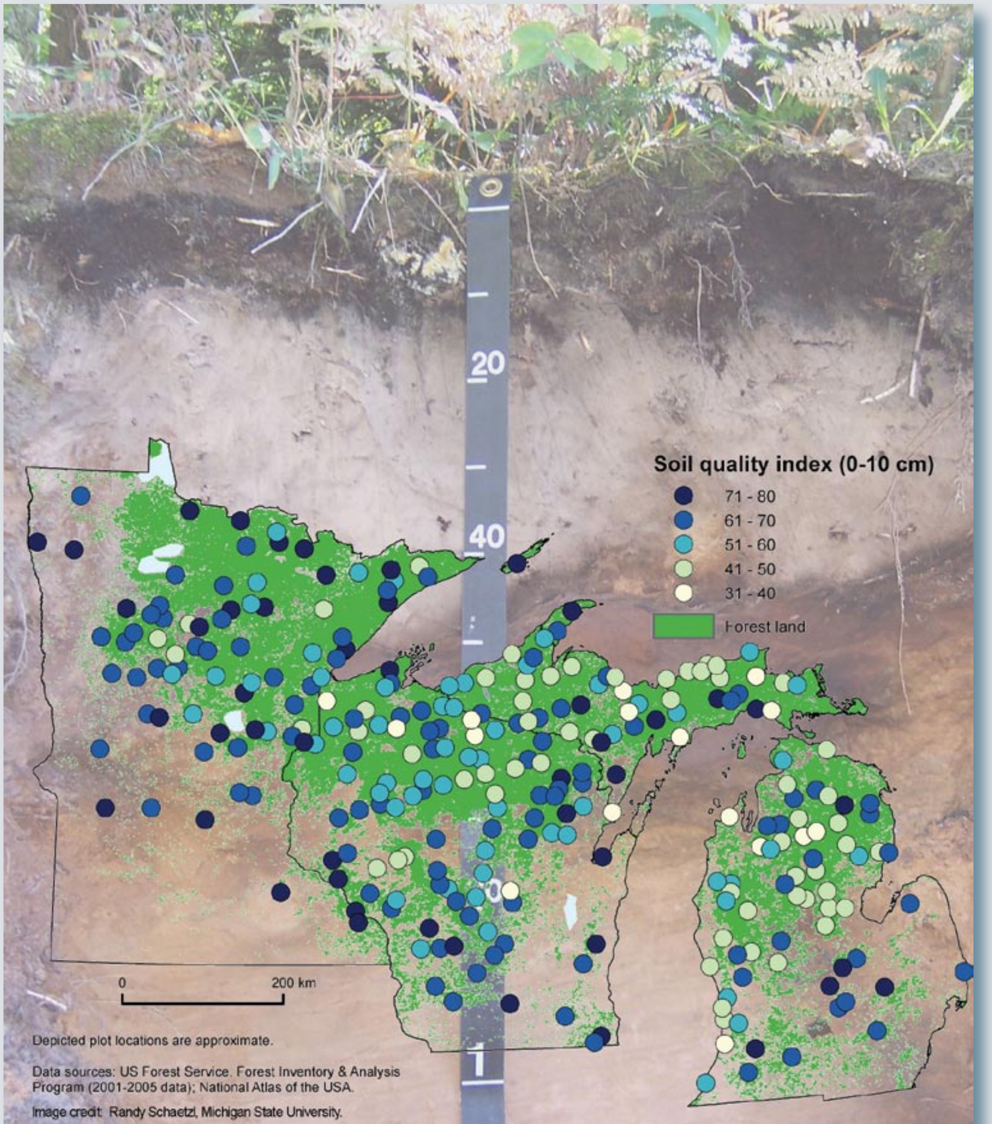
Soil Vital Signs: A New Soil Quality Index (SQI) for Assessing Forest Soil Health

Michael C. Amacher, Katherine P. O'Neill, and Charles H. Perry



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Abstract

The Forest Inventory and Analysis (FIA) program measures a number of chemical and physical properties of soils to address specific questions about forest soil quality or health. We developed a new index of forest soil health, the soil quality index (SQI), that integrates 19 measured physical and chemical properties of forest soils into a single number that serves as the soil's "vital sign" of overall soil quality. Regional and soil depth differences in SQI values due to differences in soil properties were observed. The SQI is a new tool for establishing baselines and detecting forest health trends.

