Soil quality assessment in domesticated forests – a southern pine example

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Abstract

Maintenance and enhancement of soil productivity is central to the long-term success of intensive forest management. A simple technique is required for monitoring the effects of different management practices on soils as an aid in developing codes of practice that foster maintenance and enhancement of soil productivity. The objective of our work was to determine if management impacts on soil productivity could be assessed using the soil-quality concepts developed in agriculture. A soil-quality index (SQI) model, that measures the effects of management practices on five key growth-determining attributes of forest soils, namely (1) promote root growth, (2) store, supply and cycle nutrients, (3) accept, hold, and supply water, (4) promote gas exchange, and (5) promote biological activity, was developed and tested as part of a controlled study in intensively-managed pine plantations on the Lower Coastal Plain of South Carolina. Three 20-ha, 20-year-old loblolly pine plantations were harvested under wet and dry conditions to create a broad gradient in soil disturbance. Within each harvested plantation, a subset of 3-ha plots were site prepared by either bedding or mole-plowing plus bedding, then all sites were established as third-rotation pine plantations. Field data were collected spatially for soil bulk density, net N mineralization, water table depth, soil aeration, and soil moisture. Literature-based sufficiency values were determined for each property and substituted into the SQI model as surrogate indicators for the five key attributes, thus obtaining spatial SQI predictions within each harvesting and site preparation treatment. Our study results demonstrate how SQI monitoring could be used to identify the effects of management practices on soil productivity, which should aid in developing codes of practice as a component of achieving long-term sustainability in domesticated forests. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Soil quality; Productivity; Harvesting; Site preparation; Loblolly pine

1. Introduction

The pine plantations located in the Lower Coastal Plain region of the southeastern United States are among the most intensively managed forests in the country (Allen and Campbell, 1988), and produce ≈60% of the nation's wood fiber (USDA Forest Service, 1987). These plantations are examples of the 'domesticated forest', as defined by Stone (1975), wherein site quality is subject to considerable manipulation via cultural practice. The malleability of

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site quality in the domesticated forest enables silvicultural technologies to continuously evolve towards ever higher management inputs with an expectation that higher inputs will produce higher outputs in the form of increased wood production per hectare and shorter rotations.

Commensurate with increasing inputs is a concern that intensive culture may ultimately have a negative impact on the long-term productivity of domesticated forests. The rationale behind our concern over long-term site productivity is rooted in the ethical responsibility of foresters not to degrade the forest site (Ford, 1983), and as Gessel (1981) stated, "It is less costly to maintain and/or enhance productivity than it is to restore it." Thus, for over 30 years, numerous site productivity studies have been conducted to answer the questions: does intensive culture reduce the amount of harvestable biomass produced in successive rotations on the same site? if so, what are the key factors causing the decline? and, what codes of practice can be developed to prevent decline and sustain productivity?

In the domesticated forests of the Lower Coastal Plain, long-term productivity concerns are centered around site hydrology, which plays a major role in regulating both, management access and productivity (Morris and Campbell, 1991). A combination of nearly level topography, poorly drained soils, and high rainfall results in a perched water table which inundates the soil surface several times each year; when timber is harvested under these wet conditions severe soil disturbances including compaction, displacement, and waterlogging can occur (Hatchell et al., 1970; Gent et al., 1983; Aust et al., 1993; Aust et al., 1995). The negative impacts of these soil disturbances can be at least partially mitigated through a combination of drum chopping, disking and/or bedding (McKee and Shoulders, 1974; Haines et al., 1975; Gent et al., 1983; Morris and Campbell, 1991); however, these practices also accelerate organic matter decomposition (McKee and Shoulders, 1974) and nitrogen mineralization (Vitousek and Matson, 1985; Burger and Pritchett, 1988), thereby disrupting the natural synchrony of nutrient supply and demand (Allen et al., 1990).

As it takes a rotation-length study to determine if tree growth was affected by management practices, the benefits or deleterious effects of cultural practices on long-term site productivity are largely unknown (Morris and Miller, 1994). In a review of studies that reported tree productivity declines in domesticated forests located across the globe, Powers et al. (1990) concluded that declines were most likely explained by soil compaction and organic matter removal. Tiarks and Haywood (1996) reported that disking and bedding reduced tree growth following two rotations on the same site. The negative growth response to disking was attributed to decreased root penetration in the second rotation, as evidenced by higher soil strengths measured using a cone penetrometer. Accelerated nutrient depletion with bedding during the first rotation was suggested as the cause for reduced growth with bedding in the second rotation.

Traditional field studies, such as the one reported by Tiarks and Haywood (1996), and the several reviewed by Morris and Miller (1994), are seldom conclusive with respect to management impacts on long-term productivity. There are several contributing factors that may explain the lack of definitive results. First, tree height, diameter, and above-ground volume are almost always used as measures of productivity, yet we know that these measurements only capture a small fraction of actual site productivity (Powers, 1991), with the remaining productivity being associated with roots, foliage, reproduction, and litter production; relying solely on above-ground data may give us an incomplete and perhaps false indication of management impacts on long-term productivity. Second, the productivity measurements are exacerbated by additional factors that also affect our traditional bioassay measurements, namely the extrinsic site factors, genetic differences, competition, and catastrophic events (e.g. fire, insects, disease), which may all act together in non-definable ways unrelated to soil conditions to affect tree growth. Finally, long-term productivity experimental designs are often confounded by uncontrolled factors resulting in questionable and/or weak conclusions (Morris and Miller, 1994).

We argue that the soil quality concepts and methods currently being discussed within the agricultural community should form the basis for more soil-based assessments of management impacts on the long-term productivity of forests. The objectives of this paper are to advance the discussion on using the concept of soil quality as a basis for assessing sustainability in domesticated forests, and to demonstrate a method that

integrates the components of soil quality into an easily interpretable measure of management impacts on soils.

2. Measuring soil quality

2.1. Historical context

Burger (1996), in his critical evaluation of using bioassays to assess soil productivity change due to management, demonstrated that tree growth was not always a reliable measure of management-induced productivity change, concluding thereby that management impacts on long-term productivity should be assessed by direct measurements of soil properties and processes. An obvious advantage of measuring soil properties rather than a bioassay, is management attention as focused on the productivity-determining factors that are being manipulated.

Agricultural soil scientists recognized the problems of using bioassays, observing that "soil was the most stable attribute of the land, being unaffected by non-land inputs that influence crop yield" (Huddleston, 1984), and therefore a productivity rating system should be based on soil properties. The first soil-productivity index was developed by Storie (1933), using ratings developed for soil texture, soil depth, drainage, alkalinity, and profile morphology. Storie considered soil texture to be a surrogate indicator for the general effects of soil porosity, permeability, and soil tilth on productivity. Numerical ratings ranging from 0% to 100% were assigned to each soil property using an inductive rating system that was developed based mainly on subjective judgment concerning the effects of each soil property on the overall potential productivity of the soil. Though yield data were not used to develop the rating system, soil productivity ratings were calibrated with yield data as a check on system reliability. Storie's soil-productivity index has been used successfully to classify sites into potential yield classes for various agricultural crops.

