

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

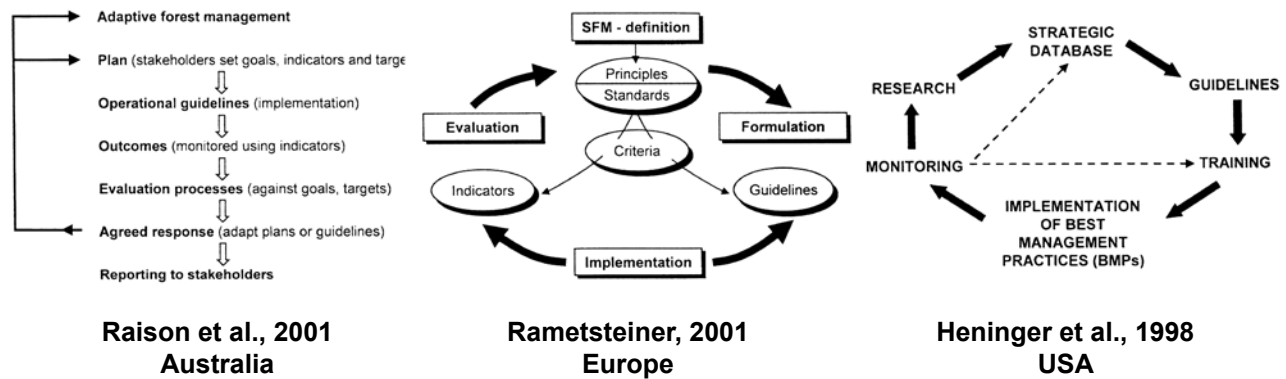


Figure 1. Examples of adaptive management models used for achieving sustainable forest management.

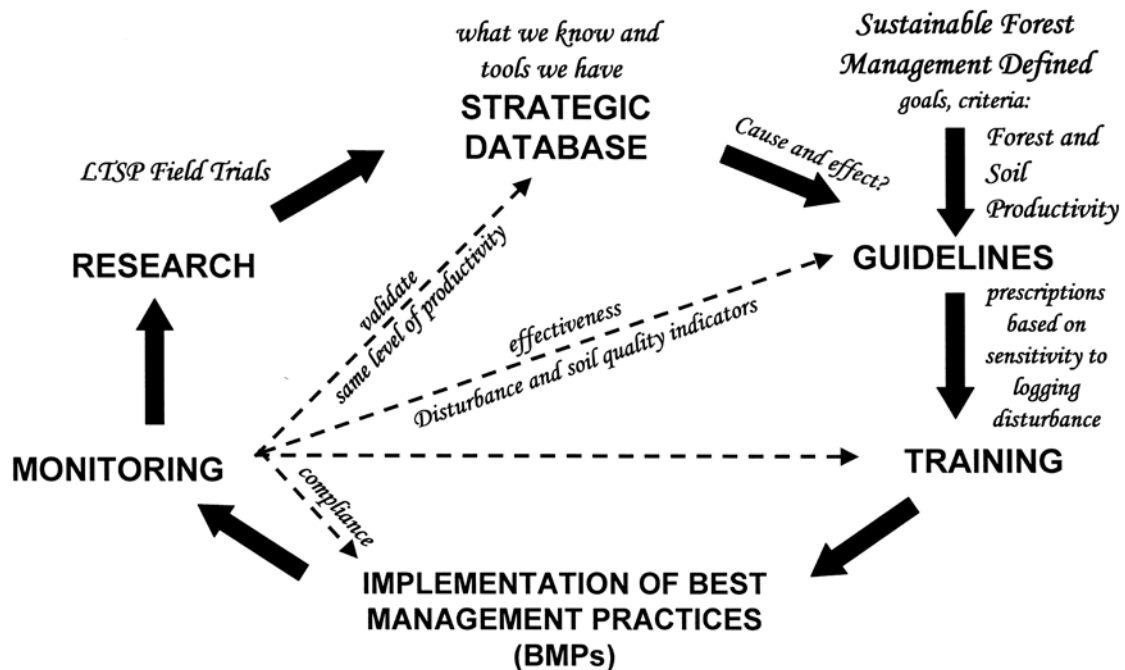


Figure 2. Components of an adaptive management model.