Keywords: forest soil health, Forest Inventory and Analysis, soil indicator database, soil quality index

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Introduction

Numerous physical and chemical properties of soils are measured as part of the FIA forest health indicators program to evaluate the status of, and to detect, trends in forest soil quality. Unless a particular indicator of forest health is strongly related to a specific soil property, the individual physical and chemical properties are often of little value to scientists trying to assess overall forest health. Typically, individual biological indicators of forest stand health (for example, dieback or productivity) are correlated with a range of soil physical and chemical properties in an attempt to identify which property or properties are associated with forest health. Variables with statistically significant positive or negative correlations are used to develop multivariate regression equations to explain or predict forest health as a function of measured soil properties. Because this approach is predominantly site specific, it is of little use as a routine assessment tool. Also, many soil properties are associated with each other (for example, low pH associated with low nutrient levels) such that using a single "dependent" variable in isolation may not provide a complete and accurate assessment of forest health.

To assist ecologists and FIA analysts in assessing the potential impacts of changes in soil properties on forest health, it would be desirable to develop a soil quality index (SQI) that integrates the measured soil physical and chemical properties into a single parameter that could be used as an indicator of overall forest soil quality. Thus, in concept, this index would serve as a measure of the soil's "vital sign."

The use of indexes to measure trends is well established. Perhaps the most well known example is use of the Dow-Jones Industrial Average as an indicator of stock market activity and economic health. The use of index values to integrate or summarize soil properties is not a new concept. Others have suggested and developed such indexes for agricultural systems (for example, Doran and Parkin 1996), but a similar index as an indicator of forest soil health is lacking. The development and application of a soil quality index to a nationally consistent forest soil monitoring program would provide a mechanism for evaluating changes in soil properties across the landscape.

Here, we develop and present an SQI that integrates 19 soil physical and chemical properties measured in the FIA program into a single number that can be used to monitor changes in forest soil properties with time. The SQI may also have some potential as an indicator of increased or decreased risk of forest decline, but this will depend on its accuracy to predict soil related forest health status and trends, an assessment which has yet to be made. The SQI may also be an indicator of the potential for soil quality to change because of the influence of environmental stressors (for example, atmospheric deposition, changes in global cycles, and so forth).

Methods

A brief description of the development of the soil indicator and the FIA plot network is given in O'Neill and others (2005a,b). Three forest floor and two mineral soil core samples are collected from each FIA Phase 3 plot. At each forest floor sample location, the complete forest floor (litter + humus layers) is collected from a 30.5-cm diameter sampling frame and sent to one of the regional FIA laboratories for determinations of sample weight, water content, and total carbon and nitrogen. Two mineral soil cores (0 to 10 cm and 10 to 20 cm) are collected from one sampling location using an impact-driven soil coring tool. Analysis of the mineral soil cores includes sample weight, bulk density, water content, coarse fragment content, water and salt pH, carbon (total, organic, and inorganic C), total nitrogen (N), 1 M NH_4Cl exchangeable cations (sodium [Na], potassium [K], magnesium [Mg], calcium [Ca], aluminum [Al]), 1 M NH_4Cl extractable trace elements (manganese [Mn], iron [Fe], nickel [Ni], copper [Cu], zinc [Zn], cadmium [Cd], lead [Pb]), 1 M NH_4Cl extractable sulfur (S), and Bray 1 or Olsen extractable phosphorus (P). Details of the FIA plot layout, soil sampling, and soil analysis methods are presented elsewhere (Amacher and others 2003; O'Neill and others 2005a,b; USDA Forest Service 2005). In this report, we focus solely on the development of the SQI from the measured soil properties of the mineral soil cores, give some examples of calculated SQIs using a partial FIA soils database, and provide recommendations on its application to FIA data. Because only a few properties are measured on the forest floor samples, they are not used to calculate SQIs.

Mineral soil property threshold levels, interpretations, and associated soil index values are listed in table 1. The rationale for the threshold levels selected is given in the Appendix. The individual index values for all the mineral soil properties measured on an FIA plot are summed to give a total SQI:

$$\text{Total SQI} = \sum \text{individual soil property index values}$$

The maximum value of the total SQI is 26 if all 19 soil properties are measured. The total SQI is then expressed as a percentage of the maximum possible value of the total SQI for the soil properties that are measured:

$$\text{SQI, \%} = (\text{total SQI} / \text{maximum possible total SQI for properties measured}) \times 100$$

Thus, missing properties do not contribute to the index. However, we recommend that SQIs based on only a few of the 19 measured soil properties not be included in any data analysis since these values could provide a distorted assessment of soil quality because they are based on too few measured properties.

Table 1—Soil quality index values and associated soil property threshold values and interpretations.