Based on the work of Kiniry et al. (1983), Pierce et al. (1983) developed a model for determining the effects of soil erosion on soil productivity. The model used soil properties that affect the quantity and quality of available rooting volume: bulk density, available water, and pH. Sufficiency levels were determined for each soil property by horizon, and the product of the sufficiency levels was multiplied by a horizon weighting factor based on an ideal root distribution. The within-horizon values were then summed across all horizons to obtain an overall soil-productivity rating. The model has been partially validated with corn-yield data and other productivity indexes in southeastern Minnesota. The model represented a significant step because it could not only be used to estimate soil productivity, but it could also be used to determine the effects of agricultural management practices on soil productivity.

The potential of the Pierce et al. (1983) model was recognized by forest soil scientists Gale and Grigal (1988) who adapted the model to estimate forest soil productivity in Minnesota. Their model, called the productivity-index (PI) model, successfully accounted for 55–85% of measured above-ground biomass in white spruce (*Picea glauca* Voss.), aspen (*Populus tremuloides* Michx.), and jack pine (*Pinus banksiana* Lamb.) stands, indicating the model has tremendous potential for use in estimating soil productivity in managed forests. They also suggested that the PI model could be used to evaluate management impacts on forest productivity, a statement that is supported by the conclusions of Burger (1996).

2.2. Soil-quality models

The PI model approach is the basis of current models being developed for measuring soil quality. Detailed discussions of soil-quality model development and monitoring as a component of sustainable forest management are provided by Burger and Kelting (1999a) and also by Burger and Kelting (1999b) as a companion paper in this volume, hence only an outline of the process will be presented here.

Soil quality is a concept that has been explored in detail within the agricultural community (see, e.g. Doran et al., 1994; MacEwan and Carter, 1996), and has been defined as "the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" (Doran et al., 1998). It should be recognized that soil productivity, which is typically equated with biomass or crop production, is contained within this definition of soil quality.

Soil is a complex living body of myriad interacting chemical, physical, and biological processes which are constantly in flux, heterogeneous in nature, and often elusive to measurement; combine this with a definition of soil quality that recognizes the multiple functions of soil, and we quickly realize that measuring the quality of such a complex system will be difficult at best. Agricultural scientists have dealt with these difficulties by explicitly defining the functions of soil quality, identifying the attributes of each function, and then selecting a minimum data set of indicators to measure each attribute (Doran and Parkin, 1994; Karlen and Stott, 1994; Larson and Pierce, 1994).

The functions of soil quality are what soils 'do' for us; in the domesticated forest, the function of greatest interest is maintaining tree productivity. In other situations, other functions may be of greater interest; thus, soil quality, and the relative importance of its components, is defined by the objectives of the 'user'. Burger and Kelting (this volume) give several examples of soil functions in forest systems.

The attributes are a qualitative list of the key components of a given function. For example, the attributes of the soil quality function 'maintaining tree productivity' are: the soil must:

(i) promote root growth;
(ii) accept, hold, and supply water;
(iii) hold, supply, and cycle nutrients;
(iv) promote optimum gas exchange; and
(v) promote soil biological activity (Larson and Pierce, 1994).

Intuitively we know that when these five soil attributes operate at their full potential on a given site, high soil quality and tree productivity should be achieved.

Soil scientists have been studying the five attributes of maintaining productivity for decades, so we have amassed considerable knowledge on various components of each attribute. Agricultural scientists have used this knowledge to select soil properties to use as 'indicators' of the attributes for use in soil-quality modeling. Indicators should be selected based on their (i) close relationship to the attribute, (ii) low resistance to disturbance, (iii) known relationships with the chosen function, and (iv) relative ease of measurement. To minimize costs and complexity, and thereby maximize the likelihood that the approach will be adopted by practitioners, a minimum data set of indicators should be selected.

Once the minimum data set of indicators is selected, sufficiency curves need to be developed for each indicator. Forest scientists should be familiar with using sufficiency curves, as they are analogous to the critical-level approach used in diagnosing nutrient deficiencies in trees (Lambert, 1984; Olsen and Bell, 1990). Sufficiency curves provide the link between the soil quality attributes and the desired function of the soil-quality model. If the function of the soil-quality model is to improve plant productivity, then the sufficiency curves must show the relationship between each soil quality attribute and productivity. Sufficiency curves are developed based on the literature, experimentation, and professional expertise.

In order to integrate the sufficiency values into a single assessment of soil quality, Karlen and Stott (1994) suggested a simple model which is similar in basic principle to the PI model. With their model, soil quality (Q) is determined using an additive model,

$$Q = q_1(\text{wt}) + q_2(\text{wt}) + \ldots + q_k(\text{wt}). \qquad (1)$$

where, the q_k variables represent sufficiency values for different soil-quality attributes, and wt the relative weight applied to each attribute. The relative weights represent the importance of each attribute in determining soil quality on a given site, and they are assigned based on the literature, experimentation, and professional expertise.

Burger et al. (1994) used a soil-quality model in a study that examined changes in productivity due to mined land reclamation. Their research, and that of others, showed that the minimum dataset of indicator variables for reclaimed mined land were bulk density, pH, P fixation, and excess soluble salts. They developed sufficiency curves for each variable and predicted soil quality for 36 different mine soils. Their soil-quality predictions were highly correlated with growth measurements of 10-year-old white pine (*Pinus strobus* L.) located on the same sites. Using the average productivity of natural white pine stands growing in the same region as a productivity standard, they were able to develop a soil-quality standard using the model predictions. Reclaimed sites with predicted soil qualities less than the standard would need to undergo remedial treatments to bring their soil qualities up to the standard.

Burger et al. (1994) demonstrated the use of a soil-quality model for assessing productivity of disturbed sites and developing soil-quality standards for reclaimed sites. However, soil quality assessments must be soil, site, and objective specific; the same attributes would be measured, but the indicators of each attribute and their respective threshold levels may change with differing soils, sites, and objectives.

2.3. SQI – an integrated assessment

A preliminary additive model, constructed using the recommendations of Karlen and Stott (1994), is being used to combine the five soil attributes of forest productivity to arrive at a soil-quality index (SQI) rating that detects management-induced changes in soil quality. The SQI model is,

$$SQI = PRG^*0.20 + AHSW^*0.20 + HSCN^*0.20$$
$$+POGE^*0.20 + PBA^*0.20 \qquad (2)$$

where, PRG, AHSW, HSCN, POGE, and PBA are the sufficiencies of (i) promoting root growth, (ii) accepting, holding, and supplying water, (iii) holding, supplying, and cycling nutrients, (iv) promoting optimum gas exchange, and (v) promoting biological activity, respectively. The model assumes that the five attributes are equally important (same weights). [See Burger and Kelting (this volume) for a discussion on weighting attributes.]

Data collected from a long-term site productivity study underway in loblolly pine (*Pinus taeda* L.) plantations will be used to demonstrate the SQI model.

