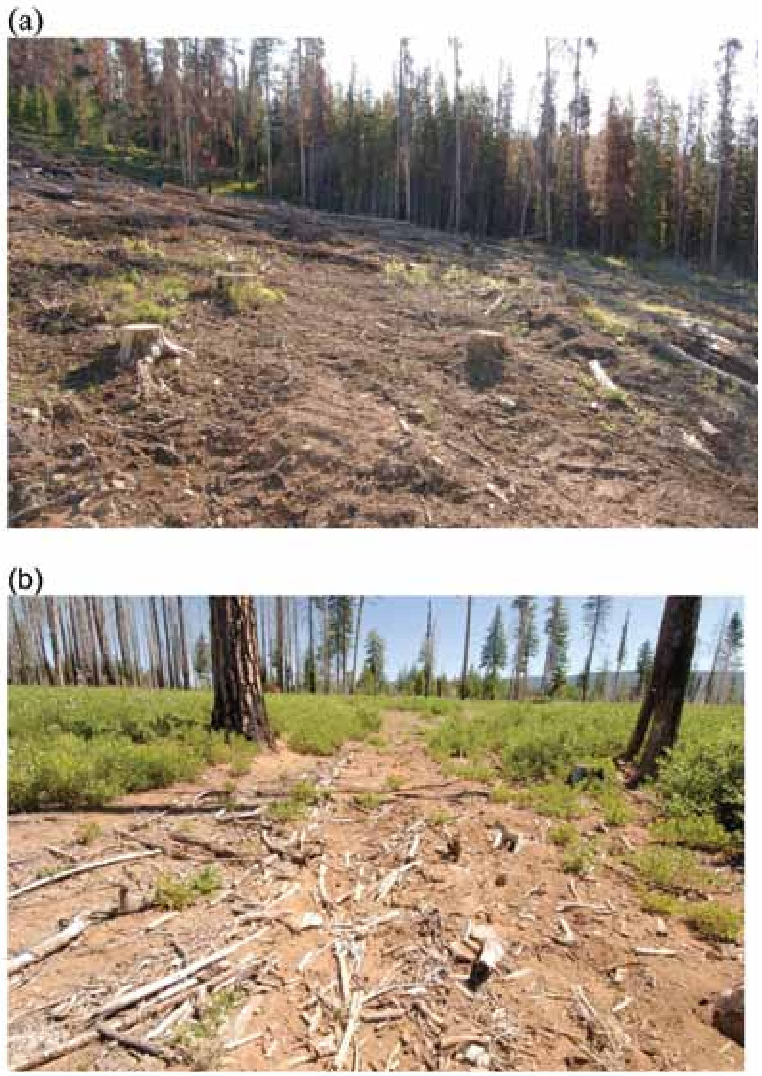


Figure 11. Soil disturbance class 2, low, from the San Dimas Technology Development Center Soil Disturbance visual Guide for (a) lodgepole pine, and (b) ponderosa pine (Napper and others, 2009).

Table 8—SoLo soil disturbance monitoring form basic site data (adapted from SoLo 2008).

SoLo soil disturbance monitoring form header data		
General details	**Location information**	**Sampling details**
Project	GPS start point	Date
Unit identification	Latitude/Longitude	Monitoring type
Observer	UTM coordinates E & W	Point spacing
	UTM zone	Confidence level
		Minimum required Samples
		Interval width

long-term soil productivity and forest sustainability. As with the British Columbia Ministry of Forests project, these disturbance classes need to be locally validated to ensure visual classes and forest growth are appropriately defined.

An integral component of the Protocol (figure 10) is the soil risk rating system (Curran and others 2005; Reynolds and others, in preparation). Its function is to predict the degree of risk of environmental degradation from detrimental soil disturbance. It accounts for variations in soil texture, rock content, organic matter, and vegetation. Like a lot of other soil monitoring systems in the world, the risk rating system is meant to provide

Table 9—SoLo soil disturbance monitoring form detailed soil data (adapted from SoLo 2008).

Direction:							
Sample point	1	2	3	4	5	6	7
f. floor depth (cm):							
Forest floor impacted?							
Live plant?							
Invasive plant?							
Fine woody? <7 cm							
Coarse woody? >7cm							
Bare soil?							
Rock?							
Topsoil displacement?							
Erosion?, comment!							
Rutting? <5cm							
Rutting? 5-10cm							
Rutting? >10cm							
Burning light							
Burning moderate							
Burning severe							
Compaction? 0-10 cm							
Compaction? 10-30 cm							
Compaction? >30cm							
Platy/massive/puddled structure 0-10 cm							
Platy/massive/puddled structure 10-30 cm							
Platy/massive/puddled structure >30 cm							
N Needed (round UP)							
#DIV/0!							
Estimated soil disturbance class							
Detrimental? Enter 1 if Yes, 0 if No							
Comments							

input to Project planning to ensure that adequate Best Management Practices are employed during the operations phase of projects. One attempt at "soil Best Management Practices" has been described by Page-Dumroese and others (2010).

Another important component of the soil monitoring Protocol is training to ensure uniform evaluations of soil conditions by different field crews across the country. As part of this effort, work is in progress to develop a "standardized" training curriculum and materials as well as preparation of a task book similar to those used for Incident Team positions to ensure mastery of key elements. Future web site development will involve additional training modules.

Summary and Conclusions

This paper has reviewed a number of approaches to soil monitoring in Australia, New Zealand, the European Union, Canada, and the United States. Specific cases were evaluated in Tasmania, New Zealand, Ireland, British Columbia, Weyerhaeuser, and the U.S. Forest Service. These States, Companies, and Agencies all have guidance directives from Codes of Forest Practice, Company policy, or National management that focus on soil disturbance. They rely on adaptive management, co-regulation between forest operations and government regulatory authorities, operations planning, and Best Management Practices. The scientific basis for soils monitoring comes from the involvement of Research and Development organizations. Constant feedback from monitoring results and Research and Development efforts results in the type of soil management that will maintain future forest site productivity.

References

Allen, T.F.H.; Hoekstra, T.W. 1994. Toward a definition of sustainability. p. 98-107. In: Covington, W.W.; DeBano, L.F., (tech. coords.). Sustainable Ecological Systems: Implementing an Ecological Approach to Land Management. Gen. Tech. Rep. RM-247. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 363 p.

Amacher, M.C.; Perry, C.H. 2010. The soil indicator of forest health in the Forest Inventory and Analysis Program. In: Page-Dumroese, Deborah; Neary, Daniel; Trettin, Carl, tech. eds. Scientific background for soil monitoring on National Forests and rangelands; workshop proceedings; April 29-30, 2008; Denver, CO. Proc. RMRS-P-59. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Breckenridge, R.P.; Kepner, W.G.; Mouat, D.A. 1995. A process for selecting indicators for monitoring conditions of rangeland health. Environmental Monitoring and Assessment 36: 45-60.

British Columbia Ministry of Forests. 2001. Soil Conservation Surveys Guidebook. 2nd edition. Forest Practices Code Guidebook. Forest Practices Branch, British Columbia Ministry of Forests, Victoria, British Columbia. http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/SOILSURV/Soil-toc.htm. [06/12/09]

Burger, J.A. 2002. Chapter 6: Environmental sustainability of forest energy production, 6.2: Soil and Long-Term Site Productivity Values. p. 7-36. In: Richardson, J.; Smith, T.; Hakkila, P. Bioenergy from Sustainable Forestry: Guiding Principles and Practices. Elsevier, Amsterdam. 344 p.

Cline, R.G.; Ragus, J.; Hogan, G.D.; Maynard, D.G.; Foster, N.W.; Terry, T.A.; Heninger, R.L.; Campbell, R.G.; Carter, M.C. 2006. Policies and practices to sustain soil productivity: perspectives from the public and private sectors. Canadian Journal of Forest Research 36: 615-625.

Curran, M.P.; Miller, R.E.; Howes, S.W.; Maynard, D.G.; Terry, T.A.; Heninger, R.L.; Niemann, T.; Van Rees, K.; Powers, R.F.; Schoenholtz, S.E. 2005. Progress towards a more uniform assessment and reporting of soil disturbance for operations, research, and sustainability protocols. Forest Ecology and Management 220: 17-30.

Curran, M.; Maynard, D.; Heninger, R.; Terry, T.; Howes, S.; Stone, D.; Niemann, T.; Miller, R.E. 2007. Elements and rationale for a common approach to assess and report soil disturbance. The Forestry Chronicle 83: 852-866.

Doran, J.W.; Parkin, T.B. 1994. Defining and assessing soil quality. p. 3-21. In: Soil Science Society of America Special Publication No. 35, Madison, WI.

Doran, J.W.; Jones, A.J., (eds.). 1996. Methods for Assessing Soil Quality. Soil Science Society of America, SpecialPublication No. 49, Madison, WI.

Doran, J.W.; Jones, A.J.; Arshad, M.A.; Gilley, J.E. 1998. Chapter 2: Determinants of soil quality and health. p.17- 38. In: Lal, R., (ed.). 1998. Soil Quality and Soil Erosion. 329 p.

Elzinga, C.L.; Salzer, D.W.; Willoughby, J.W.; Gibbs, J.P. 2001. Monitoring Plant and Animal Populations. Blackwell Science, Malden, MA.

Eurostat. 2009. European Commission Statistics Database. http://epp.eurostat.ec.europa.eu/portal/page/portal/forestry/data/main_tables. [24 July 2009]

Forestry Commission Tasmania. 1993. Forest Practices Code. Tasmanian Forestry Commission, Hobart, Tasmania. 98 p.

Grove, C. (Compiler). 2007. A Guide to Planning Approvals for Forestry in Tasmania. Local Government Forestry Consultative Committee, Hobart, Tasmania. 43 p.

Hall, Andrew. 2008. (Personal communication). July 1. Mansfield, United Kingdom. United Kingdom Forestry Commission, East Midlands Region.

Hart, J.V.; Hart, S.C. 1993. A review of factors affecting soil productivity in rangelands, and woodlands of the southwestern United States. School of Forestry Report 40-8371-2-0733. Northern Arizona University. 75 p.

Helsinki Process. 1994. Proceedings of the Ministerial Conferences and Expert Meetings. Liaison Office of the Ministerial Conference on the Protection of Forests in Europe. Helsinki, Finland.

Heninger, R.L.; Terry, T.A.; Dobkowski, A.; Scott, W. 1997. Managing for sustainable site productivity: Weyerhaeuser's forestry perspective. Biomass and Bioenergy 4-5: 255-267.

Heninger, R.L.; Scott, W.; Dobkowski, A.; Miller, R.; Anderson, H.; Duke, S. 2002. Soil disturbance and 10-year growth response of west Douglas-fir on nontilled and tilled skid trails in the Oregon Cascades. Canadian Journal of Forest Research 32: 233-246.

Herrick, J.E.; Van Zee, J.W.; Havstad, K.M.; Burkett, L.M.; Whitford, W.G. 2005a. Monitoring Manual for Grassland, Shrubland, and Savanna Ecosystems. Volume I: Quick Start. USDA-ARS Jornada Experimental Range and The University of Arizona Press. 42 p.

Herrick, J.E.; Van Zee, J.W.; Havstad, K.M.; Burkett, L.M.; Whitford, W.G. 2005b. Monitoring Manual for Grassland, Shrubland, and Savanna Ecosystems. Volume II: Design, Supplementary Methods, and Interpretation. USDA-ARS Jornada Experimental Range and The University of Arizona Press. 206 p.

Howes, S.; Hazard, J.; Geist, M.J. 1983. Guidelines for Sampling Some Physical Conditions of Surface Soils. R6-RWM-145. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 34 p.

International Cooperative Programme on Modelling and Mapping of Critical Loads & Levels and Air Pollution Effects, Risks and Trends (ICP). 2004. ICP Modeling and Mapping, Manual on Methodologies and Criteria for Modeling and Mapping Critical Loads and Levels and Air Pollution Effects, Risks and Trends—revision 2004. http://www.icpmapping.org. [06/10/2009]

Ireland Forest Service. 2000. Code of Best Forest Practice—Ireland. Forest Service, Department of Marine and Natural Resources, Dublin, Ireland. 101 p.

Johnson, D.W.; Curtis, P.S. 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management. 140: 227-238.

Karlen, D.L.; Mausbach, M.J.; Doran, J.W.; Cline, R.G.; Harris, R.F.; Schuman, G.E. 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Science Society of America Journal 61: 4-10.

Lovett, G.M.; Burns, D.A.; Driscoll, C.T.; Jenkins, J.C.; Mitchell, M.J.; Rustad, L.; Shanley, J.B.; Likens, G.E., Haeuber, R. 2007. Who needs environmental monitoring? Frontiers in Ecology and the Environment 5: 253-260.

Moir, W.H.; Mowrer, H.T. 1995. Unsustainability. Forest Ecology and Management 73: 239-248.

Montreal Process. 1995. Criteria and indicators for the conservation and sustainable management of temporal and boreal forests. Catalogue Fo42-238/1995E. Hull, Quebec: Canadian Forest Service.

Morvan, X.; Saby, N.P.A.; Arrouays, D.; Le Bas, C.; Jones, R.J.A.; Verheijen, F.G.A.; Bellamy, P.H.; Stephens, M.; Kibblewhite, M.G. 2007. Soil monitoring in Europe: a review of existing systems and requirements for harmonization. Science of the Total Environment. 301: 1-12.

Napper, C.; Howes, S.; Page-Dumroese, D. 2009. Soil disturbance field guide. 0819 1815-SDTDC. San Dimas, CA: San Dimas Technology Center. 103 p.

National Forest Inventory. 2008. Australia's State of the Forests Report 2008. Australian Government, Department of Agriculture, Fisheries, and Forestry, Canberra, Australia. 250 p.

Natural Resources Canada. 2009. Canada's Forests, Environment, Quick Facts. http://nrcan.gc.ca. [06/12/09].

O'Neill, K.P.; Amacher, M.C.; Palmer, C.J. 2005a. Developing a national indicator of soil quality on U.S. forest lands: methods and initial results. Environmental Monitoring and Assessment 107: 59-80.

O'Neill, K.P.; Amacher, M.C.; Perry, C.H. 2005b. Soils as an indicator of forest health: A guide to the collection, analysis, and interpretation of soil indicator data in the Forest Inventory and Analysis Program. Gen. Tech. Rep. GTR-258. St Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.

Page-Dumroese, Deborah S.; Abbott, Ann M.; Rice, Thomas M. 2009a. Forest Soil Disturbance Monitoring Protocol: Volume I: Rapid assessment. Gen. Tech. Rep. WO-GTR-82a. Washington, DC: U.S. Department of Agriculture, Forest Service. 31 p.

Page-Dumroese, Deborah S.; Abbott, Ann M.; Rice, Thomas M. 2009b. Forest Soil Disturbance Monitoring Protocol: Volume II: Supplementary methods, statistics, and data collection. Gen. Tech. Rep. WO-GTR-82b. Washington, DC: U.S. Department of Agriculture, Forest Service. 64 p.

Page-Dumroese, D.S.; Jurgensen, M.F.; Tiarks, A.E.; Ponder, F., Jr.; Sanchez, F.G.; Fleming, R.L.; Kranabetter, J.M.; Powers, R.F.; Stone, D.M.; Elioff, J.D.; Scott, D.A. 2006. Soil physical property changes at the North American Long-Term Soil Productivity study sites: 1 and 5 years after compaction. Canadian Journal of Forest Research 36: 551-564.

Page-Dumroese, Deborah S.; Jurgensen, Martin; Terry, Thomas. 2010. Maintaining soil productivity during forest or biomass-to-energy thinning harvests in the western Unites States. Western Journal of Applied Forestry. 25(1):5-11.

Powers, R.F.; Alban, D.H.; Miller, R.E.; Tiarks, A.E.; Wells, C.G.; Avers, P.E.; Cline, R.G.; Loftus, N.S., Jr.; Fitzgerald, R.O. 1990. Sustaining productivity of North American forests: Problems and prospects. p. 49-79. In: Gessel, S.P.; Lacate, D.S.; Weetman, G.F.; Powers, R.F. (eds.). Sustained Productivity of Forest Soils, Proceedings of the 7th North American Forest Soils Conference; 24-28 July 1988; Vancouver, BC. University of British Columbia Faculty of Forestry, Vancouver, British Columbia, Canada.

Powers, R.F.; Scott, D.A.; Sanchez, F.G.; Voldseth, R.A.; Page-Dumroese, D.S.; Elioff, J.D.; Stone, D.M. 2005. The North American long-term soil productivity experiment: findings from the first decade of research. Forest Ecology and Management 220(1-3): 31-50.

Reynolds, K.M.; Hessburg, P.F.; Jensen, M.; Miller, R.E.; Meurisse, R.T.; Salter, R.B. (In press). Predicting risk of soil degradation associated with wildfire and ground-based logging. Soil Science Society of America Journal.

Smith, W.B.; Vissage, J.; Sheffield, R.; Darr, D. 2001. Forest statistics of the United States, 1997. Gen. Tech. Rep. GTR-NC-219. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.

SoLo. 2008. Soil monitoring data form. http://forest.moscowfsl.wsu.edu/smp/solo/documents/monitoring/forms/SoLoSDM_Form_081202_AMA.xls. [06/12/09].

Sparling, G.P.; Schipper, L.A. 1998. Soil quality monitoring in New Zealand: concepts, approach and interpretation. Landcare Research Technical Report LCR 9798/060, Hamilton, New Zealand. 30 p.

Sparling, G.P.; Schipper, L.A. 2002. Soil quality at a national scale in New Zealand. Journal of Environmental Quality 31: 1848-1857.

U.S. Forest Service. 1993. The principle laws relating to Forest Service activities. Washington, DC: U.S. Department of Agriculture, Forest Service.

U.S. Forest Service. 1999. Forest Service Manual, Missoula, Montana, FSM-2500—Watershed Management, R-1 Supplement No. 2500-99-1, Chapter 2500 Soil Management, 2554 Soil Quality Monitoring, Effective November 12, 1999. 9 p.

USDA Natural Resources Conservation Service (NRCS). 2001. Guidelines for soil quality assessment in conservation planning. Soil Quality Institute. 38 p.

Vaughan, L.; Visser, R.; Smith, M. 1993. New Zealand Forest Code of Practice. 2nd edition. Logging Industry Research Organisation, Rotorua, New Zealand.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

The Soil Indicator of Forest Health in the Forest Inventory and Analysis Program

Michael C. Amacher, Research Soil Scientist, Forest Inventory and Analysis Program, Rocky Mountain Research Station, Logan, UT

Charles H. Perry, Research Soil Scientist, Forest Inventory and Analysis Program, Northern Research Station, St. Paul, MN

Abstract—Montreal Process Criteria and Indicators (MPCI) were established to monitor forest conditions and trends to promote sustainable forest management. The Soil Indicator of forest health was developed and implemented within the USFS Forest Inventory and Analysis (FIA) program to assess condition and trends in forest soil quality in U.S. forests regardless of ownership. The Soil Indicator differs from intensive site monitoring programs in that it is a nationally applied, landscape-scale, grid-based design across all ecoregions, forest types, and land ownership categories. To date, the Soil Indicator has provided the only national assessment of soil erosion potential, areal extent of soil compaction, measured organic C stocks inventory, and soil physical and chemical properties of forest soils in the United States.

Introduction

Forested lands comprise approximately 750 million acres in the United States, about 33 percent of total land area (Smith and others, in press). Forest soils have unique properties, in part because of the types of vegetation, microbial activity, and soil organisms that influence forest soil development. But organisms are not the only factor influencing soil development. Soils on the landscape are the result of five interactive soil forming factors (Jenny 1994): parent material, climate, landscape position (topography), organisms (vegetation and soil organisms), and time.

Many external forces can have a profound influence on forest soil condition and hence forest health. These include agents of change or disturbances to apparent steady-state conditions such as shifts in climate, fire, insect and disease activities, land use activities, and land management actions. Yet, until recently, a systematic monitoring or assessment program that tracks changes in indicators of environmental condition for many resource bases was lacking.

