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Biological indices of soil quality: an ecosystem case study of their use

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Abstract

Soil quality indices can help ensure that site productivity and soil function are maintained. Biological indices yield evidence of how a soil functions and interacts with the plants, animals and climate that comprise an ecosystem. Soil scientists can identify and quantify both chemical and biological soil-quality indicators for ecosystems with a single main function, such as agricultural lands and forest plantations. However, quantifying these indices in complex ecosystems — that have multiple uses or goals such as maintaining biodiversity, aesthetics, recreation, timber production and water quality — is much more difficult. In an ecosystem context all components — plants, animals and humans — interact with the soil differently, making soil quality indices variable. These interactions result in a combination of biological processes that make each ecosystem unique. We examined the soil and site quality of five forest stands (xeric oak-pine; two mixed hardwood, cove hardwood, northern hardwood), within the 2185-ha Coweeta Hydrologic Laboratory. An initial rank of soil quality based on soil chemical and physical properties was assigned. The ranking was then compared with four common groups of soil biological indicators: (1) nitrogen availability; (2) litter decomposition; (3) soil microarthropod populations; and (4) carbon availability. We also examined estimates of overstory productivity, overstory biodiversity and total aboveground productivity for each site as indices of site quality. We found that soil and site quality rankings varied with the indicator, showing that the soil or site of greatest quality may change depending on the use or goal of the ecosystem under examination. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

"...soil science still has to fight for recognition. Its heaviest burden is its present dependence on Agricultural Chemistry, which, primarily an applied science, has to subserve practical purposes" (Ramann, 1928). Dr. Ramann hoped that "the period during which the properties of soils were studied only with regard to their practical application to the growth of plants is now drawing to a close, and the newer view is beginning to meet general approval — the view that the soil should be considered as a subject for pure scientific research." Although appealing to soil scientists, studying soil for its own sake is as impractical as

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studying plant growth or environmental quality while ignoring the soil component of the system. Doran and Parkin (1994) identified the three main functions of soil:

1. to act as a medium for plant growth;
2. to regulate and partition water flow; and
3. to serve as an environmental buffer.

Soil scientists have always endeavored to link soil type and soil variables to potentials or limitations of land use. This is evident in the estimates of forest and agricultural productivity as well as use for recreation, wildlife, building and other uses listed in county soil surveys. As pressures on available land and issues of its proper use increase, so does the movement to identify and set standards of quality for both agricultural and forest soils. The definition of soil quality is "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health" (Soil Science Society of America, 1997). Soil quality is a combination of the physical, chemical and biological properties that contribute to soil function. Indicators of soil quality should be responsive to management practices, integrate ecosystem processes, and be components of existing, accessible data bases. These indicators must be quantified to document the improvement, maintenance or degradation of soil quality (Larson and Pierce, 1994). Quantifying these variables through long-term monitoring may lead to an understanding about the effects of land management practices and natural or human-caused disturbances on the soil component of ecosystems. However, as with any indicator or experiment, an appropriate baseline or reference is critical to its utility and interpretation.

Soil formation entails the interaction, over time, of inherent site factors such as parent material, temperature, rainfall patterns and vegetation, insect, animal and microbial populations (Ramann, 1928; Jenny, 1941). Because these factors are complex and the effects of land-use history are lasting, soil quality can be difficult to characterize. Indicators of soil quality for soil with a single primary use or function can be established to maintain or improve that specific soil function. In agricultural or plantation soils, where plant production is the primary function, the chemical, physical and biological properties that contribute to a high quality soil can be identified and used to preserve nutrient availability, soil structure and bulk density for optimal root growth and soil utilization. However, management of soils for a specific application should not preclude changes in land use in the future (Eijsackers, 1998).

When examining an ecosystem or plant community composed of many species, additional problems of quantifying soil and site quality emerge. Each plant species in the community may differ in its response to changes in certain aspects of soil quality, and these differences may change with plant age (Chapin et al., 1986; Ryan et al., 1997). Nutrient cycling processes in forest ecosystems make them fundamentally different from agricultural systems involving annual crops. The internal cycling of nutrients in forests allows growth on soils that would have limited value for crop production (Perala and Alban, 1982). In general, native plants have lower maximum growth rates and may not respond to nutrient additions (Chapin et al., 1986).

