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Review

A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities☆

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Abstract

Foresters have always relied on a knowledge of chemical and physical properties of soils to assess capacity of sites to support productive forests. Recently, the need for assessing soil properties has expanded because of growing public interest in determining consequences of management practices on the quality of soil relative to sustainability of forest ecosystem functions in addition to plant productivity. The concept of soil quality includes assessment of soil properties and processes as they relate to ability of soil to function effectively as a component of a healthy ecosystem. Specific functions and subsequent values provided by forest ecosystems are variable and rely on numerous soil physical, chemical, and biological properties and processes, which can differ across spatial and temporal scales. Choice of a standard set of specific properties as indicators of soil quality can be complex and will vary among forest systems and management objectives. Indices of forest soil quality which incorporate soil chemical, physical, and biological properties will be most readily adopted if they are sensitive to management-induced changes, easily measured, relevant across sites or over time, inexpensive, closely linked to measurement of desired values, and adaptable for specific ecosystems. This paper traces development of the concept of soil quality, explores use of soil chemical and physical properties as determinants of forest soil quality, and presents challenges and opportunities for forest soil scientists to play a relevant role in assessment and advancement of sustainable forest management by developing the concept of soil quality as an indicator of sustainability. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Foresters have always relied on a knowledge of chemical and physical properties of soils to assess capacity of sites to support productive forests. Recently, the need for assessing soil properties has expanded because of growing public interest in determining consequences of management practices on the quality of soil relative to sustainability of forest ecosystem functions in addition to plant productivity (e.g. Montreal and Helsinki processes). The concept of soil quality (SQ) includes assessment of soil properties and processes as they relate to ability of soil to function effectively as a component of a healthy ecosystem. Soil quality, like site quality or forest productivity, is a value-based concept related to the objectives of ecosystem management, and hence will be management- and ecosystem-dependent. Soil quality may be

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broadly defined to include a capacity for water retention, carbon sequestration, plant productivity, waste remediation, and other functions, or it may be defined more narrowly. For example, a forest plantation manager may define soil quality as the capacity of a soil to produce biomass.

This paper traces development of the concept of soil quality, explores use of soil chemical and physical properties as determinants of soil quality, and presents challenges and opportunities for forest soil scientists to play a relevant role in assessment and advancement of sustainable forest management by developing the concept of soil quality as an indicator of sustainability.

International and national calls for management of forestry on a sustainable basis have consistently included maintenance or enhancement of forest soil quality as a criterion of sustainability. Monitoring of function and long-term sustainability of forest ecosystems relies on use of *indicators*. In the case of soil quality, an indicator is a measurable surrogate of a soil attribute that determines how well a soil functions (Burger and Kelting, 1999). For example, if soil productivity is the soil function of interest, a soil quality indicator should measure soil productivity from site to site, and detect management-induced changes within a site. Many soil quality indicators have been rationalized and proposed, and a few have been tested and validated. The overall approach is that specific processes or properties that indicate changes in direction of ecosystem function are monitored as indicators of sustainability.

2. Evolution of the concept of soil quality in agriculture and forestry

There are centuries-old reports of agrarian peoples comparing the relative productivity of land and soils as they used them for crop production (Warkentin, 1995). Early delineation of landscapes based on productive potential was largely a process of trial and error. Location of the best soils and some of the factors associated with good soil productivity became indigenous knowledge that was passed to succeeding generations. Delineating the natural productive potential of soils became more precise and a matter of record as taxonomic, survey, and mapping systems were fully developed in the last century.

Productivity changes within a field or soil type due to management were recognized later, especially with the advent of post-WW-II agricultural development. Changes in soil productivity were positive due to drainage, tillage, and addition of lime and fertilizer, and negative due to soil erosion, loss of organic matter and physical structure, and other degrading processes. Both positive and negative processes occurred simultaneously, making it difficult to associate changing yields with certain cultural practices. Differences in soils due to natural or human-induced change were measured indirectly using relative crop yield, but other factors such as draft requirements for tillage, or the cost of inputs required to achieve a certain yield were equally important (Warkentin, 1995). Farmers manipulate soils intensively; therefore, a comparative measure of soil quality has traditionally included more than a simple measure of crop yield.

Foresters, by comparison, have traditionally measured soil productivity using tree growth or wood yield. Soil productivity is usually defined by foresters as the 'ability of a soil to produce biomass per unit area per unit time' (Ford, 1983). On the other hand, agronomists and farmers most often define soil quality as 'the suitability of a soil to function for different uses' (Warkentin, 1995), which illustrates a broader concept, and the fact that agriculture has traditionally been more soil-interactive than silviculture. Soil quality includes a measure of a soil's ability to produce plant biomass, maintain animal health and production, recycle nutrients, store carbon, partition rainfall, buffer anthropogenic acidity, remediate added animal and human wastes, and regulate energy transformations. Soil serves these functions in forest ecosystems as well, and both soil productivity as a measure of plant biomass and soil quality should be expanded to include the ability of soils to serve these multiple functions in forests.

Evaluating and measuring the quality of the soil resource was prompted by this increasing awareness that soil serves multiple functions in maintaining worldwide environmental quality (Doran and Parkin, 1994). Public awareness was raised when the National Academy of Sciences published 'Soil and Water Quality: An Agenda for Agriculture' (National Research Council, 1993). In response, a group within the Soil Science Society of America set about to define soil quality, examine its rationale and

justification, and identify methods for evaluating it (Karlen et al., 1997).

The committee defined soil quality as 'the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation'. The rationale for addressing soil quality, according to the committee, is that conservation efforts to protect soil resources and environmental quality are not receiving appropriate attention. Evaluation would be based upon soil function and soil indicators that measure function. Soil function would be defined in terms of physical, chemical, and biological properties and processes and measured against some definable standard to determine whether a soil is being improved or degraded (Karlen et al., 1997).

Soils are being degraded worldwide through processes of erosion, anaerobiosis, salinization, compaction and hard-setting, organic matter depletion, and nutrient imbalance. Central to sustainable agroecosystems must be the protection and enhancement of soil quality. The concept of soil resource management (separate from crop or forest management) for sustaining the productivity of plant systems was needed to ensure the reality of sustainable agriculture and environmental protection. Measuring soil quality, if properly characterized, should serve as an indicator of the soil's capacity to produce safe and nutritious food, enhance human and animal health, and overcome degradative processes (Papendick and Parr, 1992). Therefore, the overall purpose of this renewed emphasis on soil quality is to develop a more sensitive and dynamic way to document a soil's condition, how it responds to management, and its resilience to stresses imposed by cultural practices.

Towards this aim, several national and international symposia have been held on the subject of soil quality. The Rodale Institute Research Center held a workshop 'Assessment and Monitoring of Soil Quality', 11–13 July 1991, in Emmanus, PA (Youngberg, 1992). On 28 September–2 October 1992, in Budapest, the Hungarian Academy of Sciences and the International Society of Soil Science organized a symposium 'Soil Resilience and Sustainable Land Use' to draw attention to the importance of soil resilience (Greenland and Szabolcs, 1994). Also in the Fall of 1992, a symposium on soil quality was held at the American Society of Agronomy annual meeting in Minneapolis, MN, to identify the major components of soil that define soil quality, and to quantify soil-derived indicators of soil quality. The proceedings were published in a book entitled 'Defining Soil Quality for a Sustainable Environment' (Doran et al., 1994). 'Methods for Assessing Soil Quality' is a Soil Science Society of America publication that develops methodologies to assess soil quality for a range of soils and their uses (Doran and Jones, 1996). Finally, an international symposium 'Advances in Soil Quality for Land Management: Science, Practice, and Policy' was held on 17–19 April 1996 at The University of Ballarat, Vic., Australia. Its purpose was to improve understanding of functions, processes, attributes, and indicators of soil/land quality, and examine the application of the soil quality concept in land management and land use policy (MacEwan and Carter, 1996).