The Montreal Process Criteria and Indicators (MPCI) program was developed to assess the condition and trend of forest resources of member countries (Montreal Process Working Group 2005). This information is used for sustainable forest management and includes indicators of forest health. The condition and trend of forest soils is part of those indicators of forest health that are inventoried by the USFS Forest Inventory and Analysis (FIA) program. This paper will review the development of the Soil Indicator of forest health and present a review and summary of recent Soil Indicator condition assessments. Topics to be covered include:

- Overview of FIA and forest health indicators program
- History of Soil Indicator development
- Forest health monitoring and the USFS integrated monitoring framework
- Broad-scale (landscape-scale) versus intensive site monitoring
- Attributes and strengths of forest health indicators including the Soil Indicator
- Soil Indicator monitoring questions and objectives
- Sampling design
- Field and laboratory analysis methods

- Quality control/quality assurance
- Data analysis and reporting framework including post-analysis stratification approaches
- Status of U.S. forest soils—review and summary of recent findings
- Sampling variability
- Soil Indicator weaknesses
- Soil Indicator and Soil Quality Standards monitoring

Forest Health Indicators and the FIA Program

The Soil Indicator and all other forest health indicators are part of the FIA program. FIA is the nation's forest census. It began some 80 years ago as a periodic inventory of timber resources and has evolved into a continuous, annualized inventory of U.S. forest resources across all public and private ownership categories (Smith 2008; USDA Forest Service 2009a).

FIA collects and reports data on the status and trend of

- Forest area and locations,
- Species, size, and health of trees,
- Total tree growth, mortality, and removals,
- Wood production and utilization,
- Forest land ownership, and
- Forest health.

Various indicators of forest health are included as part of the FIA program:

- Crown condition (Schomaker and others 2007)
- Ozone injury to vegetation (Smith and others 2007)
- Tree growth, damage, and mortality (Bechtold 2003a,b)
- Lichen communities (McCune 2000)
- Understory vegetation structure and diversity (Schulz and others 2009)
- Down woody material (Woodall and Monleon 2008)
- Soil quality (O'Neill and others 2005c)

Soil Indicator Development

Although a comprehensive history of the development of the Montreal Criteria and Indicators process and the development of the FIA indicators of forest health is beyond the scope of this paper, some historical background will be presented to indicate how the Soil Indicator evolved. The Soil Indicator actually began as part of the U.S. Environmental Protection Agency (EPA) Environmental Monitoring and Assessment Program (EMAP) (USEPA 2009a). The purpose of EMAP is to develop the tools needed to monitor and assess the status and trend of national ecological resources at multiple spatial and temporal scales (USEPA 2009a). But beyond that, forest status and trend assessment programs are driven by MPCI concepts and framework of sustainable ecosystems (Montreal Process Working Group 2005).

Following its beginnings within EMAP, the Soil Indicator was pilot tested throughout the 1990s within the Forest Health Monitoring (FHM) program. At the time, FIA conducted forest inventories whereas FHM conducted forest health assessments. In 2000, the FHM forest health indicators transitioned from FHM to FIA. By then, many changes, improvements, and add-ons had been made to the Soil Indicator. From 2001 onward, the Soil Indicator of forest health was fully implemented as part of the FIA forest health indicators program with little change to its core measurements and protocols.

Because the forest health indicators were developed within the FHM program, a brief review of the four core areas of FHM is needed to better understand overall indicator development and implementation. Forest Health Monitoring previously consisted of four programmatic areas:

- Detection monitoring—Uses the FIA P3 plot grid consisting of one plot for every 96,000 acres. Detection monitoring is used to uncover forest health threats as they develop.
- Evaluation monitoring—This is a more spatially intensive monitoring of forest health problems uncovered by Detection Monitoring. Examples would include intensified grid special project monitoring on National Forests.
- Intensive site monitoring (ISM)—Generally, more detailed, process-oriented research at specific sites. An example includes the joint USGS-USFS Delaware River Basin project (USDA Forest Service 2009b).
- Research on monitoring techniques (ROMT)—Basically, a monitoring tool development program.

The relationship among the various monitoring programs and scales can best be described with the USFS Integrated Monitoring Framework (fig. 1). In phase 1, remote sensing is used to delineate forest from nonforest lands. Next in scale are various local management inventories. These may be done using temporary or permanent plots at various spatial scales, for example, National Forest Systems (NFS) inventory projects on individual forests.

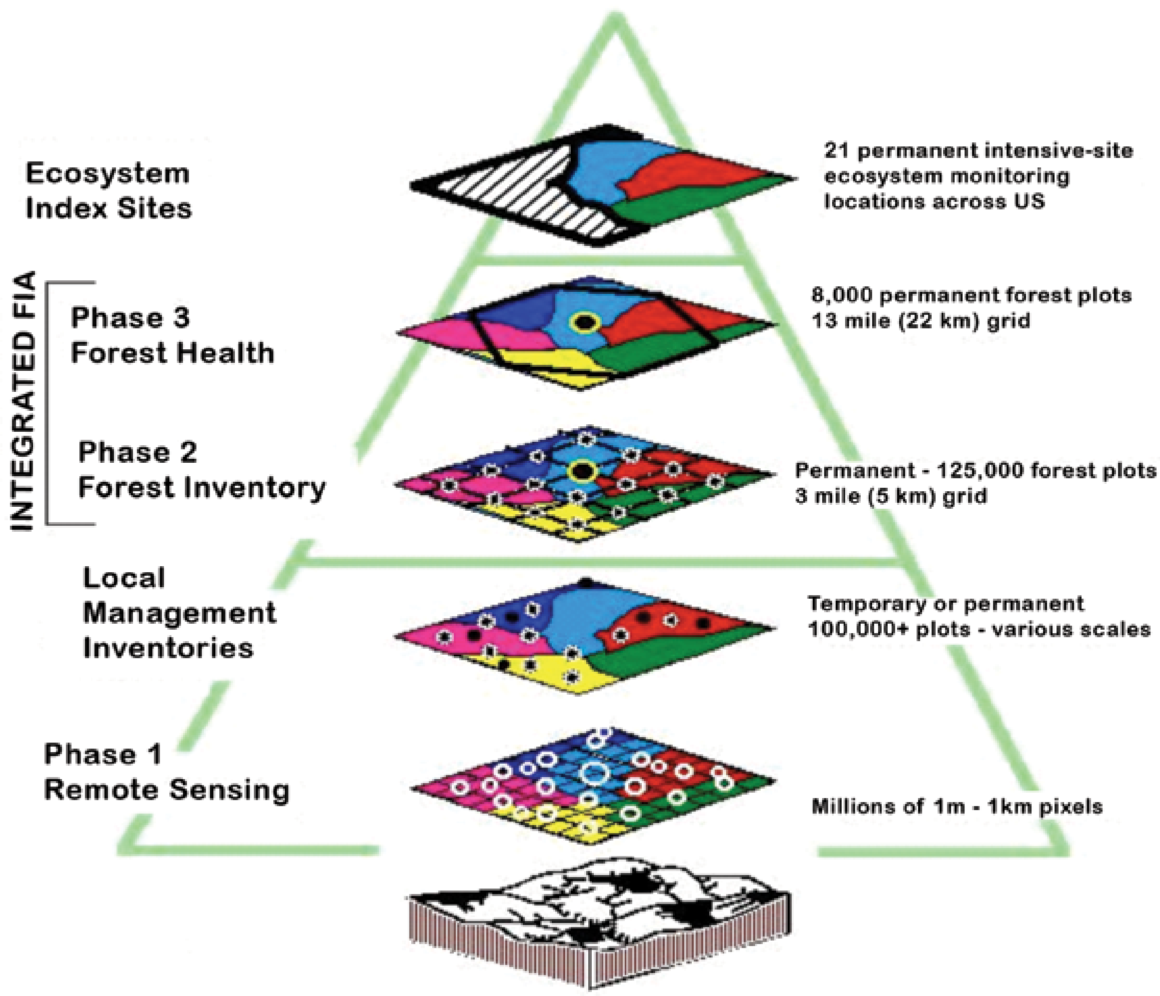


Figure 1. USFS integrated monitoring framework showing the relationship of FIA P1, P2, and P3 plot network to the forested landscape.

Field measurements in the integrated FIA program are done in two phases. Phase 2 (P2) is the annualized forest inventory and consists of a permanent plot network with approximately 125,000 forest plots on a 3-mile (5-km) grid. Phase 3 (P3) is the forest health monitoring part of the program and is a 1/16 subset of the P2 grid (about 7,800 permanent plots on a 13-mile (22-km) grid. Ecosystem index site monitoring consists of 21 permanent intensive monitoring sites across the United States.

Landscape-Scale Versus Intensive Site Monitoring

Figure 1 clearly shows the relationship among multiple spatial monitoring scales. At this point, it is worthwhile to contrast broad or landscape-scale monitoring with intensive site monitoring because the purpose and objectives of these two monitoring program are vastly different.

There are three main landscape-scale monitoring programs in the United States:

- USEPA EMAP—Develop the tools needed to monitor and assess the status and trend of national ecological resources at multiple spatial and temporal scales.
- National Resource Conservation Service (NRCS) programs:
  - National Cooperative Soil Survey (USDA NRCS 2007, 2008a)—Basically a soil mapping program.
  - National Resources Inventory (NRI) (Nusser and Goebel 1997; Nusser and others 1998; USDA NRCS 2008b)—Statistical survey of land-use and natural resource condition and trend on U.S. non-federal lands. The NRCS NRI is somewhat analogous to the Forest Service FIA program.
- U.S. Forest Service FIA (Smith 2002; USDA Forest Service 2009a)—Continuous, annualized inventory of U.S. forest resources across all public and private ownership categories. FIA collects and reports data on the status and trend of forest resources and forest health.

The principal similarity among all three programs is that they all collect data to assess condition and trend of various U.S. resources at the landscape scale using a grid-based monitoring system. Or to describe this in a simplified way, if you want to know what is going on ‘out there,’ you have to measure it. And ‘it’ needs to be measured at a sufficient spatial scale to provide a reasonably accurate snapshot of current conditions and to provide a suitable baseline to track future trends, if any.

A very different approach is used by intensive site monitoring projects. These tend to be focused on gaining a better understanding of ecosystems processes operating at a fixed number of sites representing key ecosystems or areas. They often rely on spatially and temporally intensive measurements to quantify key ecosystem processes. Findings from intensive site projects are often extrapolated elsewhere on the landscape. This works for sites with similar characteristics, but is unreliable for different areas.

The following are examples of intensive site monitoring networks:

- Experimental forests, rangelands, and watersheds (fig. 2) (Adams and others 2008; USDA Forest Service 2008);
- Long-term ecological research (LTER) sites (fig. 3) (Hobie and others 2003; U.S. Long Term Ecological Research 2007);
- Long-term soil productivity (LTSP) sites (fig. 4) (Powers and others 2005);
- Fire and fire-surrogate plots (fig. 5) (Fire Research and Management Exchange Systems 2008);
- National Ecological Observatory Network (NEON)—Continental-scale research platform for discovering and understanding impacts of climate change, land-use change, and invasive species on ecology (fig. 6) (National Ecological Observatory Network 2008); and
- Critical-Zone Exploration Network (CZEN)—Established to investigate the coupling between physical, chemical, geological, and biological processes in the critical (life-supporting) zone (Critical Zone Exploration Network 2008).

Figure 2. Map of experimental forests, rangelands, and watersheds in North America.

Figure 3. Map of long-term ecological research (LTER) sites in North America. The site names corresponding to the site abbreviations are AND = Andrews , ARC = Arctic, BES = Baltimore Ecosystem Study, BNZ = Bonanza Creek, CAP = Central Arizona – Phoenix, CCE = California Current Ecosystem, CDR = Cedar Creek, CWT = Coweeta, FCE = Florida Coastal Everglades, GCE = Georgia Coastal Ecosystems, HFR = Harvard Forest, HBR = Hubbard Brook, JRN = Jornada Basin, KBS = Kellogg Biological Station, KNZ = Konza, LUQ = Luquillo, MCM = McMurdo Dry Valleys, MCR = Moorea Coral Reef, NWT = Niwot Ridge, NTL = North Temperate Lakes, PAL = Palmer Station, PIE = Plum Island Ecosystem, SBC = Santa Barbara Coastal, SEV = Sevilleta, SGS = Shortgrass Steppe, VCR = Virginia Coastal Reserve.

Figure 4. Map of long-term soil productivity (LTSP) sites in North America.

Figure 5. Map of U.S. fire and fire surrogate plots.

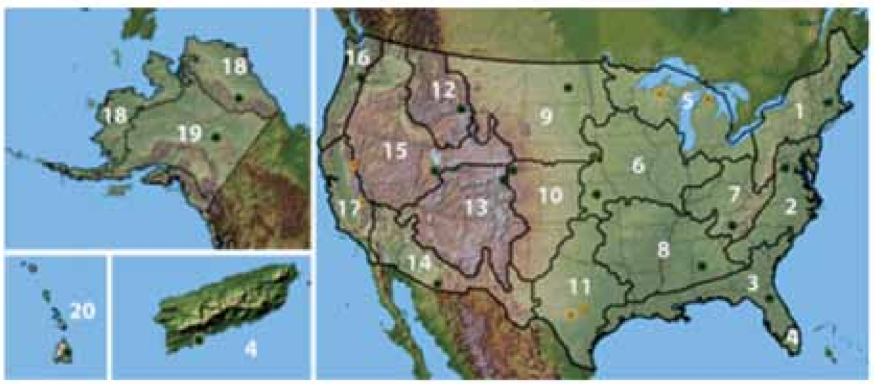


Figure 6. Map of National Ecological Observatory Network (NEON) monitoring areas. The core site areas corresponding to the numbered regions are 1 = Northeast, 2 = Mid-Atlantic, 3 = Southeast, 4 = Atlantic Neo-Tropical, 5 = Great Lakes, 6 = Prairie Peninsula, 7 = Appalachian Cumberland, 8 = Ozarks Complex, 9 = Northern Plains, 10 = Central Plains, 11 = Southern Plains, 12 = Northern Rockies, 13 = Southern Rockies, 14 = Desert Southwest, 15 = Great Basin, 16 = Pacific Northwest, 17 = Pacific Southwest, 18 = Tundra, 19 = Taiga, 20 = Pacific Tropical.

A main difference between NEON and CZEN is that NEON is more ecology oriented whereas CZEN is more geosciences oriented.

The landscape-scale and intensive site monitoring programs listed above tend to be land-based although they often include water and air measurements. There are monitoring programs run by the USEPA and U.S. Geological Survey (USGS) that are focused primarily on air and water quality assessments.

- Air quality monitoring
  - National Atmospheric Deposition Program (NADP) (National Atmospheric Deposition Program 2008)
  - Clean Air Status and Trends Network (CASTNET) (USEPA 2009b)
- Water quality monitoring
  - USEPA National Assessment Database (USEPA 2009c)
  - USGS Hydrologic Benchmark Network (HBN) (USGS 2002)
  - USGS National Stream Quality Accounting Network (NASQAN) (USGS 2009a)
  - USGS National Water Quality Assessment (NAWQA) (USGS 2009b)

One way to link landscape-scale and intensive site monitoring is to co-locate landscape-scale monitoring plots, such as FIA P3 plots, on intensive site monitoring areas. This provides a direct linkage between what would otherwise be disparate databases and allows for more reliable quantitative estimates of ecosystem states and rates of change. This approach was used for the joint USGS-USFS Delaware River Basin project.

Since this paper is an overview of the FIA Soil Indicator, it is instructive to list the key attributes of the Soil Indicator program:

- Condition and trend assessments at multiple spatial and temporal scales—detection and monitoring of soils-related forest health problems and threats;
- Integration with other forest data and with other forest health indicators;
- Standardized, unbiased, grid-based measurement and sampling design;
- A national and comprehensive scope: all U.S. forest lands are measured regardless of ownership; all ecoregions, forest types, and forest soil types are included;
- Standardized, reproducible, nationally consistent protocol;
- Standardized nationally consistent training;
- Quality Control and Quality Assurance (QC/QA) programs; and
- Standardized estimation and reporting of forest resources inventory data.

These key attributes are major strengths in that they directly overcome major weaknesses in intensive site monitoring programs. The Soil Indicator shares these attributes with other FIA program indicators.

Before turning to a detailed description of the Soil Indicator, we must also indicate that the Soil Indicator does not replace or overlap existing USDA NRCS soils programs. Specifically, the Soil Indicator is not a soil survey, is not a soil mapping program, and is not a soil characterization program, although it does characterize (measure properties of) some aspects of forest soils.

Soil Indicator and Monitoring Questions

The Soil Indicator was developed to specifically address monitoring questions posed by the Montreal Process Criteria and Indicators (MPCI): What is the current status and projected trend in the area and percent of forest land with

- Accelerated soil erosion?
- Compaction or change in soil physical properties resulting from human activities?
- Changes in the amount of moisture holding capacity, internal drainage, and rooting depth?
- Diminished soil organic matter and/or changes in other soil chemical properties?
- Contributions to the global carbon budget including absorption and release of carbon?
- Accumulations of persistent toxic substances?

Thus, in summary the FIA Soil Indicator provides data to assess (1) productivity and sustainability of forest ecosystems, (2) conservation of soil and water resources, (3) contributions of forest soils to the global carbon cycle, and (4) accumulation of persistent toxic substances.

Sampling Design

The USFS integrated monitoring framework was presented in figure 1. The statistical design of the integrated FIA program is based on a hexagonal grid or network of plots (Brand and others 2000; Bechtold and Patterson 2005). Grid density is illustrated in figure 7 using the state of Minnesota as an example. In phase 1 (P1), forest land is mapped via remote sensing using 3,000,000 national 1-m pixels. The forest map of Minnesota produced by phase I mapping is shown on the left side of figure 7. In phase 2 (P2), forest inventory data are collected on a national network of approximately 125,000 plots (3-mile grid) with each one representing 6,000 acres. P2 plot density for Minnesota is represented in the middle of figure 7. A 1/16 subset of P2 plots is used to collect forest health data. This phase 3 (P3) plot network consists of approximately 7,800 plots

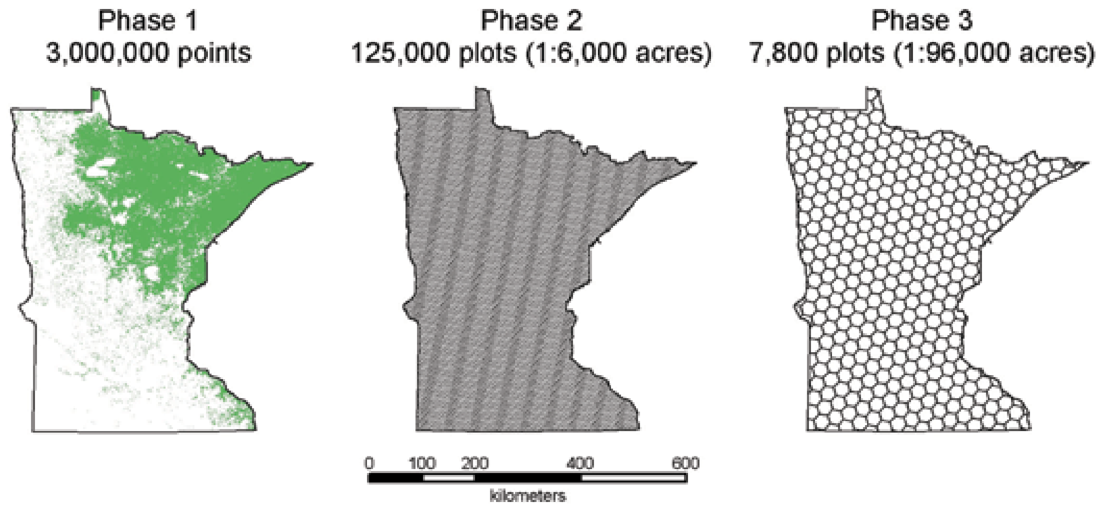


Figure 7. Map of hexagonal grid system scales using Minnesota as an example. The phase 1 (P1) grid consists of 3,000,000 points across the United States. A map of forested areas within Minnesota defined using this scale is shown on the left. The phase 2 (P2) grid consists of 125,000 plots (1 plot per 6,000 acres on a 3-mile (5-km) grid). P2 plot density for Minnesota is shown on the middle map. The phase 3 (P3) grid consists of 7,800 plots (1 plot per 96,000 acres on a 13-mile (22-km) grid). P3 plot density for Minnesota is shown on the right side map.

(13-mile grid) with each plot representing 96,000 acres. P3 plot density for Minnesota is shown on the right side of figure 7.