In this paper, we examine the relationships among several groups of soil biological quality indicators and soil chemical and physical properties. After discussing the biological indicators, we apply them to five sites within the Coweeta Hydrologic Laboratory. Soil quality is also compared with common measures of site quality — wood production, aboveground net primary productivity and overstory biodiversity.

2. Biological indicators of soil quality

Biological indicators represent different aspects of soil quality in different ecosystems (Elliott, 1997). These indicators strive to monitor or measure three basic functions or parameters:

1. soil structure development;
2. nutrient storage; and
3. biological activity (Gregorich et al., 1994).

Many indicators relate to the cycling of soil organic matter, a key component of soil quality (Gregorich et al., 1997). Soil organic matter is important for nutrient availability, soil structure, air and water infiltration, water retention, erosion and the transport or immobilization of pollutants. Many biological indicators of soil quality measure the processes or components of soil organic matter accumulation and

mineralization. Biological indicators often recommended include: nitrogen mineralization, microbial biomass, microbial biomass to total carbon ratios, soil respiration, respiration to microbial biomass ratios, faunal populations and rates of litter decomposition (Anderson, 1994; Duxbury and Nkambule, 1994; Linden et al., 1994; Rice and Garcia, 1994; Sparling, 1997; van Straalen, 1997). For discussion purposes we have combined these indicators into four groups:

1. nitrogen availability;
2. litter decomposition and forest floor characteristics;
3. fauna populations; and
4. carbon availability.

2.1. Nitrogen availability

Nitrogen availability is a common indicator of soil quality. Nitrogen mineralization (N_{min}) is the release of inorganic nitrogen from soil organic matter. This process is regulated by soil properties, such as quality of soil organic matter, microbial biomass and activity and soil temperature and moisture. Measured rates of soil N_{min} conducted either in the laboratory or in situ are used as indices of N availability to plants. Powers (1990) found that using the ratio of N_{min} to total soil N takes variability among sites into account and places the focus on the environmental controls of N_{min}.

N_{min} is useful as an indicator because it is very responsive to site disturbance (Bormann and Likens, 1967) although it does exhibit considerable spatial and temporal variability. Disturbances such as insect outbreaks, forest management practices, and climatic variations, often lead to increases in the rates of soil N_{min} with the potential for short-lived N losses from the ecosystem (Vitousek, 1983; Swank et al., 1988; Waide et al., 1988; Donaldson and Henderson, 1990). These increased rates of N_{min} suggest a more rapid cycling of organic matter and greater amounts of nutrients available to support soil macro- and microorganisms and early successional vegetation growth. However, when N availability exceeds the uptake capabilities of site vegetation and soil microorganisms in undisturbed ecosystems the sites are said to be N saturated (Aber et al., 1989). Nitrogen saturation can negatively affect soil quality and ecosystem function. The presence of NO_3 in subsoil solutions represents the potential for N to leave the soil system through leaching. Nitrate leaching may also result in the leaching of base cations that diminishes soil quality through nutrient losses and may also decrease water quality by increasing NO_3 concentration.

Results have varied in studies examining the relationship between N_{min} and site productivity. In some studies N_{min} rates correlate well with site productivity and forest growth (Keeney, 1980) while in others they do not (Grigal and Homann, 1994). Reich et al. (1997) extensively studied the relationship between N_{min} and aboveground net primary productivity (ANPP) across Wisconsin and Minnesota and found that it varied with soil order and soil texture. Both ANPP and N_{min} were more dependent on soil type and parent material than on forest type. However, within localized areas, rates of soil N_{min} differ with forest type, elevation and topographic position (Powers, 1990; Garten and van Miegroet, 1994; Garten et al., 1994; Knoepp and Swank, 1998). These differences are attributed to site variations in soil organic matter quality, temperature and soil water availability (Powers, 1990; Garten et al., 1994).