Parameter	Level	Interpretation	Index
Bulk density (g/cm^3)	> 1.5	Possible adverse effects	0
	≤ 1.5	Adverse effects unlikely	1
Coarse fragments (percent)	> 50	Possible adverse effects	0
	≤ 50	Adverse effects unlikely	1
Soil pH	< 3.0	Severely acid – almost no plants can grow in this environment	-1
	3.01 to 4.0	Strongly acid – only the most acid tolerant plants can grow in this pH range and then only if organic matter levels are high enough to mitigate high levels of extractable Al and other metals	0
	4.01 to 5.5	Moderately acid – growth of acid intolerant plants is affected depending on levels of extractable Al, Mn, and other metals	1
	5.51 to 6.8	Slightly acid – optimum for many plant species, particularly more acid tolerant species	2
	6.81 to 7.2	Near neutral – optimum for many plant species except those that prefer acid soils	2
	7.21 to 7.5	Slightly alkaline – optimum for many plant species except those that prefer acid soils, possible deficiencies of available P and some metals (for example, Zn)	1
	7.51 to 8.5	Moderately alkaline – preferred by plants adapted to this pH range, possible P and metal deficiencies	1
	> 8.5	Strongly alkaline – preferred by plants adapted to this pH range, possible B and other oxyanion toxicities	0
Total organic carbon in mineral soils (percent)	> 5	High – excellent buildup of organic C with all associated benefits	2
	1 to 5	Moderate – adequate levels	1
	< 1	Low – could indicate possible loss of organic C from erosion or other processes, particularly in temperate or colder areas	0
Total nitrogen in mineral soils (percent)	> 0.5	High – excellent reserve of nitrogen	2
	0.1 to 0.5	Moderate – adequate levels	1
	< 0.1	Low – could indicate loss of organic N	0
Exchangeable Na percentage (exchangeable Na/ECEC x 100)	> 15	High – sodic soil with associated problems	0
	≤ 15	Adverse effects unlikely	1
K (mg/kg)	> 500	High – excellent reserve	2
	100 to 500	Moderate – adequate levels for most plants	1
	< 100	Low – possible deficiencies	0
Mg (mg/kg)	> 500	High – excellent reserve	2
	50 to 500	Moderate – adequate levels for most plants	1
	< 50	Low – possible deficiencies	0
Ca (mg/kg)	> 1000	High – excellent reserve, probably calcareous soil	2
	101 to 1000	Moderate – adequate levels for most plants	1
	10 to 100	Low – possible deficiencies	0
	< 10	Very low – severe Ca depletion, adverse effects more likely	-1
Al (mg/kg)	> 100	High – adverse effects more likely	0
	11 to 100	Moderate – only Al sensitive plants likely to be affected	1
	1 to 10	Low – adverse effects unlikely	2
	< 1	Very low – probably an alkaline soil	2
Mn (mg/kg)	> 100	High – possible adverse effects to Mn sensitive plants	0
	11 to 100	Moderate – adverse effects or deficiencies less likely	1
	1 to 10	Low - adverse effects unlikely, possible deficiencies	1
	< 1	Very low – deficiencies more likely	0
Fe (mg/kg)	> 10	High – effects unknown	1
	0.1 to 10	Moderate – effects unknown	1
	< 0.1	Low – possible deficiencies, possibly calcareous soil	0
Ni (mg/kg)	> 5	High – possible toxicity to Ni sensitive plants, may indicate serpentine soils, mining areas, or industrial sources of Ni	0
	0.1 to 5	Moderate – effects unknown	1
	< 0.1	Low – adverse effects highly unlikely	1
Cu (mg/kg)	> 1	High – possible toxicity to Cu sensitive plants, may indicate mining areas or industrial sources of Cu	0
	0.1 to 1	Moderate – effects unknown, but adverse effects unlikely	1
	< 0.1	Low – possible deficiencies in organic, calcareous, or sandy soils	0

(continued)

Table 1 (Continued)