Figure 7 clearly shows that a hexagonal sampling design can be used at any spatial scale. Thus, sample 'hexes' can be virtually any size. The various FIA plots are assigned to the hexes. One of the requirements of the legislative authorization of the annualized FIA inventory is that plot locations are not released as public information. This is to protect landowner confidentiality. EMAP hexagons are often used to represent P3 data since they are approximately the same size. A national network of EMAP hexes containing a plot already visited for Soil Indicator measurement and sampling is shown on the U.S. map in fig. 8, but plot locations within the hexes are not disclosed.

The FIA program is a continuous annualized inventory of U.S. forest resources, but resources do not permit every plot to be assessed each year. Thus, hexes and plots within hexes are assigned to one of five panels and only one panel of plots (20% of plots) is sampled each year. In a 5-year cycle, all five panels would be visited and measured.

Each P3 plot is measured and sampled once every 10 years for Soil Indicator variables. In the eastern United States (Northern and Southern FIA regions), the Soil Indicator alternates with the Lichen Indicator over a 10-year cycle of the 5 panels of plots. In one cycle of 5 panels, each plot is sampled for soils over the 5-year cycle (one panel of plots per year). In the next 5-year cycle, each plot is sampled for lichens. Thus, after a 10-year cycle, the plots in the first panel are again sampled for Soil Indicator variables and so on. In the western United States (Interior West and Pacific West FIA regions), plots within each panel are assigned to sub-panels. In year 1, plots in sub-panel A of panel 1 are sampled. In year 2, plots in sub-panel B of panel 1 are sampled. In year 3, plots in sub-panel A of panel 2 are sampled, and so forth. Thus, it takes 10-years to visit each plot and then the process begins again. Thus, Soil Indicator data are collected on each plot in the East and West every 10 years, but the panel schedules differ among the FIA regions.

The standard FIA plot design consists of four circular subplots (24-ft radius) arranged in a triangle design with 120 ft between subplot centers (fig. 9). Forest inventory and forest health indicator measurements are made within each subplot. Surrounding each subplot is an annular plot (59-ft radius) reserved for sampling.

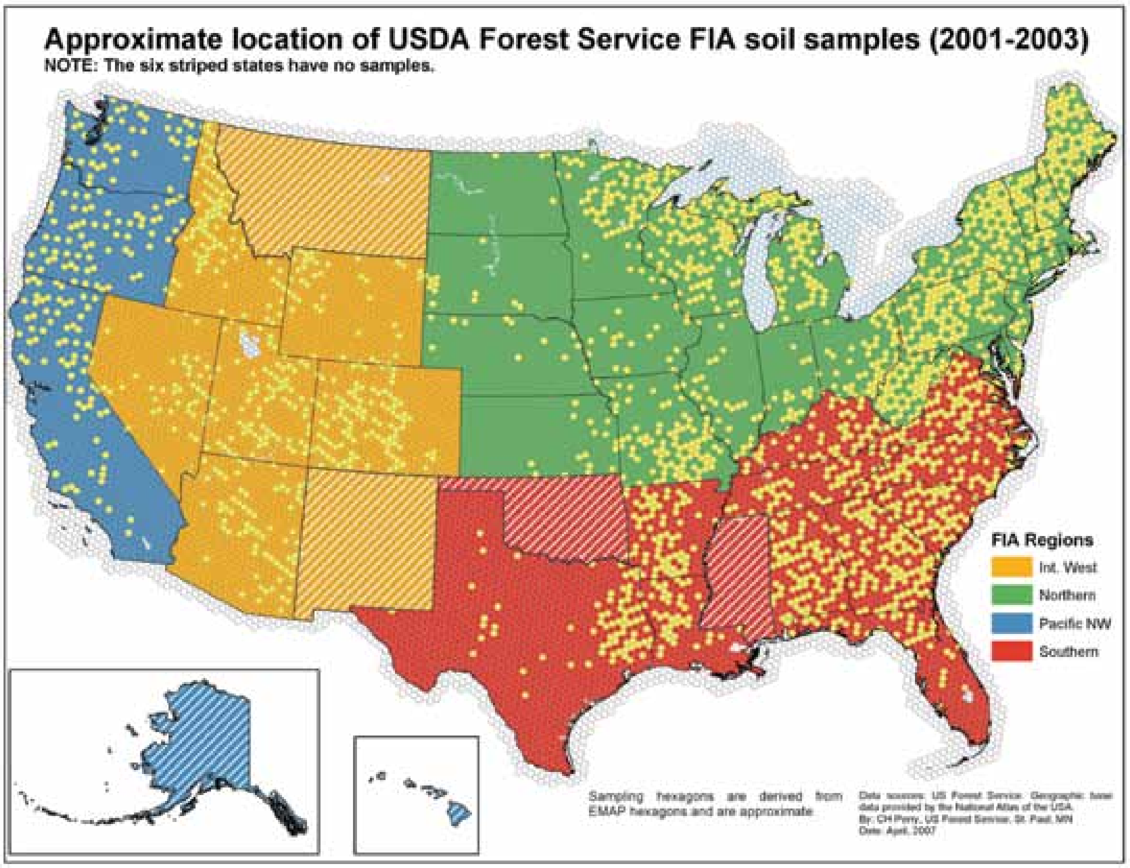
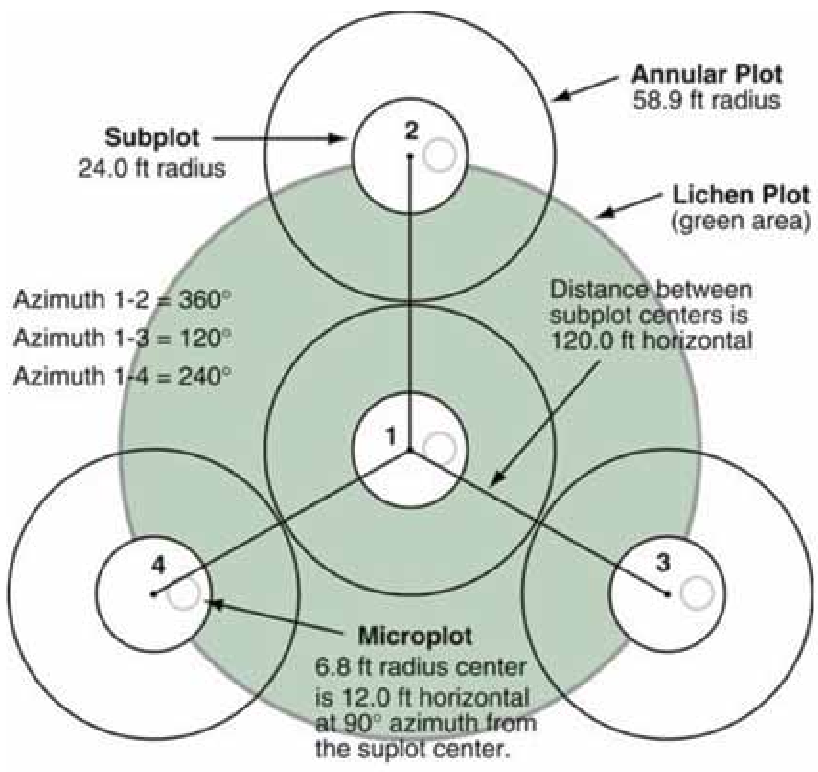


Figure 8. U.S. map of P3 plot hexagons that have been sampled for the Soil Indicator from 2000 through 2005.

Figure 9. Standard FIA plot design.



Measurement and Sampling Protocols

The FIA Soil Indicator consists of three main assessments:

1. Erosion assessment
   a. Percent of each subplot area with bare soil
2. Soil compaction assessment
   a. Percent of each subplot area with evidences of compaction
   b. Compaction type
3. Soil sampling and associated measurements
   a. Forest floor and litter thickness
   b. Forest floor sample collection
   c. Depth to restrictive layer
   d. Soil core collection for mineral or organic soils
      i. 0–10 cm
      ii. 10–20 cm
   e. Soil texture

Protocols for these measurements and soil sampling have been established and are outlined in detail in the FIA P3 field manual (USDA Forest Service 2007). A general description of the measurements and sampling is given below.

Visual estimation of the area of bare soil within each of the four subplots is expressed as percent of subplot area in 5 percent classes (table 1). Field crews are trained to identify bare soil and then to estimate the percent of plot area consisting of bare soil. Bare soil is the single most important variable in assessing erosion potential. Bare soil along with additional soil data (soil texture) and ancillary data (precipitation history from nearby weather stations, slope, and plot area) can be used to estimate soil erosion potential with the Watershed Erosion Prediction Program (WEPP) (Elliot and others 2000). Because the areal extent of bare soil on FIA plots is estimated to assess soil erosion potential, bare soil is defined in terms of particle sizes most likely to move via raindrop impact and runoff. For the FIA Soil Indicator, bare soil is defined as follows:

- Bare mineral soil consisting of fine gravel (2–5 mm), sand, silt, and clay sized particles.
- Bare organic soil; although interlocking organic fibers usually guard against organic soil erosion.
- Bedrock outcrops, rocks, and talus are excluded; rock cover often provides some measure of erosion protection in all but the most extreme storm events.

Table 1—Bare soil as a percent of subplot area data attributes for soil erosion potential assessment in the FIA P3 Soil Indicator (FIA 2008).

- Where collected: subplots 1, 2, 3, and 4.
- When collected: any portion of a subplot containing at least one accessible forested condition class.
- Field width: 2 digits
- Tolerance: ± 10 percent
- Measurement quality objective (MQO): within tolerance 75 percent of the time.

PDR code: bare soil range			
00: none	25: 21-25	55: 51-55	85: 81-85
01: trace	30: 26-30	60: 56-60	90: 86-90
05: 01-05	35: 31-35	65: 61-65	95: 91-95
10: 06-10	40: 36-40	70: 66-70	99: 96-100
15: 11-15	45: 41-45	75: 71-75	
20: 16-20	50: 46-50	80: 76-80	

- Cryptobiotic crusts are excluded; these are mats of living organisms (*e.g.*, cyanobacteria and algae) covering bare soil and are usually present in arid ecosystems. They provide some measure of erosion protection against raindrop impacts.
- Basal tree area and stumps are excluded; these usually occupy a very small total area of a plot and protect against raindrop impact and runoff.

After assessing areal extent of bare soil on each subplot, field crews next look for evidences of compaction. Field crews are trained to identify several disturbances as evidences of soil compaction (table 2). They then estimate the area of compaction within each of the four subplots (percent of subplot area) in 5 percent classes (table 3). Following this, field crews identify the type of compaction (table 4). All the bare soil and compacted area and type data are entered into data recorders or are recorded on standardized data recording forms for later computer data entry.

Following bare soil and compaction estimations, forest floor and soil core samples are collected and forest floor and litter thicknesses, depth to restrictive layer (if any), and soil texture measurements associated with soil sampling are made. Soil samples are collected in the annular plots surrounding subplots 2, 3, and 4 (fig. 10). Soil sampling

Table 2—Evidence of soil disturbance related to compaction.

Visual disturbance	Evidence of compaction
Change in density	A noticeable change in density compared to nearby undisturbed soil. Most easily recognized by a difference in resistance to penetration with a soil probe assuming similar soil moisture content.
Platy structure	Coarse platy structure not evident in nearby undisturbed soil.
Loss of structure	Loss of normal soil structure found in nearby undisturbed soil (e.g., soil puddling, pulverized dust).
Ruts	Ruts at least 2 inches (5 cm) deep in mineral soil or 6 inches (15 cm) deep from undisturbed forest litter surface.
Mottling	Formation of mottles in disturbed area. Not present in nearby undisturbed soil.

Table 3—Compacted soil area (percent of subplot area) data attributes for areal extent of soil compaction assessment in the FIA P3 Soil Indicator (FIA 2008).

- Where collected: subplots 1, 2, 3, and 4.
- When collected: any portion of a subplot containing at least one accessible forested condition class.
- Field width: 2 digits
- Tolerance: ± 15 percent
- MQO: within tolerance 75 percent of the time.

PDR code: compacted area range

00: none	25: 21-25	55: 51-55	85: 81-85
01: trace	30: 26-30	60: 56-60	90: 86-90
05: 01-05	35: 31-35	65: 61-65	95: 91-95
10: 06-10	40: 36-40	70: 66-70	99: 96-100
15: 11-15	45: 41-45	75: 71-75	
20: 16-20	50: 46-50	80: 76-80	

Table 4—Types of soil compaction in the FIA P3 Soil Indicator.

Type of compaction	Definition
Rutted trail	Ruts at least 2 inches deep in mineral soil or 6 inches deep from top of undisturbed forest litter surface.
Compacted trail	Linear compacted feature resulting from multiple passes by people, animals, or vehicles.
Compacted area	Examples include junctions of skid trails, landing areas, work areas, campsites, animal bedding areas.
Other	Explanation entered into plot notes.

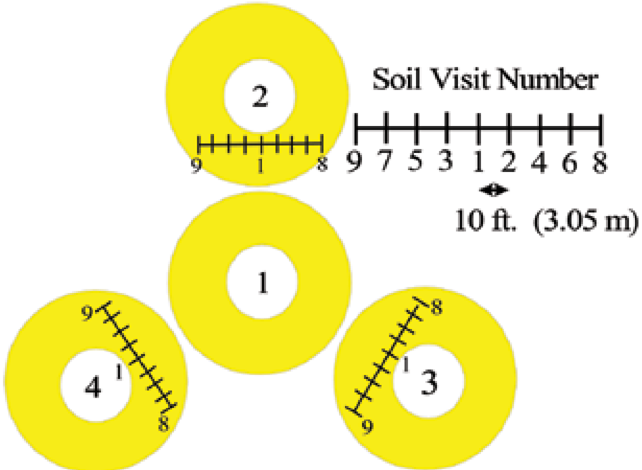


Figure 10. Location of soil sampling points along transects within annular plots surrounding subplots 2, 3, and 4. The sampling line associated with subplot 2 is located 30 ft due south (azimuth 180 deg) from the center of subplot 2. The sampling line associated with subplot 3 is located 30 ft northwest (azimuth 300 deg) from the center of subplot 3. The sampling line associated with subplot 4 is located 30 ft northeast (azimuth 60 deg) from the center of subplot 4.

transects with sampling points for each visit are located 30-ft from the centers of subplots 2, 3, and 4 as shown in figure 10. On the initial Soil Indicator visit, samples are collected at point 1 on each transect. Ten years later, on the second visit, samples are collected at point 2, which is located 10 ft from point 1. Subsequent visits at 10-year intervals are at points 3 through 9. On the next cycle, sampling begins again at point 1.

At each sample point associated with subplots 2, 3, and 4, forest floor samples are collected. Soil cores (0-10 and 10-20 cm) are collected at the sampling point associated with subplot 2 only. There are certain sampling rules governing if and where samples get collected:

- Soil samples are only collected if the soil sampling location in the annular plot is in a forested condition class regardless of the forested condition of the subplot.
- If cultural artifacts are found, soil samples are not collected.
- Certain other conditions may prevent soil sample collection (table 5).
- Field crews may collect a soil sample set within a 5-ft radius circle around the soil sampling point (fig. 10). A 5-ft radius circle does not impinge on the next soil sampling point that would be visited in 10 years, but allows for sample collection if there is an obstruction (*e.g.*, large log or rock) directly over the sample point.

Table 5—Soil sampling status codes for FIA P3 Soil Indicator.

- Where collected:
- Forest floor: Soil sampling points associated with subplots 2, 3, and 4.
- 0-10 and 10-20 cm soil cores: Soil sampling points associated with subplot 2 only.
- When collected: Soil sampling point is in a forested condition.
- Field width: 1 digit
- Tolerance: no errors
- MQO: at least 99 percent of the time.

PDR code	Soil sample status
1	Sampled
2	Not sampled: non-forest
Not sampled codes for forested condition	
3	Not sampled: too rocky
4	Not sampled: water or too boggy
5	Not sampled: access denied
6	Not sampled: too dangerous
7	Not sampled: obstruction in sampling area
8	Not sampled: broken or lost equipment
9	Not sampled: other (explanation entered in plot notes)

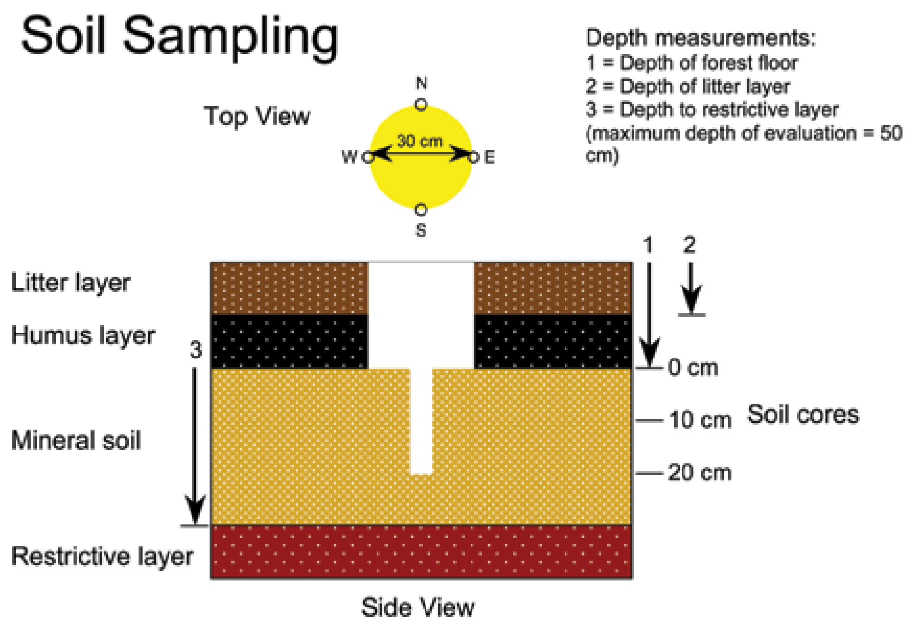


Figure 11. Cross-section diagram of forest floor and litter thickness measurements, depth to restrictive layer (if any), and forest floor and soil core sampling.

The cross-section diagram (fig. 11) shows the forest floor and litter thickness and depth to restrictive layer measurements associated with forest floor and soil core sampling. A general description of the measurement and sampling protocol is as follows:

- The entire forest floor (litter + humus) within a 30-cm diameter plot frame is collected down to the surface of the mineral soil. Woody pieces larger than 0.25-cm diameter are discarded (coarse and fine down wood are assessed as part of the down woody material indicator).
- Forest floor and litter thicknesses are measured at the north, south, east, and west compass points along the inner edge of the sample frame (fig. 11).
- A probe is used to measure depth to any restrictive layer (soil physical condition limiting root growth) within 50 cm of the mineral soil surface. Five measurements are made (center, north, south, east, west compass points) and the median of the five measurements is recorded. The maximum depth of evaluation is 50 cm.
- Two 2-inch diameter soil cores (0-10 and 10-20 cm) are collected using a coring head with two 10-cm long soil core liners attached to a slide hammer attachment. The volume of the cores is known and the soil weights (oven-dry basis) within the cores are used to calculate soil bulk density. If excessive coarse fragment content prevents soil core collection, then a hand excavation method is used to collect soil samples. Bulk density calculations are not made for manually excavated soil samples.
- The soil texture of the 0-10 and 10-20 cm mineral soil layers is determined with small samples from the sides of the coring or excavation hole.

The entire forest floor thickness and the litter layer thickness are measured as part of the sampling protocol. Field crews are trained to recognize the boundary between litter layer and humus layers:

- Litter layer—Decomposing plant parts can still be identified (*e.g.*, leaves, needles, twigs, bark, etc).
- Humus layer—Plant parts can no longer be identified because decomposition has proceeded to the point where stable humus has been formed (dark color—almost black—crumbly, organic layer).

Since the entire forest floor is sampled, field crews are taught to distinguish between the bottom of the forest floor (humus) layer and the top of the mineral soil. Sometimes the boundary is indistinct and the forest floor transitions into the underlying mineral soil. Field crews are taught to look for the following distinguishing characteristics:

- Evidence of plant parts—If they can be seen still decomposing in place, then that is still part of the forest floor.
- Texture—Crumbly (humus), or gritty (sand), silty, or clayey. The latter three are evidence that the mineral soil has been reached.
- Shiny flecks of mica or quartz—Will only help in those soils with that type of mineral soil mineralogy clearly present.
- Change in color—Humus layer is nearly black to black. Mineral soil is more brown color.
- Change in density—Humus layer is light. Mineral soil feels more dense.