3. Materials and methods

3.1. Location and description of study site

The study sites are located on the Lower Coastal Plain in Colleton County, South Carolina, ≈65 km west of Charleston. The climate is warm temperate. Precipitation averages 132 cm annually, with the majority of rainfall occurring during the summer months (May–September). The average growing season is between 240 and 280 days, with precipitation during this period averaging between 86 and 94 cm. Average summer and winter temperatures are 31° and

18°C, respectively (Stuck, 1982). The region is nearly level, being dissected by many broad valleys containing wide meandering streams which terminate in estuaries along the coast. Natural drainage systems are poorly defined, and water moves slowly via lateral drainage through the upper soil horizons (Runge, 1977). Soils are developed from nearly level beds of unconsolidated sands, clays, and soft limestone. The study area is dominated by two soil series, Argent loam and Santee loam, in the Ochraqualfs and Argiaquolls great groups (Stuck, 1982), respectively, based on U.S. Soil Taxonomy (Soil Survey Staff, 1992). Sandy-loam textured A and E horizons are present and average 40 cm deep, combined. A deep (>140 cm) sandy clay loam Bt horizon underlies the surface horizons. Hydraulic conductivity of the Bt horizon is very slow, resulting in a perched water table on top of the Bt horizon after heavy rainfall. The Argent and Santee soils are among the highest quality soils for pine production and receive no fertilizer inputs.

3.2. Layout of harvesting and site preparation treatments

In 1991, three study blocks were selected based on similarity of drainage patterns and soil type. Each block was subdivided into six 3 ha plots, and two operational harvesting treatments were randomly assigned to five plots per block: (i) two dry harvests; and (ii) three wet harvests. Three levels of site preparation, (i) none; (ii) bedded; and (iii) mole plowed and bedded, were randomly assigned to the wet harvested plots. Two levels of site preparation were randomly assigned to the dry harvested plots: (i) none; and (ii) bedded. In the fall of 1993 and spring of 1994, five plots per block were operationally harvested. The stands were harvested when the volumetric moisture content of the surface soil exceeded 30% for the wet harvest (March, 1994), and was <15% for the dry harvest (August, 1993). Harvesting was done with mechanized fellers (Hydro-Axe, Model 411, Blount, Owatonna, MN; and Franklin, Model 105, Franklin Equipment, Franklin, VA) and wide-tired (81.3 cm) skidders (Franklin, Model 170; Caterpillar, Model 518, Caterpillar, Peoria, IL; and Timberjack, Model 450C, Timberjack Group, Helsinki, Finland), with tire inflation pressures from 30 to 35 psi. The mole plow treatment was installed in October 1995 with a mole

plow constructed using Spoor design (Spoor, 1986). Mole channels were installed on a 20×20 m^2 grid system at 80 cm deep, creating a 10-cm diameter channel in the Bt horizon for promoting water flow throughout the plot. The beds were installed in November 1995 using a six-disk bedding plow equipped with 91.4-cm disks (Model 110, Savannah Forestry Equipment, Savannah, GA,). Genetically improved loblolly pine seedlings (Westvaco, Summerville, SC) were then hand-planted on the site in early February 1996.

3.3. Field measurements and laboratory analysis

A 5×5 organic matter and soil disturbance matrix was defined (Fig. 1), and mapped spatially on each wet and dry harvest plot prior to site preparation. A 1/125-ha plot was established on a 20×20 m grid already in place for measuring shallow water table depth. The 1/125-ha plots were divided into quadrants, and the percent area covered by each organic matter and soil disturbance class was estimated to the nearest 10% in each quadrant. The soil disturbance and organic matter classes were mapped spatially using the weighted averages from each quadrant (Fig. 2).

Measurement points were selected in each plot that represented the average condition with respect to each level of organic matter and soil disturbance. At each point, several soil variables are being measured to evaluate their potential use as indicators for the five attributes in the SQI model (Fig. 2). Assuming that the data being collected at each point is representative of non-measured points in the same class, the results can
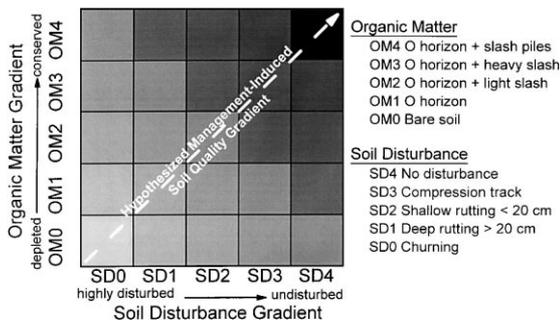

Fig. 1. Five by five organic matter/soil disturbance matrix used to classify each well location on a 20×20 m grid into one of 25 different combinations of organic matter and soil disturbance.

be extrapolated to all points to obtain spatial interpretations of management impacts at the plot level. The spatial extrapolations are refined by developing relationships between the monthly measurements and the water table, which is being monitored monthly on the 20×20 m grid, and continuously at a subset of locations.

For this paper, only a subset of indicators, namely A horizon bulk density, water table depth, nitrogen mineralization, soil aeration, and the ratio of soil moisture and total porosity are being used initially as indicators.

We began monitoring the potential soil indicators shown in Fig. 2 in May 1996, after the site preparation treatments were installed. On a monthly basis (i) the perched water table is being measured by 90 cm deep PVC observation tubes of 5 cm i.d., (ii) the TRASE system (Soil Moisture Equipment, Goleta, CA), based on time domain reflectometry, is being used to measure surface soil moisture from 0 to 30 cm, (iii) oxidation depth on steel rods (rusty rods) from 0 to 90 cm is being measured as an index of soil aeration (McKee, 1978), and (iv) the buried bag technique (Eno, 1960) is being used to measure net N-mineralization in the surface 30 cm. Bulk density and total porosity (Blake and Hartge, 1986) were calculated from two 5 cm i.d. by 10 cm long intact soil cores collected from the A horizon using a hammer-driven core sampler.

For the net N-mineralization determinations, 10 subsamples were collected monthly at each location using a 2.5 cm i.d. by 30 cm long push-tube soil sampler. The subsamples were composited in the field, and one-half of the sample was incubated in a polyethylene bag buried vertically in the A horizon. The initial inorganic N was determined from the remaining non-incubated sample. Monthly net N-mineralization was calculated as the difference in inorganic N concentration between the incubated and initial samples. The inorganic N was extracted from all soil samples with 2 M KCl and analyzed for NO_3–N and NH_4–N using a Technicon Autoanalyzer II (Technicon, 1973). The data were corrected for soil-moisture content and converted to kg/ha based on the bulk density measurements. A composite of the monthly soil samples collected for N-mineralization was used to determine soil particle size with the hydrometer method (Gee and Bauder, 1986).
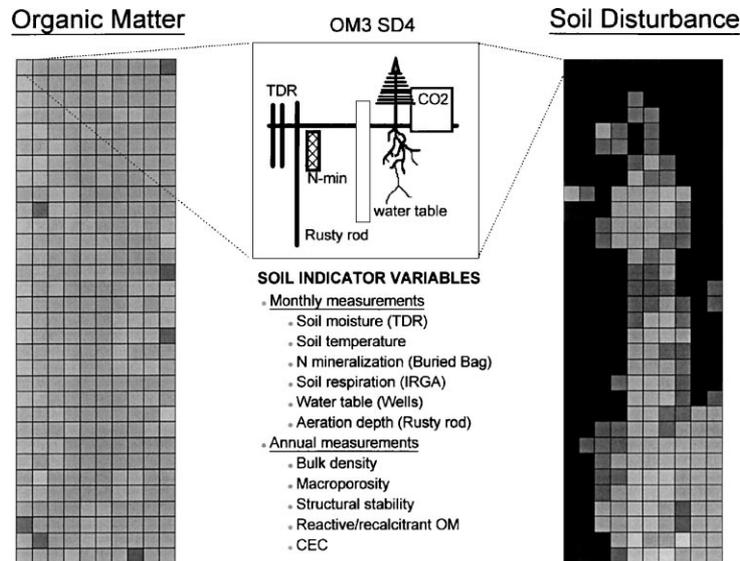
Organic Matter   OM3 SD4   Soil Disturbance

SOIL INDICATOR VARIABLES
- Monthly measurements
  - Soil moisture (TDR)
  - Soil temperature
  - N mineralization (Buried Bag)
  - Soil respiration (IRGA)
  - Water table (Wells)
  - Aeration depth (Rusty rod)
- Annual measurements
  - Bulk density
  - Macroporosity
  - Structural stability
  - Reactive/recalcitrant OM
  - CEC

Fig. 2. Spatial maps of organic matter and soil disturbance for one plot. Also shown are the soil indicator variables being measured at all levels of organic matter and soil disturbance.