2.2. Litter decomposition and forest characteristics

Litter decomposition is a useful biological indicator involving the interaction of vegetation, soil nutrient availability, micro- and macrofauna and microbial populations. The end result is the forest floor. Decomposition rates can provide an accurate prediction of soil and site quality or productivity (Johansson, 1994). Increasing rates of litter decomposition accelerate nutrient cycling rates within the site and indicates increased soil quality. The formation of the forest floor is a long-term process that is indicative of the nutrient cycling rate on a site. The humus layer in forests plays an important role in forest growth on soils that are too low in nutrients for agricultural crops (Perala and Alban, 1982), because the roots of many forest species utilize nutrients in this layer. Rauland-Rasmussen and Vejre (1995) found that roots of plantation trees utilized the forest floor more extensively on sandy soils than on loamy soils with higher nutrient availability. The mass of the humus or Oa layer can, therefore, be used as an index of overall nutrient availability, building up on sites where litter decomposes slowly or nutrients are limiting. Coarse woody

debris (CWD) may persist for hundreds of years as part of the forest floor (McFee and Stone, 1966) and could, therefore, be used as an index of long-term forest floor processes. CWD represents a large C pool, affects soil development, reduces erosion, and provides nutrients, water and habitat for decomposers and heterotrophs (Harmon and Hua, 1991).

On a global scale, rates of litter decomposition are regulated by climate (Johansson et al., 1995). However, within a particular climatic region, litter chemistry is the best indicator of decomposition rates (Aerts, 1997). In a comparison of decomposition rates of western red cedar, western hemlock and lodgepole pine, Keenan et al. (1996) found that litter species, not site microclimate differences, regulated decomposition rates. They concluded that litter type controlled site differences in N availability. Taylor et al. (1991) found that litter quality generally controls rates of decomposition, regardless of the environmental condition. Improving overall litter quality by mixing slow and rapidly decomposing litter types yields rates most similar to the rapidly decomposing species (Taylor et al., 1989).

Rates of decomposition and patterns of nutrient release are indicative of site nutrient availability. Foliar nutrient content is often representative of soil nutrient content or availability (Stump and Binkley, 1993; Wang and Klinka, 1997). Nutrient release and immobilization patterns during the initial phases of decomposition suggest which nutrients are limiting on a site (Monleon and Cromack, 1996). However, Prescott et al. (1993) found that foliar concentrations of N and phosphorus influenced immobilization during decomposition, but were not related to soil nutrient availability. Fertilization and nutrient additions may not increase rates of decomposition (Lukumbuzya et al., 1994; O'Connell, 1994). Lukumbuzya et al. (1994) hypothesized that fertilizers negatively affect forest floor decomposer populations.

2.3. Fauna populations

Soil fauna (arthropods and invertebrates) populations influence soil biological processes, nutrient cycling and soil structure. Several properties or functions of soil fauna can be used to indicate soil quality: the presence of specific organisms and their populations or community analysis (functional groups and biodiversity) and biological processes such as, soil structure modification and decomposition rates (Linden et al., 1994). Measurements of soil fauna may be difficult due to spatial and temporal variation (Powers et al., 1998). However, stratified sampling procedures mitigate some of these problems and the abundance of soil fauna has been linked to litter quality and nutrient cycling rates. Soil arthropods affect soil quality directly and indirectly depending on their size and specific activity. Macroarthropods (millipedes, centipedes, insect larvae, termites, ants and others) have the ability to modify soil structure by decreasing bulk density, increasing soil pore space, mixing soil horizons and improving aggregate structure (Abbott, 1989). Arthropods and earthworms can rearrange the soil profiles, mixing soil horizons through burrowing and nest-building activities. Depending on the densities of the arthropod populations, the effects of their activities range from minor to major disruptions. The term insect mull has been used to describe forest floors whose O and A horizons have been restructured by the activities of macroarthropods.

Microarthropods, primarily mites and collembolans, affect soil structure indirectly and nutrient cycling directly (Powers et al., 1998). Some microarthropods feed on decomposing litter, reducing its mass and exposing broken surfaces to increased rates of nutrient release (Lussenhop, 1992). Others feed on fungal hyphae, even scraping hyphae from root surfaces or on soil bacteria, increasing nutrient cycling and affecting soil aggregation. Field experiments using insecticides show that excluding microarthropods reduces rates of forest litter decomposition (Seastedt and Crossley, 1983; Blair et al., 1992).