Soil texture is collected primarily as a variable needed in the WEPP program for soil erosion potential assessment. For the FIA Soil Indicator, five soil texture classes estimated by feel are used: organic, loam, clay, sand, coarse sand. Organic soils are also tentatively identified in the field using texture, color, landscape setting, and vegetation characteristics. If an organic soil is being sampled, the forest floor is only the litter layer, and soil cores are collected from the underlying organic layer as with mineral soils.

Following collection, forest floor samples and soil cores are placed in sealed plastic bags and are sent to one of three FIA regional soil analysis laboratories for the north, south, and western states. The complete list of physical and chemical properties measured on the forest floor and soil cores is listed in table 6. Confirmation of organic soils is made using the percent organic C content of the soil cores. Since the entire solum is not sampled, an organic soil within the FIA Soil Indicator has an organic C content of 20 percent or greater in both sampled cores (0-10 and 10-20 cm).

Along with standardized training, quality control and quality assurance (QC/QA) are important components of measurement and sampling protocols. Quality control is the set of processes used to establish measurement quality objectives (MQOs) and to ensure quality standards are met. Quality assurance is the documentation that quality control protocols were followed. Tolerance levels and MQOs have been established for forest health indicators. Some of these Soil Indicator MQOs are listed in tables 1, 3, and 5. In addition to tolerance and MQOs, a series of interactive and non-interactive field plot checks has also been established (table 7). In addition, to provide an unbiased estimate of measurement and sampling variance, 5 percent of the plots are re-measured and re-sampled within the same field season.

Table 6—Soil physical and chemical properties measured in the FIA P3 Soil Indicator program.

Forest floor	Soil cores
Physical properties:	**Physical properties:**
Field-moist and air-dry weights	Field-moist and air-dry weights
Subsample oven-dry weight	Subsample oven-dry weight
Field-moist, residual, and total water content	Field-moist, residual, and total water content
Chemical properties:	Coarse fragments (>2 mm)
Total C (organic)	Bulk density
Total N	**Chemical properties:**
Total S (special project)	Organic, inorganic (carbonates), and Total N
Total Hg (special project)	Soil pH (water and 0.01 M $CaCl_2$)
	1 M NH_4Cl extraction:
	• Exchangeable cations (Na, K, Mg, Ca, Al)
	• Extractable metals (Mn, Fe, Ni, Cu, Zn, Cd, Pb)
	• Extractable S (SO_4-S)
	Extractable P:
	• Bray 1 (0.03 M NH_4F + 0.025 M HCl)
	• Olsen (pH 8.5, 0.5 M $NaHCO_3$)

Table 7—Field data collection QA/QC in the FIA program.

Type of QC/QA	QC/QA steps
Hot checks	Interactive—crews are present. Auditors review protocols with crew members, identify problems, suggest corrective actions, and conduct independent measurement checks.
Cold checks	Non-interactive—crews not present. Auditors conduct spot checks and do follow-up corrections.
Re-measurement and re-sampling (5 percent of plots)	Used to provide unbiased estimate of sampling variance.

The FIA regional soil laboratories also have their own separate QC/QA programs for the lab portion of the Soil Indicator. These QC/QA programs include

- Reagent and method blanks—Reagent blanks are used to establish baseline instrument calibrations. Method blanks are carried through all procedural steps of a given analysis method and are used to monitor for contamination.
- Instrument calibration standards—Used to calibrate instrument operation.
- Instrument check standards—Independent standards used to verify correct instrument operation and quantify analysis precision, bias, and accuracy. Accuracy is the sum of precision and bias measurements.
- Method check samples—Samples with ‘known’ or established values and tolerances based on repeat measurements among multiple laboratories and if possible, using multiple methods. These are used to check overall method repeatability and reliability.
- North American Proficiency Testing (NAPT) program—Quarterly sample exchange program administered by the Soil Science Society of America and involving more than 100 soil analysis laboratories.

Status of Forest Soils in the United States: Example of Soil Indicator Results to Date

Soil Indicator data along with that of other P3 forest health indicators plus the P2 forest inventory data are loaded into the FIA National Information Management System (NIMS). FIA also has an on-line datamart, which is the publicly accessible portion of the data known as FIADB (see http://fiatools.fs.fed.us). Various FIA analysts as well as the Forest Health Indicator Advisors and outside users access the database to analyze FIA data to assess various forest resource inventory questions.

Much of the data analysis uses post data collection stratification to derive population estimates (Scott and others 2005). For the Soil Indicator, data could be stratified by ecoregion, forest type, soil type, and major resource land area (USDA NRCS 2006). Results are often presented as shaded point maps, data distribution plots (box plots, histograms, cumulative frequency plots), and statistical summary tables (*e.g.*, means and/or medians and various measures of data variability (*e.g.*, standard deviation, coefficient of variation, standard error). Stratified results may also be presented as pixilated maps or summary tables with values reported by strata.

Once data analysis is complete, various data reporting and results interpretation outlets are available to communicate findings to science users, clients, and various publics. Following are some examples of how FIA Soil Indicator results get reported:

- National and international reports
    - MPCI Sustainable Forests reports: 2003 printed report with web-based background technical reports (O’Neill and others 2004)
    - Resource Planning Act (RPA) report (Perry and Amacher, in press)

- ◦ FHM National Technical reports: The 2001 and 2005 reports contain Soil Indicator data and interpretations (O'Neill and others 2005a; Perry and Amacher 2007a,b,c)
- ◦ Scientific literature (book chapter, journal papers, Forest Service research papers, general technical reports (GTRs), proceedings)—Examples include Perry and others 2008; O'Neill and others 2005b,c; Amacher and others 2007.

- Regional reports—none devoted to Soil Indicator yet
- State reports (resource bulletins)—Examples of state reports with Soil Indicator data include those of Minnesota (Miles and others 2007) and Virginia (Rose 2007).

Examples from recent publications showing Soil Indicator results give a snapshot of current forest soil conditions in the United States. Western forests tended to have more bare soil than eastern forests (fig. 12) because of lower overall tree canopy coverage and lesser amounts of forest floor material.

Soil compaction is not a widespread problem on forest soils of the United States. Most FIA P3 plots showed no evidence of compaction (fig. 13). Observed evidences of soil compaction tended to be found more in eastern forests than in the west (fig. 13) perhaps reflecting higher density of forest usage.

The impact of soil compaction on soil bulk density and forest productivity is complex (Powers and others 2005). Soils with bulk densities greater than 1.4 g/cm^3 tend to resist compaction. Forest productivity response to soil compaction depends on soil texture and understory vegetation. Production declined on compacted clay soils, increased on sandy soils, and was unaffected if an understory was absent (Powers and others 2005).

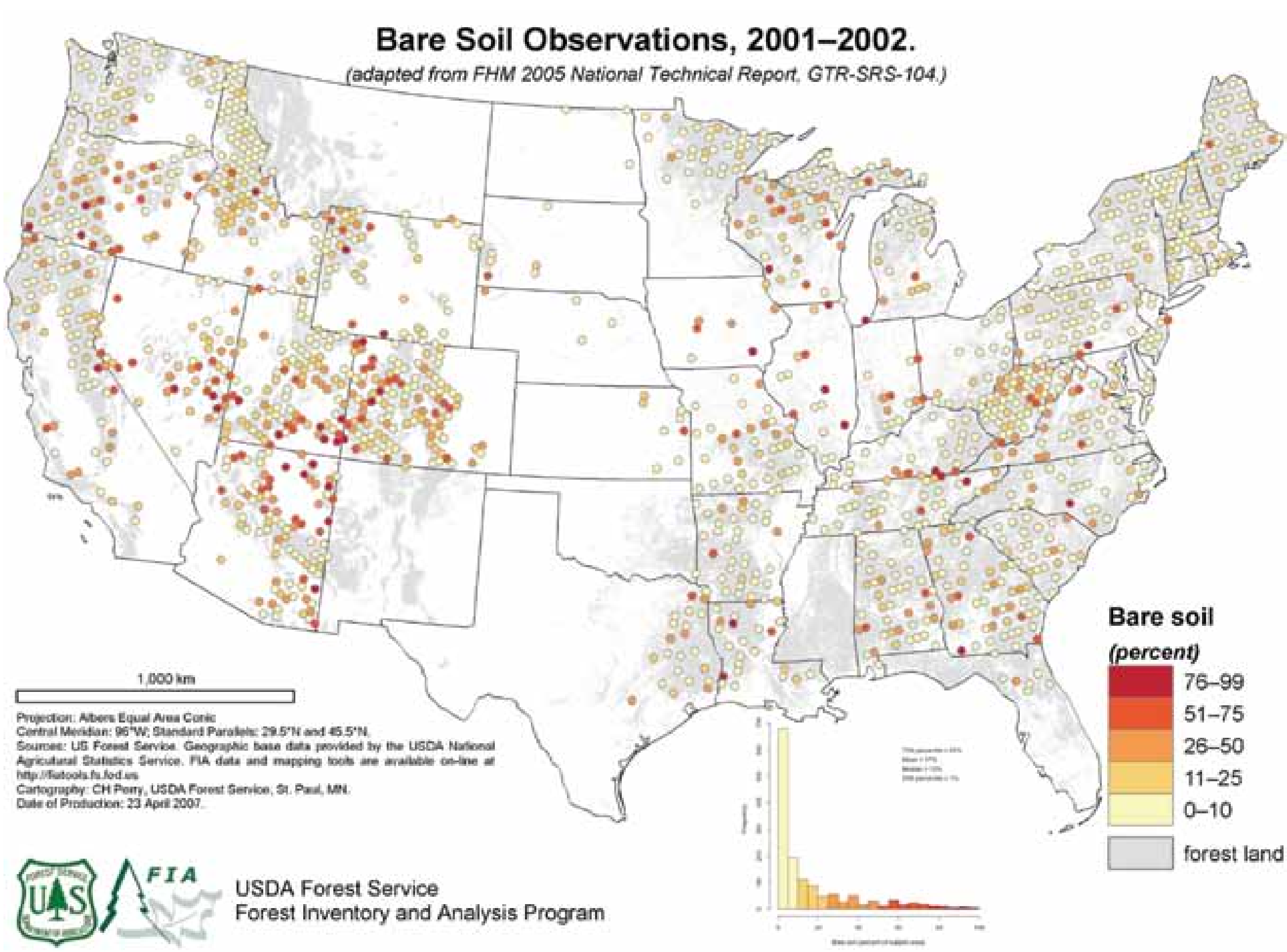


Figure 12. Spatial distribution of maximum observed percent bare soil by EMAP hexagon for FIA plots visited in 2001-2007.

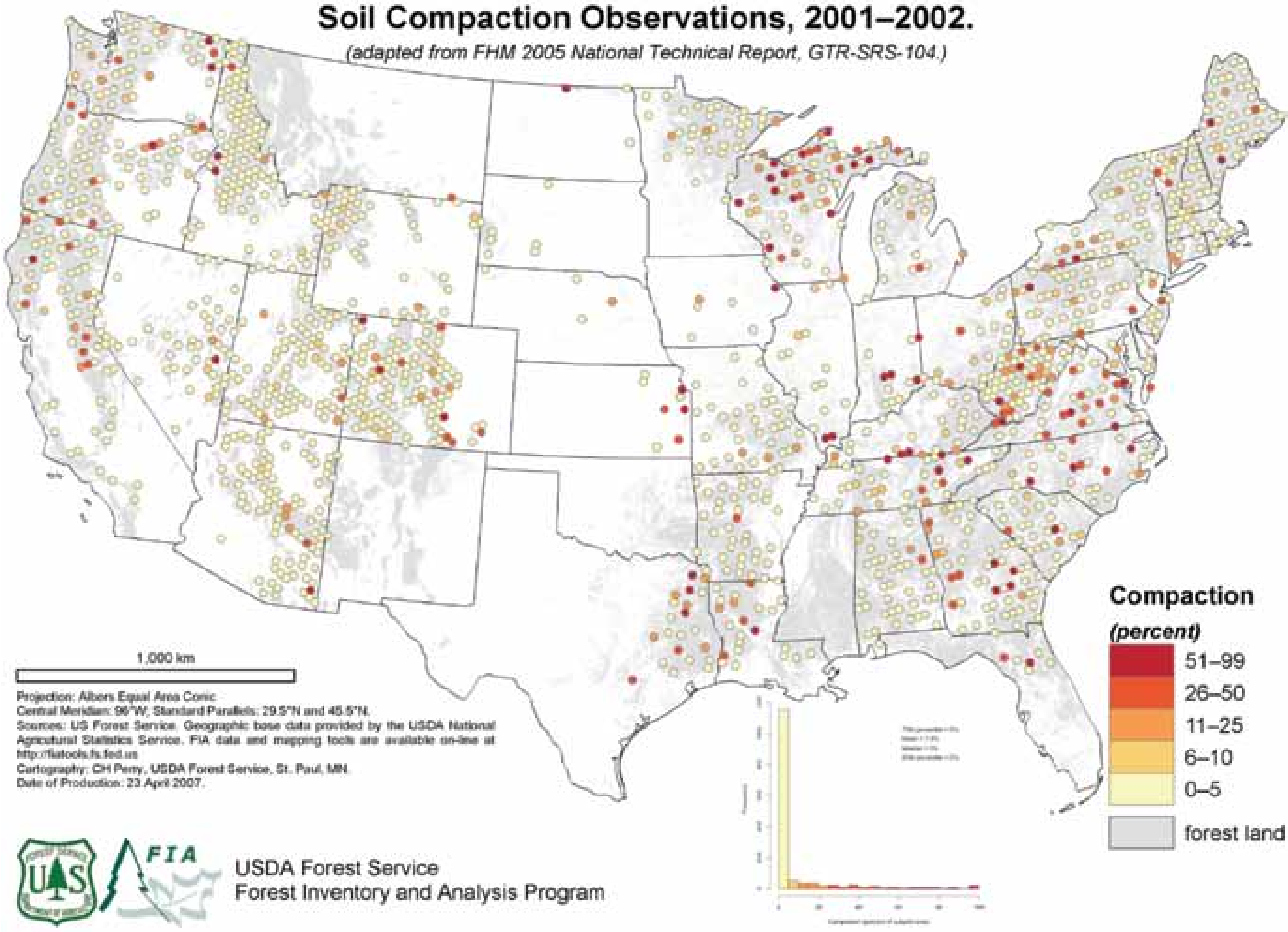


Figure 13. Spatial distribution of maximum observed percent compacted area by EMAP hexagon for FIA plots visited in 2001-2007.

Low soil nutrient and high acidity conditions may be found in forest soils throughout the United States, but strongly acid soils with low Ca and high Al levels are concentrated in the Northeast and South, primarily in the Appalachian regions (fig. 14). The most serious soils-related landscape-scale forest health threat uncovered by the FIA detection monitoring network is increasing soil acidity and associated decreases in soil Ca reserves along with potentially toxic levels of exchangeable Al. Calcium depletion and associated increases in available Al is strongly linked to atmospheric deposition (Driscoll and others 2001). Cronan and Grigal (1995) used soil solution Ca/Al molar ratios as an indicator of forest stress and indicated a near 100 percent probability of adverse impacts to forest health at a soil solution Ca/Al molar ratio of 0.2. The Ca/Al ratios presented in fig. 14 are 1M NH_4Cl exchangeable values rather than soil solution values, but exchangeable and soil solution concentrations are closely associated via exchange coefficients.

The FIA Soil Indicator has provided the first national inventory of measured C stocks in U.S. forest soils to a depth of 20 cm. Forest soils in colder wetter regions tend to have higher organic C levels (fig. 15). These latitudinal and elevational gradients in soil organic C levels are expected since organic matter decomposition rates tend to be higher under warmer and drier conditions (Schlesinger 1997). Regional organic C and total N amounts in the forest floor and 0-10 and 10-20 cm layers are summarized in fig. 16. More organic C is stored in the Northeast and Pacific States FIA regions than in the South or Interior West. The Northeast and North Central FIA regions store the most total N.

At the request of Soil Indicator analysts and users, a Soil Quality Index (SQI) was developed that integrates 19 separate measured physical and chemical properties into a

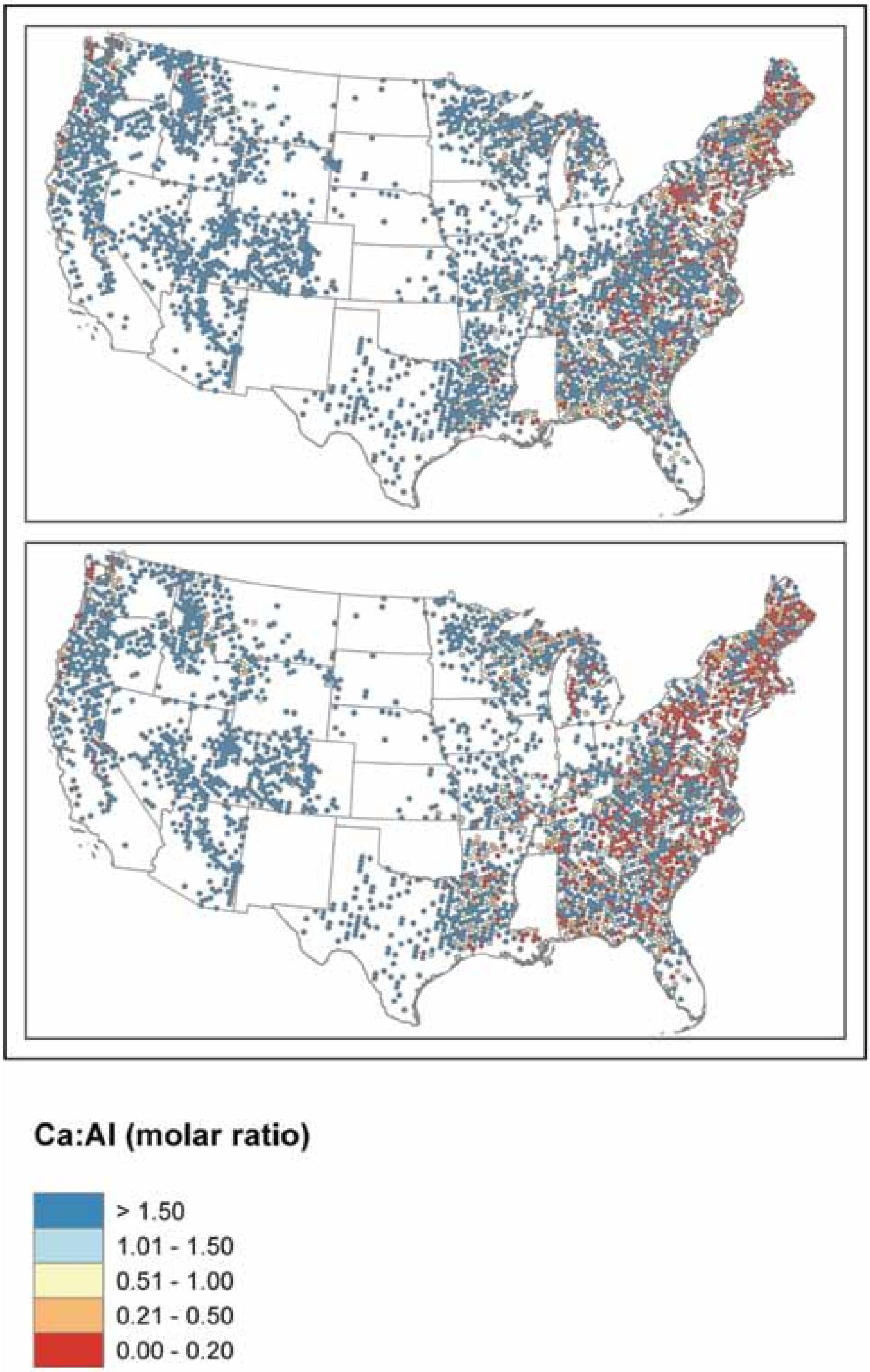


Figure 14. Spatial distribution of minimum observed exchangeable Ca/Al molar ratios by EMAP hexagon and soil depth (top: 0-10 cm; bottom: 10-20 cm) for FIA plots sampled in 2000-2007. Source: USFS FIA Soil Indicator. Geographic base data provided by the National Atlas of the U.S.A. EMAP hexagons provided by the U.S. EPA.

single index number that can be used to track soil quality condition and trend (Amacher and others 2007). Soils with lower SQI levels (< 50 %) are at increased risk of soils-related forest health decline. These soils tend to be concentrated in the Northeast and South where soils are more highly weathered and depleted of nutrients (fig. 17).