This worldwide activity is indicative of the extent to which the soil quality concept is being defined, researched, and applied in the agricultural community. As our collective concept of soil resources develops, some feel that incorporation of soil quality concepts in sustainable agriculture initiatives and national policy is inevitable. Objectives that have been suggested include (1) establishing soil–air–water quality parity so that soils receive the same attention and treatment as air and water resources; (2) emphasizing soil management and soil restoration as explicit objectives of farm and ranch conservation plans; (3) extending the focus beyond highly erodible lands to our most productive lands where we have the most to lose from soil degradation; and (4) using soil quality concepts to achieve environmental objectives as well as productivity increases (Cox, 1995).

Others in the forestry community frequently emphasize soils as simply 'part of the forest', as opposed to a separate resource in its own right, and have not generally invoked the concept of soil quality as a component of sustainable forestry (Burger and Kelting, 1998). However, the concept of site quality that includes climate, geologic, and topographic factors as well as soil, is well understood and widely used by foresters. Site quality is usually indexed with the height of the tree canopy at a given age (Carmean, 1975). By definition, soil quality (as part of site quality) is expressed only in terms of tree growth or biomass production, which is only one of several

important functions of soil (i.e. regulating water quality and quantity, carbon sequestration, remediation of human and animal wastes, regulating energy flow). Furthermore, the contribution of soil to site index is confounded by the interactions of other site factors, tree breeding, and silvicultural practices that manipulate soil function.

Soil is the foundation of the forest system. Forest management must be based on a holistic understanding of forest ecosystems, but in practice, silviculture is by definition reductionist. That is, silviculture is reduced to a set of practices that change the forest and soil to meet certain objectives. Measuring and monitoring parts of the forest that change in response to silviculture is necessary for the process of adaptive forest management for a sustainable forestry. The rationale for managing the forest soil resource, especially in plantation systems, is the same as that used for managing the soil resource in agroecosystems. That is, forest soils serve multiple production and environmental functions; forest soils are highly manipulated by forest practices; and maintaining and enhancing forest soil function is a crucial component of sustainable forest management.

3. Chemical properties as indicators of soil quality

It is often difficult to clearly separate soil functions into chemical, physical, and biological processes because of the dynamic, interactive nature of these processes. This interconnection is especially prominent between chemical and biological indicators of soil quality, such that some authors may consider the same characteristic (e.g. mineralizable N) in either category (Doran and Parkin, 1994; Reganold and Palmer, 1995; Powers et al., 1998). In our effort to rate relative performance of a soil in terms of critical functions (whatever the ecological, economical, environmental, or social function(s) we assign to it), we must resort to describing a set of identifiable attributes that such soil must possess in order to perform these functions, and then translate these attributes into first- or second-level measurable surrogates (i.e. soil properties or processes). Consequently, there is seldom a one-to-one relationship between function and indicator; more likely, a given function (e.g. sustain biological productivity) is supported by a number of soil attributes, while any given soil property or process may be relevant to several soil attributes and/or soil functions simultaneously (Harris et al., 1996; Burger and Kelting, 1999). A good example of the latter is soil organic matter, which plays a role in almost every soil function (e.g. Henderson, 1995; Harris et al., 1996; Nambiar, 1997). Also, many soil chemical properties directly influence microbiological processes (e.g. via nutrient and carbon supply), and these processes, together with soil physical–chemical processes determine (1) the capacity of soils to hold, supply, and cycle nutrients (including carbon), and (2) the movement and availability of water. Water relations, in turn, influence nutrient relations either directly, through exchange reactions, weathering, nutrient redistribution, or leaching export; or indirectly, by affecting biological activity and biologically-mediated nutrient release reactions. Soil chemical indicators are used mostly in the context of nutrient relations and may therefore also be referred to as 'indices of nutrient supply' (e.g. Powers et al., 1998).

A summary of the soil chemical properties cited in recent literature pertaining to soil quality in agricultural, grassland and forest soils is provided in Table 1. They can be divided into two categories: static (i.e. point-in time) and dynamic (i.e. process-related) soil parameters. They can further be grouped into parameters related to soil carbon status, soil acidity, and measures of nutrient availability. They express to some extent, the dichotomy between the need for simplicity and practicability, which tends to favor static parameters that are easily and routinely measured, but are hierarchically several levels removed from soil function, and the desire to more accurately represent the dynamic processes that underlie site productivity, which tend to involve more laborious and/or costly assays.

Although several soil chemical indicators are similar for agricultural and forest soils, there are nevertheless significant differences between agriculture and forestry as far as their use and assessment are concerned. As Powers et al. (1998) point out, many analytical soil testing methods frequently used in agriculture have proven marginally useful in predicting forest growth. The primary function of agricultural lands is to produce crops, while issues of biodiversity, environmental quality, or social value are often secondary to productivity. Resource inputs and outputs

Table 1
Soil chemical properties that have been proposed as indicators of nutrient supplying capacity of agricultural, rangeland and forest soils

Indicator	Reference	Comments
Soil organic carbon status		
Organic C	Larson and Pierce, 1994	Part of minimum dataset for agronomic soils; element of pedotranfer functions to calculate CEC, bulk density, and water retention.
Organic C	Doran and Parkin, 1994	Soil chemical characteristic to be included as basic indicator of soil quality.
Organic C	Reganold and Palmer, 1995	Used as a biological indicator of soil quality in different grass management systems.
Organic C	Manley et al., 1995	Change in organic C pool to a given soil depth used as indicator of soil quality change due to grazing.
Organic C	Harris et al., 1996	One of the chemical parameters of nutrient availability with specific scoring functions to be used for plant productivity, and/or environmental components of soil quality.
Organic C	Aune and Lal, 1997	Crop yield was positively correlated with soil organic carbon in tropical Oxisols, Ultisols, and Alfisols; above 1% soil organic carbon crop yield was less influenced by SOC.
Organic matter	Papendick, 1991 (cited in Karlen and Stott, 1994)	Suggested as first-order chemical indicator.
Organic matter	Soil Conservation Service (cited in Karlen and Stott, 1994)	Proposed as chemical indicator.
Organic matter	Romig et al., 1996	Part of a farmer-based qualitative assessment system (score-card) of chemical 'health' of agronomic soils.
Nutrient availability		
Fertility	SCS (cited in Karlen and Stott, 1994)	Proposed as chemical indicator.
Soil N, P, K	Romig et al., 1996	Part of a farmer-based qualitative assessment system (score-card) of chemical 'health' of agronomic soils.
Total N	Reganold and Palmer, 1995	Chemical soil property used to evaluate differences in soil quality between different grass management systems in New Zealand.
Organic N	Doran and Parkin, 1994	Soil chemical characteristic to be included as basic indicator of soil quality.
Organic N	Manley et al., 1995	Change in organic N pool to a given soil depth used as indicator of soil quality change due to grazing.
Mineral N	Doran and Parkin, 1994	Soil chemical characteristic to be included as basic indicator of soil quality.
Extractable NH_4	Harris et al., 1996	One of the chemical parameters of nutrient availability with specific scoring functions to be used for plant productivity, and/or environmental components of soil quality.
NO_3-N	Harris et al., 1996	One of the chemical parameters of nutrient availability with specific scoring functions to be used for plant productivity, and/or environmental components of soil quality.
Mineralizable N	Doran and Parkin, 1994	Soil biological characteristic to be included as basic indicator of soil quality.
Mineralizable N	Reganold and Palmer, 1995	Used as a biological indicator of soil quality in different grass management systems.
Mineralizable N	Powers et al., 1998	Proposed as a good index for the nutrient supplying capacity of soils.
Net N mineralization	Kelting et al., 1999	Used as indicator of nutrient sufficiency term in an additive SQI for southern pine.
Total P	Reganold and Palmer, 1995	Chemical soil property used to evaluate differences in soil quality between different grass management systems in New Zealand.
Mineral P	Doran and Parkin, 1994	Soil chemical characteristic to be included as basic indicator of soil quality.
Extractable P	Burger et al., 1994	Used in SQI of mine soil reclamation with pine; P sufficiency curve to account for P deficiencies due to high P fixation capacity of substrate.