Parameter	Level	Interpretation	Index
Zn (mg/kg)	> 10	High – possible toxicity to Zn sensitive plants, may indicate mining areas or industrial sources of Zn	0
	1 to 10	Moderate – effects unknown, but adverse effects unlikely	1
	< 1	Low – possible deficiencies in calcareous or sandy soils	0
Cd (mg/kg)	> 0.5	High – possible adverse effects	0
	0.1 to 0.5	Moderate – effects unknown, but adverse effects less likely	1
	< 0.1	Low – adverse effects unlikely	1
Pb (mg/kg)	> 1	High – adverse effects more likely, may indicate mining areas or industrial sources of Pb	0
	0.1 to 1	Moderate – effects unknown, but adverse effects less likely	1
	< 0.1	Low – adverse effects unlikely	1
S (mg/kg)	> 100	High – may indicate gypsum soils, atmospheric deposition, mining areas, or industrial sources	0
	1 to 100	Moderate – adverse effects unlikely	1
	< 1	Low – possible deficiencies in some soils	0
0.03 M NF_4 + 0.025 M HCl (Bray 1) P (mg/kg)	> 30	High – excellent reserve of available P for plants in acid soils, possible adverse effects to water quality from erosion of high P soils	1
	15 to 30	Moderate – adequate levels for plant growth	1
	< 15	Low – P deficiencies likely	0
pH 8.5, 0.5 M $NaHCO_3$ (Olsen) P (mg/kg)	> 30	High – excellent reserve of available P in slightly acidic to alkaline soils, possible adverse effects to water quality from erosion of high P soils	1
	10 to 30	Moderate – adequate levels for plant growth	1
	< 10	Low – P deficiencies likely	0

Results and Discussion

A histogram of the distribution of SQIs for soil samples collected from FIA base grid plots in 2000 through 2004 shows that most of the plots are clustered around the mid-range of SQI values (fig. 1). SQIs for each region of the country are plotted as separate bars to allow for regional comparisons among the different ranges of SQI values. The south tended to have more plots with lower SQI values whereas the west tended to have more plots at higher SQI values. The two soil core depths (0 to 10 and 10 to 20 cm) are plotted separately. Both soil core depths tend to have the same relative distribution in SQI values. One of the advantages of an index for assessing forest soil quality is that the index values tend to follow a normal distribution even though individual soil properties that are used to calculate the index are often non-normally distributed.

The range of observed SQI values are shown for each region of the country and each soil core depth in box plots (fig. 2). Minimum, mean, and maximum values for each region and soil core depth are summarized in table 2. The south tended to have lower SQI levels than other regions of the country. This is a response to the fact that large areas of more highly weathered soils tend to be concentrated in the south. More highly weathered soils tend to have lower organic carbon and nutrient contents and lower pH levels and higher acidity (as measured by exchangeable Al levels) than soils in less intensively weathered regions of the country. The SQI calculations take this into account. Other considerations being equal, there may be an increased risk of soil-related forest decline on soils with lower SQI levels.