Sample Variability

Magnitude of variability for a given Soil Indicator source of variation generally increases in the order shown in figure 18. Repeat analysis usually has the least variation while variation among plots has the most. Since the FIA Soil Indicator is designed to

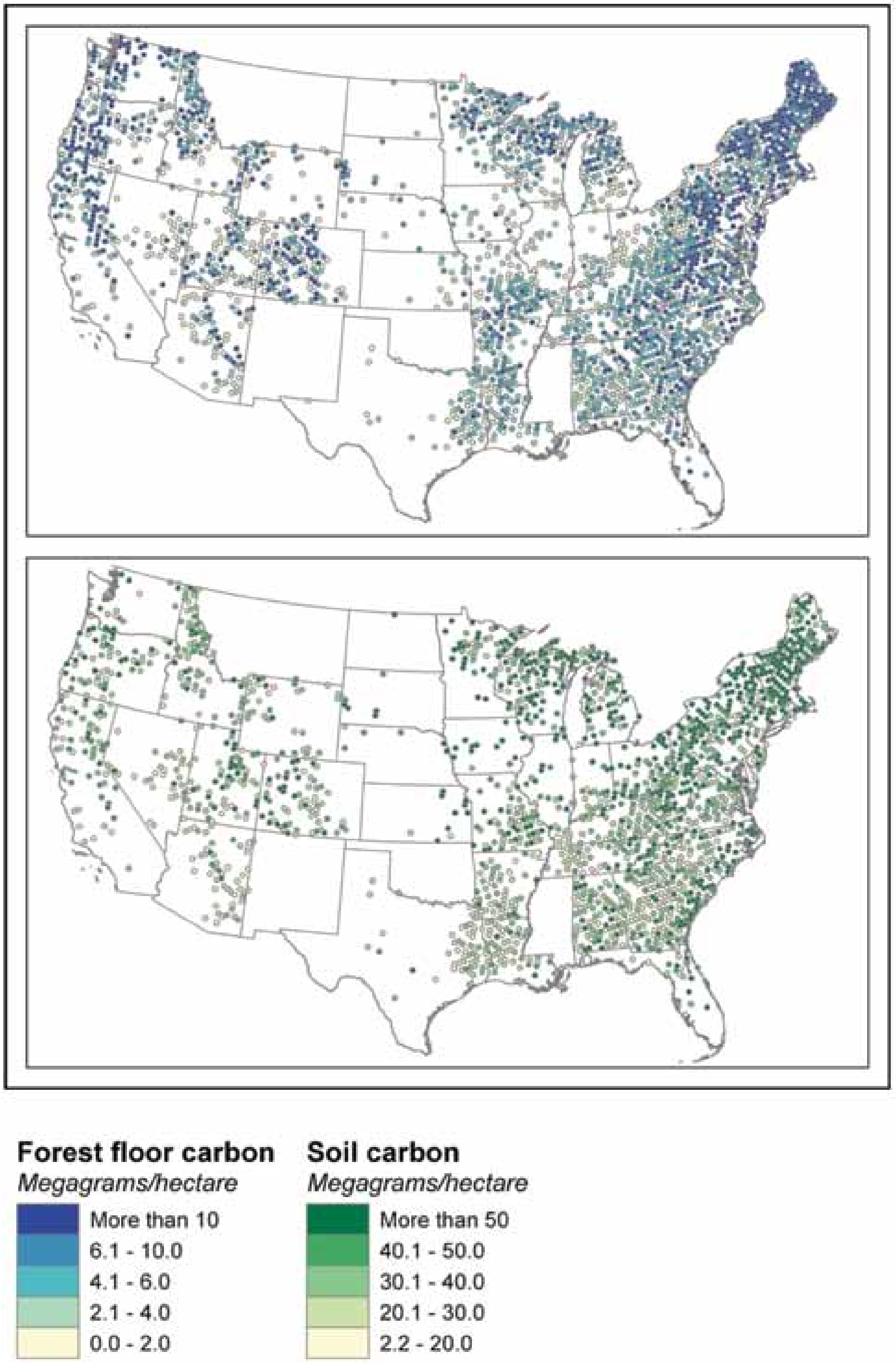


Figure 15. Spatial distribution of forest floor (top) and 0-20 cm soil (bottom) organic C by EMAP hexagon for FIA plots sampled in 2000-2004. Source: USFS FIA Soil Indicator. Geographic base data provided by the National Atlas of the U.S.A. EMAP hexagons provided by the U.S. EPA.

measure condition and trend at the landscape scale, the number of plots within a stratification layer (ecoregion, forest type, etc.) is an important factor influencing measured variance. The Soil Indicator is not designed to measure small-scale soil spatial variability. It is well recognized, based on decades of research, that soil properties are variable at multiple spatial scales (Gassner and Schnug 2006). It is also well established that closely spaced samples in time or space tend to be more closely correlated to each other. The central concept of spatial autocorrelation was first stated in Tobler's first law of geography: Everything is related to everything else, but near things are more related than distant things (ESRI 2006). Thus, landscape-scale assessments rely on spacing plots at far enough distance apart to reduce spatial correlation among samples to achieve a truer assessment of changes across the entire landscape.

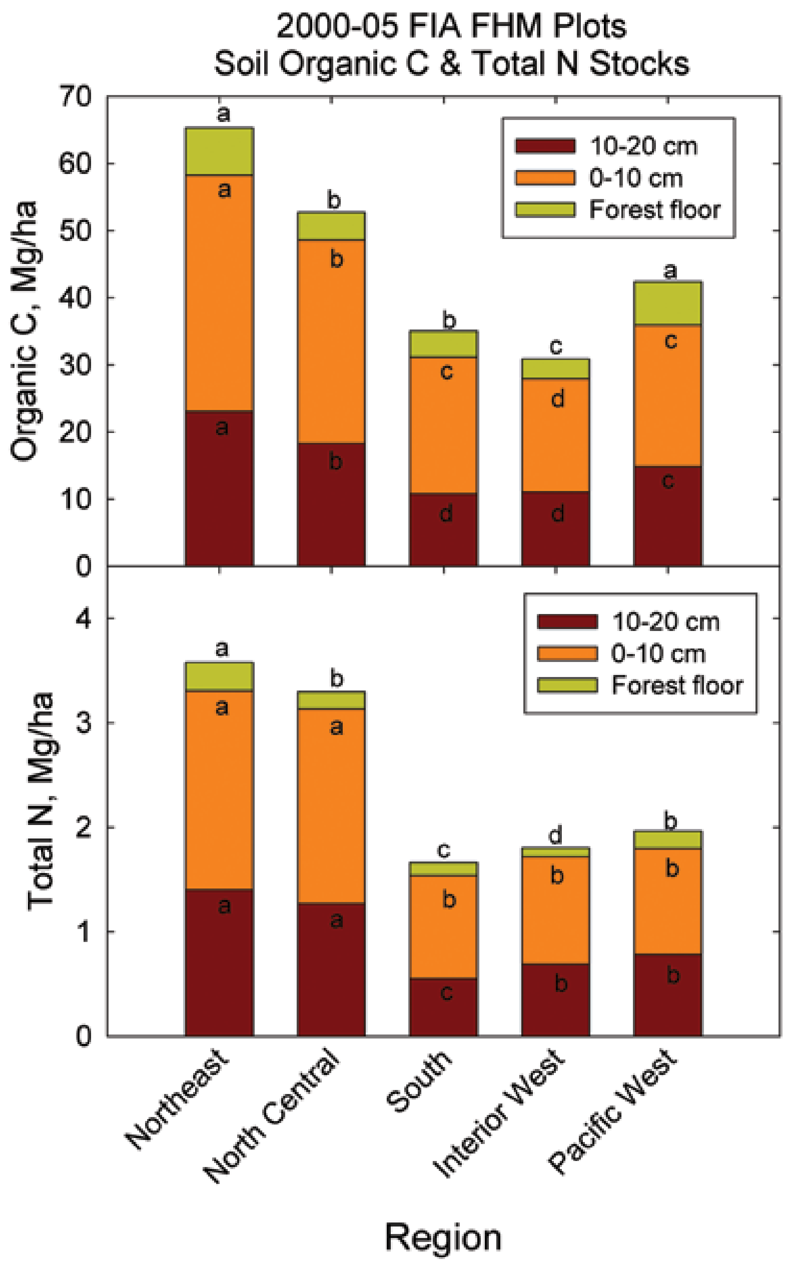


Figure 16. Regional soil organic C and total N amounts in the forest floor and 0-10 and 10-20 cm layers for FIA plots sampled in 2000-2005. Means for each layer (stacked bars) not indicated by the same letter across regions are significantly different.

Table 8—Sources of variance in the FHM soil C re-measurement study (Conkling and others 2000). Thirty plots in Georgia were measured.

Soil depth	Source of variation	Bulk density	Percent C	C stock
	Percent variance			
0–5 cm	Plots (30)	70.8 **	72.2 **	77.8 **
	Subplots (3/plot)	22.4 **	21.8 **	17.5 **
	Within subplots	6.8 ns	6.0 ns	4.7 ns
5–10 cm	Plots (30)	65.3 **	62.7 **	70.0 **
	Subplots (3/plot)	25.1 **	35.0 **	27.5 **
	Within subplots	9.5 ns	2.3 ns	2.6 ns
10–20 cm	Plots (30)	63.4 **	69.4 **	71.4 **
	Subplots (3/plot)	34.6 **	25.1 **	20.5 **
	Within subplots	2.0 ns	5.4 ns	8.1 ns

** = Significant at $p < 0.0001$, ns = not significant.

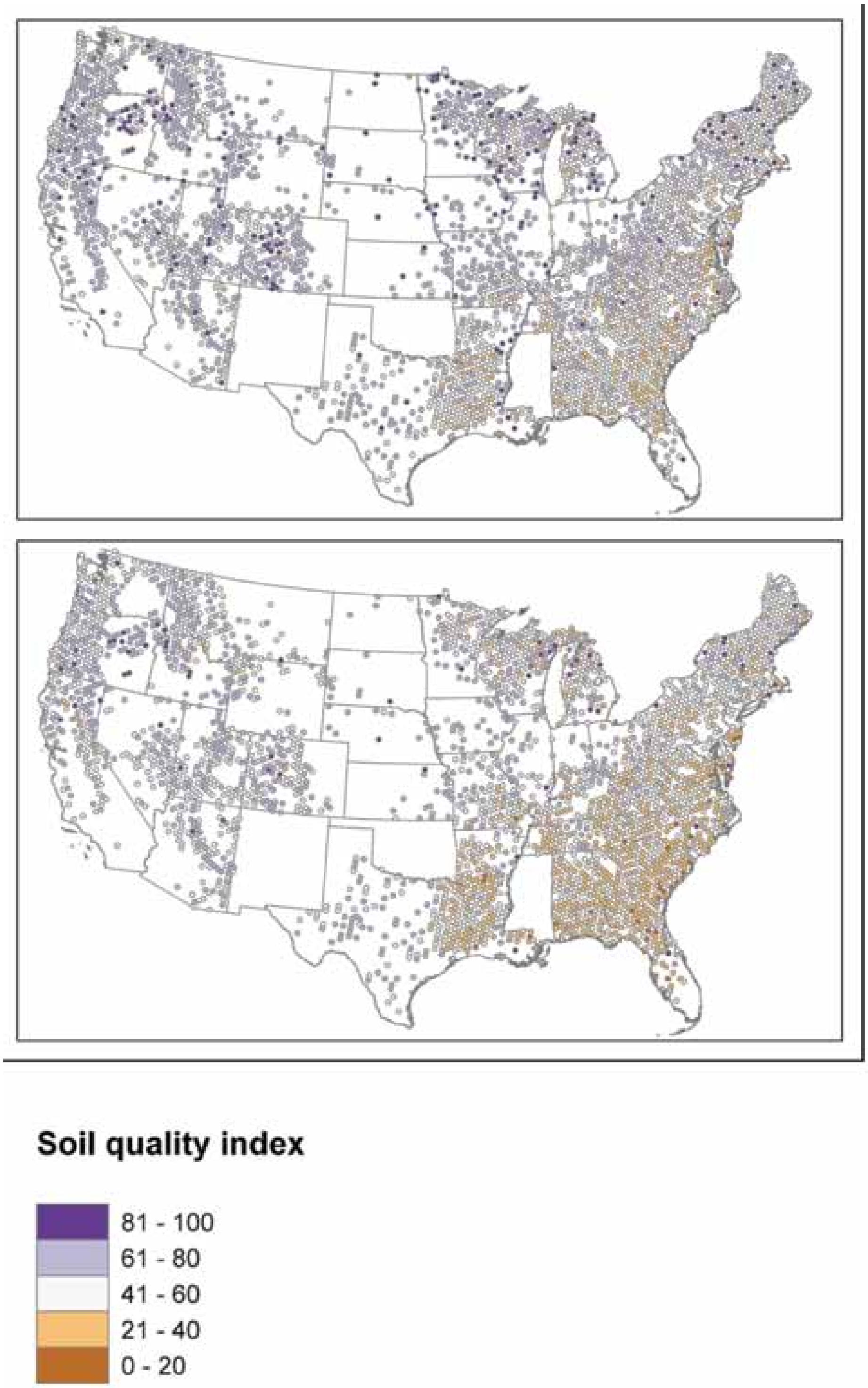


Figure 17. Spatial distribution of soil quality index (SQI) relative to the mean by EMAP hexagon and soil depth (top: 0-10 cm; bottom: 10-20 cm) for FIA plots sampled in 2000-2007. Source: USFS FIA Soil Indicator. Geographic base data provided by the National Atlas of the U.S.A. EMAP hexagons provided by the U.S. EPA.

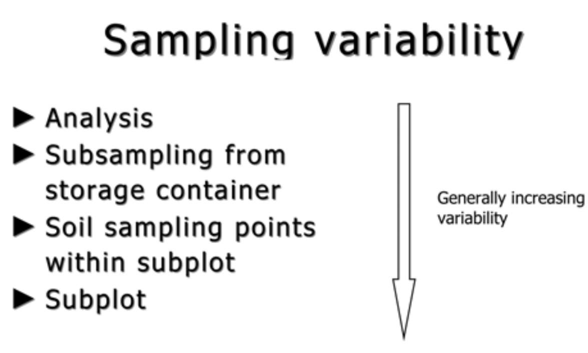


Figure 18. Sources of variation in Soil Indicator measurements arranged in order of increasing magnitude of variability.

Table 9—Median coefficients of variation (standard deviation as a percent of mean) for selected soil properties calculated from the population of FIA P3 plot re-measurement pairs.

Soil property	Number of pairs of soil cores	Median cv. (percent)
Bulk density	119	10.0
Coarse fragments	145	37.2
Organic C	368	15.3
Total N	368	14.3
Water pH	144	2.5
Effective cation exchange capacity (ECEC)	146	10.7
Extractable P (Bray 1 and Olsen)	129	22.7
	42	23.3

ECEC = sum of exchangeable cations (Na, K, Mg, Ca, Al).

The FHM C re-measurement study using 30 FIA plots in Georgia showed the magnitude of variability (percent variance) within subplots, among subplots, and among plots for three Soil Indicator variables (bulk density, percent organic C, and C stocks) at three soil depths (0-5, 5-10, and 10-20 cm) (Conkling and others 2000) (table 8). Within subplot variance was not significant compared to among subplot variance. As expected, the greatest variance was among plots. To fully capture spatial variability at the landscape scale, more plots across landscape scale strata are needed rather than more samples per plot, which only captures within-site variance.

To provide an unbiased estimate of measurement and sampling variance, 5 percent of plots are re-measured and re-sampled in the same sampling year (Hansen and others, in press). Re-sampling is done adjacent to the sample hole associated with the established sampling point for that plot visit. Thus re-sampling produces a paired set of soil samples that represents about 5 percent of the total plot population. For each pair of samples from re-sampled plots, mean, standard deviation and coefficient of variation statistics are computed. Because the magnitudes of the various soil properties display a wide range of values, expressing the standard deviation of each pair of soil samples as a percentage of the mean (coefficient of variation, cv) normalizes the standard deviations and makes for easier comparisons over the complete range of observed values and among different soil properties. The least and most variable soil properties within a sampling site can be assessed at a glance.

Median cv values for several important soil properties are shown in table 9. The numbers of pairs of soil samples are also shown. Coarse fragment content is the most spatially variable soil property within sample sites with a median cv of 37 percent. Water pH is the least spatially variable soil property with a median cv of only 2.5 percent. Table 9 provides valuable information about which soil properties tend to be the most or least spatially variable within the sampling area for a large population of re-sampled plots across multiple ecoregions, forest types, and soil types. As the database grows, we will be able to identify those areas with the most within-plot spatially variable soil properties. Within-plot sampling variability data can be used to design more efficient sampling intensification for follow-up evaluation monitoring studies.

Soil Indicator Weaknesses

Key strengths of the Soil Indicator were listed and discussed previously. However, there are some weaknesses within the program as it is presently constituted.

- This is a forest health detection monitoring program at the landscape scale. Small-scale spatial variability is not captured with the current strategic approach to sampling design. However, one of the valuable attributes of the hexagonal sampling grid is that the grid can be intensified to address specific monitoring questions: (1) spatially-intensified evaluation monitoring projects based on detection monitoring results; (2) National Forest intensified-grid measurement and sampling, (3) Intensive site monitoring (*e.g.*, Delaware River Basin study).
- The Soil Indicator is currently confined to an inventory of soil properties within the upper 20-cm of mineral or organic soil beneath the forest floor (the entire forest floor

within a plot frame is sampled). Thus, in the case of C, the total organic C inventory for the entire solum is not measured. Soil bulk density and organic C levels change with depth. In general, bulk density will increase with depth while organic C levels will decrease in mineral soils, but will remain at high levels in organic soils such as forested peat bogs. Soil depth to parent material is highly variable on the landscape. Furthermore, mineral soil profiles often grade into parent material lithology without distinct boundaries. Without an unambiguous definition of what constitutes the entire solum for sampling and inventory purposes, any soil inventory defaults to an operationally defined program based on a fixed sampling depth. The Soil Indicator program allows for deeper sampling for special projects. Although the current protocol samples the upper 20-cm of soil, manually operated soil core samplers can sample to 30-cm in all but the rockiest soils. Sampling deeper than 30 cm almost always requires a motor-driven soil core sampler. Hand augering can collect soil samples to depths of 1 m or more if coarse fragment content is low. However, hand augering precludes soil bulk density measurements because augered samples are disturbed and don't preserve the original weight/volume ratio of undisturbed soil cores.

- The Soil Indicator does not include several highly important soil property measurements as yet. For example, no measures of soil biological properties are included. Such properties as enzyme activity, microbial population activity (*e.g.*, microbial community-level physiological profiling (Biolog)), and in situ soil respiration and C and N mineralization/utilization would provide valuable additional information.

Potential Use of FIA Soil Indicator for Soil Quality Standards Monitoring

The concept of soil quality standards to maintain soil productivity and hence forest productivity following timber harvest activities is undergoing increased scrutiny. Typically, soil quality standards monitoring occurs at the project scale within various National Forests. Soil quality standards monitoring is chiefly concerned with documenting severity of soil disturbance (Neary and others 2010), whereas the FIA Soil Indicator documents the areal extent of bare soil (whether disturbance-related or not) and evidences of compaction within FIA subplot areas. It is possible to link the two approaches.

Potentially, FIA plots could be established on delineated project areas. Furthermore, FIA forest productivity and other indicator data linked to Soil Indicator data can be used to establish current and historic conditions for forest and soil types similar to proposed project areas. In addition, the soil quality standards disturbance severity protocols could be added to Soil Indicator protocols as a regional add-on for more intensified soil monitoring.

One of the Soil Indicator's greatest strengths is the collection of data across the broader landscape. The collection of Soil Indicator data in or around projects would facilitate comparisons with areas not included in the project or held by adjacent landowners. In this regard, Soil Indicator data could answer questions about the unique impact of Forest Service land management.

Summary

The Soil Indicator was developed to assess the condition and trend of forest soils throughout the United States regardless of ownership as part of a larger forest health indicators monitoring effort within FIA. It is the first comprehensive national inventory of forest soil properties using common protocols with a QC/QA program. The Soil Indicator was developed in response to Montreal Process Criteria and Indicators monitoring questions. Two key accomplishments of the Soil Indicator are the first comprehensive national inventory of organic C stocks in forest soils based on measured values and the first landscape-scale assessment of the severity of Ca depletion and associated high levels of soil Al in forest soils of the Northern and Southern Appalachians. Since current soil conditions are now well-quantified, the Soil Indicator provides the means to track changes in forest soil conditions going forward. This can lead to a refinement of the MPCI as well as refine the Soil Indicator assessment process to better measure soils-related forest health risks.