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
Forest productivity Regulated hydrologic cycle Regulated carbon balance Waste bioremediation	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
	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
	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.

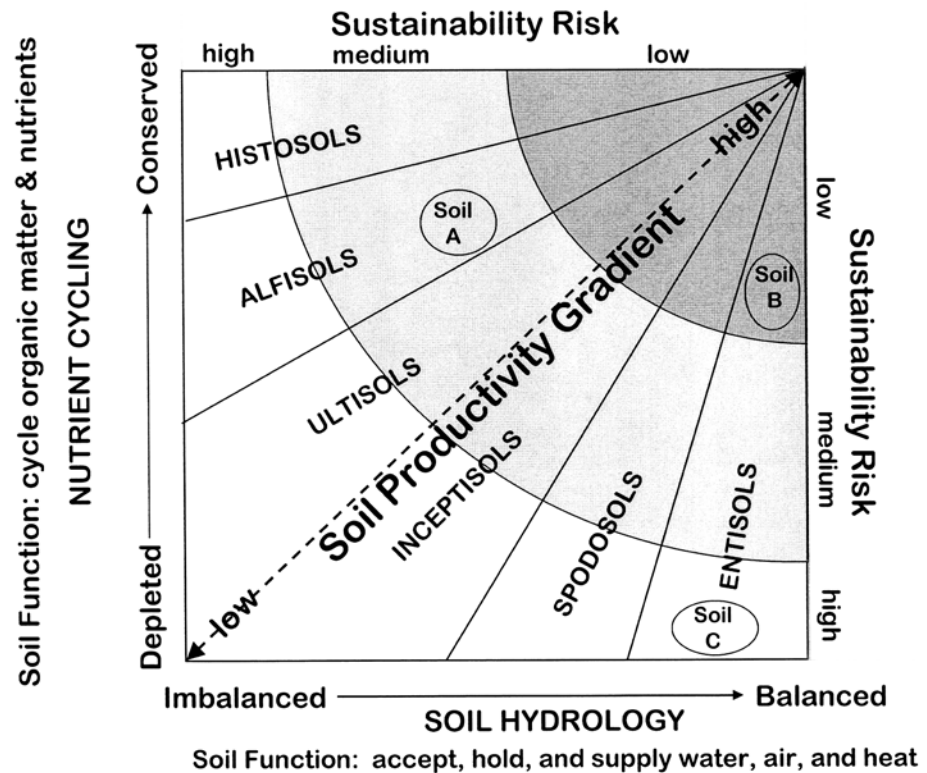
Perhaps the most serious monitoring pitfall is using indicators with no cause-and-effect relationship with the soil service (*e.g.*, soil productivity) (Powers and others 1998; Miller and others, in preparation). Many forest disturbances, both natural and human-induced, are totally benign. In fact, the 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 CO₂.
- 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.

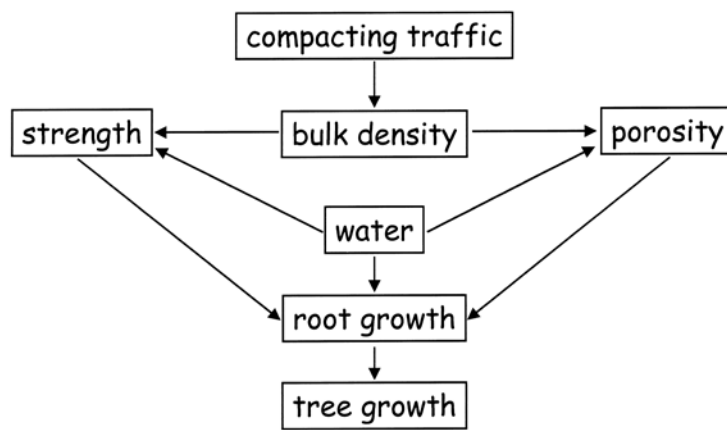


Figure 4. Root and tree growth as a function of soil compaction effects on bulk density, soil strength, porosity, and water content (after Greacen and Sands 1980).

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 Greacen 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).