Table 1 (*Continued*)

Indicator	Reference	Comments
Extractable P	Reganold and Palmer, 1995	Chemical soil property used to evaluate differences in soil quality between different grass management systems in New Zealand.
Bray P	Harris et al., 1996	One of the chemical parameters of nutrient availability with specific scoring functions to be used for plant productivity, and/or environmental components of soil quality.
Bray P	Aune and Lal, 1997	Positive (Mitscherlich-type) relationship between crop yield and this indicator of P availability in tropical Oxisols, Ultisols, and Alfisols. Critical P level defined as 7–10 mg kg^{-1}.
P sorption	Larson and Pierce, 1994	Calculated through pedotransfer function using oxalate extractable Fe and Al.
Extractable S	Reganold and Palmer, 1995	Chemical soil property used to evaluate differences in soil quality between different grass management systems in New Zealand.
CEC	Papendick, 1991 (cited in Karlen and Stott, 1994)	Suggested as first-order chemical indicator.
CEC	Larson and Pierce, 1994	Calculated through pedotransfer function using organic carbon and clay content.
CEC	USDA NRCS (cited in Karlen and Stott, 1994)	Proposed as chemical indicator.
CEC	Reganold and Palmer, 1995	Chemical soil property used to evaluate differences in soil quality between different grass management systems in New Zealand.
K	Doran and Parkin, 1994	Soil chemical characteristic to be included as basic indicator of soil quality.
Exchangeable K	Harris et al., 1996	One of the chemical parameters of nutrient availability with specific scoring functions to be used for plant productivity, and/or environmental components of soil quality.
Exchangeable K	Aune and Lal, 1997	Positive (Mitscherlich-type) relationship between crop yield and this indicator of K availability in tropical Oxisols, Ultisols, and Alfisols. Critical P level defined as 0.7–0.8 $mmol_c$ $kg^{-1.}$
Extractable K, Ca, Mg	Reganold and Palmer, 1995	Chemical soil property used to evaluate differences in soil quality between different grass management systems in New Zealand.
Soil acidity		
pH	Kiniry et al., 1983	First incarnation of PI for agricultural soils; nothing in the acid range, i.e. below pH 4.4.
pH	Papendick, 1991 (cited in Karlen and Stott, 1994)	Suggested as first-order chemical indicator.
pH	Gale et al., 1991	PI for white spruce; with lower (pH=3) and upper limit (pH=8) and optimum (pH=5–7) in the sufficiency curve for pH.
pH	Larson and Pierce, 1994	Part of minimum dataset for agronomic soils; used in pedotransfer functions for rooting depth and soil productivity attributes.
pH	Doran and Parkin, 1994	Soil chemical characteristic to be included as basic indicator of soil quality.
pH	Burger et al., 1994	Used in SQI of mine soil reclamation with pine using pH sufficiency curves per Gale et al. (1991); with optimum(pH=5–6) and linear declines in sufficiencies above and below this optimum.
PH	Reganold and Palmer, 1995	Chemical soil property used to evaluate differences in soil quality between different grass management systems in New Zealand.
PH	Harris et al., 1996	One of the chemical parameters of nutrient availability with specific scoring functions to be used for plant productivity, and/or environmental components of soil quality.
PH	Romig et al., 1996	Part of a farmer-based qualitative assessment system (score-card) of chemical 'health' of agronomic soils; suboptimal pH set below pH=6.
pH	Aune and Lal, 1997	Positive relationship between crop yield and this indicator of soil acidity in tropical Oxisols, Ultisols, and Alfisols. Not considered a sensitive indicator of soil acidity; critical limits around pH=5.

Al saturation	Aune and Lal, 1997	Considered better indicator of soil acidity in tropical Oxisols, Ultisols, and Alfisols. Inverse relationship between crop yield and Al saturation with critical limit vastly different among acid-tolerance classes.
Salinity		
Salinity	Papendick, 1991 (cited in Karlen and Stott, 1994)	Suggested as first-order chemical indicator.
EC	Kiniry et al., 1983	First incarnation of PI for agricultural soils; to account for salinity reducing productive capacity of soils.
EC	Larson and Pierce, 1994	Part of minimum dataset for agronomic soils; used in pedotransfer function for soil productivity attribute.
EC	Doran and Parkin, 1994	Soil chemical characteristic to be included as basic indicator of soil quality.
EC	Burger et al., 1994	Used in SQI of mine soil reclamation with pine to account for high soluble salt levels in substrate; EC sufficiency curves developed based on empirical growth data for white pine.

can be measured with relative accuracy measured over a short time period, and the intensive research and information from many subsequent crop rotations has generated good databases to correlate soil properties to crop performance and to provide reliable *deductive* ratings (Warkentin, 1995; Aune and Lal, 1997). Lack of such long-term correlative data, especially outside the arena of production forestry, makes assessments of many soil properties rather *inductive*, i.e. inclusion and evaluation of soil properties in soil quality assessment is largely based on inference regarding their role in critical forest soil functions (e.g. organic matter) rather than being based on concrete data, and critical threshold values are seldom available (as per Aune and Lal, 1997). Inductive ratings are also only as good as our understanding of the underlying mechanisms (Henderson et al., 1990). Furthermore, forest ecosystems encompass a large spectrum of structural complexity, management intensity, and societal function (Nambiar, 1997; Burger and Kelting, 1999), which does not lend itself to simple one-size-fits-all soil property ratings. In the context of plantations and short-rotation woody crops, which are functionally and structurally more similar to agronomic systems than to natural forest, relationships between soil chemical property (e.g. soil acidity, limiting nutrient availability) and soil function (sufficiency curve) and/or forest productivity (productivity index (PI), site index, forest soil quality) may be available for some target species (e.g. Gale et al., 1991; Burger et al., 1994; Kelting et al., 1999). In most cases, however, these relationships still need to be verified or established for other species and genera, and their predictive capacity may vary with time (i.e. age and structure of the stand) (Gale et al., 1991; Nambiar, 1997). Even less information is available that relates inherent chemical soil quality parameters to total net primary production of vegetation in natural and less-intensively managed forests.

Soil organic matter (SOM) (or soil organic carbon (SOC)) is commonly recognized as one of the key chemical parameters of soil quality, yet quantitative assessment of its contribution to soil quality is often lacking. Through its role in aggregate stability it influences soil porosity, and thus gas exchange reactions and water relations. It is a critical pool in the carbon cycle and a repository of nutrients, and through its influence on many fundamental biological and chemical processes it plays a pivotal role in nutrient release and availability (Johnson, 1985; Henderson et al., 1990; Henderson, 1995; Nambiar, 1997). Organic C is included in the minimum data set (MDS) of soil quality assessment proposed by Larson and Pierce (1994) for agricultural soils, where it is used in pedotransfer functions (Bouma, 1989) to calculate bulk density, water retention capacity, leaching potential, cation exchange capacity (CEC), rooting depth, and soil productivity.