References

Adams, Mary Beth; Loughry, Linda; Plaugher, Linda. 2008. Experimental forests and ranges of the USDA Forest Service. Gen. Tech. Rep. NE-321 Revised. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 178 p. [CD ROM]

Amacher, Michael C.; O'Neill, Katherine P.; Perry, Charles H. 2007. Soil vital signs: a new index for assessing forest soil health. Res. Pap. RMRS-RP-65-WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 12 p.

Bechtold, William A. 2003. Tree growth. FIA Fact Sheet Series. Washington, DC: U.S. Department of Agriculture, Forest Service.

Bechtold, William A. 2003. Tree mortality. FIA Fact Sheet Series. Washington, DC: U.S. Department of Agriculture, Forest Service.

Bechtold, William A.; Patterson, Paul L. 2005. The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. GTR-SRS-80. Ashville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p.

Brand, Gary J.; Nelson, Mark D.; Wendt, Daniel G.; Nimerfro, Kevin K. 2000. The hexagon/panel system for selecting FIA plots under an annual inventory. p. 8-13. In: McRoberts, Ronald E. and others, eds. Proceedings, First annual Forest Inventory and Analysis symposium. 2-3 Nov., 1999, San Antonio, TX. Gen. Tech. Rep. GTR-NC-213. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.

Conkling, Barbara L.; Hoover, Coeli M.; Smith, William D.; Palmer, Craig J.; Bechtold, William A. 2000. Soil C remeasurement study internal project report. Washington, DC: U.S. Department of Agriculture, Forest Service.

Critical Zone Exploration Network. [Homepage of Critical Zone Exploration Network], [Online]. Available: http://www.czen.org/. [August 26, 2009].

Cronan, Christopher S.; Grigal, David F. 1995. Use of calcium/aluminum ratios as indicators of stress in forest ecosystems. J. Environ. Qual. 24: 209-226.

Driscoll, Charles T.; Lawrence, Greg B.; Bulger, Art J.; Butler, Tom J.; Cronan, Chris S.; Eagar, Chris; . Lambert, Kathleen F.; Likens, Gene, E.; Stoddard, John L.; Weathers, Kathleen C. 2001. Acid rain revisited: Advances in scientific understanding since the passage of the 1970 and 1990 Clean Air Act Amendments. Hubbard Brook Research Foundation. Science Links™ Publication. Vol. 1, no.1. [Online]. Available: http://www.hubbardbrookfoundation.org/article/view/12940/1/2076/. [August 26, 2009].

Elliot, William J.; Hall, David E.; Scheele, Dayna L. (2000, February—last update). Disturbed WEPP: WEPP interface for disturbed forest and range runoff, erosion, and sediment delivery. Technical documentation. [Online]. Available: http://forest.moscowfsl.wsu.edu/fswepp/docs/distweppdoc.html. [August 26, 2009].

Environmental Systems Research Institute. (2006, October 31—last update). GIS Dictionary. [Online]. Available: http://support.esri.com/index.cfm?fa=knowledgebase.gisDictionary.gateway. [August 26, 2009].

Fire Research and Management Exchange Systems. (n.d.) [Homepage of Fire Research and Management Exchange Systems], [Online]. Available: http://frames.nbii.gov/portal/server.pt. [August 26, 2009].

Gassner, Anja; Schnug, Ewald. 2006. Geostatistics for soil science. p. 760-764. In: Lal, Rattan, ed. Encyclopedia of Soil Science. London: Taylor and Francis.

Hansen, Mark H.; Perry, Charles H.; Amacher, Michael C. (In press). Soil quality indicator. In: Forest Inventory and Analysis national assessment of data quality for forest health indicators. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.

Hobbie, John E.; Carpenter, Stephen R.; Grimm, Nancy B.; Gosz, James R.; Seastedt, Timothy R. 2003. The US long term ecological research program. BioScience 53(1): 21-32.

Jenny, Hans. 1994. Factors of soil formation—a system of quantitative pedology. Dover Edition. New York: Dover Publications. 191 p.

McCune, Bruce. 2000. Lichen communities as indicators of forest health. The Bryologist 103(2): 353-356.

Miles, Patrick D.; Jacobson, Keith; Brand, Gary J.; Jepsen, Ed; Meneguzzo, Dacia; Mielke, Manfred E.; Olson, Casandra; Perry, Charles H.; Piva, Ronald J.; Wilson, Barry T.; Woodall, Christopher W. 2007. Minnesota's forests 1999-2003 (Part A). Resour. Bull. NRS-12A. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 92 p.

Montreal Process Working Group. (1998-2005—copyright). The Montreal Process. [Homepage of the Montreal Process Working Group], [Online]. Available: http://www.rinya.maff.go.jp/mpci/. [August 26, 2009].

National Atmospheric Deposition Program. (n.d.) [Online]. Available: http://nadp.sws.uiuc.edu/. [August 26, 2009].

Neary, Daniel; Trettin, Carl; and Page-Dumroese, Deborah. 2010. Soil quality monitoring: examples of existing protocols. In: Page-Dumroese, Deborah Neary, Daniel; Trettin, Carl, eds. Scientific background for soil monitoring on national forests and rangelands; 29-30 April, 2008; Denver, CO. Proc. RMRS-P-59. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

National Ecological Observatory Network. (n.d.) [Homepage of National Ecological Observatory Network], [Online]. Available: http://www.neoninc.org/. [August 26, 2009].

Nusser, S.M.; Breidt, F.J.; Fuller, W.A. 1998. Design and estimation for investigating the dynamics of natural resources. Ecological Applications 8(2): 234-245.

Nusser, S.M.; Goebel, J.J. 1997. The National Resources Inventory: a long-term multi-resource monitoring program. Environmental and Ecological Statistics 4(3): 181-204.

O'Neill, Katherine P.; Amacher, Michael C.; Conkling, Barbara L. 2005a. Criterion 4—Conservation of soil. p. 83-100. In: Conkling, Barbara L.; Coulston, John W.; Ambrose, Mark J., eds. Forest health monitoring 2001 national technical report. Gen. Tech. Rep. GTR-SRS-081. Ashville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

O'Neill, Katherine P.; Amacher, Michael C.; Palmer, Craig J. 2005b. Developing a national indicator of soil quality on U.S. forestlands: Methods and initial results. Environmental Monitoring and Assessment 107: 59-80.

O'Neill, Katherine P.; Amacher, Michael C.; Perry, Charles H. 2005c. Soils as an indicator of forest health: A guide to the collection, analysis, and interpretation of soil indicator data in the Forest Inventory and Analysis Program. Gen. Tech. Rep. GTR-NC-258. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 53 p.

O'Neill, Katherine P.; Stolte, Kenneth; Amacher, Michael C; Chojnacky, David. 2004. Criterion 4: Conservation and maintenance of soil and water resources. p. 12, 32, 35, 36, 39, 93-94. In: National Report on Sustainable Forests—2003. FS-766. Washington, DC: U.S. Department of Agriculture, Forest Service.

Perry, Charles H.; Amacher, Michael C. 2007a. Physical properties of forest soils. p. 51-58. In: Ambrose, Mark J.; Conkling, Barbara L., eds. Forest health monitoring 2005 national technical report. Gen. Tech. Rep. GTR-SRS-104. Ashville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Perry, Charles H.; Amacher, Michael C. 2007b. Chemical properties of forest soils. p. 59-66. In: Ambrose, Mark J.; Conkling, Barbara L., eds. Forest health monitoring 2005 national technical report. Gen. Tech. Rep. GTR-SRS-104. Ashville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Perry, Charles H.; Amacher, Michael C. 2007c. Soil carbon. p. 67-72. In: Ambrose, Mark J.; Conkling, Barbara L., eds. Forest health monitoring 2005 national technical report. Gen. Tech. Rep. GTR-SRS-104. Ashville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Perry, Charles H.; Amacher, Michael C. (In press). Forest soils. In: Smith, W. Brad; Miles, Patrick D.; Hoppus, Michael., tech. coords. Forest resources of the United States, 2007. Gen. Tech. Rep. GTR-WO-XXX. Washington, DC: U.S. Department of Agriculture, Forest Service.

Perry, Charles H.; Woodall, Christopher W.; Amacher, Michael C.; O'Neill, Katherine P. 2008. An inventory of carbon storage in forest soil and down wood of the United States. In: McPherson, B.J.; Sundquist, E., eds. The science and technology of carbon sequestration: Assessment and verification of natural and deliberate carbon sinks. Washington, DC: American Geophysical Union.

Powers, Robert F.; Scott, Andrew D.; Sanchez, Felipe G.; Voldseth, Richard A.; Page-Dumroese, Deborah; Elioff, John D.; Stone, Douglas M. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. Forest Ecol. & Manage. 220: 31-50.

Rose, Anita K. 2007. Soils. p. 56-60. In: Virginia's forests, 2001. Resour. Bull. SRS-120. Ashville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 140 p.

Schlesinger, William H. 1997. Biogeochemistry—an analysis of global change. 2nd ed. SanDiego: Academic Press. 588 p.

Schomaker, Michael E.; Zarnoch, Stanley J.; Bechtold, William A.; Latelle, David J.; Burkman, William G.; Cox, Susan M. 2007. Crown-condition classification: a guide to data collection and analysis. Gen. Tech. Rep. SRS-102. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 78 p.

Schulz, Bethany K.; Bechtold, William A.; Zarnoch, Stanley J. 2009. Sampling and estimation procedures for the vegetation diversity and structure indicator. Gen. Tech. Rep. PNW-GTR-781. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 53 p.

Scott, Charles T.; Bechtold, William A.; Reams, Gregory A.; Smith, William D.; Westfall, James A.; Hansen, Mark H.; Moisen, Gretchen G. 2005. Sample-based estimators used by the Forest Inventory and Analysis National Information Management System. p. 53-77. In: Bechtold, William A.; Patterson, Paul L., eds. The enhanced Forest Inventory and Analysis Program: national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Smith, W. Brad. 2002. Forest inventory and analysis: a national inventory and monitoring program. Environmental Pollution. 116: S233-S242.

Smith, Gretchen C.; Smith, William D.; Coulston, John W. 2007. Ozone bioindicator sampling and estimation Gen. Tech. Rep. NRS-20. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 34 p.

Smith, W. Brad; Miles, Patrick D.; Perry, Charles H.; Pugh, Scott A. (In press). Forest resources of the United States, 2007. GTR-WO-000. Washington, DC: U.S. Department of Agriculture, Forest Service.

U.S. Department of Agriculture, Forest Service. 2007. Phase 3 field guide: Soil measurements and sampling, ver. 4.0. [Online]. Available: www.fia.fs.fed.us/library/field-guides-methods-proc/. [August 26, 2009].

U.S. Department of Agriculture, Forest Service. 2008. (October 3—last update). Experimental Forests and Ranges. Available: http://www.fs.fed.us/research/efr/. [August 26, 2009].

U.S. Department of Agriculture, Forest Service. 2009a. (April 23—last update). Forest Inventory and Analysis National Program. [Online]. Available: http://www.fia.fs.fed.us/. [August 26, 2009].

U.S. Department of Agriculture, Forest Service. 2009b. (April 6—last update). National Forest Health Monitoring Program. [Online]. Available on-line: http://fhm.fs.fed.us/. [August 26, 2009].

U.S. Department of Agriculture, Natural Resources Conservation Service. 2006. Land resource regions and major land resource areas of the United States, the Caribbean, and the Pacific Basin. Agric. Handb. 296. Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service.

U.S. Department of Agriculture, Natural Resources Conservation Service. 2007. National Soil Survey Handbook, title 430-VI. [Online] Available: http://soils.usda.gov/technical/handbook/. [August 26, 2009].

U.S. Department of Agriculture, Natural Resources Conservation Service. 2008a. (August 19—last update). National Cooperative Soil Survey. [Online]. Available: http://soils.usda.gov/partnerships/ncss/. [August 26, 2009].

U.S. Department of Agriculture, Natural Resources Conservation Service. 2008b. (January 2—last update). National Resources Inventory. [Online]. Available: http://www.nrcs.usda.gov/technical/NRI/. [August 26, 2009].

U.S. Environmental Protection Agency. 2009a. (April 24—last update). Environmental Monitoring and Assessment Program. [Online]. Available: http://www.epa.gov/emap/. [August 26, 2009].

U.S. Environmental Protection Agency. 2009b. (April 24—last update). Clean Air Status and Trends Network. [Online]. Available: http://www.epa.gov/castnet/. [August 26, 2009].

U.S. Environmental Protection Agency. 2009c. (April 24—last update). National Assessment Database. [Online]. Available: http://www.epa.gov/waters/305b/index.html. [August 26, 2009].

U.S. Geological Survey. 2002. (May 31—last update). Hydrologic Benchmark Network. [Online]. Available: http://ny.cf.er.usgs.gov/hbn/. [August 26, 2009].

U.S. Geological Survey. 2009a. (March 13—last update). National Stream Quality Accounting Network. [Online]. Available: http://water.usgs.gov/nasqan/. [August 26, 2009].

U.S. Geological Survey. 2009b. (April 23—last update). National Water-Quality Assessment Program. [Online]. Available: http://water.usgs.gov/nawqa/. [August 26, 2009].

U.S. Long Term Ecological Research Network. (2007—copyright). [Homepage of U.S. Long Term Ecological Research Network], [Online]. Available: http://www.lternet.edu/. [August 26, 2009].

Woodall, Christopher W.; Monleon, Vicente J. 2008. Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.

Statistical Sampling Methods for Soils Monitoring

Ann M. Abbott, Moscow Forestry Sciences Laboratory, Rocky Mountain Research Station, Moscow, ID.

Abstract—Development of the best sampling design to answer a research question should be an interactive venture between the land manager or researcher and statisticians, and is the result of answering various questions. A series of questions that can be asked to guide the researcher in making decisions that will arrive at an effective sampling plan are described, and a case study is used to explain how the sampling effort was designed for the Forest Soil Monitoring Protocol.

Introduction

In general, the goal of statistics is to be able to make inferences about a population based on information gathered from a sample of units from that population. For the inferences to have meaning, then, the sample must be representative of the entire population in question.

To appropriately draw a sample from a population, there are several considerations that must be met.

- The sampling must be done in such a way that it will meet the objectives of the research.
- The sample itself must be representative of the population.
- The sampling plan must be feasible, and the plan must be cost effective.

An appropriate sampling plan is the result of answering a series of questions, and it is the answers to the questions that lead to the best sampling design, data analysis methods, and subsequent interpretation of the analysis. Knowing the questions to ask, therefore, is the key to designing a good sampling plan. Some of questions that must be asked include:

- What are the objectives of the research?
- What is the population about which inferences will be made?
- What are the sampling units?
- What is the translation of the objectives into specific questions that can be answered with measurements from the sampling units?
- What preliminary information is available about the population?
- What choice of sampling design will be used?
- What sample size is necessary to answer the research questions with acceptable accuracy?
- Are there any auxiliary variables that can provide additional information?
- How will the randomization be performed?
- How will the results of the sampling effort be recorded?
- How will the data be analyzed?

This paper will explain how to design a sampling plan using the Forest Soil Monitoring Protocol as a Case Study.

Questions

What Are the Objectives of the Research?

It is imperative that clear objectives be stated prior to beginning any data collection. They must be clearly and explicitly stated, and the reasons for undertaking the research must also be documented. A subsequent step in defining the objectives of the research is to translate the objectives into precise questions that the sample measurements can answer. The translation of the objective into precise questions is the link between the initial research question and a question that may be answered with sampling and statistics. To answer a question about a population with statistics, the question must be asked in terms of measurements that may be taken on individuals within a population.

An example of defining and translating objectives is as follows:

- The amount of soils disturbed by management activities must be documented.
- The objective, then, is to quantify the disturbance. While this is a good objective, it is not, as stated, something that can immediately be answered with sampling.
- A precise question is "What proportion of points within a transect is compacted to 10 cm?"

What Is the Population About Which Inferences Will Be Made?

Once the initial objectives or research questions have been formulated, the population about which information is desired must be defined, which can be a somewhat circular process. Often, the definition step will refine the overall population about which information is desired into a population from which a sample may be drawn. When considering the population, it is helpful to think of it as a collection of individuals or sampling units that can be listed. Such a list may also be used as the sampling frame, from which the sample will be drawn. Defining the population as a collection of individuals that may be listed will determine whether any constraints are present that will limit the overall population into a smaller segment that can be sampled. This will also help ensure that the sampling units are representative of the population. It is possible that the population from which the sample is drawn may be different from the population as a whole if the entire population cannot be sampled.

What Are the Sampling Units?

Sampling units are defined as 'non-overlapping collections of elements from the population that cover the entire population.' A successful sampling scheme includes the selection of an appropriate sampling unit. The sampling unit is the individual within the population on which measurements and inferences will be made, so it is critical that the unit be carefully defined and possible to measure, as well as meet the objectives of the study. The sampling unit is also the subject of the randomization scheme for the study. Some examples of sampling units include quadrats, leaves of a plant, individual organisms, belt transects, or points.

Further questions that should be asked when considering the choice of sampling unit include:

- Are the sampling units naturally defined?
- If not, how will they be defined?
- Is the number of sampling units finite?
- If it is finite, is the total number of units in the population large enough to ignore finite sampling considerations?
- Is the definition of the sampling units appropriate to the objectives?

There are some important considerations that should be made when choosing the unit for sampling. The sampling unit must be the unit upon which you wish to make inferences and estimates. It is the subject of the randomization process used in the sampling design. Although it is common that the measurements taken in the study are performed on the sampling unit, it is not a requirement and usually occurs when the measurements cannot be performed on the randomization units. When the objects upon which the measurements are taken are not those which were randomly selected, however, the analysis is performed on the randomized units.

Sampling units for estimates of characteristics of a particular area can be either point samples or area samples. For either a point sample or an area sample, they should be sampled without replacement to ensure that any particular sampling unit is only sampled once. Point samples allow inferences to be made on the number of observations in the sample, and the inferences are often made on the means or percentages from the sample observations. Area samples are generally measured with densities of percent of area covered, and inferences are made by extrapolating the sample density to the entire area. Area samples can yield more detailed information but can also be more time consuming to carry out.

Translating the Objectives

The translation of the research objectives into specific questions that can be answered with measurements from the sampling units is often the most challenging step and a good time to consult with a statistician. The translation is the integration of the research question into the quantitative question “What exactly is to be estimated or tested?”

Part of the translation step will identify whether the required estimates are proportions, totals, means, totals or means over subpopulations, or some other quantitative estimate. Constructing the blank data sheet for recording observations will assist in the translation step as that step will clearly identify the measurements that will be taken. It is critical that once the data sheets have been constructed and the measurements to be taken are identified that one revisit the research question to ensure that the observations and resulting summaries will, in fact, answer the research question.

What Preliminary Information Is Available About the Population?

Information that can be gathered about the population of interest prior to sampling can help ensure that the sampling design will be successful in providing the necessary information to answer the research question. Such information includes whether estimates of the likely variability are available. If variability estimates are available, they can be used to determine the necessary sample size to provide estimates within specified confidence levels.

If there are no variability estimates, then one should determine whether a pilot study is desirable and/or feasible. A pilot study can be used to determine variability estimates as well as to test the sampling methods.

If there are factors within the population that affect the results of the observations, it is possible that such factors can be used to stratify the population into separate groups for randomization. This information, if available prior to sampling and when used to develop a stratified sampling design, can reduce the variability around the estimates, thus improving the statistical efficiency of the estimates.

Accounting for Variability

The variation that is inherent in soils data must be accounted for during the design phase of a soil sampling plan, including the sampling design, data collection procedures, and data analysis. Researchers have long been cautioned about failing to consider the variability in soil sampling when dealing with any study of the soils system (Cline 1944).

Variability can be accounted for by ensuring that the sample adequately covers the entire population, by reporting the variability estimates along with central tendency estimates and by reporting interval estimates.

A good sampling design will use an interactive approach to balance the data quality needs and resources with designs that will either control variation, stratify to reduce variation, or reduce the influence of variation on the decision process.