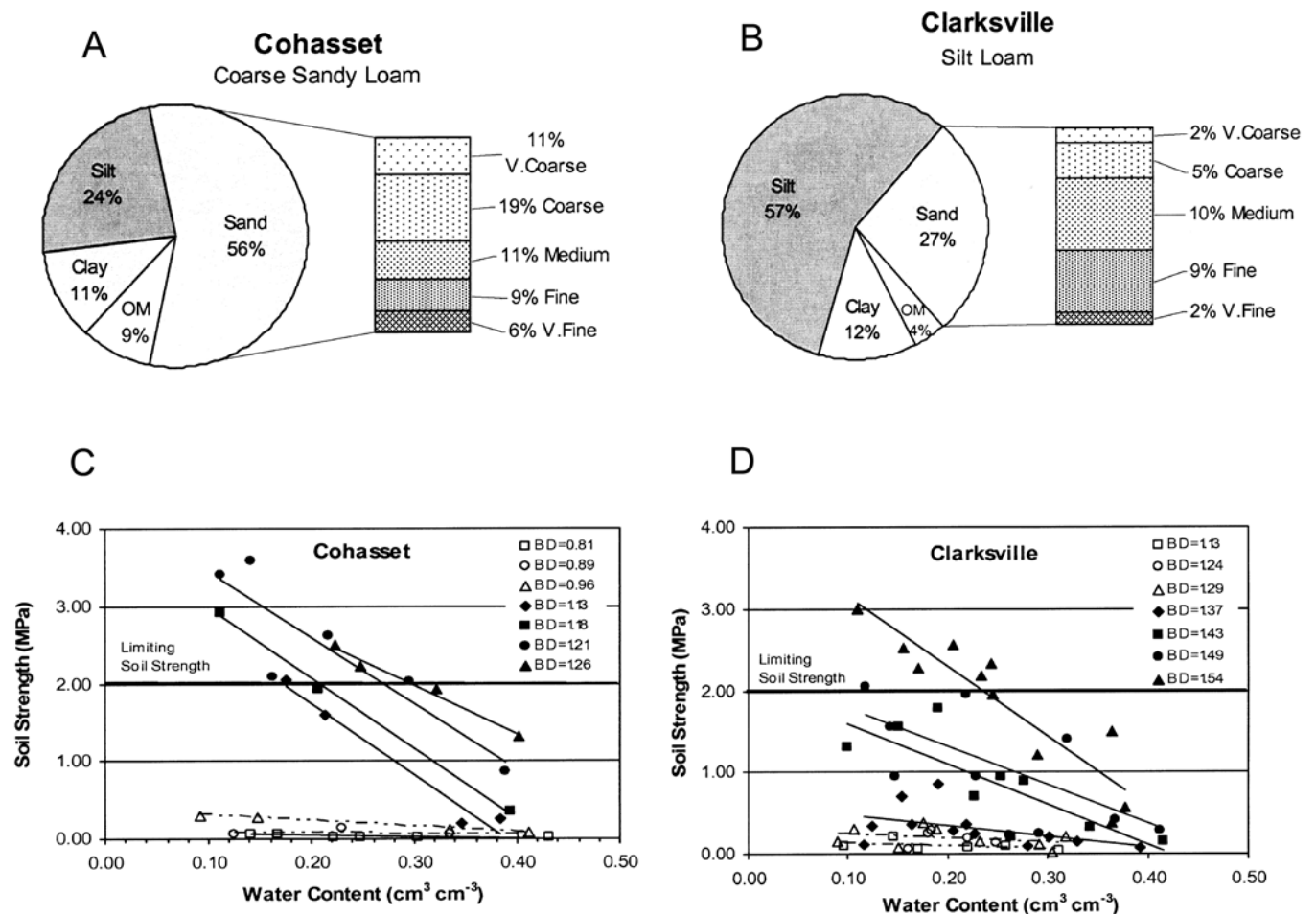


Figure 5. Particle size distribution of a Clarksville and Cohasset soil series from MO and CA LTSP study sites, respectively (from Siegel-Issem and others 2005).