One example of practical and user-friendly assessment of the role of SOM in soil quality is the Wisconsin Soil Health Scorecard, where SOM is one of the qualitative measures of soil health in a farmer-based scoring system, using specific thresholds to indicate healthy (SOM=4–6%), unhealthy (SOM<2 or >8%), or impaired (SOM=2–4 or 6–8%) soil conditions (Romig et al., 1996). Aune and Lal (1997) provide quantitative relationships between SOC and crop yield for tropical Oxisols, Ultisols, and Alfisols. They found that over the entire range of values, the relationship between SOC and productivity was generally weak (r^2=0.37); however, below a certain threshold value (SOC=1%), decreasing SOC had a strongly negative impact on productivity. The importance of SOC as a structural and functional component of soil productive capacity and in providing the critical linkage between management and productivity is widely recognized for forest soils also (Henderson et al., 1990; Henderson, 1995; Burger, 1997; Nambiar, 1997). However, no quantitative relationships (deductive or inductive) between this critical parameter and soil quality or forest productivity have yet been established (Nambiar, 1997). Defining qualitative criteria for SOC is further hampered by the fact that critical threshold values may be vastly different among soils orders (e.g. same percentage organic C translates into different soil productive capacity in Ultisols vs. Mollisols), climatic regions and land-use/species composition (Doran and Parkin, 1996; Burger, 1997; Burger and Kelting, 1999).

Many chemical reactions that influence nutrient availability (e.g. chemical form, adsorption, precipitation) are influenced by the soil chemical environment, and soil pH in particular. Thus, it is logical that pH should be included as a key chemical indicator, especially since it is routinely included in soil surveys and soil data bases and is easily and inexpensively mea-

sured when such data are not available. Because pH influences so many biological and chemical relationships simultaneously, soil pH in and of itself provides little direct information as to which soil process is critically affected by it and in turn critically affects the productive capacity of a soil. Rather, soil pH is simply a surrogate for this complex of potentially nutrient-limiting processes, must be evaluated against the sensitivity of the target vegetation, and may in some instances not be the best measure of soil acidity and soil quality degradation (Aune and Lal, 1997). Soil pH appears in nearly every type of soil quality assessment in agricultural soils: (1) as a constituent of the MDS to be used further in pedotransfer functions (Larson and Pierce, 1994); (2) in qualitative scoring systems (Romig et al., 1996), or (3) as a component of PI and sufficiency curves (Kiniry et al., 1983). Because the original pH sufficiency curves developed for agricultural soils in the temperate region did not extend below pH=4.5, modifications have been necessary to make pH-soil quality relationships consistent with tree responses under more acid forest soil conditions. These alterations have included defining an optimum pH range and describing the relative decline in tree productivity below and above that optimum in recognition of the fact that in forest soils higher pHs are not necessarily better and can indeed negatively affect nutrient availability (e.g. Gale et al., 1991; Burger et al., 1994).

It is interesting to note that in the typically more acid tropical Ultisols and Oxisols, Al saturation (inverse of percent base saturation) was found to be a much more sensitive and meaningful indicator of crop response than soil pH (Aune and Lal, 1997). This underscores the importance of the composition of the exchange complex (i.e. base saturation), rather than CEC itself, as an index of base cation availability in soils that are naturally more extensively leached (e.g. most forest soils and many tropical and subtropical agricultural soils), and are unlikely to have received regular amendments of limiting nutrients (bases). This essential difference in nutrient management between agricultural soils and forest soils underlies the inclusion of CEC as a critical attribute in the capacity of an agricultural soil to hold and supply nutrient (e.g. Larson and Pierce, 1994), while this measure is less meaningful and therefore often absent in the assessment of forest soil quality. The underlying assumption of 'good' management (i.e. alleviation of nutrient deficiencies through routine fertilizer amendments) also explains why Kiniry's original PI for agricultural soils did not include any reference to nutrient chemistry (Kiniry et al., 1983). Where particular exchangeable cations are suspected to limit productivity (mostly K in agricultural soils), exchangeable cation concentration may be included as a routine chemical measurement (see Table 1).

In acid forest soils, CEC per se is far less important to the soil's nutrient supplying power than percent base saturation (BS), that is the relative abundance of base nutrients on the exchange complex. Soil acidification is a natural pedogenic process in soils underlying forest ecosystems, as the result of organic acid formation associated with organic C turnover, cation uptake, and vertical leaching (Johnson et al., 1983; Johnson et al., 1988). Except in cases where liming has been used to alleviate nutrient imbalances due to extreme acidity (e.g. Derome, 1990; Matzner and Meiwes, 1990), base cations are not routinely added to managed forests. It is therefore base saturation that determines the influence of the exchange complex on soil solution chemistry and acidity (Reuss, 1983; Reuss and Johnson, 1986) and whether significant cation depletion (high and medium base saturation soils) or increased soil solution acidity and elevated Al concentrations leading to possible toxicity (low saturation soils), may be the expected consequence of accelerated anion-mediated leaching. The former (cation depletion) was the center of many discussions on the impacts of harvesting intensity on soil nutrient status (e.g. Bormann et al., 1974; Hornbeck and Kropelin, 1982; Johnson et al., 1982; Johnson and Todd, 1987; Mann et al., 1988), whereas the latter (solution acidification and potential Al toxicities) has received a lot of attention within the context of atmospheric acid deposition effects as a potential cause for forest decline (e.g. Godbold et al., 1988; Shortle and Smith, 1988; Schulze, 1989).

Molar Ca/Al ratios in solution have been proposed as an ecological indicator of potential nutritional stress because of suspected detrimental effects of elevated Al levels on root proliferation and on base cation uptake and nutrition (primarily Ca and also, to some extent, Mg). Based on a comprehensive review of the available experimental data regarding tree and seedling responses to Al stress, Cronan and Grigal (1995)

concluded that threshold conditions identifying forest ecosystems at risk are made up of four successive measurement endpoints, two of which are related to soil chemistry (%BS<15% of effective CEC, soil solution Ca/Al molar ratio<1.0); and two of which are related to plant tissue concentrations (fine root tissue Ca/Al molar ratio<0.2, foliage Ca/Al molar ratio<12.5). Soil solution Al levels and/or Ca/Al ratios are not currently included as chemical indicators of soil quality, possibly because of the limited scope of this potential problem and the difficulty and cost of Al speciation.

The remaining chemical indicators in Tables 1 and 2 primarily reflect specific abiotic (geology and soil type, climate) and biotic (vegetation type, species) conditions that differentiate nutritional problems among locations. Which chemical indicator is identified as critical and what analysis technique is used seems to vary considerably among the sources in the literature, although they most frequently involve some form of nitrogen (N) or phosphorus (P) assay. Adequate background information on chemical analysis methods is critical when data are to be compared among studies or threshold values are to be applied elsewhere. The synthesis effort by Aune and Lal (1997) illustrates this point, in that several different P extraction techniques first had to be normalized to a single uniform assay (in this case Bray-1 extraction), before P availability-crop yield curves could be constructed for highly adsorptive tropical forest soils. A related issue is the units in which soil chemical parameters are expressed. Doran and Parkin (1996) make a strong argument that indicators should be expressed volumetrically (i.e. as $kg\,ha^{-1}$ per unit topsoil or to a given solum depth) rather than gravimetrically (e.g. as $g\,kg^{-1}$ dry soil) to also incorporate differences in bulk density that may have been induced by management practices. Reganold and Palmer (1995) illustrated the divergent outcomes regarding the effect of various grassland management regimes on soil quality, depending on whether gravimetric or volumetric measurements were used.

Measures expressing N availability and N supplying capacity of soils are even more divergent and range from simple extractions (static measure) to aerobic or anaerobic N mineralization assays (Tables 1 and 2). Powers et al. (1998) strongly advocate inclusion of mineralizable N by anaerobic laboratory incubation as a basic nutrient supply index. They point out that the test is practical, can be performed routinely on a large number of soil samples, and is less prone to disturbance-induced anomalous observations that often plague field sampling (e.g. Van Miegroet, 1995). Furthermore, it appears to be closely related to biological soil function (microbial decomposition of soil organic matter) and is highly correlated with a number of other measures of nutrient release (e.g. soil C:N; total organic C and N, P mineralization, site index, foliar N). It should be recognized, however, that the predictive capacity of this indicator may deteriorate in systems where N is not the main growth-limiting factor.