3.4. Development of sufficiency curves

Using the field data, sufficiency levels of the indicator variables were determined for each location based on sufficiency curves developed using the scientific literature. The sufficiency values were substituted into Eq. (2) to obtain point-level SQI estimates. The point-level sufficiencies and SQIs were extrapolated to the plot-level using the organic-matter and soil-disturbance maps (e.g. Fig. 2).

There is considerable controversy over using soil bulk density as an indicator of tree growth or soil rootability. Relationships found between bulk density and either root or above-ground biomass production have been positive, negative, and non-existent (Greacen and Sands, 1980); however, in cases where bulk density is related to growth, it can be a good indicator measurement because it is a relatively simple number to obtain and is sensitive to management impacts. Recognizing that the critical and limiting bulk-density values decrease as particle size decreases, Pierce et al. (1983) developed sufficiency curves for each family textural class (sandy, coarse loamy, fine loamy, coarse silty, fine silty, 35–45% clay, and >45% clay). Gale et al. (1991) used the same curves in their PI model with good success. Until we have definitive data to either support or refute bulk density as a useful indicator for

the soils and operational conditions in this study, we will use the sufficiency curves developed by Pierce et al. (1983). The appropriate curve from Pierce et al. (1983) was selected based on the particle-size analysis, and applied to the bulk-density data to obtain a sufficiency of bulk density. A sample sufficiency curve is shown for the fine silty textural class (Fig. 3).

Lowering the water table using drainage, increasing the depth to the water table via bedding, or a combination of the two generally produces significant increases in pine growth on low lying, poorly drained, sites (McKee and Shoulders, 1970; Terry and Hughes, 1975; Gent et al., 1986). McKee and Shoulders (1974) quantified the relationship between pine productivity and water table depth under three levels of site preparation (none, disking, and bedding) in an eight-year-old slash pine plantation growing in poorly drained soils on the Lower Coastal Plain in Louisiana. Bedding increased biomass production by 25% compared to disking and no site preparation, both of which produced similar amounts of biomass. The bedding effect was largely explained by an increase in arable rooting volume created when the bedding plow mounded the soil above the elevation of the original soil. A regression analysis showed that wood production was most highly, and positively, correlated with average depth to the water table during the winter.
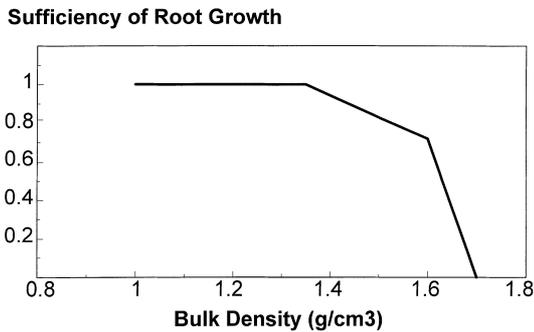
Sufficiency of Root Growth

Fig. 3. Sufficiency curve for the 'promote root growth' soil attribute, as measured using A horizon bulk density as an indicator. Adapted from Pierce et al. (1983).
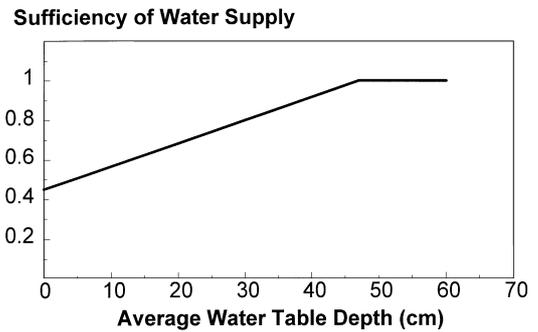
Sufficiency of Water Supply

Fig. 4. Sufficiency curve for the 'accept, hold, and supply water' soil attribute, as measured using the average water table depth during the winter as an indicator. Adapted from McKee and Shoulders (1974).

Depth to the water table in winter explained 88% of the variation in stemwood production. The authors theorized that lower water tables during the winter allowed roots to penetrate deeper into the soil profile, increasing accessibility to water during summer droughts. Based on the regression analysis, McKee and Shoulders (1974) calculated the critical water table depth for maximum productivity at 45 cm, with productivity between 0 and 45 cm water table depth being predominantly controlled by the water table. Terry (1978) also reported that water table levels in winter had the highest correlations with tree height in a seven-year-old plantation, and suggested that high winter water tables damaged tree roots, which reduced the size of the root mass and decreased above-ground growth in the spring. In agreement with McKee and Shoulders (1974), White and Pritchett (1970) showed that five-year growth increment for loblolly and slash pine was optimum at a 45-cm water table depth and decreased above, and below, 45 cm. McKee and Shoulders (1974) regression function was used to develop a sufficiency curve for relative-productivity response to average winter water table depth (Fig. 4).

Most natural stands and plantations of Southern pines are N deficient (Dougherty, 1996); therefore, we would expect a general trend of increasing biomass production with increasing N availability. This is supported by Reich et al. (1997) who showed that across a wide climatic and soils gradient, and across both hardwood and softwood species, wood production increased linearly with net N-mineralization, with

net N-mineralization explaining 50% of the variation in wood production. Based on Reich et al. (1997) regression equation combined with an estimated annual above-ground production of 11.5 $Mg\ ha^{-1}\ year^{-1}$ calculated using inventory data collected from the last rotation, it would take about 140 (kg N) $ha^{-1}\ year^{-1}$ to achieve the level of production measured on the previous rotation on our sites. This estimate falls slightly outside the 20–137 $kg\ ha^{-1}\ year^{-1}$ net N-mineralization range Reich et al. (1997) used to develop their equation, so the validity of our estimate is unknown. Wells and Jorgensen (1975) estimated the annual N requirement for a 16-year-old loblolly pine plantation growing on the Piedmont in North Carolina at 117 $kg\ ha^{-1}\ year^{-1}$, with ca. 25% of this requirement being met through retranslocation. Assuming that atmospheric deposition supplies ca. 10 (kg N) $ha^{-1}\ year^{-1}$ in the Southeastern US (Allen and Gholz, 1996), then the remaining 78 $kg\ ha^{-1}\ year^{-1}$ must be supplied by the soil, which is about 60 $kg\ ha^{-1}\ year^{-1}$ less than the amount estimated for our sites. Our annual production estimate is ca. 35% higher than those reported by Wells and Jorgensen, hence our calculated annual N-mineralization requirement may be reasonable given the much higher productivity. Certainly, the work reported by Reich et al. (1997), as well as other studies conducted in forest stands ranging from 29 to >100 years of age (Lennon et al., 1985), has shown that N-mineralization can supply large amounts of N in forest soils. We used the regression function given by Reich et al. (1997) to develop a first-approximation
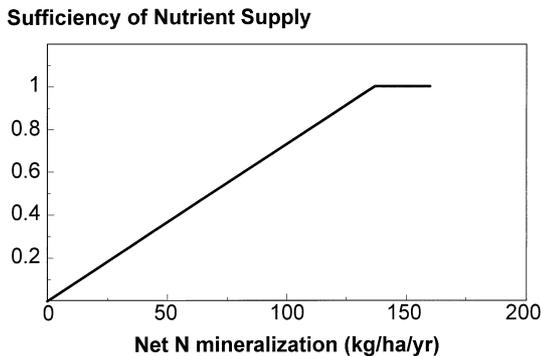
Sufficiency of Nutrient Supply