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 (Lafren 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

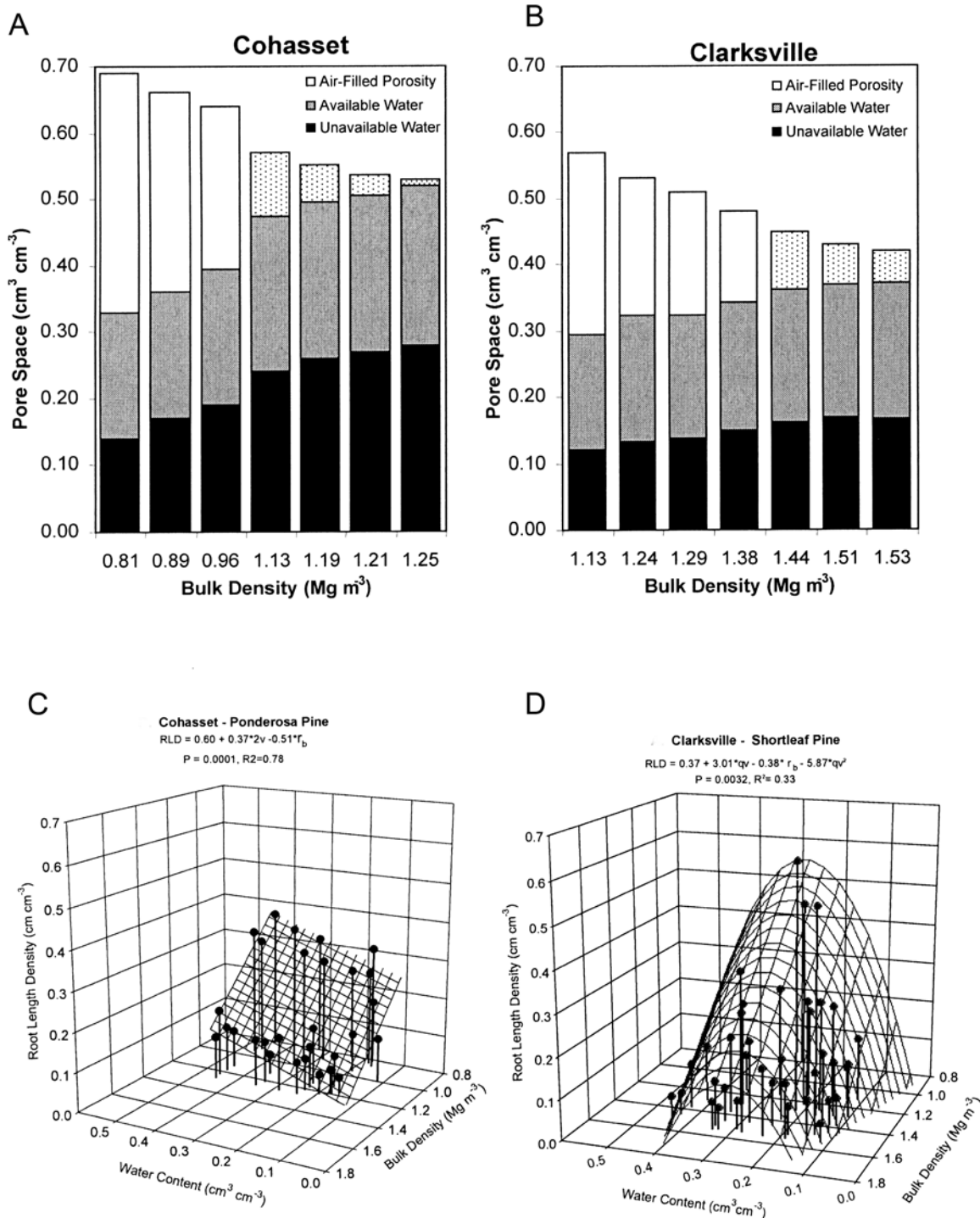


Figure 6. Pore space distribution and root length density of shortleaf pine seedlings and ponderosa pine seedlings grown on Clarksville and Cohasset soils, respectively, as a function of soil bulk density and volumetric water content (Siegel-Issem and others 2005).

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.