Electrical conductivity as a measure of ion concentration and the potentially negative effect of salinity on the osmotic potential (i.e. water relations) and nutrient imbalances (Na dominance in sodic soils) is primarily used in agricultural soils. Its application to forest soils is usually limited to very specific circumstances (e.g. reclamation of mine soils) where highly concentrated soil solutions are known or suspected to inhibit forest growth and productivity (e.g. Burger et al., 1994).

Many of the soil chemical indicators, and especially those used in soil quality indices and PI relationships, base the level of soil adequacy on a belowground response, particularly root proliferation and distribution. Although it is generally correct to assume that serious limitations in rooting volume (either because of shallow soils, a physical impediment, or toxic soil conditions) are likely to restrict water and nutrient uptake, and thus overall plant productivity, it does not necessarily imply a direct positive correlation between root proliferation and productivity. First, as demonstrated by Hoyle (1971), negative root responses to ambient chemistry need not translate to similar aboveground growth responses. Furthermore, research by Keyes and Grier (1981) and Friend et al. (1990) indicate that root proliferation is stimulated by low overall site fertility and localized nutrient enrichments, reflecting the need for greater soil exploration in low fertility soils and the positive stimulus when high nutrient pockets are encountered. The study by Keyes and Grier (1981) further underscores our bias towards aboveground biomass (wood) production in soil quality assessment. Indeed, significantly higher fine root proliferation occurred in low-fertility sites at the expense of aboveground C allocation (i.e. stem

Table 2
Summary of soil chemical indicators cited in the literature and their use in agricultural, rangeland and forest soil quality assessment

Reference	Comments on the proposed chemical indicators:
	Agriculture
Kiniry et al., 1983	First incarnation of a multiplicative PI formula for agronomic soils which includes pH and EC as the only chemical soil indicators.
Papendick, 1991 (cited in Karlen and Stott, 1994)	Suggests as first-order soil chemical indicators: pH, salinity, CEC, organic matter, and site-specific toxicities.
SCS (cited in Karlen and Stott, 1994)	CEC, 'fertility', and organic matter proposed as chemical indicators; no further information on how to be used.
Doran and Parkin, 1994	Suggests the following soil chemical characteristics to be included as basic indicators of soil quality: Total organic C and N, pH, EC, extractable N, P, and K. Potentially mineralizable N (anaerobic incubation) is included as a biological soil characteristic in this minimum dataset.
Larson and Pierce, 1994	pH, EC and organic C are the chemical characteristics measured directly and used in the pedotransfer functions to calculate bulk density; water retention, soil productivity, root depth; CEC derived indirectly through pedotransfer functions using organic C and clay content of the soil; P sorption capacity calculated through pedotransfer function using oxalate extractable Fe and Al.
Harris et al., 1996	Description of qualitative assessment as per Romig et al. (1996); quantitative assessment includes Bray P, exchangeable K, pH, Organic C, extractable NH_4, and NO_3-N as parameters of nutrient availability and their respective scoring functions to be used for plant productivity and environmental quality functions of agricultural soils.
Romig et al., 1996	In the development of a qualitative, farmer-based score-card for soil quality, soil chemical (analytical) parameters assessed are: organic matter; pH; soil N, P, and K levels, and micronutrient deficiencies. Soil properties are individually scored as healthy, imbalanced or unhealthy. Nutrient deficiencies are also assessed indirectly based on visual plant symptoms and plant health rating.
Aune and Lal, 1997	Established functional relationships between agricultural crop yield in tropical Oxisols, Ultisols, and Alfisols and the following soil chemical parameter: soil organic carbon, available (Bray-extractable) P, exchangeable K, and soil acidity (expressed as soil pH and Al saturation). Defined critical limits (80% of maximum yield) for each of the parameters.
	Rangeland/grassland soils
Manley et al., 1995	Soil organic C and N content used as indicators of soil quality change due to grazing; emphasizes the importance of expressing results as pool rather than concentration to account for changes in bulk density due to management.
Reganold and Palmer, 1995	Use CEC; soil pH; total N and P; and extractable P, S, Ca, Mg, and K as chemical soil properties to evaluate differences in soil quality between different grass management systems; Organic C and mineralizable N is used as a biological indicator.
	Forest soils
Henderson et al., 1990	Suggest that the PI should also contain some measure of nutrient status, with the exact chemical parameter depending on the external stressor or anthropogenic impact. Possible critical soil chemical indicators may be organic matter, available N, soil P, and soil acidity (pH, base depletion, Al toxicity).
Gale et al., 1991	pH is only chemical characteristic used in the PI for white spruce, but indicates that nutrient sufficiency curves (e.g. P) need to be determined.
Burger et al., 1994	In the reclamation of mined lands, a multiplicative soil quality model for white pine was used based on sufficiency relationships for: $NaHCO_3$-extractable P (to account for high P-fixation capacity), EC (to account for high salinity levels), and pH (as per Gale et al. (1991) with optimum range pH=5–6; and upper and lower sufficiencies).

Table 2 (*Continued*)

Reference	Comments on the proposed chemical indicators:
Burger, 1997	Proposes soil organic matter as structural component and organic matter decomposition and N mineralization as functional components of soil productivity
Burger and Kelting, 1999	Soil organic matter as soil indicator may measure several soil functions simultaneously.
Kelting et al., 1999	N mineralization is used as indicator of sufficiency for holding, supplying and cycling nutrients in and additive SQI for southern pine.
Powers et al., 1998	Potentially mineralizable N (anaerobic incubations) proposed as a good indicator of soil nutrient supply based on positive correlation with site index and foliar N, with total organic C and N, and its use as an index for microbial biomass (i.e. biological function).

growth) compared to the more fertile site; however, when total net primary productivity was compared between sites, differences were far less pronounced. Finally, soil chemistry-based assessment implies that nutrient uptake from the mineral soil is the first and foremost regulator of growth. While this is generally true, it does, however, neglect the role of nutrient cycling as a means of meeting plant nutrient requirements, either through internal retranslocation or through the external cycle of litterfall and organic matter decomposition. The relative role of soil fertility in growth thus varies with time and stand development (Miller, 1981; Nambiar, 1997). While young seedlings or plants established on bare mineral soils are dependent on the mineral soil for their nutrient supply, gradual buildup of aboveground biomass and a detritus layer represent another important repository of nutrients that may be utilized by the plant. This is sometimes reflected in an upward shift in fine root production towards greater exploitation of the forest floor as forests mature (Grier et al., 1981). This decreasing dependency on the mineral soil with stand age may also explain why the PI developed by Gale et al. (1991) performed better in younger white spruce plantations than in older stands.

Although we mechanistically understand many relationships that underlie the soil chemical–nutrient supplying aspect of soil quality, we are still faced with a number of challenges, including identification of critical relationships that affect forest productivity at any given site and establishment of baselines and reference conditions against which to judge the relative level at which a given soil is functioning. There are also issues of scale (e.g. ability of point samples to reflect soil conditions in the larger landscape unit) and temporal variability (e.g. ability of sampling at given point in time to represent growing season conditions). Spatial heterogeneity, either natural or management induced, can cause problems establishing clear linkages between measured soil characteristics and overall stand performance (Nambiar, 1997; Powers et al., 1998). Seasonal variations in biologically driven parameters are somewhat expected and often predictable, but several studies have also demonstrated significant seasonal variations in chemical characteristics that are generally considered more stable (e.g. CEC and exchangeable bases) (Haines and Cleveland, 1981; Peterson and Rolfe, 1982; Johnson et al., 1988). Finally, our soil quality indices have not even begun to assess the critical role played by the forest floor and its dynamics on storage and release of nutrients.