Fig. 5. Sufficiency curve for the 'store, supply, and cycle nutrients' soil attribute, as measured using net N-mineralization as an indicator. Adapted from Reich et al. (1997).
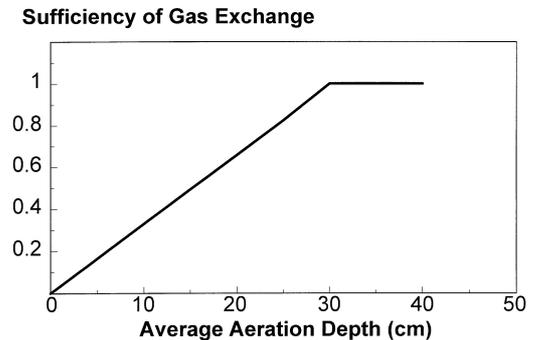
Sufficiency of Gas Exchange

Fig. 6. Sufficiency curve for the 'promote gas exchange' soil attribute, as measured using the average aeration depth during the growing season as an indicator. Adapted from Hook et al. (1987).

sufficiency curve for net N-mineralization (Fig. 5). The curve's asymptote is 140 (kg N) ha^{-1} year^{-1} which corresponds with our estimate of the N required to achieve the same production level measured from the first rotation.

The oxygen supply is quickly depleted in a saturated soil because oxygen diffuses through liquid $\approx 10\,000$ times slower than through air (Bohn et al., 1985). The resultant anaerobic soil conditions reduce root growth (Ouyang and Boersma, 1992) and dramatically alter soil chemical and biological processes (Ponnamperuma, 1972). The growing season is characterized as a period of increased soil biological activity and plant growth; thus, when anaerobic conditions occur during the growing season, reductions in these processes may occur. A correlation analysis of our data showed that seedling volume was most highly correlated with aeration depth during the growing season (April through September), with a mean correlation coefficient of 0.55 vs. 0.26 for the remaining months. Based on a combination of the results of the correlation analysis on our data and the work of Hook et al. (1987), we developed a sufficiency relationship between tree growth and average growing season aeration depth (Fig. 6).

Soil temperature, moisture, and aeration are the major controlling factors for soil biological processes. We know that within the normal range of soil temperatures (0–30°C), biological activity follows a Q_{10} relationship with temperature (Paul and Clark, 1989). In fact, researchers have been successful in modeling soil biological processes using only temperature-driven Q_{10} functions (Stanford et al., 1973; Kladivko and Keeney, 1987). Paul and Clark (1989) presented a generalized function for relative microbial activity from 0° to 60°C. Their function showed that maximum microbial activity occurred between 25° and 35°C, and decreased linearly on both sides of this range. The microbial response to moisture and aeration is not so straightforward. Skopp et al. (1990) developed a conceptual framework and model for understanding the effects of soil water on microbial activity. Their model assumes that microbial activity is strongly influenced by soil water because soil-water content affects oxygen and substrate diffusion rates. Sustained and enhanced microbial activity require constant supplies of electron acceptors (oxygen) and energy and nutrients (substrate). Higher water contents favor increased substrate diffusion and lower water contents favor increased oxygen diffusion. Since the maximum diffusion rates for the two processes directly oppose one another, microbial activity is highest at the water content at which the limiting effects of the two processes are minimized. Using literature-derived diffusion coefficients for oxygen and substrate, Skopp et al. determined that the optimum water content (i.e. least limiting for both processes) was 60% of the total porosity. They partially verified the model using data from the literature, and found that optimum water contents for maximum microbial activity ranged between 55% and 61% of the total porosity for a variety of soils. In interpreting this optimum water content, they stated that, because the diffusion coefficients for oxygen and substrate were very similar, the
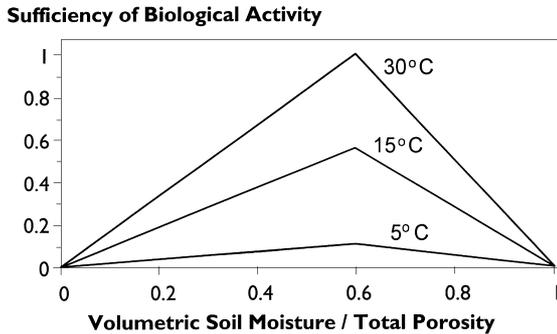
Sufficiency of Biological Activity

Fig. 7. Sufficiency curve for the 'promote biological activity' soil attribute, as measured using the ratio of volumetric soil moisture/ total porosity adjusted for temperature as an indicator. Three temperature adjusted example curves are shown. Adapted from Skopp et al. (1990) and Paul and Clark (1989).

theoretical optimum water content should be 50% of the total porosity; a shift toward a higher optimum water content suggests that substrate diffusion limits microbial activity more than oxygen diffusion for a variety of soils. An important additional point from their work is that the effects of soil water on microbial activity are best described using soil water content as opposed to water potential because soil water content affects diffusion rates while water potential does not. The theoretically based soil-water content–microbial activity response curves generated by Skopp et al. were used to develop a sufficiency curve for soil-microbial activity as a function of volumetric soil water/total porosity. The curve was modified by adding a soil-temperature adjustment function based on the generalized relationship between temperature and microbial activity discussed by Paul and Clark (1989). Fig. 7 shows the sufficiency curve developed for biological activity at three soil temperatures.

3.5. Relations between productivity, soil properties and processes, and SQI

In the short term, the relationship between productivity, soil properties and processes, and the SQI predictions is being determined from 'bioassay' plots collocated with a subset of soil-process measurement points. Fifty-four identically spaced loblolly pine bioassay plots were planted concurrently with the operational planting (i.e. February 1996). The plots are 2.1×6.3 m, and the seedlings are planted at

30×30 cm spacing within each plot. The plot dimension was chosen so that the plots would span an entire soil-disturbance class, and the seedlings were planted at 30×30 cm spacing to encourage competition for soil resources within one year. Because all of the plots are at identical spacing, any differences in growth observed between plots should be a function of soil quality.

The total heights and ground-line diameters of the seedlings in the internal rows (external row was left as a buffer) were measured in March 1997. Seedling volume was then estimated using the D^2H formula (Clutter et al., 1983).