2.4. Carbon availability

The availability of carbon (C) is important in controlling nutrient cycling and soil biological activity. It is more advantageous to use a suite of variables that characterize C availability, such as CO_2 efflux, microbial biomass C (C_{mic}), respiratory quotient (qCO_2); and the microbial efficiency quotient (qC_{mic}) to evaluate soil quality. Soil CO_2 efflux is an index of total soil biological activity including soil microorganisms, macro-fauna and plant roots. Measurement of CO_2 efflux yields an index of total carbon availability. As noted by Sparling (1997), microbial respiration

(which is often the bulk of soil respiration) is highly variable and can show wide natural variation depending on substrate variability, moisture and temperature. The variability in respiration makes this measure, taken alone, difficult to interpret in terms of soil quality or health. To compensate for spatial variability, Dulohery et al. (1996) used large static chambers, 0.5 m×1.0 m, to measure CO_2 flux from timber harvested areas mitigated by bedding and fertilization. They found a 34% decrease in CO_2 efflux rates from plots where severe soil damage had occurred. To detect more subtle differences between soils, respiration measurements are often made under controlled laboratory conditions (Sparling, 1997).

Respiratory quotients (qCO_2) (g CO_2-C h^{-1} (mg $C_{mic})^{-1}$) , have been recommended by Anderson and Domsch (1990) and Insam and Haselwandter (1989) to investigate soil development, substrate quality, ecosystem development and ecosystem stress. Brooks and McGrath (1984) observed higher respiratory quotients in soils containing heavy-metal contaminated sewage sludge, compared with control soils containing no heavy metals. However, Wardle and Ghani (1995) found that the qCO_2 might be insensitive to disturbance and ecosystem development, failing to distinguish between disturbance and stress. Their findings suggest that this indicator does not decline predictably as ecosystems develop or along successional gradients.

3. Ecosystem case study

We used N-availability; litter decomposition and forest floor characteristics; soil fauna; and C availability as biological indicators to estimate soil quality on five sites located within the Coweeta Hydrologic Laboratory and compared them with aboveground measures of forest site quality. These sites have been extensively studied as part of Coweeta's Long-Term Ecological Research Program. Our five study sites represent a gradient in both vegetation and elevation within the Laboratory and include xeric oak–pine (OP), cove hardwood (CH), mesic mixed-oak low elevation (MO-L), mesic mixed-oak high elevation (MO-H) and mesic northern hardwood (NH) vegetation types (Table 1). Elevations range from 782 m at OP to 1347 m at NH and growing season (May through October) precipitation varies from 884–1121 mm with higher precipitation at higher elevations (Lloyd W. Swift, Jr., unpublished data). Table 1 presents information about each site including dominant vegetation, landscape position, soil series and soil subgroup.

The soil quality at each of the five sites was ranked using the soil chemical and physical characteristics (CP rank) including; total C and N concentrations, cation (K, Mg and Ca) concentrations, P concentrations, pH and bulk density (Table 2). Sites were ranked for each of the variables listed using 1 as the lowest

Table 1
Selected characteristics of the elevation gradient stands[a]

Site	OP	CH	MO-L	MO-H	NH
Elevation (m)	782	795	865	1001	1347
Aspect (deg)	180	340	15	75	20
Slope (deg)	34	21	34	33	33
Vegetation type	oak-pine	cove hardwoods	mixed oak	mixed oak	northern hardwoods
Dominant species	*Kalmia latifolia*, *Quercus prinus*, *Q. rubra*, *Carya* spp.	*Liriodendron tulipifera*, *Quercus rubra*, *Tsuga canadensis*, *Carya* spp.	*Rhododendron maximum*, *Quercus coccinea*, *Q. prinus*	*Rhododendron maximum*, *Quercus rubra*, *Q. prinus*	*Betula allegheniensis*, *Liriodendron tulipifera*, *Quercus rubra*
Moisture regime	xeric	mesic	mesic	mesic	mesic
Soil series and subgroup (s)	Evard/Cowee, Chandler, Edneyville/Chestnut, Typic Hapludults, Typic Dystrochrepts	Saunook, Tuckaseegee, Humic Hapludults, Typic Haplumbrepts	Trimont, Humic Hapludults	Chandler, Typic Dystrochrepts	Plott, Typic Haplumbrepts

[a] Data compiled from Coweeta Long-term Ecological Research Program records.