4. Physical properties as indicators of soil quality

Productive forest soils have attributes that (1) promote root growth; (2) accept, hold, and supply water; (3) hold, supply, and cycle mineral nutrients; (4) promote optimum gas exchange; (5) promote biological activity; and (6) accept, hold, and release carbon (Burger and Kelting, 1999). All of these attributes are, in part, a function of soil physical properties and processes. Some of these soil physical properties are static in time, and some are dynamic over varying time scales. Some are resistant to change by forest management practices, while some are changed easily in positive and negative ways. If changed, some properties and processes will recover at varying rates while others are irreversible. All of these factors will determine the extent to which each soil property or process is useful for measuring soil quality and monitoring the maintenance of soil quality through time.

Table 3 is a list of physical indicators that has been proposed by various researchers. Basic soil quality indicators like soil texture and depth are useful for comparing soil quality among soil types, and within a soil type before and after some management practice has been imposed. Soil texture is the most fundamental qualitative soil physical property controlling water, nutrient, and oxygen exchange, retention, and uptake. It is a master soil property that influences most other properties and processes. Soil depth is a quantitative property influencing the amount of resources available to plants per unit area. The relative thickness of soil horizons could also be a sensitive indicator of several soil functions.

Soil indicators sensitive to variations in management are needed to compare the effects of a management practice on soil through time. If they are insensitive to changes in management, they are of little use in monitoring soil quality change (Doran and Parkin, 1994). Soil texture and depth are soil properties that would change little through time for a given soil, and so they would not be very useful for assessing management effects. Soil bulk density varies among soils of different textures, structures, and organic

Table 3
Physical soil quality indicators recommended or used by soil researchers

Indicators of soil quality	Role or contribution to soil quality	Type or units of measure	Recommended or used by
Static indicators			
Soil texture	Retention and transport of water and nutrients	%sand, silt, clay	Doran and Parkin, 1994
Soil depth, topsoil depth	Total nutrient, water, oxygen availability	Thickness (cm)	Larson and Pierce, 1991; Arshad and Coen, 1992; Doran and Parkin, 1994; Gomez et al., 1996
Soil bulk density	Root growth, rate of water movement, soil volume expression	Core sampling (g cm^{-3})	Larson and Pierce, 1991; Arshad and Coen, 1992; Doran and Parkin, 1994; Kay and Grant, 1996
Available water holding capacity	Plant available water, erosivity	Water (cm), 33>1500 kPa	Larson and Pierce, 1991; Arshad and Coen, 1992; Doran and Parkin, 1994; Kay and Grant, 1996
Soil roughness	Erosivity, soil tilth	Tilled/flat ratio	Larson and Pierce, 1991
Saturated hydraulic conductivity	Water and air balance, hydrology regulation	Water flow in soil column (cm^3 s^{-1})	Larson and Pierce, 1991; Arshad and Coen, 1992
Soil loss	Total soil, water, nutrients for plant use	Soil loss (cm)	Harris et al., 1996; USDA, 1991
Soil strength	Root growth	Resistance to penetration (Mpa)	Powers et al., 1998; Burger and Kelting, 1998
Porosity	Water/air balance, water retention, root growth	%soil volume	Powers et al., 1998
Aggregate stability and size distribution	Root growth, air/water balance	Wet-sieving method	Arshad and Coen, 1992; Kay and Grant, 1996
Soil tilth	Root growth	Index (Singh et al., 1993)	Papendick, 1991; Burger and Kelting, 1998
Dynamic indicators			
Least limiting water range	Water/air balance, root growth	Water retention curves, penetration resistance	Arshad and Coen, 1992; da Silva et al., 1994; Kay and Grant, 1996; Burger and Kelting, 1998
Trafficability	Ability to operate	Model (Wosten and Bouma, 1985)	Wagenet and Hutson, 1997
Leaching potential	Transport, transform, attenuate applied chemicals	Model (Petach et al., 1991)	Wagenet and Hutson, 1997
Erosion potential	Available soil, water, nutrient, root growth, environmental concern	WEPP (Nearing et al., 1989) SEP (Timlin et al., 1986)	Wagenet and Hutson, 1997

matter content, but within a given soil type, it can be used to monitor degree of soil compaction and puddling. Changes in soil bulk density affect a host of other properties and processes that influence water and oxygen supply. However, a measure of soil strength using a cone penetrometer may be the best way to index the influence of soil density on root proliferation and growth (Powers et al., 1998). Relationships between root growth and soil strength are well established (Taylor et al., 1966; Sands et al., 1979). Bulk density is, nonetheless, needed in a minimum data set of soil quality indicators to convert mass estimates of soil components to volume estimates. Soils are commonly sampled as volumes to specific depths, but they are analyzed on a gravimetric basis. Soil quality interpretations should be made on a volumetric basis using bulk density as a conversion factor (Reganold and Palmer, 1995).

Soil loss due to wind or water erosion is perhaps the most widespread degrading soil process. However, it is of minor concern in forestry where the soil surface usually remains covered with vegetation or leaf litter. Plantation forests become vulnerable if harrowed or bedded during stand conversion, but soil is exposed for only short periods over the length of the crop cycle (Dissmeyer and Bennett, 1990). For this reason, 'soil roughness', proposed as an indicator of soil quality for agriculture (Larson and Pierce, 1991), would be of limited value in forestry.

Indicators of water infiltration, retention, availability, drainage, and water/air balance are universally important for monitoring all soil functions. Available water holding capacity and saturated hydraulic conductivity are the two most frequently found in minimum data sets of soil quality indicators. Available water holding capacity measures the relative capacity of a soil to supply water, and saturated hydraulic conductivity is an indicator of the rate of soil drainage that can be used to judge water/air balance in soils. Soil porosity is redundant in some respects, but a separate measure of the ratio of non-capillary and capillary porosity may be a sensitive indicator of management-induced physical change that leads to water and air imbalances.

Soil structure refers to the size and shape of soil aggregates held together by organic matter and other chemical precipitates. Like soil texture, it influences a myriad of soil physical, chemical and biological properties. Aggregate stability describes the ability of the soil to retain its arrangement of solid and void space when exposed to different stresses (Kay, 1990). Stability characteristics are generally specific for a structural form and the type of stress being applied. A measure of aggregate stability could serve as a surrogate for soil structure, which is critical for development of root systems (Kay and Grant, 1996).

Soil quality indicators may be simple state variables as just described, or they can be more complex con structs of several soil variables such as 'soil tilth index', which includes measures of bulk density, strength, aggregate uniformity, soil organic matter, and plasticity index (Singh et al., 1990). Furthermore, they may include a time or rate dimension which makes them dynamic, These indicators are termed pedotransfer functions (Bouma, 1989) and are generally used to describe functions in which routinely-measured properties are used to predict other properties that are not measured (Kay and Grant, 1996).

The least limiting water range (LLWR) is defined by water contents at which aeration, water potential and mechanical impedance reach values that limit plant growth (Letey, 1985). The lower limit is defined by the water content at which soil resistance to penetration becomes limiting, and the upper limit is defined by the water content at which aeration becomes limiting. As bulk density increases, the range between the lower and upper limits decreases. da Silva and Kay (1996) have shown that growth of corn plants decreases linearly with increasing frequency at which soil water content falls outside the LLWR. In effect, this is an indicator of the potential for roots to grow in a given soil volume through the growing season as a function of soil type, mechanical impedance, water content, bulk density and soil porosity. This concept may have potential for forestry, but relatively high levels of horizontal and vertical variability in many forest soils may limit its practicality.

Several other examples of dynamic soil quality indicators are trafficability (Wosten and Bouma, 1985), leaching potential (Petach et al., 1991), and erosion potential (Timlin et al., 1986). Trafficability refers to the number of workable days in the year; leaching potential is an index of a soil's ability to retain nutrients; and erosion potential is a well-understood estimate of soil loss. These indicators are advocated by Wagenet and Hutson (1997) who argue for

the inclusion of simple dynamic models in soil quality models.