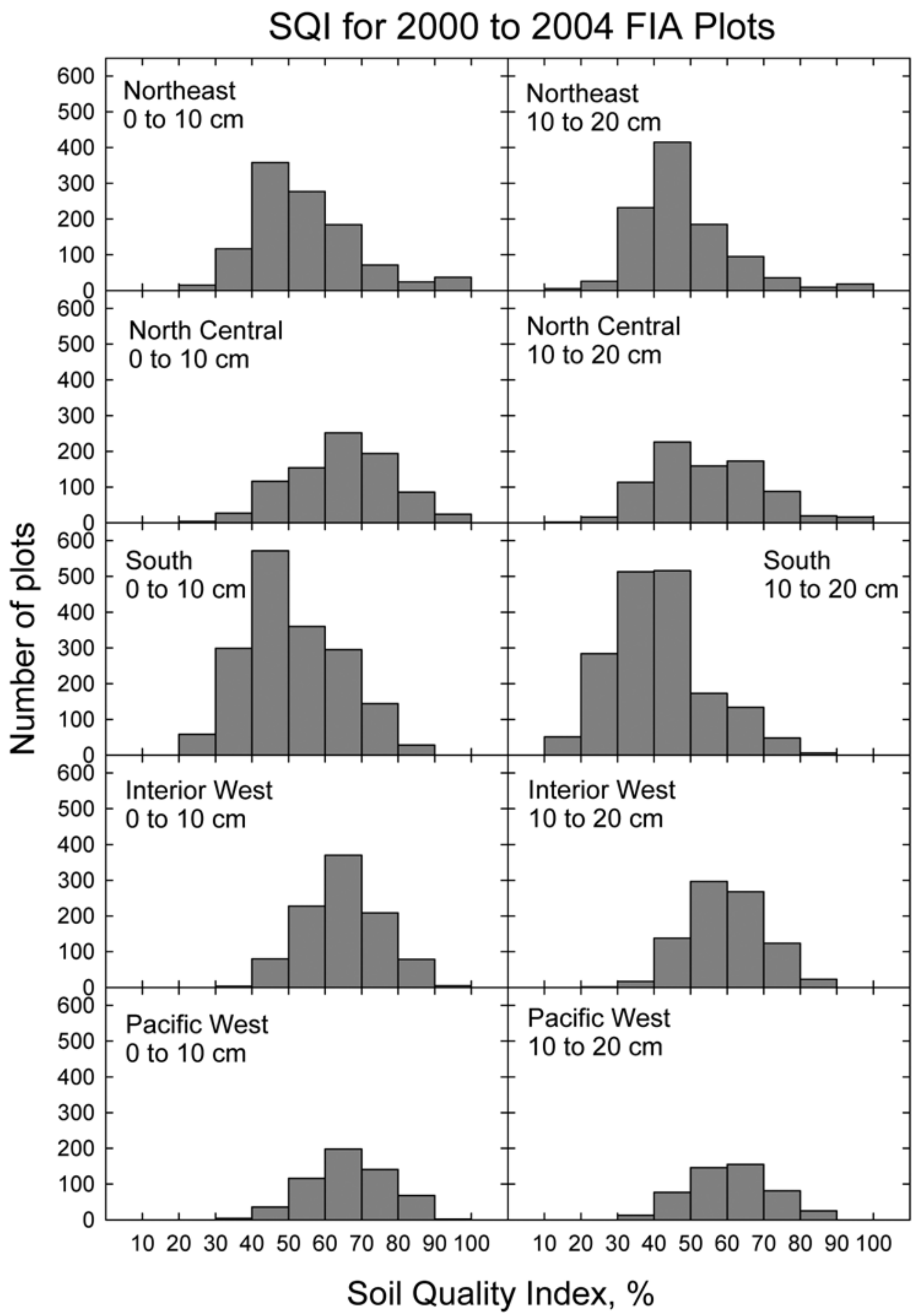

Figure 1—Histogram of SQI levels for the 0 to 10 cm (left) and 10 to 20 cm (right) soil cores from the 2000 to 2004 FIA plots from the Northeast, North Central, South, Interior West, and Pacific West FIA regions of the United States.

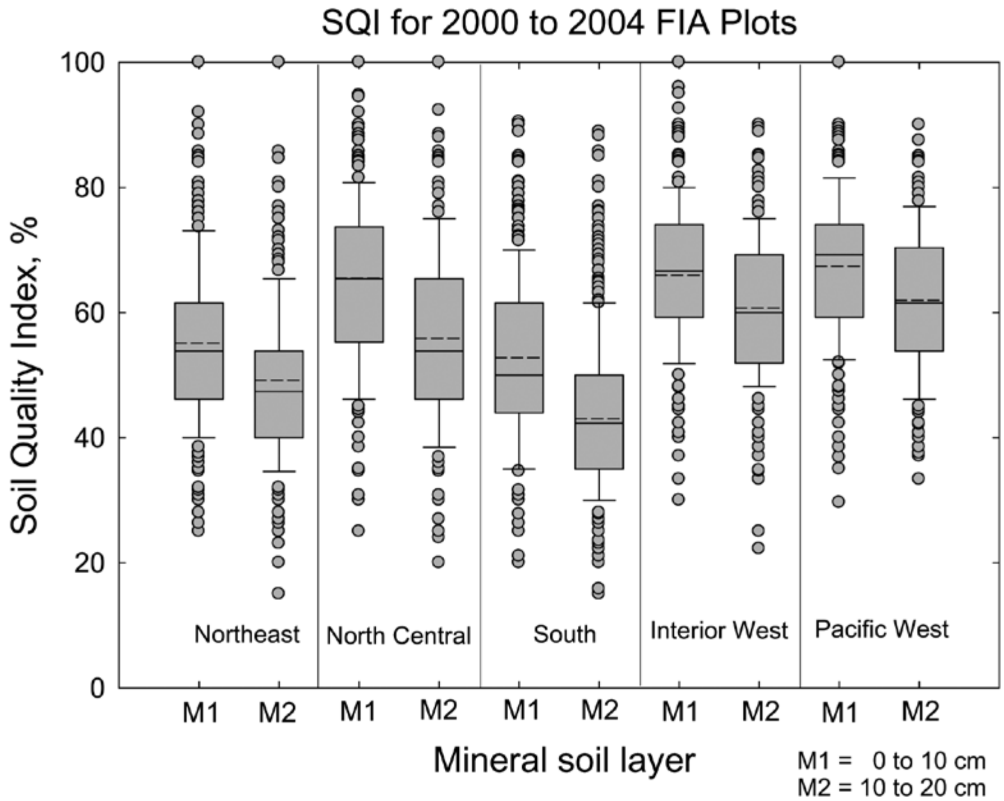

Figure 2—Box plots of SQI levels for the 0 to 10 cm and 10 to 20 cm soil cores from the 2000 to 2004 FIA plots from the Northeast, North Central, South, Interior West, and Pacific West FIA regions of the United States. The 25th and 75th percentiles are shown as a box around the median (solid line) and mean (dotted line), the 10th and 90th percentiles are shown as error bars, and the 5th and 95th percentiles and outlier data points are shown as circles.