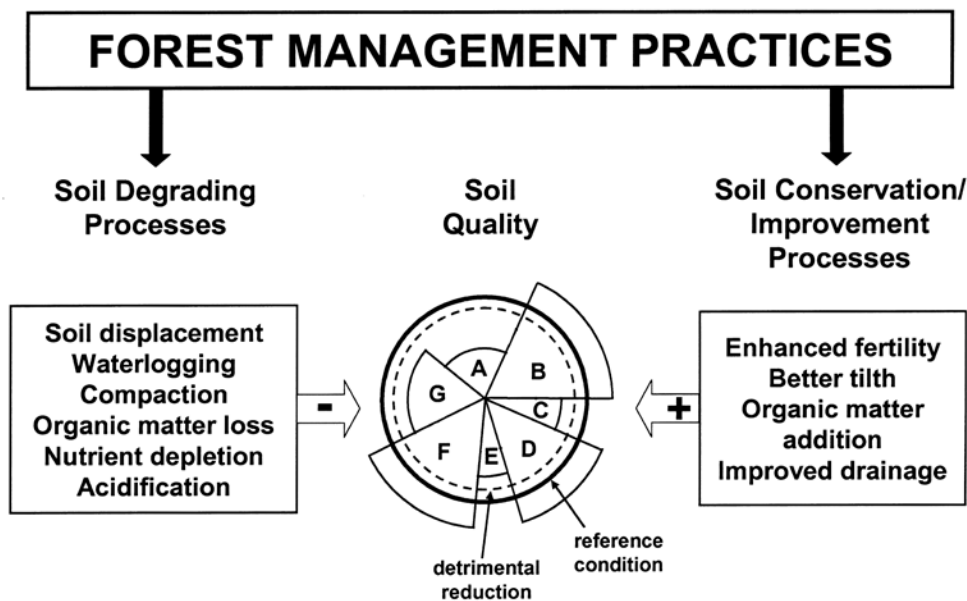


Figure 7. Conceptualization of the effects of forest management practices on soil quality.

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

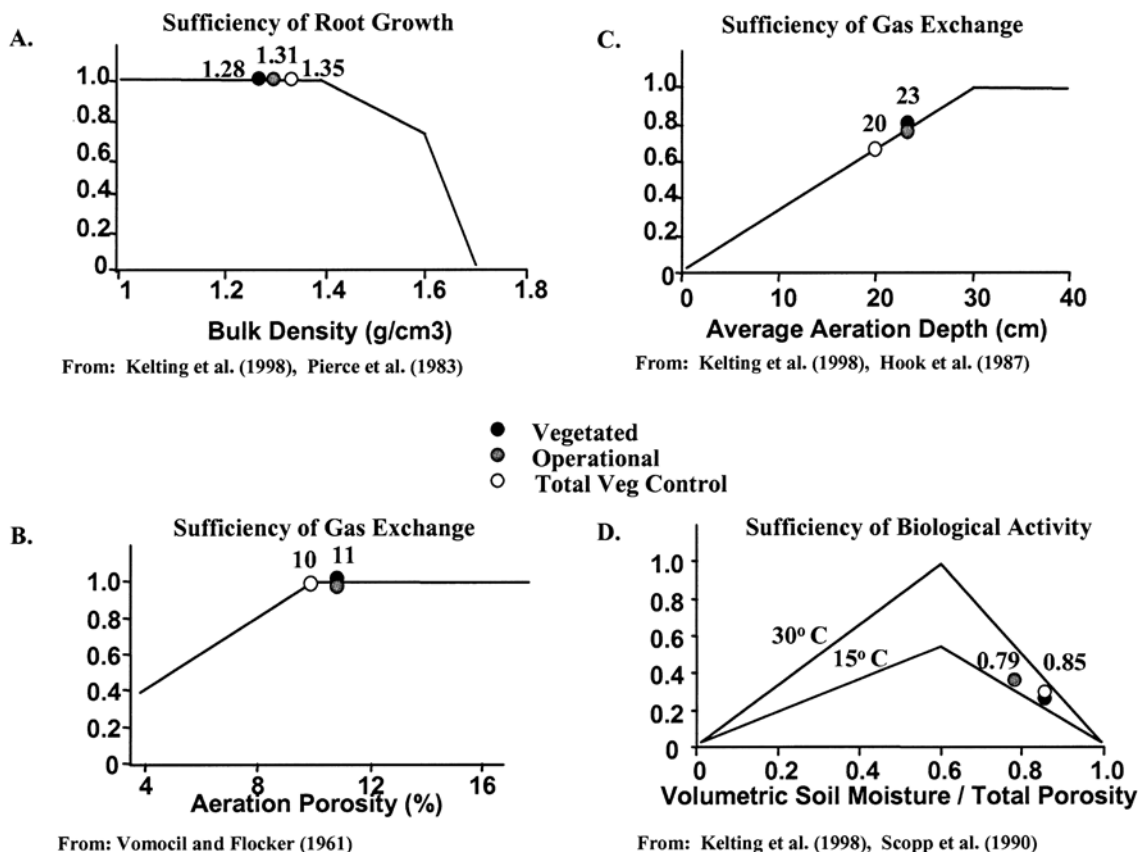


Figure 8. Sufficiency curves for vegetation treatment effect on (A) the soil rooting environment, (B and C) aeration, and (D) soil biological activity.