As these indicators suggest, a soil quality model can be built from a minimum data set that includes simple soil properties and more complex dynamic sub-models of processes. The complexity of a soil quality model will depend on its use as a monitoring or forecasting tool, and the ability of the user to collect the input data and interpret the model.

5. Development of a soil quality model

Forests are managed at various intensities; therefore, the extent to which forest soils are surveyed for productive potential, and the degree to which they are disturbed and managed, will vary. Burger (1997) depicted a forest management gradient ranging from managed natural forests on one end of the spectrum to short-rotation bioenergy crops on the other. In the extensively-managed forest, monitoring natural levels of soil productivity may be the only use of a soil quality model, while forecasting the effects of tillage, fertilization, and logging disturbance may be the goal of a soil quality model developed for biomass plantations. The model must be management-specific because the cultural input varies greatly among these systems. Soil quality indicators would also need to be soil type-specific due to the inherent differences among soils (Burger, 1997). For example, a soil quality model for monitoring a young, droughty Entisol derived from marine sand dunes would not be the same as one developed for monitoring soil quality on older, poorly-drained Alfisols derived from marine lacustrine deposits (Burger and Kelting, 1998, 1999).

The first step in developing a soil quality model is to qualitatively describe the attributes of a high-quality soil, where soil quality is defined based on its capacity to perform a certain function. If the soil's function is to promote forest productivity, it should (1) allow unimpeded root growth; (2) accept, hold, and regulate water and air to optimize delivery to plants; (3) store, supply, and cycle nutrients at levels and rates that are synchronized with demand; (4) promote optimum gas exchange; and (5) facilitate biological activity to maintain necessary symbiotic relationships and promote nutrient cycling (Burger and Kelting, 1998, 1999). The second step is to substitute quantitative measurements for the qualitative soil attributes, and combine them in a model that provides a relative index of soil quality.

An early example of a soil quality model is the 'Storie Index' (Storie, 1933) that creates a soil-rating chart based on measured values of four or five soil properties. Each soil property is scaled from 0 to 1 based on its suitability for agricultural crop production. The scales, or ratings, for the four factors are then multiplied to create a relative soil rating. Kiniry et al. (1983) used the same approach to develop a PI for agricultural soils in Missouri. The soil factors in the model were available water capacity, bulk density, aeration, pH, and electrical conductivity. The sufficiency, or scaling, of each soil factor was based on an ideal root distribution in the soil volume, and the PI was the sum of the ratings of each soil layer weighted by its relative contribution to the total soil volume for root growth. Pierce et al. (1983) used the same approach for determining the effects of soil erosion on soil productivity. The model was validated with corn yield data in Minnesota. It was an important application because it was used to determine management effects on soil productivity. Gale et al. (1991) modified and tested the PI model for forest soils in Minnesota. Important modifications for their use were calculating the geometric mean rather than the product for each horizon, and including site factors such as slope along with soil factors. Their model successfully accounted for 55–85% of aboveground biomass in white spruce (*Picea glauca* Voss.), aspen (*Populus tremuloides* Michx.), and jack pine (*Pinus banksiana* Lamb.) stands.

Proposed soil quality models are similar in concept and approach except that they include soil properties representing soil functions in addition to soil productivity (e.g. regulation of hydrologic cycle, bioremediation of wastes, carbon sequestration). Karlen and Stott (1994) suggested a simple additive model:

$$Q = q_1(\mathrm{wt}) + \cdots q_k(\mathrm{wt}) \quad (1)$$

where the q_k variables represent sufficiency values for different soil quality attributes, and wt is the relative weight applied to each attribute. Relative weights represent the importance of each attribute in determining soil quality on a given site and provide inherent flexibility for the model.

Burger et al. (1994) used a soil quality model in a study that examined changes in productivity due to mined land reclamation. Their research identified a minimum set of indicator variables that included bulk density, pH, P fixation, and excess soluble salts. Their soil quality predictions were highly correlated ($p<0.02$) with growth measurements of 10-year-old white pine (*Pinus strobus* L.) located on similar sites. Using the average productivity of natural white pine stands growing in the same region as a productivity standard, they developed a soil quality standard using the model predictions.

Soil properties from three replications of a chornosequence of bottomland hardwood forest restoration sites in the Lower Mississippi Alluvial Valley were used in an additive soil quality model to assess restoration of soil properties and functions (Schoenholtz, unpublished data). Three undisturbed forests served as benchmarks to develop sufficiency ratings for bulk density, total porosity, macro-porosity, saturated hydraulic conductivity, total C, total N, and pH. Soil properties at depths to 25 cm were compared to the reference forests (which had sufficiency ratings of 1.0 on a scale of 0–1 for each soil property). Weighting factors of 0.4, 0.3, and 0.3 were used for soil depths of 0–5, 5–13, and 13–25 cm, respectively, and all soil properties at each depth were weighted equally. Soil quality indices were 0.69, 0.78, 0.82, and 1.00 for currently-farmed soybean fields, 3-year-old Nuttall oak (*Quercus nuttallii* Palmer) plantings on former soybean fields, 5–18-year-old Nuttall oak plantings on former soybean fields, and 68–75-year-old bottomland hardwood forests, respectively. The aim of this approach is to develop bottomland hardwood forest soil restoration assessments that will lead to the ability to project recovery rates of ecosystem functions in these systems.

In another application in forestry, Kelting et al. (1999) report a study wherein they applied soil quality concepts to identify the effects of intensive forest management practices on soil productivity. Their approach includes steps that establish the forest and site type; identify soil functions, attributes, and indicators; combine indicator responses in a soil quality model; establish baseline conditions for comparing soil change; validate relationships between indicators and productivity; and implement a sampling scheme to measure indicators, analyze trends, and interpret change for adapting forest practices to maximize their effectiveness. They found that a soil quality index using water table depth, net N mineralized, and aeration depth as indicator variables explained 60% of the variation in first-year loblolly pine (*Pinus taeda* L.) volume.

The US Forest Service uses regional assessments that incorporate the concept of soil quality standard thresholds of disturbance associated with harvesting on national forests (Powers et al., 1998). The US Forest Service also established in 1989 the North American long-term soil productivity study (LTSP) which utilizes a network of >60 study sites in North America to provide data for evaluation of soil quality thresholds (Powers and Avers, 1995). The LTSP has standardized full factorial combinations of soil-porosity and site organic-matter manipulations to (1) determine how site carrying capacity for net primary productivity is affected by pulse changes in soil porosity and site organic matter; (2) develop a fundamental understanding of the controlling processes; (3) develop practical soil-based indicators for monitoring changes in site carrying capacity for net primary productivity; and (4) develop generalized estimation models for site carrying capacity based on soil and climatic variables (Powers et al., 1998).

The rationale for developing soil quality models has mostly centered on retrospective monitoring of soil quality change due to management practices applied in agriculture and forestry. However, Wagenet and Hutson (1997) argued that prospective prediction of future soil quality based on combined models of dynamic soil processes is needed if soil quality is to be maintained or enhanced. They advocate soil quality models that use simulation modeling combined with direct measurement to indicate future soil conditions that may result from the accumulative effects of management practices over time. Including dynamic soil indicators such as least-limiting water range, trafficability, leaching potential, and erosion potential in the minimum data set of soil indicators (Table 3) is a way of building in forward-looking predictions of soil quality change.

Adding complexity to soil quality models to improve their accuracy and forecasting ability must be balanced with the ability of practitioners to apply them to their management systems. To help the practitioner meet his or her management goals, the best

model would be conceptually simple, cheap to develop, and easy to apply. Soil quality assessment is a process of applying existing knowledge to achieve land management aims, namely sustainable forests and agro-ecosystems. This process should not be confused with the goals of forest science, a process of developing new knowledge for a deeper understanding of nature.