Table 2—Minimum, mean, and maximum SQIs of FIA soil samples collected between 2000 and 2004.

Region	Soil mineral layer (cm)	N	Minimum	Mean	Maximum
			- - - - - - - - - - -	*Percent*	- - - - - - - - - -
Northeast (CT, MA, ME, NH, NJ,	0 to 10	1083	25	55	100
OH, PA, RI, VT, WV)	10 to 20	1021	15	49	100
North Central (IA, IL, IN, KS, MI,	0 to 10	857	25	66	100
MN, MO, ND, NE, SD, WI)	10 to 20	813	20	56	100
South (Al, AR, FL, GA, KY, LA, MS,	0 to 10	1757	20	53	90
NC, OK, SC, TN, TX, VA)	10 to 20	1725	15	43	89
Interior West (AZ, CO, ID, MT, NM,	0 to 10	976	30	66	100
NV, UT, WY)	10 to 20	869	22	61	90
Pacific West (CA, OR, WA)	0 to 10	566	30	67	100
	10 to 20	497	33	62	90

However, because risk of decline is dependent on soil and forest type and type of disturbance, these factors must be considered in any assessment of soil-related forest decline.

The 10 to 20 cm soil cores tended to have lower SQI levels than the 0 to 10 cm soil cores (fig. 2, table 2). The 10 to 20 cm soil cores tended to have higher bulk density and lower organic carbon and nitrogen levels than the 0 to 10 cm soil cores, which would skew the SQI levels to lower numbers.

Many soil properties tend to be correlated with each other. Since the SQI is based on 19 measured soil properties, some of these variables are expected to be interrelated. To assess the degree of association among the measured variables, Pearson product moment correlation coefficients were calculated and the highest significant correlation coefficients are presented in table 3.

The variables that were expected to be strongly associated were found to have significantly high correlation coefficients. Soil bulk density is influenced by soil organic matter (SOM) levels because high amounts of lighter weight SOM will result in lower bulk densities. Total organic carbon (TOC) and total N are indirect measures of the amount of SOM. Thus, the negative correlation between bulk density and TOC or total N is expected. Similarly, there is a strong positive correlation between TOC and total N because these are major constituents of SOM. A strong positive correlation between soil pH and exchangeable Ca is expected because high pH soils tend to be calcareous because of the presence of carbonate minerals high in Ca. A strong negative correlation between soil pH and exchangeable Al is also expected, because exchangeable Al is the major source of acidity in strongly acid soils. Exchange sites on clay minerals tend to have more Ca and Mg than other elements, thus accounting for the strong positive association between exchangeable Ca and Mg. Zinc and Cd are group IIB elements in the periodic table and have similar chemistries and reactions in soils. Thus, high levels of extractable Zn tend to be accompanied by high levels of extractable Cd.

The highly interrelated variables such as high TOC and total N, low bulk density, higher pH, low exchangeable Al, and high base cation levels (K, Mg, and Ca) would tend to yield high SQI levels.

Table 3—Significantly high Pearson product moment correlation coefficients among the soil variables.

	TOC[1]	Total N	Ex[2] Mg	Ex Ca	Ex Al	Ex Cd
Bulk density	–0.380	–0.333				
TOC		0.728				
Water pH			0.407	0.648	–0.534	
Ex K			0.394	0.458		
Ex Mg				0.594		
Ex Ca					–0.304	
Ex Zn						0.423

[1]TOC = total organic carbon
[2]Ex = 1 M NH_4Cl extractable

Recommendations for Interpreting and Using SQI Values

The SQI was developed to integrate 19 measured soil physical and chemical properties into a single index number, which can be used to assess trends in forest soil quality and establish baseline levels for different soil and forest types. We urge FIA and FHM analysts and scientists interested in forest health issues to begin exploring any statistical associations between SQI and measures of forest health, including damage, dieback, crown transparency, biomass, productivity, species diversity, lichens, and so forth. If the SQI is able to successfully quantify increased risk of soil-related forest decline, then we expect to find decline associated with low SQI levels. A lack of association, however, may indicate that inaccurate threshold values were selected, other soil properties not measured in the FIA program are contributing to forest decline, or the causative agent of decline is not soils related. More accurate threshold levels and index computational algorithms can be developed only through repeated and rigorous evaluations of the SQI.