Precision, Bias, and Accuracy

Precision is a measure of the reproducibility of the measurements of a particular soil condition or constituent. Precision is increased as the variability around the estimates is decreased. If the variability in the observations is constant, precision can also be increased by taking a larger number of measurements (increasing the sample size). The statistical techniques seen in soil sampling are designed to measure precision and not accuracy.

Bias is a systematic error that contributes to the difference between the mean of a large number of test results and an accepted reference value. Bias is often the result of an imperfect measurement technique (the characteristic measured does not match the characteristic in question in a systematic way) or an imperfect measurement instrument (the measurement tool must be calibrated).

Accuracy is the correctness of the measurement and cannot be directly measured. It is the sum of precision and bias, and can be improved by taking care that the estimates are as precise as is required and that bias is as small as possible.

Sampling Designs

The choice of a sampling design often depends on what is available for a sampling frame, whether the population can be divided into a natural grouping in terms of the measurement variables, variability within the population, and the cost of sampling. There are three initial questions that can be posed when considering the four commonly used sampling designs:

- Does the population contain a natural grouping in terms of the variables that will be measured?
- Does the grouping variable affect the results of the measurement variable?
- Can the efficiency of the sampling effort be improved by separating the population into such groups?

If there are no natural groupings, then two possible sampling designs are Simple Random Sampling and Systematic Random Sampling. The choice between these two designs depends on the answer to the question "Is a comprehensive list of sampling units available?"

Simple Random Sampling—Simple Random Sampling is the basis for most other sampling designs. It is used when a comprehensive list of all population units is available and either no information is known about the population or a natural grouping does not exist. A randomization scheme is used to select individuals for measurement in which each element in the population has an equal probability of being selected. Simple random sampling is the basis for all probability sampling techniques and is the point of reference from which modifications to increase sampling efficiency may be made. Alone, simple random sampling may not give the desired precision.

A formal definition of simple random sampling is:

> If a sample of size n is drawn from a population in such a way that every possible sample of size n has the same chance of being selected, the sampling procedure is called *simple random sampling* and the sample thus obtained is called a *simple random sample*.

To draw a simple random sample, all of the possible elements in the population are listed to form a sampling frame. A randomization scheme, often from a random number table, is used to draw elements from the sampling frame without replacement.

Common estimators calculated for continuous variables are the estimator of the population mean, the variance of the population mean (to evaluate the goodness of the estimated mean), a confidence interval around the estimated mean, and a required sample size to estimate the population mean. For binomial variables (those with either a yes or no response), the estimator of the proportion of the population possessing the yes response is often of interest, along with it's variance, confidence interval and sample size.

To calculate the estimators, we use the following equations:
Estimator of the population mean:

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \qquad [1]$$

where y_i is the observation from element *i* and *n* is the number of elements sampled.
Estimator of the population variance:

$$\hat{V}(\bar{y}) = \frac{s^2}{n}\left(\frac{N-n}{N}\right) \qquad [2]$$

where s^2 is the sample standard deviation.

$\left(\frac{N-n}{N}\right)$ is the finite population correction factor (fpc). When *n* is small relative the population size *N*, the fpc is close to unity.

$$s^2 = \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n-1} \qquad [3]$$

Confidence interval around the estimated mean:

$$\bar{y} \pm t_{\alpha/2, n-1}\sqrt{\hat{V}(\bar{y})} \qquad [4]$$

where $t_{\alpha/2, n-1}$ is the coefficient from *t* distribution with *n* -1 degrees of freedom.
Estimator of the population proportion:

$$\hat{p} = \bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \qquad [5]$$

Estimated variance of the population proportion:

$$\hat{V}(\hat{p}) = \frac{\hat{p}(1-\hat{p})}{n}\left(\frac{N-n}{N}\right) \qquad [6]$$

Confidence interval around the population proportion:

$$\hat{p} \pm z_{\alpha/2}\sqrt{\hat{V}(\hat{p})} \qquad [7]$$

Systematic Random Sampling—Systematic Random Sampling is an alternative to simple random sampling. It is used when a comprehensive list of sampling units is not available but an estimate of the total number of units within the population can be obtained. The randomization aspect occurs in the starting point. When systematic random sampling is performed, the sample size must be determined so that a sampling interval may be computed. When a random start is selected within the first sampling interval, then each subsequent element from the following intervals are also random by default.

The goal of systematic random sampling is to provide better coverage of the study area or population than that provided by a simple random sample or from a stratified random sample, and is a simple random sample based on spatial distribution over the population. To use systematic random sampling, some estimate of the total number of sampling units in the population must be estimated. The required sample size must also be known so that the interval for sampling can be calculated.

Systematic random sampling is a useful alternative to simple random sampling:

1. Systematic sampling is easier to perform in the field and hence is less subject to selection errors by field workers than either simple random sampling or stratified random sampling.
2. Systematic random sampling can provide greater information per unit cost than simple random sampling can provide.

Transect sampling is a version of systematic random sampling, and when using transects, they should be randomly oriented or the starting point should be randomly chosen.

A danger in systematic random sampling is that if the sampling interval is chosen in such a way that it matches any periodicities in the population, the resulting estimates could be biased. Knowledge of the population is useful to avoid this danger so that care can be taken to avoid sampling along any periodicities.

Estimators from systematic random sampling can be calculated using the same equations as those used for simple random sampling.

If there are natural groups within the population, then the question becomes "Are the groups likely to be similar to each other in terms of the measurement variables or are the groups different?" An alternative phrasing for this question is "Is the variability within groups larger than the variability between groups?"

Stratified Random Sampling—Stratified random sampling is used when the groups are different from each other, or when the variability is larger between the groups compared to variability within groups. Each group (stratum) is sampled individually, using either a simple random sample or a systematic random sample.

Prior knowledge of the sampling area and information obtained from background data are required for stratified random sampling. The goal is to increase precision and control sources of variability in the data, and a potential result is that the overall sample size may be reduced. For stratified random sampling to be efficient (the overall variability estimates from a stratified design are smaller than those from simple random sampling), the variability between strata must be larger than variability within strata.

The advantages of stratified random sampling include obtaining estimates for subgroups, potentially more precise estimates than those from simple random sampling, and can be more convenient to implement. Disadvantages are that prior information about the population is necessary and the computations are more complex.

Some additional notation is required for computational formulas for stratified random sampling.

L = number of strata
N_i = number of sampling units in stratum i
N = number of sampling units in the population = $N_1 + N_2 + \ldots + N_L$

Estimator of the population mean from a stratified random sample:

$$\bar{y}_{st} = \frac{1}{N}[N_1\bar{y}_1 + N_2\bar{y}_2 + \cdots + N_L\bar{y}_L] = \frac{1}{N}\sum_{i=1}^{L} N_i\bar{y}_i \qquad [8]$$

Estimated variance of the mean from a stratified random sample:

$$\hat{V}(\bar{y}_{st}) = \frac{1}{N^2}[N_1^2\hat{V}(\bar{y}_1) + N_2^2\hat{V}(\bar{y}_2) + \cdots + N_L^2\hat{V}(\bar{y}_L)] \qquad [9]$$

Confidence interval around the estimated mean:

$$\bar{y}_{st} \pm t_{\alpha/2,n-1}\sqrt{\hat{V}(\bar{y}_{st})} \qquad [10]$$

The goal of the allocation scheme to divide the overall sample size into the different strata depends on three factors:

3. The total number of elements in each stratum.
4. The variability of observations in each stratum.
5. The cost of obtaining an observation from each stratum.

The number of elements in each stratum affects the quality of information in the sample. A sample size 20 from a population of 200 elements should contain more information than a sample of 20 from 20,000 elements. Thus, larger sample sizes should be assigned to strata containing larger numbers of elements. Variability must be considered because a larger sample is needed to obtain a good estimate of a population when the observations are less homogeneous. If the cost of obtaining a sample varies from stratum to stratum, smaller samples from strata with higher costs is advisable when the goal is to keep the cost of sampling at a minimum.

An approximate allocation that minimizes cost for a fixed value of $\hat{V}(\bar{y}_{st})$ or that minimizes $\hat{V}(\bar{y}_{st})$ for a fixed cost:

$$n_i = n\left(\frac{N_i s_i/\sqrt{c_i}}{N_1 s_1/\sqrt{c_1} + N_2 s_2/\sqrt{c_2} + \cdots + N_L s_L/\sqrt{c_L}}\right) \qquad [11]$$

where N_i denotes the size of the ith stratum, s_i^2 is the estimated variance from the ith stratum, and c_i is the cost of obtaining a single observation from the ith stratum.
Estimator for the population proportion from stratified random sample:

$$\hat{p}_{st} = \frac{1}{N}\left(N_1\hat{p}_1 + N_2\hat{p}_2 + \cdots + N_L\hat{p}_L\right) \qquad [12]$$

Estimator of the variance of the estimated proportion from a stratified random sample:

$$\hat{V}(\hat{p}_{st}) = \frac{1}{N^2} N_1^2\hat{V}(\hat{p}_1) + N_2^2\hat{V}(\hat{p}_2) + \cdots + N_L^2\hat{V}(\hat{p}_L) \qquad [13]$$

Confidence interval around a proportion from a stratified random sample:

$$\hat{p}_{st} \pm z_{\alpha/2}\sqrt{\hat{V}(\hat{p}_{st})} \qquad [14]$$

Approximate allocation that minimizes cost for a fixed value of $\hat{V}(\hat{p}_{st})$ or minimizes $\hat{V}(\hat{p}_{st})$ for a fixed cost:

$$n_i = n\frac{N_i\sqrt{\hat{p}_i(1-\hat{p}_i)/c_i}}{N_1\sqrt{\hat{p}_1(1-\hat{p}_1)/c_1} + N_2\sqrt{\hat{p}_2(1-\hat{p}_2)/c_2} + \cdots + N_L\sqrt{\hat{p}_L(1-\hat{p}_L)/c_L}} \qquad [15]$$

Post-stratification can be used when stratification is appropriate for some key variable, but cannot be done until after the sample is selected. This is often appropriate when a simple random sample is not properly balanced according to major groupings. While the mean from a post stratification scheme is calculated in the same way as for a

designed stratified random sample, the variance must be estimated differently since the stratification was not designed into the plan.
Estimated variance of the mean from post stratification:

$$\hat{V}_p(\bar{y}_{st}) = \frac{N-n}{Nn}\sum_{i=1}^{L} W_i s_i^2 + \frac{1}{n^2}(1-W_i)s_i^2 \qquad [16]$$

where W_i is the weight proportion for each stratum.

Cluster Sampling—Cluster sampling is used when the groups are similar to each other (there is more variability within groups than among groups). Here, the clusters themselves are randomly sampled so that not every cluster within the population is sampled. In some cases, individuals within clusters are also randomly sampled for measurement (multistage sampling), and in others every element within the cluster is sampled.

Cluster sampling can be less costly than simple or stratified random sampling if the cost of obtaining a frame that lists all population elements is very high or if the cost of obtaining observations increases as the distance separating the elements increases.

To calculate the estimators obtained in a cluster sample, we use the following equations:
Estimator for the sample mean from a cluster sample:

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{m} m_i} \qquad [17]$$

where m_i is the number of elements in cluster i.
Estimated variance of the sample mean from a cluster sample:

$$\hat{V}(\bar{y}) = \frac{N-n}{Nn\bar{M}^2} s_r^2 \qquad [18]$$

where

$$s_r^2 = \frac{\sum_{i=1}^{n}(y_i - \bar{y}m_i)^2}{n-1} \qquad [19]$$

and $\bar{M} = \frac{\sum_{i=1}^{n} m_i}{N}$ (the average cluster size for the population), and can be estimated with $\bar{m}_i = \frac{1}{n}\sum_{i=1}^{n} m_i$ (the average cluster size for the sample).

Confidence interval around the estimated mean for a cluster sample:

$$\bar{y} \pm t_{\alpha/2, n-1}\sqrt{\hat{V}(\bar{y})} \qquad [20]$$

Estimate of the population proportion from a cluster sample**:**

$$\hat{p} = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} m_i} \qquad [21]$$

Estimated variance of the estimated population proportion from a cluster sample:

$$\hat{V}(\hat{p}) = \left(\frac{N - n}{Nn\overline{M}^2} \right) s_p^2 \qquad [22]$$

where $s_p^2 = \dfrac{\sum_{i=1}^{n} (y_i - \hat{p}m_i)^2}{n-1}$

Confidence interval around a proportion from a cluster sample:

$$\hat{p} \; \pm z_{\alpha/2} \sqrt{\hat{V}(\hat{p})} \qquad [23]$$

To aid in the selection of the best sampling design, a series of questions can be asked that will help make the best choice:

- If there is no information on population groupings, will simple random sampling or systematic random sampling better meet the objectives?
- Is simple random sampling likely to be effective?
- If not, have the reasons for not using simple random sampling been clearly stated?
- If systematic random sampling is chosen, what interval will separate the sampling units?
- Is there a likelihood that the interval will coincide with periodicity in the data?
- If so, what steps will be taken to avoid the resulting bias in the estimates?
- If there is a grouping in the population, will stratification improve the precision of the estimates?
- Has the efficiency of the stratification been calculated?
- What is the basis of the stratification?
- How will the sampling units be allocated?
- If there is a grouping in the population, is there an advantage to cluster sampling?
- Has the efficiency of using clusters been calculated?

What Sample Size Is Necessary to Answer the Research Questions With Acceptable Accuracy?

Once the sampling design has been chosen, the number of observations (sample size) must be calculated. Sample calculations are based on the variability within the population and the desired precision of the estimate (the confidence level). In order to calculate sample size, one must obtain an estimate of the variability within the population to be sampled, either from prior data or from a pilot study. One must then decide what level of confidence is required for the estimates, realizing that as the confidence level increases, so does the number of observations required to make the estimate.

Sample sizes for the four sampling designs described here are as follows:

Sample size to estimate the population mean with an interval width *w* for a simple random sample:

$$n = \frac{t^2_{\alpha/2, n-1} s^2}{D} \qquad [24]$$

where

$$D = \frac{w^2}{4}$$

Sample size to estimate the population proportion with an interval width *w* for a simple random sample:

$$n = \frac{N\hat{p}(1-\hat{p})}{(N-1)D + \hat{p}(1-\hat{p})} \quad [25]$$

Sample size for estimating the population mean from a stratified random sample:

$$n = \frac{\sum_{i=1}^{L} N_i^2 s_i^2 / w_i}{N^2 D + \sum_{i=1}^{L} N_i s_i^2} \quad [26]$$

where w_i is the fraction of observations allocated to stratum *i*.
Sample size to estimate a population proportion from a stratified random sample with interval width *w*:

$$n = \frac{\sum_{i=1}^{L} N_i^2 \hat{p}_i (1-\hat{p}_i) / w_i}{N^2 D + \sum_{i=1}^{L} N_i \hat{p}_i (1-\hat{p}_i)} \quad [27]$$

Sample size to estimate the population mean from a cluster sample with interval width *w*:

$$n = \frac{Ns_r^2}{ND + s_r^2} \quad [28]$$

where $D = (w^2 \overline{M}^2)/4$.
Sample size to estimate the proportion from a cluster sample:

$$n = \frac{Ns_p^2}{ND + s_p^2} \quad [29]$$

where $D = w^2 \overline{M}^2 / 4$ and $s_p^2 = \frac{\sum_{i=1}^{n} (y_i - \hat{p}m_i)^2}{n-1}$

How Will the Randomization be Carried Out?

It is critical that the randomization be carried out according to an objective mechanism. The sampling units must be chosen by an explicit randomization procedure that should be documented in the research. Any constraints in the sampling should be documented as well.

How Will the Results of the Sampling Effort be Recorded?

It can aid the sampling design process to create the data sheets for recording results of the sampling early on in the process. This will clarify the variables that will be measured and recorded, and will guide the analysis procedures.

How Will the Data be Analyzed?

The analysis methods that will be used to answer the research questions should be determined prior to collecting the data. Once the data sheets are created, one can see the data structure, which will help with this step. It is critical to check again, to make sure that the variables collected and the analysis methods will meet the objectives of the research.

Case Study in Sampling Design: The Forest Soil Monitoring Protocol

The goal in developing a soil monitoring protocol for the Northern Region was to develop an easy-to-implement, cost effective and statistically defensible monitoring protocol for disturbance. The sampling design and analysis methods were arrived at by answering the questions illustrated in the previous section, and are described here.

Stating the objectives: The objective of the sampling effort was to characterize the activity area in terms of management related disturbance.

Defining the population: The population was defined to be all possible 'points' within the activity area.

What are the sampling units? The sampling units were defined as points along a transect where a point is a 6-inch radius. Since there are an infinite number of possible points in the population, finite sample correction factors do not need to be used.

What is the translation of the research objectives into specific questions that can be answered with measurements from the sampling units? It was decided to characterize the amount of disturbance related to management within a unit by measuring forest floor depth and observing a series of binomial (presence/absence) variables, such as presence of forest floor, displacement of topsoil, mixing of topsoil and subsoil, presence of erosion, presence of rutting, presence of burning, presence of compaction, and presence of five forest floor variables. By using the percents of observation that record 'present' for these variables, an estimate of management-related disturbance can be made.

What preliminary information about the population is available? The size and shape of the activity area is known, and in some cases soils information is available. In most cases, site specific estimates of variability are not known. Harvest history is generally available.

What sampling design will be used? Since there is not always information about groupings within activity areas, neither stratified nor cluster sampling were chosen as the first choice in sampling design. It is to be noted, however, that considerations are made for the use of both of these designs within the protocol when such information is available. For the ease of obtaining observations and to ensure that the entire activity is accounted for within the sampling, systematic random sampling was chosen as the optimal design, using a line transect to choose observation points.

What sample size is necessary to answer the research questions with acceptable accuracy? The proportions of the binomial indicator variables listed above were used to choose the sample size, all with an interval width of ±5 percent of the estimated proportion. The protocol allows for varying levels of confidence to be used with direction from the line officer. Once the sample size is computed for each of the individual variables, the largest sample size is chosen for sampling to be conservative. The first 30 observations made along the transect were used to calculate the site specific variability for each activity area.

How will the randomization be performed? The observations are randomized by choosing a random orientation for the beginning of the transect. Subsequent turns in the transects are made by choosing an angle in advance on which to turn when the transect reaches the activity area boundary.

How will the results of the sampling effort be recorded? An Excel spreadsheet was developed to record the results of sampling. Observations can either be recorded on a paper sheet or directly into an electronic data recorder.

How will the data be analyzed? Confidence intervals are computed for each of the indicator variables, along with the estimated proportions. Summaries for multiple areas can be calculated using the methods for stratified random sampling.

References

Devore, Jay L. 1995. Probability and statistics for engineering and the sciences. 4th Edition. Duxbury Press. 743 p.

Raj, D. 1968. Sampling theory. New York: McGraw-Hill. 302 p.

Scheaffer, Richard L.; Mendenhall, William; Ott, Lyman. 1996. Elementary survey sampling. 5th Edition. Duxbury Press. 501 p.

Soil Quality Standards Monitoring Program Administration and Implementation

Randy L. Davis, USDA Forest Service, Washington, DC

Felipe Sanchez, USDA Forest Service, Southern Research Station, Research Triangle Park, NC

Sharon DeHart, USDA Forest Service, Job Corp, Fort Collins, CO

Abstract—Forest managers and resource scientists and specialists are engaged in a partnership to sustain the natural resource value of our national forests. Managers are faced with deciding which activities provide the best resource benefits with the least resource damage. Many, but not all, aspects of the decision process must be based on the science supporting our current understanding of natural resources. Scientists are charged with continuing to build these understandings and interpreting their effects in an applications setting. The roles of land managers, subject matter experts (field soil scientists), and research soil scientists are distinctly different. Each brings unique skills to the resource management problem. Together they form a powerful team that can sustain forest and rangeland ecosystems and enhance resource values.

Organizational Structure

Organizationally, the USDA Forest Service (USDA FS) soil management program is divided between the National Forest System (NFS) division and the Research and Development (R&D) division. NFS is charged with managing lands and their respective resources while R&D provides the scientific foundations to improve land and resource management decisions on NFS lands.

NFS has three levels of administration: national, regional, and national forests or grasslands. There are nine regions and 175 national forests and grasslands. R&D has three levels of administration: national headquarters, experimental forests and grasslands, and research stations.