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:

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

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

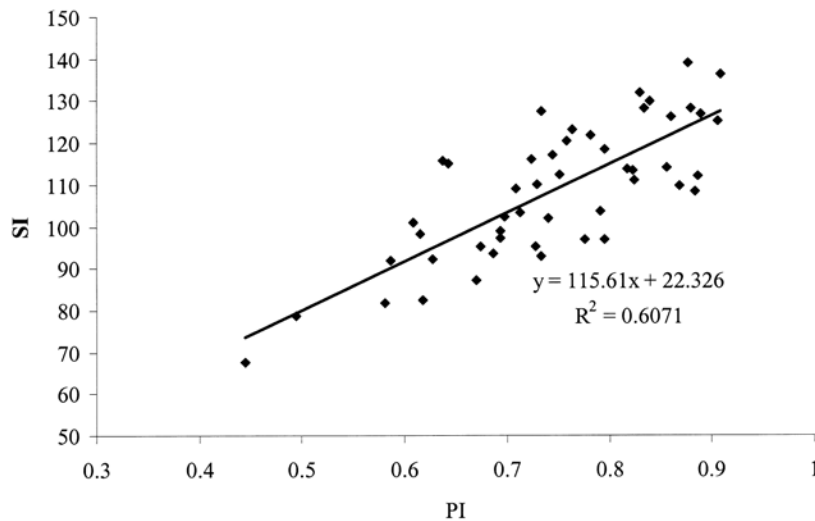


Figure 9. Relationship between site index (tree height at age 50) of white pine and a productivity index (soil quality) calculated from literature-based sufficiency curves for pH, soluble salts, soil density, slope, coarse fragment content, and aspect. Site index and soil measurements were for 52 reclaimed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

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

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.

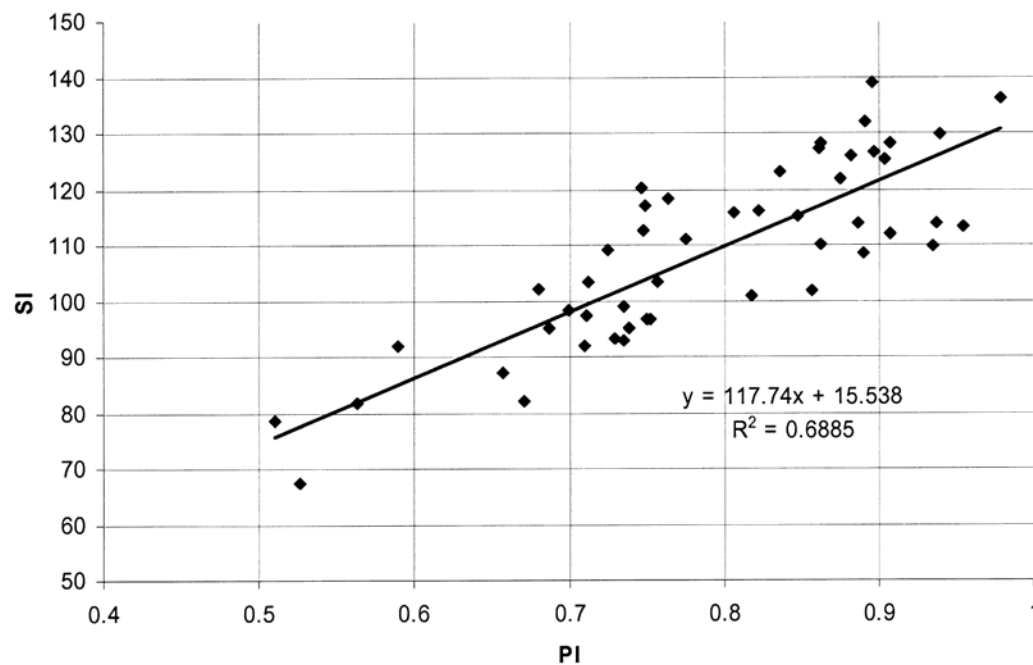
The SQI model (Eq. 2) assumes that all soil variables are equally important, which is unlikely. Jones and co-workers refined the model to make it locally specific. They regressed measured SI with measured soil properties from the 52 study sites. Standardized coefficients were calculated and used to develop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