Following additional testing and refinement, we anticipate that calculation of SQI values will be done automatically as part of the FIA soil database and made readily available to other scientists. The database can be stratified by ecoregion, forest type, soil type, and so forth. and appropriate population estimates can be calculated. Map products showing the spatial distribution of SQI levels can then be prepared. Soil property threshold levels and weighting factors may need to be refined for different regions of the country to take into account different soil and forest types. This could improve spatial resolution of SQIs within a region.

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Appendix: Rationale for Soil Property Threshold Levels Listed in Table 1

Bulk density—Soil bulk density may indicate soil compaction but is dependent on many soil factors including particle size distribution, soil organic matter content, and coarse fragment content. Generally, bulk density increases with increasing sand and rock content and decreases with increasing organic matter content. A mineral soil with "ideal" physical properties has 50 percent solids and 50 percent pore space occupying a given volume of space. At optimal water content, half the pore space is filled with water. Such a soil will have a bulk density of 1.33 g/cm^3. In general, roots grow well in soils with bulk densities of up to 1.4 g/cm^3 and root penetration begins to decline significantly at bulk densities above 1.7 g/cm^3 (Fisher and Binkley 2000; Sutton 1991). We selected 1.5 g/cm^3 as the threshold value for bulk density, above which there is an increasing probability of adverse effects from soil compaction or high rock content.

Coarse fragments—Soils with a coarse fragment content of > 50 percent to have a greater probability of adverse effects from infiltration rates that are too high, water storage capacity that is too low, more difficult root penetration, and greater difficulty in seed germination and seedling growth. High coarse fragment contents have been shown to limit forest soil productivity (Rodrigue and Burger 2004).

Soil pH—Although many plant species are adapted to acidic or alkaline soils, vegetation diversity tends to decline at strongly acid (pH < 4) or strongly alkaline (pH > 8.5) pH levels. Also, the availability of many plant nutrients (for example, P), non-essential elements (for example, Al, Cd, Pb), and essential trace elements (for example, Mn, Fe, Cu, Zn) is strongly dependent on soil pH (Miller and Gardiner 2001). Generally, metal cations (for example, Mn, Fe, Ni, Cu, Zn, Cd, Pb) become more available as pH decreases, while oxyanions (for example, SO_4) become more available at alkaline pH levels. Only the most acid- or alkaline-tolerant plant species can survive at the very acidic or alkaline ends of the pH scale. Soil pH is also strongly dependent on the chemical weathering environment. Soils in hot, humid areas (for example, southeastern United States) and even mesic, wetter areas (for example, New England, mid-Atlantic, Pacific Northwest) tend to be more acidic than those of much drier areas (for example, portions of the southwestern and interior western United States). Vegetation communities in those areas tend to be adapted to the soil conditions in which they developed. However, few plant communities are adapted to strongly or severely acid soils, particularly if those conditions developed as a result of acidic atmospheric deposition more rapidly than the plant communities could adapt.

Organic carbon and nitrogen—Organic matter is a key component of soils because of its influence on soil physical and chemical properties and soil biota (Fisher 1995). Soil organic matter is composed of many elements, but C and N are two of the most important. The organic C and N contents of soils are the result of all the inputs and outputs and soil forming processes, but generally, higher levels of organic C and N are found in colder and wetter soils (for example, boreal forests, wetlands) where organic matter tends to accumulate. Lesser amounts are found in more intensively weathered soils such as those in the southeastern United States and in hotter, drier areas of the country such as the desert southwest where biomass production is more limited and organic matter breakdown is rapid because of warmer temperatures. Various disturbances and land management practices can result in decreased soil organic matter levels (Henderson 1995; Schlesinger 1997). Soils with total organic carbon (TOC) and total N contents of less than 1 percent and 0.1 percent, respectively, are at a greater risk of decline if soil erosion and/or other disturbances that accelerate organic matter loss continue to result in a net loss of soil organic matter, particularly in areas where nearby undisturbed, native soils are found to have higher levels of TOC and total N (USDA-NRCS-SQI 2003).