6. Use of nutrient cycling models to predict long-term sustainability

Expressing site quality and site productivity solely in terms of inherent physical, chemical, and biological terms, as is often the case in agronomic context, may be inappropriate for forest ecosystems. It ignores the many soil–plant interactions and the role of nutrient cycling in forest ecosystems. Indeed, crop growth is almost entirely dependent on the nutrient-supplying power of mineral soil supplemented by fertilizer amendments, and the nutrient flux largely occurs from soil to plant. The longevity of forests however, results in gradual shifts in nutrient pools and nutrient fluxes as the stand develops, which results in greater accumulation of nutrients in living biomass and detrital material, the return of nutrients from the plant to the mineral soil, and the decreasing dependence of trees on the mineral soil to meet annual requirements in favor of internal retranslocation and nutrient release through decomposition of the forest floor (Cole and Rapp, 1981; Miller, 1981; Johnson, 1985). Actual distribution and cycling patterns vary with nutrient, vegetation type and tree species (e.g. Cole and Rapp, 1981). Nutrient demands by trees are also dynamic and change with time: generally, nutrient requirements and soil uptake by plantation trees are greatest prior to canopy closure and significantly decline in the later stages of stand development when nutrient uptake is primarily driven by wood increment. The shift in nutrient distribution away from the mineral soil, and the greater reliance on organic matter decomposition for external nutrient supply to plants can be reflected in an upward shift in fine root distribution with stand age (e.g. Grier et al., 1981). It may also account for late-rotation nutrient deficiency in some conifer forests due to excessive forest floor accumulation when low nutrient status causes a positive feedback in that nutrient-poor litter is produced due to higher nutrient-use efficiency and retranslocation, which, in turn, lowers forest floor decomposition rates and further accentuates nutrient limitations (Miller, 1981; Johnson, 1985).

How do management practices affect these nutrient cycling patterns and how can we predict future changes in site productivity that result? Because specific long-term empirical data sets are missing, the use of computer simulation models is a logical step to bridge that gap and provide field practitioners or soil scientists with the relevant answers. Models are necessarily a simplified or conceptualized representation of reality and therefore inherently incomplete and/or inaccurate. The choice then between simple and more complex model formulations is driven by the intended goal for their development, and if models are applied outside this framework, outcomes should be interpreted with caution (Yarie, 1990; Boote et al., 1996; Monteith, 1996; Passioura, 1996; Sinclair and Seligman, 1996; Johnson, 1997). Empirical relationships, for example, are very suitable for predictive purposes. They are often based on the synthesis of large datasets. However, they may miss important processes that determine ecosystem response and, if driver variables that are not explicitly included in the model change, then the projected relationship may become invalid (see discussion in Binkley, 1986; Kimmins, 1989).

Process-oriented nutrient cycling models tend to focus more on critical processes that are hypothesized to govern ecosystem response, and largely reflect the current state of knowledge (Yarie, 1990). However, the complexity of forest nutrient cycling and its controlling factors make it very difficult to accurately model, especially if the objective is to predict long-term effects of management practices or project future forest productivity. Here again, one is faced with the dilemma between using simple models that are easy to use and understand (but may omit potentially crucial variables), and striving for more complex models that: (1) offer greater opportunity to simulate the dynamics of real systems; (2) have more intensive data needs for parameterization (which are seldom met and therefore often replaced with user- or expert-defined ‘guesstimates’); (3) are more difficult to understand; (4) are frequently impossible to validate; (5) tend to be unwieldy to the non-expert user; and (6) may be inappropriate for prediction of certain ecosys-

tem responses (Binkley, 1986; Kimmins, 1989; Boote et al., 1996; Monteith, 1996; Passioura, 1996; Sinclair and Seligman, 1996; Johnson, 1997). They can, however, greatly increase our understanding of the underlying processes, especially when they fail to reflect patterns observed in the field, implying that either the conceptual model construct or its parameter definition is flawed and needs to be revised (Johnson, 1997; Kimmins, personal communication).

A synopsis and critical discussion of various existing nutrient models (FORCYTE, FORNUTS, FORTNITE, LINKAGES, NITCOMP, NuCM, SOILN-FORESTSR) is provided by Johnson and Dale (1986), Binkley (1986), Yarie (1990) and Johnson (1997). FORCYTE is considered a hybrid between an empirical and a process model in that it utilizes historical data in the form of growth and yield tables and combines this with a representation of management effects on the N cycle. Most of the models (with the exception of NuCM) focus primarily on the role of N dynamics on stand growth over several rotations, but differ significantly in the formulation of the belowground (soil) control of N supply and how it is affected by various management scenarios. The NuCM model, on the other hand, depicts the biogeochemistry of all major macronutrients with a strong emphasis on soil solution chemistry. It allows evaluation of the effects of harvesting and forest conversion on base cation status also (and potential future productive capacity of the site) as a balance between cation losses via biomass removal and leaching and replenishment through mineral weathering (Johnson et al., 1995). The above model simulation for the conversion from loblolly pine (*P. taeda*) to mixed oak in the southeastern US also proved useful in demonstrating the limitations of field measured data in determining long-term responses. Nutrient budget analysis based on a few years-worth of nutrient cycling data (in this case leaching) extrapolated to an entire rotation can result in misleading conclusions, as leaching rates are known to change with time. As with all long-term model simulations, results can never be truly validated for lack of appropriate multi-rotational field trials. Nutrient cycling models should therefore be used to determine future directions for research and where or how existing conceptual constructs of ecosystem function and indices of soil quality should be revised and/or refined. Furthermore, nutrient cycling models will have limited use for evaluation of forest soil quality unless management effects on soil physical properties are incorporated. Supplies of O_2 and water, and degree to which the soil matrix restricts root proliferation are potentially limiting factors influencing nutrient cycling and productivity (da Silva et al., 1994).

7. Summary and conclusions

Maintenance or enhancement of soil quality is a common criterion when assessing long-term sustainability of forest ecosystems. However, the task of establishing a specific criterion for soil quality is challenging because functions and subsequent values provided by forest ecosystems are variable and rely on the interplay of soil physical, chemical, and biological properties and processes which often differ significantly across spatial and temporal scales. Choice of a standard set of specific soil properties as indicators of soil quality can be complex and may vary among forest systems. Despite these challenges, development of forest soil quality indices is progressing and minimum data sets have been proposed (e.g. Burger, 1997; Powers et al., 1998) which recognize soil properties or processes that are likely to be sensitive to management perturbations and are related to forest productivity and health. These lists commonly include properties such as organic matter content, nutrient supplying capacity, acidity, bulk density, porosity, and available water holding capacity. Any of these soil properties may be relevant to several soil functions simultaneously and will have varying levels of influence which can be weighted accordingly in soil quality index models.

Indices of soil quality which incorporate chemical and physical soil properties will be most readily adopted if they are: (1) sensitive to management-induced changes; (2) easily measured; (3) relevant across sites or over time; (4) inexpensive; (5) closely linked to measurement of desired values such as productivity or biodiversity; and (6) adaptable for specific ecosystems. Indices of soil quality which meet these criteria must be developed based on our current knowledge and must be adaptable, as our understanding of the vital functions of forest soils evolves. Our challenge is to expand our knowledge of forest soil properties so that we can predict the dynamic behavior of soil processes and the impact of management

practices on those processes. Ability to meet this challenge will play a key role in determining the sustainability of forest management activities.

Public recognition of the importance of soil quality to ecosystem function and value is unprecedented. Forest soil scientists have a unique opportunity to make a vital contribution to sustainable forest ecosystem initiatives and the criteria by which they are judged.

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