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

where SQI_{ss} = 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 $9.5 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$, while another one-third was less than $3 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$ 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:

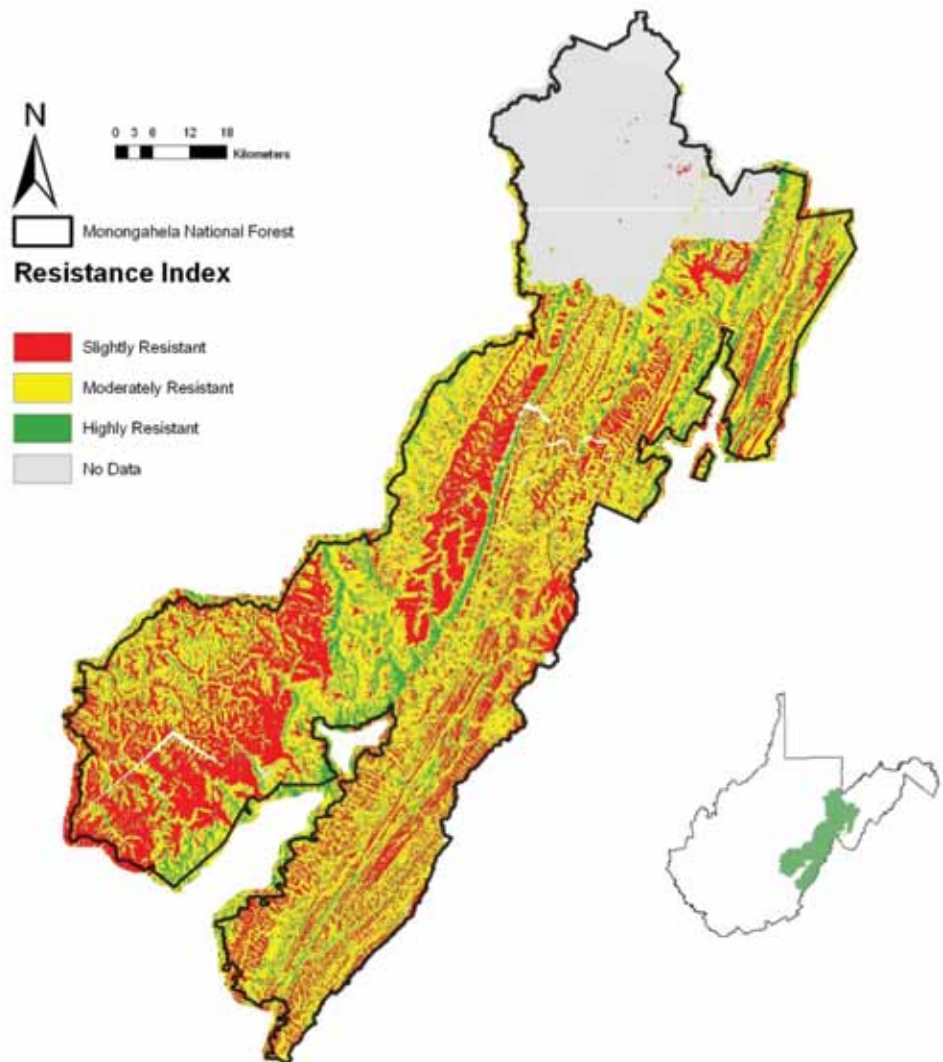
$$RI_{\text{general}} = [.2 (\text{parent material score}) + .2(\text{aspect score}) + .2(\text{elevation score}) + .2(\text{soil depth score}) + .2(\text{texture score})]^2 \quad (4)$$

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: $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$). 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.; Zaebs, 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.; Stottlemeyer, 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.; Elliott, 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.