Table 2
Data used to establish site ranking based on the soil chemical and physical characteristics of five sites in the Coweeta Hydrologic Laboratory basin[a]

Site	N (%)	C (%)	pH	Ortho-P ($mg\ kg^{-1}$)	Ca ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)	Bulk density ($g\ cm^{-3}$)
OP	0.1 (0.01)	3.3 (0.3)	3.9 (0.04)	1.7 (0.2)	28 (6.9)	61 (6.0)	19 (2.0)	0.75 (0.02)
CH	0.3 (0.02)	5.5 (0.3)	4.2 (0.04)	1.6 (0.1)	112 (14.0)	89 (6.8)	38 (2.9)	0.78 (0.03)
MO-L	0.2 (0.01)	4.4 (0.2)	4.0 (0.05)	1.2 (0.1)	49 (7.8)	69 (5.5)	25 (1.9)	0.80 (0.03)
MO-H	0.2 (0.01)	5.6 (0.4)	4.0 (0.03)	1.4 (0.1)	28 (6.7)	67 (6.2)	19 (1.5)	0.75 (0.04)
NH	0.7 (0.03)	9.9 (0.4)	4.0 (0.03)	1.3 (0.1)	441 (81.4)	83 (4.5)	55 (9.4)	0.54 (0.01)
Site/rank	Site ranking for above variable							
OP/1	1	1	1	1	1	1	1	1
CH/3	3	2	2	1	1	2	2	1
MO-L/2	2	1	2	1	1	1	2	1
MO-H/2	2	2	2	1	1	1	1	1
NH/4	4	3	2	1	2	2	3	2

[a] Ranking is based on significant differences among sites for each variable. Rank of 1 is lowest and 5 highest, rank values are summed and totals used to rank sites for overall chemical and physical quality.

quality value. Rank value assignments were based on significant differences among sites. Tukey's mean separation test (α=0.1) was conducted on data collected in replicate over two years or more to determine signficant differences. For other data presented; decay rates, ratios and calculated values such as diversity, we selected a 15% difference as a biologically significant difference. Rank values for all variables within each of the four biological indicator groups were summed for each site. Site ranking was based on the sum of the indicators for each group. This system resulted in the CP soil quality ranking of sites as OP<MO-L=MO-H<CH<NH (Table 2). In subsequent tables, sites are listed in order of CP quality ranking.

3.1. Nitrogen availability

Rates of in situ N mineralization were measured (surface 0–10 cm) 4–8 times annually for 6 years (1991–1996) on the five sites using the closed core method (Knoepp and Swank, 1995, 1998). Calculated annual rates of N mineralization followed a similar pattern as the general CP rank. OP, MO-H and MO-L had the lowest rankings, then CH and NH (Table 3). These data suggest, as others have found, that N mineralization is positively correlated with CP Ranking of soil quality. We also examined the annual net N mineralization data as a proportion of total soil N, mg N_{min} $(g\ N_{tot})^{-1}$ (N_{min}/N_{tot}) (Table 3). Powers (1990)

Table 3
Soil quality indicators examining nitrogen availability on five sites in the Coweeta Hydrologic Laboratory basin

Site/rank[a]	N_{min}[b] ($mg\ N\ kg^{-1}$ per 28 days)	$N_{min}N_{tot}^{-1}$[c] (N_{min} $(g\ N_{tot})^{-1}$)	N_{loss}[d] (%)
OP/3	1.90 (0.48)	1.9	19
MO-L/2	1.87 (0.22)	1.9	28
MO-H/1	1.89 (0.44)	1.9	50
CH/4	6.35 (1.14)	2.1	12
NH/2	33.07 (3.07)	4.7	87