The relationship between productivity and soil properties and the processes measured was examined using multilinear regression, wherein seedling volume was regressed against bulk density, average water table depth in winter, net N-mineralization, average aeration depth during the growing season, and the soil biological activity sufficiency values. The most discriminating variables were determined using the all-possible regressions procedure (Montgomery and Peck, 1992), wherein a 'best' model was selected based on the criteria of maximizing the adjusted R^2 and minimizing the mean square error. Multilinear regression on standardized (normal 0, 1) data was used to ascertain the relative importance of the variables included in the best model. The relationship between productivity and the SQI predictions was evaluated by regressing seedling volume as a function of SQI using simple linear regression.

4. Results and discussion

4.1. Relationships between productivity and soil quality indicators

The multilinear regression analysis on the full model showed that productivity was highly related to the indicator variables, with the five variables explaining ca. 64% of the variation in one-year-old seedling volume (Table 1). Productivity was positively related to water table depth, net N-mineralized, and aeration depth. The P-values for bulk density (0.898) and the biological activity indicator (0.823) indicate that these two variables are not related to productivity.

Table 1
Relationships between one-year-old seedling volume and the five soil variables chosen to represent the attributes in the SQI model. Analyzed using multilinear regression, $n = 54$

Full model			Best model [a]		
variable	coefficient	p-value	coefficient	p-value	standardized coefficient [b]
Bulk density	−0.046	0.898	–	–	–
Water table depth	0.012	0.187	0.017	0.037	0.262
Net N-mineralized	0.002	0.037	0.002	0.010	0.258
Aeration depth	0.034	0.005	0.034	0.002	0.439
Biological activity	0.166	0.823	–	–	–
	$R^2 = 0.641$	p-value > 0.001	$R^2 = 0.635$	p-value > 0.001	

[a] Best model was selected to maximize adjusted R^2 and minimize the mean square error.
[b] Data were standardized to mean $= 0$ and standard deviation $= 1$.

The bulk densities on the study sites are very low, averaging 1.11 g cm^{-3}, and ranging from 0.39 to 1.47 g cm^{-3}. With the majority of soil textures in this study occurring in the silt-to-sandy loam textural categories, the bulk densities are non-limiting for root growth according to Pierce et al. (1983) sufficiency calculations, which probably explains the lack of a relationship between bulk density and productivity. The lack of a relationship between productivity and the biological activity indicator suggests that either biological activity is non-limiting or the indicator variable needs to be modified. Given that 36% of the variation in productivity remains unexplained, modification of both, the 'promote root growth' and the 'promote biological activity' indicators is probably required.

The best model retained average water table depth in winter, net N-mineralization, and average growing season aeration depth, with all three variables being highly significant and explaining about the same amount of variation in productivity ($R^2 = 0.635$) as the full model (Table 1). The standardized regression analysis showed that average growing season aeration depth contributes the most toward explaining the variation in productivity, with the other two variables contributing equally. Adequate aeration is critical for seedling survival and early growth (Haines et al., 1975), which may explain the higher relative importance of aeration depth.

4.2. Relationship between SQI and productivity

The values of the standardized regression coefficients (Table 1) were used to assign relative weights to the soil quality attributes in the SQI model. With the relative weights assigned, the model used to calculate SQI was,

$$SQI = BD^*0.0 + WWT^*0.262 + NMIN^*0.258 + AER^*0.439 + BIO^*0.0. \tag{3}$$

where, BD, WWT, NMIN, AER, and BIO are the sufficiencies of bulk density, water table depth in winter, net N-mineralization, aeration depth, and biological activity, respectively, which were used as surrogate indicators for the five attributes of soil quality (Eq. (2)). Bulk density and the biological activity indicator were assigned a weight of zero to reflect that they were not significant indicators (Table 1). Other indicators for the attributes 'promote root growth' and 'promote biological activity' are being evaluated.

The regression analysis showed that SQI explained ca. 60% of the variation in first-year loblolly pine volume (Fig. 8), which is ca. 4% less than the variation in productivity explained by the best model (Table 1). We would expect the SQI predictions to be less related to productivity, given that the model was built using generalized sufficiency curves based on the literature. Another less important reason for the difference is the truncating nature of the sufficiency curves used in the SQI model vs. the continuum of data used in the soil variable regression model. The variation in volume about the predicted line increases at higher levels of SQI. The reasons for this behavior are unclear at this stage, but the high variation suggests that further improvements in the sufficiency curves making up the model are warranted. Also, as discussed
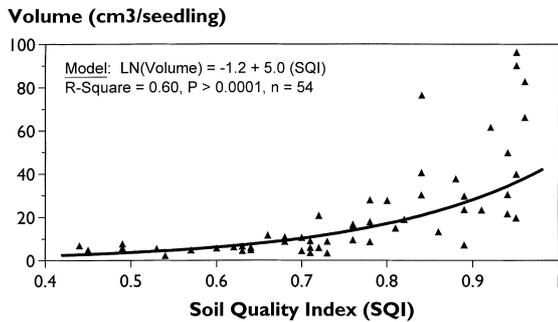
Fig. 8. The relationship between first-year loblolly pine seedling volume and the soil-quality index (SQI). Determined from a regression analysis on the SQI values at the 54 bioassay plots.

in Section 1, above-ground volume may not be the best expression of productivity. Despite these problems, the regression analysis shows that our literature-derived SQI model relates very well to measures of tree productivity, and, as such, may provide a useful tool for assessing management impacts on soil productivity.

4.3. Management effects on soil quality

In order to further illustrate the application of a SQI model, Eq. (3) was applied to data collected from one block of our treatments to show how the SQI model could be used to measure management effects on soil quality. Only one block of treatments is used to simply demonstrate the approach. Sufficiency levels for each attribute and SQI were extrapolated spatially using the methods previously described.

The spatial sufficiency of the 'accept, hold, and supply water' soil attribute increased over large areas with site preparation compared to non-site preparation (Fig. 9(a and (d))). The dry harvest/bedded treatment has the highest sufficiency of the 'hold, supply, and cycle nutrients' soil attribute as evidenced by the indicator variable net N-mineralization (Fig. 9(b)). The wet harvest/bedded treatment has the lowest net N-mineralization sufficiency. The spatial sufficiency of the 'promote optimum gas exchange' soil attribute as determined by the indicator variable aeration depth was highest on the dry harvest/bedded treatment, followed by the wet harvest/site preparation treatments (Fig. 9(c)).

Substituting the sufficiencies from Fig. 9 into Eq. (3) to obtain the overall SQI assessment showed

that the dry harvest/bedded treatment had the highest spatial sufficiency for SQI (Fig. 9(c)), followed by the wet harvest/site prepared treatments, and lastly the non-site prepared treatments (Fig. 10). Based on the spatial sufficiency of the individual indicator variables, the higher overall SQI on the dry harvest/bedded site is mainly due to improved soil aeration and increased net N mineralization on this site. These results also demonstrate that the SQI model is sensitive to management-induced changes in soil quality.

As a final interpretation of the potential utility of the SQI model for making forest management decisions, the regression function (Fig. 8) can be used to predict first-year loblolly pine volume across each harvest/site preparation treatment area. Area-weighted loblolly pine volume would be calculated by treatment using the spatial SQI sufficiency levels (Fig. 10) and the regression equation (Fig. 8). The spatial productivity estimate determined using the SQI/biomass relationship integrates the treatment effect across the site, thus providing an overall assessment of management impacts on soil productivity. This approach will be used to assess management impacts on soil productivity on our sites after we have further developed the SQI model.

4.4. Improving the SQI model

The lack of a relationship between productivity and bulk density and the biological activity indicator suggests that we need to develop better indicator variables for the soil quality attributes of promoting root growth and biological activity.