The Forest Service manages in excess of 193 million acres of federal forest and range land. The general requirements under which this land is managed are set forth in enabling legislation. Four legislative acts are of particular importance to the issue of resource sustainability and the soil resource in particular.

Laws

The Organic Administration Act of 1897 (USDA Forest Service 1993) created the National Forests and specified that "No national forest shall be established, except to improve and protect the forest within the boundaries, or for the purpose of securing favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of citizens of the United States…" The Multiple-Use Sustained-Yield Act of 1961 directs management to consider resource values but "not necessarily the combination of uses that will give the greatest dollar return or the greatest unit output…without impairment of the productivity of the land." The Forest and Rangeland Renewable Resources Planning Act of 1974 and its amendment, the National Forest Management Act of 1976 (NFMA), set forth four important points that pertain to the need for continuous monitoring. The guidelines in land management plans are required to:

- "insure research on and (based on continuous monitoring and assessment in the field) evaluation of the effects of each management system to the end that it will not produce substantial and permanent impairment of the productivity of the land" (Section 6(g)(3)(C));

- "insure that timber will be harvested from National Forest System lands only where soil, slope, or other watershed conditions will not be irreversibly damaged" (Section 6(g)(3)(E)(i)); and
- "insure that clearcutting, seed tree cutting, and other cuts…are carried out in a manner consistent with the protection of soil, watershed, fish, wildlife, recreation and esthetic resources, and the regeneration of the timber resource." (Section 6(g)(3)(F)(v)).

In addition, Section 13 of the NFMA specifies that the "Secretary of Agriculture shall limit the sale of timber from each national forest to a quantity equal to or less than a quantity which can be removed from such forest annually in perpetuity on a sustained-yield basis."

The essence of these legislative mandates is that the USDA FS is required to conduct research, monitoring, and assessments to evaluate management effects and to manage for sustained yield in perpetuity and in a manner that assures protection of all resources and values. This is a tall order; it demands from Forest Service managers a level of resource background and knowledge that does not reside in any single individual. In fact, the NFMA requires that NFS land management plans be developed by interdisciplinary teams and with public participation. This requirement makes research, monitoring, and assessment critical for both preparing plans and assuring that they can stand up under public review.

These laws are the foundation of the USDA FS soil management program. These and other laws have been used to develop the Agency's soil management policy housed in the Forest Service Manual 2550. The manual outlines objectives and policy and assigns decisionmaker responsibility for its implementation. Technical aspects of soil management, including inventory and monitoring, are addressed in the Forest Service Handbook 2509.

The need to standardize field procedures for soil monitoring has been recognized for quite some time. The urgency to move forward with a standardization grew out of several recent court rulings that resulted in two major National Environmental Policy Act (NEPA) projects being overturned, i.e., Iron Honey (Lands Council v. Powell 2004) and Lolo Post-Burn (Ecology Center v. Austin 2005).

Lawsuits

In the Iron Honey lawsuit, the USDA FS used a "spreadsheet model" to estimate soil quality based on aerial photos and samples from throughout the Forest. The court ruled that soils analysis and effects should have been tested on the ground, not estimated from a spreadsheet model. The USDA FS did not walk, much less test, the land in the activity area. The Agency conceded that it did not test the activity area but argued that because it tested similar soils within the national forest, the methodology was sound. However, the court questioned whether the USDA FS internal conclusions of the reliability of the spreadsheet model should be trusted, since the model had not been independently validated. The court went on to say that in order to be reliable, the hypothesis and prediction of the model should be verified with observation. The predictions of the model, which may be reliable across the entire National Forest, were not verified with on-the-ground analysis. The USDA FS failed because it based the soils analysis entirely on the model, with no on-site inspection or verification, which violated NFMA (Smith 2007).

In the Lolo Post-Burn lawsuit, the USDA FS looked at maps of past activities on associated soils. Data was input from the National Forest Land Systems Inventory and Burned Area Emergency Response (BAER) report into models to generate estimates of the project's possible effects. The BAER report was based on field reviews and helicopter flyovers as well as transects. Because the project was developed after the BAER transect surveys were conducted, the transect surveys did not cover the vast majority of the activity areas; only a few were crossed by coincidence. Soil sampling did not cover the vast majority of 128 sale units in BAER transects. At the time, the Northern Regional Soil Scientist, John Nesser, questioned the project soil analysis because it had failed to assess soil conditions by field testing the actual activity areas. The Draft Environmental Impact Statement states that not all proposed harvest units were visited with line transects and that much of the soil quality determination was based on information from the USDA FS Northern Region transportation and timber units with respect to past activities and regeneration level of jammer roads. The court ruled that the project was similar to that in the Lands Council v. Powell case where much of activity area was not tested; therefore, the analysis was inadequate under NEPA and NFMA (Smith 2007).

NEPA requires federal agencies to consider the environmental impacts of their proposed actions and reasonable alternatives to those actions as a means of integrating environmental values into their decisionmaking plans. National Forest land management plans typically outline, in general terms, monitoring protocols. Because there are no nationally recognized soil quality monitoring protocols, field personnel typically use the best available methodologies. Unfortunately, some of these methodologies are incompletely documented and thus subject to scientific and legal challenges when follow-up re-sampling is requested or when trend monitoring is conducted. Comparing data sets is also difficult, if not impossible, when different methodologies are used. Finally, database design and population is also complicated when similar data is collected using both well-documented and poorly documented methods.

Monitoring Methodologies

In general, there are at least three intensity levels of monitoring and assessment projects: national, regional, and project. National monitoring is generally conducted using high elevation aerial photography with statewide field sampling procedures with a data resolution to the state datasets. The best example of this protocol is the Forest Information and Analysis (FIA) project. Regional monitoring and assessment are usually conducted using National Forest and Rangeland administrative units, and use a variety of methodologies depending on the subject matter being assessed or monitored. Confidence-level for these types of efforts is generally limited to National Forest, Rangeland, or Grassland datasets but can also include associated state data. Examples of these regional types of monitoring and/or assessments include the Interior Columbia Basin Ecosystem Management Project: Scientific Assessment (Quigley and others 1999) and the Southern Forest Resource Assessment (Wear and Greis 2002).

Project level monitoring and assessments are conducted on areas within a national forest or grassland where some type of land management prescription is proposed or has been implemented (i.e., timber sales, fuel treatments, or rangeland improvements). There are three types of monitoring conducted at the project level: implementation, effectiveness, and validation. Implementation monitoring is intended to evaluate whether a particular land management prescription was conducted as directed by the NEPA decision memo and/or as directed by a project contract. Effectiveness monitoring evaluates the ability of project mitigation practices to prevent resource damage either within the project area or on adjacent resources. Validation monitoring is intended to address resource management assumptions commonly used to narrow the scope of the environmental assessment. Validation monitoring is often conducted by R&D scientists and requires a longer commitment of time to gather and analyze data. The overall protocol is intended to be used on project level monitoring efforts. As the reader might imagine, national and regional monitoring and assessments use more generalized datasets than those at the project level.

Standardization

Standardization of data collection protocols is essential at any of the levels of monitoring and assessment. Increasingly, datasets are needed and used beyond their initial purpose. All too often, inadequate documentation of how a particular dataset was obtained results in duplicated efforts or incomplete analysis of existing data because the protocol was either not well documented or unacceptable. Monitoring without adequate documentation or the use of an inappropriate protocol has resulted in the loss of project data. This type of data often cannot be used with other datasets for other levels of monitoring or analysis and consequently results in increased costs for land management projects in both time and salary. Data collection using standardized peer reviewed protocols offers at least two advantages to land management: the collected data is repeatable and will hold up to scientific and legal scrutiny. Standardized data is essential to resource condition trend analysis and to the successful defense of the data to scientific and legal challenges. Incorporating a standard statistical design of the monitoring effort is essential to assuring that the results of the collected field data provide an accurate picture of what is occurring on the project area. Understanding the reliability and the confidence of the soil data being collected is important in helping land mangers decide their level of comfort in moving forward with a particular resource management prescription. An unbiased statistical analysis will also determine the number of observations needed to accomplish a defensible on-site evaluation of potential resource impacts.

Standardization is not intended to stifle or limit data collection but rather to maximize data utilization. There are several factors of standardization to consider: (1) identification of the question(s) to be answered, (2) size of the treatment area, (3) available staff resources, and (4) the amount of risk land managers are willing to tolerate in their decisionmaking on a proposed land management project. Depending on the outcome of the problem analysis using these factors, a monitoring project can be designed using this protocol as its foundation. One example of an experiment utilizing these important monitoring considerations is the Long-Term Soil Productivity (LTSP) experiment.

North American Long-Term Soil Productivity Experiment

To properly evaluate forest management impacts on soil quality, evidence of long-term impacts is needed. Considerable information can be found in the literature on the long-term impacts of soil disturbance. However, most of this information is from isolated experiments that often were not designed for long-term scrutiny and are too site specific to be broadly useful. An exception to this is the Long-term Soil Productivity (LTSP) experiment, which was specifically designed, among other things, to develop baseline indicators of soil quality and validate these indicators over multiple installations covering a broad range of soil classifications, ecosystems, and climates. The LTSP experiment began as a cooperative between scientists in USDA FS NFS and R&D to address legislative mandates, particularly the NFMA, which require that the management of federal lands be conducted in a manner that maintains site productivity. The cooperative grew with the inclusion of partners in the private and public sectors of the United States and Canada. Currently the cooperative includes well over 100 LTSP installations and affiliated sites, comprising the world's largest coordinated network investigating the long-term impacts of forest management on sustainable site productivity. Excellent descriptions of the genesis and development of the LTSP cooperative are provided by Powers (2006) and Cline and others (2006).

The LTSP experiment specifically examines the impacts of changes in soil porosity and surface organic matter on sustainable soil productivity. These variables were selected after considerable examination of the literature elucidated that these variables are (1) directly affected by forest management, (2) can be readily monitored, and (3) regulate soil properties and processes that, in turn, directly impact site productivity. The LTSP experiment was designed to cover the entire range of soil compaction and site organic matter levels possible resulting from a harvest operation. Consequently, the LTSP experiment presents the unique opportunity to "tease out" the relative contribution of the different soil compaction and surface organic matter combinations on site productivity across a range of installations. The experiment is intended to be long-term in nature extending, at least, to the culmination of mean annual volume increment.

At a minimum, all LTSP installations collect eight core measurements, including five soil measures, at reoccurring intervals. The five soil measures are (1) moisture and temperature (collected monthly), (2) bulk density (collected every 5 years), (3) soil strength (collected seasonally every 5 years), (4) organic matter content and chemical composition (collected every 5 years) and (5) water infiltration and saturated hydraulic conductivity (collected every 5 years). These soil measures provide a template for the current discussion on soil quality metrics.

Findings

The first LTSP installation was established in 1990 on the Palustris Experimental Forest on the Coastal Plain of Louisiana and was rapidly followed by installations in California, Minnesota, and North Carolina. Additional installations were established in subsequent years, providing the LTSP cooperative with data from installations approaching 20 years in age. To date, the LTSP cooperative has produced over 300 scientific publications on various subjects including soil properties and processes and site productivity. The majority of these publications describe information obtained from a single or a few installations; however, results that integrate the observations of several installations have also been published. Fifth-year results from a combination of several installations were presented in 2000 at the Conference on Long-Term Productivity of Forest Soils in Alexandria, Louisiana, near the site of the first LTSP installation. The papers presented were published in 2006 in the Canadian Journal of Forest Research (CJFR) as a special issue on long-term soil productivity (CJFR vol. 36). In 2003, tenth-year results from installations ≥10 years old were presented at the 10th North American Forest Soils Conference in Sault Ste. Marie, Ontario, and were published by Powers and others (2005). The general findings of the conference were that organic matter removal (1) decreased soil carbon (C) concentration but not soil C content, (2) decreased soil nitrogen (N) and phosphorus (P), (3) decreased foliar N and P, but (4) did not affect productivity. Other findings showed (1) small differences between moderate and severe soil compaction, (2) bulk density increases varied with initial bulk density, (3) most sites did not exhibit bulk density recovery, and (4) the affect on productivity varied with soil texture and presence of understory.

Since that time, several other installations have reached the 10-year benchmark and will be incorporated into a presentation in 2008 at the 11th North American Forest Soils Conference in Blacksburg, Virginia.

The early results from the LTSP installations speak volumes about the resiliency of the soil to disturbance. It might be tempting to conclude from this information that forest management does not impact soil productivity in the long-term. However, caution must be taken, since the information to date describes soil conditions early in the stand rotation and may not be indicative of conditions later in the rotation or into the next rotation. The general decrease in soil and foliar N and P with increasing organic matter removal may result in some sites becoming nutrient deficient, which might translate to lower productivity in subsequent rotations. Also, Ludovici (2008) found that soil compaction decreased loblolly pine (*Pinus taeda* L.) root production, thus resulting in C allocation patterns favoring aboveground productivity. Although soil compaction did not significantly affect aboveground productivity, the decrease in belowground C and nutrient stores from fewer roots may lead to lower productivity in future rotations.

Challenges

There are many challenges to maintaining a long-term study. In some cases, we have little or no control over these challenges, for example, natural disasters such as hurricanes and tornados. The LTSP installations in Mississippi and Louisiana faced a serious threat in the form of Hurricane Katrina. Although these sites survived the onslaught, they could have been wiped out. The beauty of the LTSP cooperative is that the number and variety of installations ensure that a loss of a few installations will not be fatal to the overall study. There are other situations, such as fires and insect infestations, where we have some control, but challenges can still occur despite our best planning. However, the most serious challenge facing long-term studies is the need to maintain consistent, long-term commitment to the study. This is something that can be controlled. Over the course of a long-term study, there are invariably considerable changes in the people involved and their priorities. At a study's initiation, the partners must have a long-term vision and commitment for the study, as was the situation for the LTSP cooperative. The LTSP partners recognized the need to keep the study relevant in the face of changing national priorities. This involves more than just political support but includes financial backing and, where appropriate, involvement of new partners. Recently, the NFS Southern Region and the R&D Southern Research Station renewed their Memorandum of Understanding (MOU) in support of the installations in the South. As part of this MOU, partners in the State and Private (S&P) branch of the USDA FS were included to assist in the dissemination of the LTSP findings. It is critical to periodically assess the political and scientific climate to maintain the relevancy of the LTSP experiment. Only by maintaining the long-term nature of the LTSP study will we truly be able to address the question of forest management effects on soil quality.

The Road Ahead

As previously discussed, laws and USDA FS policies are made to protect NFS lands and resources for future generations. The need to keep existing commitments to efforts like the LTSP experiment is critical. Changes in soil are complex, and it often requires several years—even decades—to fully observe the affects of a disturbance, especially when dealing with long-lived tree species. Small changes in soil properties as a result of soil disturbance that might seem scientifically insignificant at one point may become significant when the soil disturbance is repeated in multiple rotations as an acceptable management practice. As the LTSP experiment has demonstrated, measurable changes in soil conditions tend to be site and/or soil horizon specific, and the changes in the soil capability may not be observable within the current management period. With these casual generalizations in mind, we look ahead.

The USDA FS is pursuing the use of environmental management systems (EMS) to boost its resource management and monitoring endeavors. An EMS is a set of processes and practices that enable an organization to reduce its environmental impacts and increase its operating efficiency. An intriguing aspect to EMS implementation is in the arena of third party review and evaluation. The intent of the neutral third party review is to validate that the EMS parameters are truly being adhered to outside of the Agency's influence. The 2008 Planning Rule (revision of the Forest Service's land management planning policy) includes a provision to establish an EMS on national forests and grasslands. Although the areas the EMS would address have not been completely fleshed-out, the process offers an important opportunity to include monitoring parameters related to soil function and productivity. The hope is that with a future planning rule, land management plans will incorporate monitoring or an EMS that includes soil components such as, percentage of bare soil, soil porosity, and/or soil organic matter content, especially in light of ecosystem function and watershed condition.

On another policy front, NFS and R&D have been in continuing dialogues about the need to strengthen the collaboration in the natural resource area of soil science. These efforts were given further urgency after the USDA FS lost two lawsuits (Iron Honey and Lolo Post-Burn) in which the soil analysis was deemed to be inadequate. The National Soil Information Network (SoilNet) is the culmination of these collaborative discussions. The SoilNet charter establishes a formal process to raise soil-related land management questions to the R&D community. Once the questions have been identified, SoilNet provides a mechanism to identify and organize a network of R&D scientists and facilities across the United States to address them. SoilNet has three focus areas: (1) Science Integration and Delivery, (2) Resource Monitoring and Data Management, and (3) Research and Development. Organizationally, SoilNet is composed of a Technical Team and a Steering Team. Proposals are reviewed by the Technical Team who makes a recommendation to the Steering Team. The Steering Team then makes a recommendation to the directors of the Watershed, Fish, Wildlife, Air and Rare Plants and Environmental Sciences Research who approve the proposals for potential funding.

Collaborations and Databases

The EMS and SoilNet are conduits we can use to strengthen our understanding of soil processes and functions on NFS lands. But, as often is the case, collaborations with other land managers (i.e., private land owners, other agencies) will be essential to getting the total picture of ecological processes and watershed condition. With the challenges posed by climate change, it will be more important than ever to have accurate information on associated lands and to be able to compile data across administrative boundaries. The development of electronic data warehouses with standardized protocols and well-documented monitoring records will be in greater demand as time passes. The soil quality protocol introduced in this paper is intended to advance that journey. It will only be successful if the data that is collected in the field is corporately stored in databases that are accessible by interagency resource specialists and land managers.

References

Cline, Richard G.; Ragus, Jerry; Hogan, Gary D.; Maynard, Douglas G.; Foster, Neil W.; Terry, Thomas A.; Heninger, Ronald L.; Campbell, Robert G.; Carter, Mason C. 2006. Policies and practices to sustain soil productivity: perspectives from the public and private sectors. Canadian Journal of Forest Research. 36:615-625.

Ecology Center, Inc. v. Austin 430 F.3d 1057 (9th Cir. 2005).

Lands Council v. Powell 395 F.3d 1019 (9th Cir. 2004).

Ludovici, Kimberly H. 2008. Compacting Coastal Plain soils changes mid-rotation loblolly pine allometry by reducing root biomass. Canadian Journal of Forest Research. 38:2169-2176.

Powers, Robert F. 2006. Long-term soil productivity: genesis of the concept and principles behind the program. Canadian Journal of Forest Research. 36:519-528.

Powers, Robert F.; Scott, D. Andrew; Sanchez, Felipe G.; Voldseth, Richard A.; Page-Dumroese, Deborah; Elioff, John D.; Stone, Douglas M. 2005. The North American long-term soil productivity experiment. Findings from the first decade of research. Forest Ecology and Management. 220(1-3):17-30.

Quigley, Thomas M.; Gravenmier, Rebecca A.; Arbelbide, S. J.; Cole, H. B.; Graham, Russell T.; Haynes, Richard W. 1999. The Interior Columbia Basin Ecosystem Management Project: Scientific assessment. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. CD-ROM.

Smith, Carl. 2007. Court cases with soil issues in 2006-2007. Region-3 Rangeland Managers and Staff Officers Meeting and TES/TEUI Workshop.

USDA, Forest Service. 2000. USDA Forest Service resource management and soil sustainability. Washington, DC: U.S. Government Printing Office.

USDA, Forest Service. 1993. The principle laws relating to Forest Service activities. Washington, DC: U.S. Government Printing Office.

Wear, David N.; Gries, James G. 2002. Southern forest resource assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 635 p.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

The Rocky Mountain Research Station develops scientific information and technology to improve management, protection, and use of the forests and rangelands. Research is designed to meet the needs of the National Forest managers, Federal and State agencies, public and private organizations, academic institutions, industry, and individuals. Studies accelerate solutions to problems involving ecosystems, range, forests, water, recreation, fire, resource inventory, land reclamation, community sustainability, forest engineering technology, multiple use economics, wildlife and fish habitat, and forest insects and diseases. Studies are conducted cooperatively, and applications may be found worldwide.

Station Headquarters
Rocky Mountain Research Station
240 W Prospect Road
Fort Collins, CO 80526
(970) 498-1100

Research Locations

Flagstaff, Arizona	Reno, Nevada
Fort Collins, Colorado	Albuquerque, New Mexico
Boise, Idaho	Rapid City, South Dakota
Moscow, Idaho	Logan, Utah
Bozeman, Montana	Ogden, Utah
Missoula, Montana	Provo, Utah

Federal Recycling Program Printed on Recycled Paper