Exchangeable cations (Na, K, Mg, Ca, Al)—Generally, exchangeable Ca increases with increasing pH, while high exchangeable Al levels are found in soils with a pH below 5.2. High exchangeable Al levels are deleterious to plant growth, but this can be mitigated somewhat by high organic matter levels (Hargrove and Thomas 1981). High organic matter levels can complex exchangeable Al from mineral soil weathering, thus decreasing Al toxicity to terrestrial plants and aquatic biota. Soils with very low pH, low organic matter, high exchangeable Al, and severely depleted Ca have the greatest risk of being associated with forest decline. Calcium depletion has been identified as a threat to sustainable productivity of southeastern forested watersheds (Huntington and others 2000). Exchangeable Na percentage (ESP) is computed by dividing the exchangeable Na concentration ($cmol_c/kg$) by the effective cation exchange capacity (ECEC)($cmol_c/kg$) multiplied by 100. Soils with an ESP of > 15 percent are classified as sodic or saline/sodic soils depending on the salt content of the soils as measured by the electrical conductivity of a saturated soil extract (Richards 1954). Such soils are found in more aridic areas of the United States and are more likely to exhibit adverse effects (for example, decreased infiltration) associated with too high Na levels than soils with an ESP < 15 percent. Plants growing in soils with very low levels of exchangeable K and Mg (< 100 and 50 mg/kg, respectively) have a greater probability of exhibiting deficiency symptoms than plants growing in soils with higher levels of these elements.

Exchangeable metals (Mn, Fe, Ni, Cu, Zn, Cd, Pb)—Manganese, Fe, Cu, and Zn are essential trace elements. Deficiency symptoms are more likely exhibited at very low levels of these trace elements, particularly in calcareous and sandy soils, and in the case of Cu, in soils high in organic matter (Miller and Gardiner 2001). However, toxicity to plants may be found at very high levels of these trace elements. The exchangeable fraction of these trace metals is the most plant available form in soils next to water-soluble forms. Generally, exchangeable metals extracted by 1 M NH_4Cl increase with decreasing soil pH, provided they haven't been leached from the soil profile. High levels of exchangeable Ni would only be found in some serpentine-derived soils, mining areas, downwind of Ni smelters, or in areas receiving Ni-containing industrial wastes (Kabata-Pendias 2001). High levels of exchangeable Cu, Zn, Cd, and Pb may be found in mineralized or mining areas, downwind of smelters, or in areas receiving metal-containing industrial wastes and in some cases, agricultural waste products and fertilizers (Kabata-Pendias 2001). Soils adjacent to roads may also contain elevated levels of Zn, Cd, and Pb. Threshold values for exchangeable Mn, Fe, Ni, Cu, Zn, Cd, and Pb were selected based on the range and distribution of values within the FIA soil dataset because there is insufficient information relating vegetation response to 1 M NH_4Cl exchangeable metal levels.

Exchangeable S—The dominant form of S in 1 M NH_4Cl extracts is assumed to be sulfate (SO_4). Sulfate is highly mobile in most soils. High levels of exchangeable sulfate would likely only be found in acid soils containing metal oxide minerals that can sorb the sulfate, metal sulfide mineral areas, gypsiferous soils in more aridic regions, and acidic soils receiving large amounts of high-S atmospheric deposition downwind from coal-fired power plants. Volcanic eruptions and ash particles from forest fires can also add significant amounts of S to soils. Sulfur deficiencies would be expected only in soils with very low levels of available S, such as sandy soils and some calcareous and low organic matter soils (Miller and Gardiner 2001). Threshold values for S were selected based on the range and distribution of exchangeable S values in the FIA soil database.

Extractable P—Soil P availability to plants is strongly dependent on the forms of P in soils whose solubility is controlled by soil pH. In acid soils, most plant-available P is associated with Fe and Al oxides and is best extracted with the Bray 1 extractant (0.03 M NH_4F + 0.025 M HCl). The Bray 1 extractant is applicable to soils with a pH below 6.8, but not to near-neutral or alkaline soils because the acid in the extract begins to dissolve Ca phosphates. These Ca phosphates usually release only small amounts of P for plant uptake unless they begin to dissolve under more acid conditions. Generally, deficiency symptoms are not exhibited by plants growing in soils with Bray 1 levels above 15 mg/kg (Soil and Plant Analysis Council 1999). In alkaline soils, most soil P is associated with Ca, either sorbed to carbonate minerals or existing as various Ca phosphate minerals, the most common of which is apatite. The Olsen (pH 8.5, 0.5 M $NaHCO_3$) extractant was developed to measure plant-available P in alkaline soils, but it also works in many acid soils. The bicarbonate ions release P sorbed to many mineral surfaces that is plant available without dissolving the otherwise plant-unavailable P in Ca phosphates. Plants growing in soils with Olsen-extractable P levels above 10 mg/kg generally will not show a response to added P (Soil and Plant Analysis Council 1999). Because water quality, as measured by algal growth, is strongly dependent on levels and forms of P in receiving waters, soils with very high levels of extractable P may have a deleterious effect on water quality if such soils are subjected to erosion and the soil particles end up in receiving waters.

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