The soil tilth index developed by Singh et al. (1992) is probably a much better indicator of soil conditions for promoting root growth than bulk density alone. Their index integrates bulk density, soil strength, aggregate uniformity, organic matter content, and plasticity into a single value that represents the quality of the soil physical environment for root growth. Singh et al. (1992) found that their index was significantly and positively correlated with crop production, and thus it meets the criteria of a good indicator. The 'least limiting water range' developed by da Silva (1994) as a soil structural quality index for crop production may also be a good indicator for the promote root growth attribute.
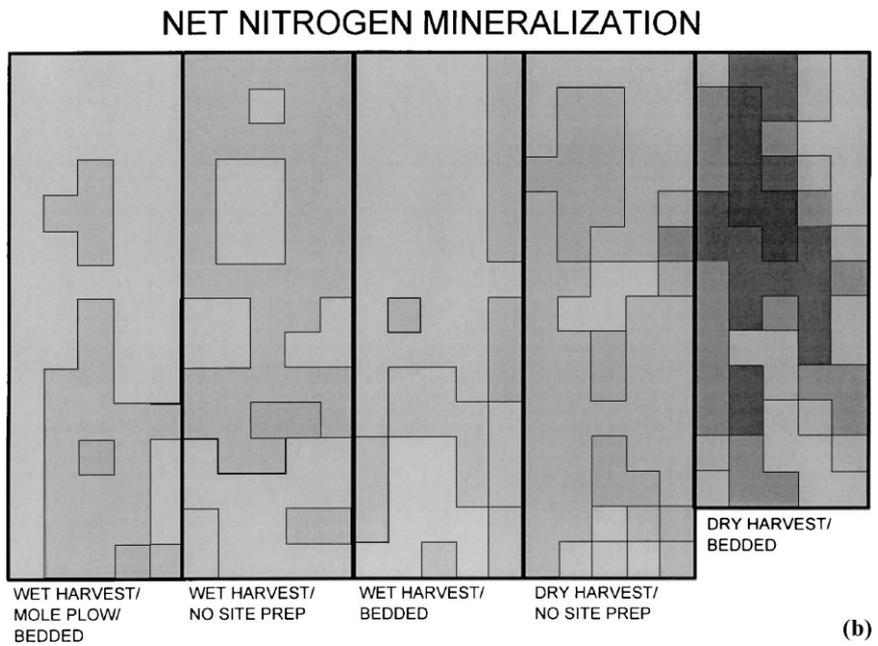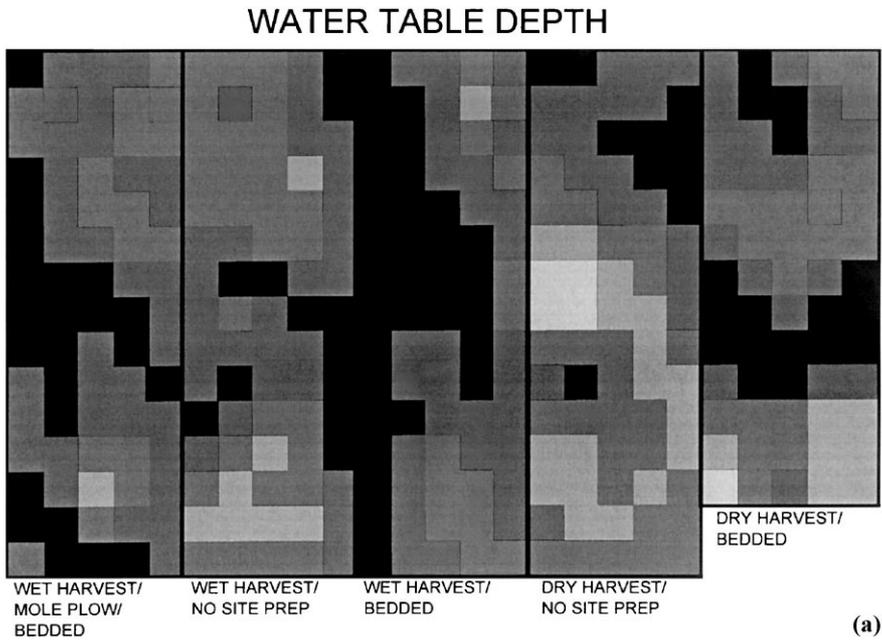
WATER TABLE DEPTH

WET HARVEST/
MOLE PLOW/
BEDDED

WET HARVEST/
NO SITE PREP

WET HARVEST/
BEDDED

DRY HARVEST/
NO SITE PREP

DRY HARVEST/
BEDDED

(a)

NET NITROGEN MINERALIZATION

WET HARVEST/
MOLE PLOW/
BEDDED

WET HARVEST/
NO SITE PREP

WET HARVEST/
BEDDED

DRY HARVEST/
NO SITE PREP

DRY HARVEST/
BEDDED

(b)

Fig. 9. Spatial sufficiencies determined for the three indicator variables used in the soil-quality index (SQI) model. Extrapolated based on the organic matter/soil disturbance maps defined by the criteria in Fig. 1.

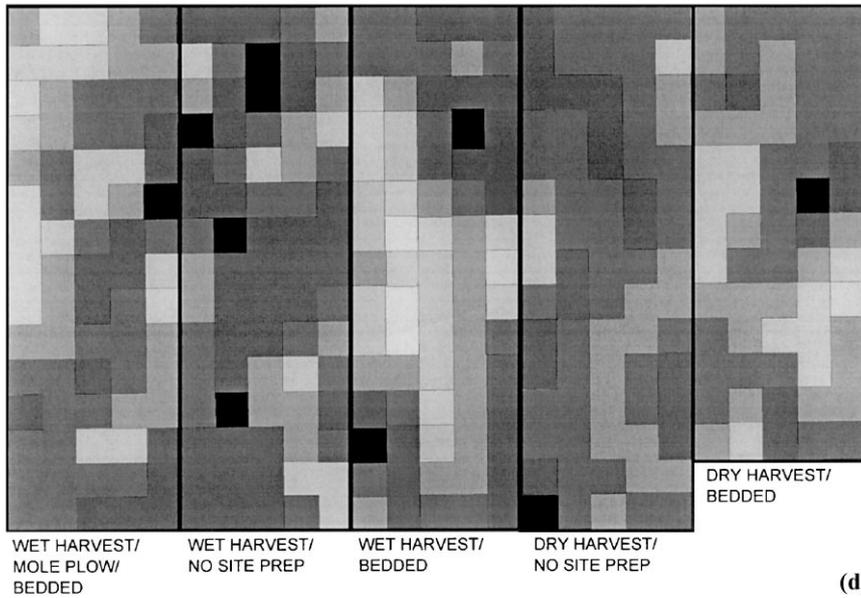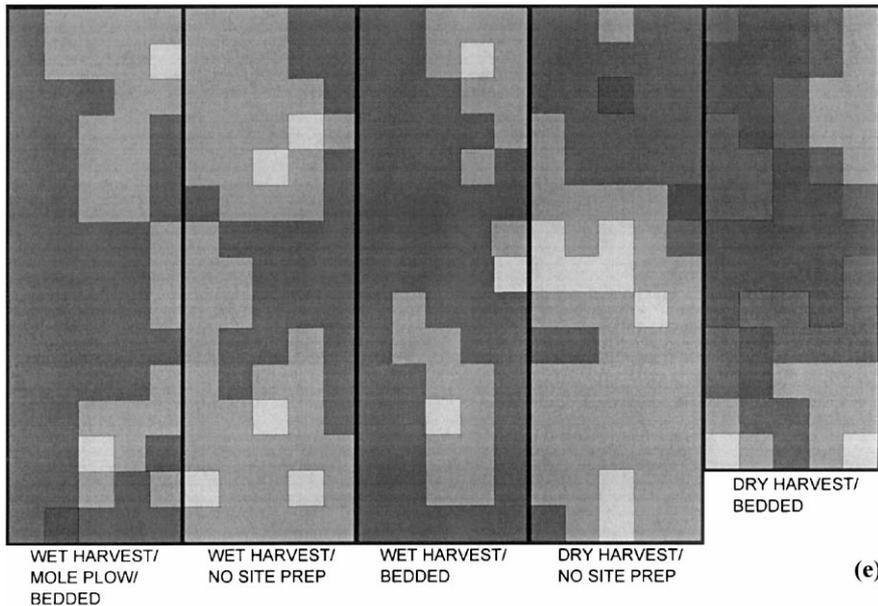## AERATION DEPTH

(c)

SOIL MOISTURE/TOTAL POROSITY

(d)
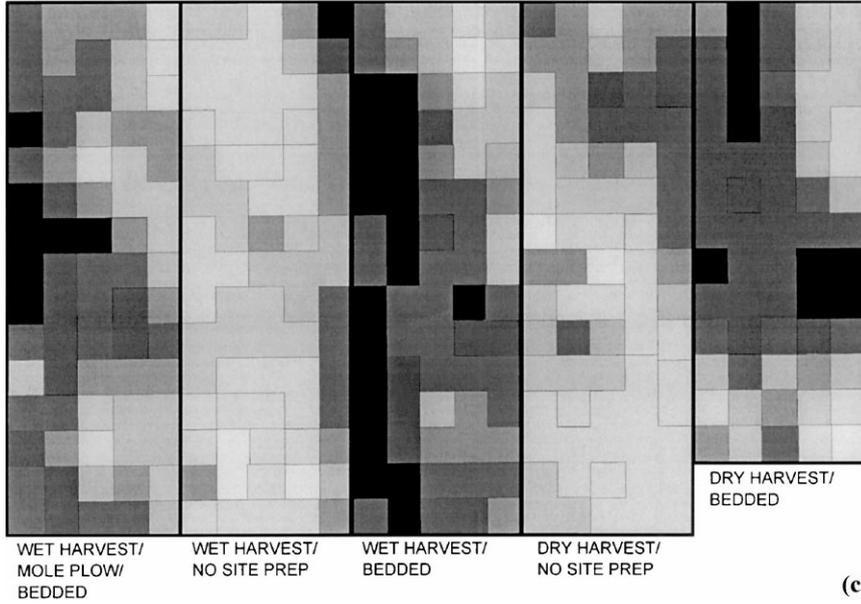
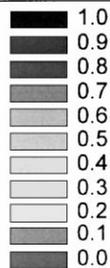Fig. 9. (*Continued*)

SOIL QUALITY INDEX (SQI)

Fig. 9. (*Continued*)

In order to reflect management-induced changes in soil biological activity, the indicator of this soil quality attribute should include some measure of organic-matter quality. Total organic carbon (TOC) would probably not be a good indicator, given that only a fraction of the TOC is reactive in the short term, and the size of the TOC pool makes TOC fairly insensitive to short-term management induced changes in soil carbon. The light fraction of soil organic matter, which contains the majority of reactive carbon and is sensitive to management impacts in the short term (Barrios et al., 1997), may be a good indicator of organic matter quality. An indicator of promoting biological activity that combines a measure

of the light fraction with the sufficiencies of soil temperature, moisture, and aeration, is currently being investigated.

We continue to monitor the relationship between the soil variables in Fig. 2 and productivity. Through this process, the SQI model will evolve until the best combination of indicator variables and appropriate weighting factors are determined.

4.5. Concluding assessment of the SQI approach

The specificity of soil quality monitoring is one of several potential problems with the method. Having to measure soil quality indicators to develop soil quality
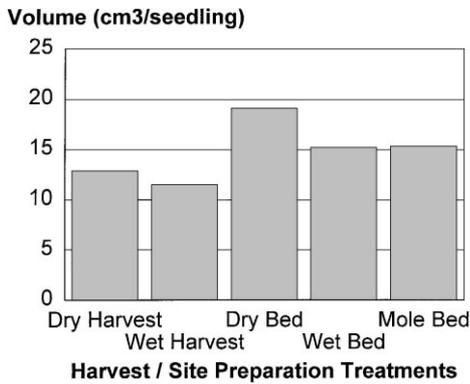
Volume (cm3/seedling)

Fig. 10. Spatial sufficiency of the soil-quality index (SQI) calculated using Eq. (3).

standards for all combinations of soils and sites is not realistic. To overcome this problem, soil quality could be measured at a small subset of locations representative of larger areas; such sites are called soil-quality benchmarks (Doran and Parkin, 1994). Codes of practice could be developed based on soil-quality measurements collected on the benchmark sites; these codes of practice could then be extrapolated to similar sites for management (see Burger and Kelting, this volume). A similar technique is currently being developed by the U.S. Environmental Protection Agency's Environmental Monitoring and Assessment Program (Larson and Pierce, 1994).

The soil-quality index model produces estimates that are essentially point-in-time measures of soil quality, yet we know that soil quality will change through time as the plantation matures. Thus, the values of the soil indicators measured at stand establishment may not reflect soil quality at a future time (e.g. stand closure). Nambiar (1996) discussed the problem of point-in-time indicators, and suggested that meaningful interpretations of indicator data could be made if comparisons with appropriate controls were available. Appropriate controls should be provided by experimental research wherein management practices can be compared side by side. The long-term site productivity (LTSP) research currently being conducted by the USDA Forest Service is an example of such research (Powers, 1991). The effects of organic matter removal and soil compaction on critical soil properties and processes are being evaluated through time on a range of sites representing the major forest and soil types (benchmarks) in the U.S., the soil

variables or indicators will be compared against net primary production so that quantitatively derived threshold levels can be determined for the soil variables being monitored. Other long-term productivity research projects discussed by Burger and Kelting (this volume) could be combined with the LTSP research to provide the appropriate comparisons suggested by Nambiar (1996).

The approach to measuring soil quality advocated here is reductionist in the way it simplifies the complex interacting relationships that occur between soil processes and between soils and plants. Critics of this reductionist approach would be correct in stating that the additive soil-quality model is not a realistic representation of what occurs is nature, favoring instead a process-based model that more closely simulates nature. A fundamentally important point to grasp is that soil quality is an applied science not meant to increase our understanding of nature, but rather to assist forest managers in making decisions that will move them toward sustainability. In this vein, soil quality models are not primarily designed to increase our understanding of management impacts on soils, but they are meant to provide an early warning tool that helps managers judge the positive and negative effects of their practices on sustainability. Having said this, we do favor using process-based models in decision-making for management, but since the utility of such models is questionable at this point (Johnson, 1997), we argue that the soil-quality index approach may provide a useful alternative.

Acknowledgements

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