[a] Site rank for nitrogen availability.
[b] Average growing season N_{min} measured using in situ closed cores from 1991–1996.
[c] Nitrogen mineralized per g total N per kg soil.
[d] Percent of months sampled where NO_3-N was greater than baseline concentration (0.005 mg NO_3-N l^{-1}) in subsoil lysimeters (>30 cm).

found that this approach removed some site variability and produced a strong positive relationship between mineralization and mean annual soil temperature (r^2=0.68) which decreased along an elevational gradient. This analysis of the mineralization data changed the ranking of soil quality. On a basis of N_{min}/N_{tot}, the four sites were the same OP, MO-L, MO-H and CH. NH was still ranked highest, mineralizing the most soil N for each gram of total N present. These data suggest that the quality of organic N at NH is superior to the other sites.

The loss of N from soils can be detrimental to the site as well as the surrounding ecosystem. Table 3 presents potential N leaching (N_{loss}) as the percent of total months (n=32) sampled where NO_3-N concentrations in soil solutions just above the B horizon were above baseline (>0.005 NO_3-N mg l^{-1}). Each gradient plot has 10 lysimeters, five located 15 cm in the soil and five placed just above the Bt or Bw horizon (>30 cm) on all sites. Lysimeters were sampled each week and composited monthly for analysis. The N_{loss} index showed high potential NO_3-N leaching from NH. This suggests that this site has or is reaching N saturation and N_{min} is occurring at a rate greater than the vegetation and microbial population can immobilize it. The other high elevation site, MO-H, also had a significant N_{loss} value.

Combining all the N availability indices (N_{min}, $N_{min}N_{tot}^{-1}$ and N_{loss}), we developed an overall ranking for the five sites (Table 3). This ranking reveals that the high elevation mixed-oak site(MO-H) is the poorest quality site, with low N_{min}, low N quality ($N_{min}N_{tot}^{-1}$) and relatively high N_{loss}. The cove hardwood site had the highest ranking, with relatively high N mineralization rates and the lowest potential leaching value.

3.2. Litter decomposition and forest floor

Litter decomposition rates and forest floor characteristics yield information about the quality of litter as well as rates of nutrient cycling within an ecosystem. Litter decomposition rates were determined on the five sites where litterbags (2-mm mesh), were left in place, placed within the forest floor for 1 year. Three species were tested, two overstory species, *Liriodendron tulipifera* and *Quercus prinus* and one evergreen understory species, *Rhododendron maximum*. On average, the two mixed-oak sites, MO-H and MO-L had the highest decay constant, followed by NH, OP and CH (Table 4).

Characteristics of the forest floor also indicate how rapidly nutrients cycle through the forest. Table 4 shows that MO-H has the greatest accumulation of Oa horizon, while the Oi is one of the lowest, suggesting low litter inputs and slow long-term decomposition rates. MO-L and OP both have Oa accumulation with large Oi horizons. Large amounts of coarse woody debris are used here as an index of forest floor stability. NH has the greatest accumulation of CWD probably due to its position in the landscape and low temperatures, which may limit decomposition at this high elevation site. OP, the warmest site with a southern aspect has the lowest amount of CWD and a moderate decomposition rate. The cove hardwood site ranks second in both CP ranking and N_{min}, yet has the lowest decomposition rate which suggests that other factors limit decomposition on this site. Ranking the

Table 4
Litter decay and forest floor characteristics in five representative sites in the Coweeta Hydrologic Laboratory basin

Site/rank[a]	Decay constant[b]	Forest floor mass[c] (kg ha^{-1})		CWD[d] (kg ha^{-1})
		Oi	Oa	
OP/2	−0.37	4648 (577)	16379 (2067)	39753
MO-L/2	−0.45	3486 (244)	16154 (1586)	45825
MO-H/2	−0.41	2839 (201)	21500 (2412)	47051
CH/1	−0.34	2169 (282)	3591 (1300)	45481
NH/3	−0.37	2961 (282)	3192 (986)	56321

[a] Site rank for litter decay and forest floor characteristics.
[b] Hoover and Crossley, 1995.
[c] Forest floor mass by horizon, standard error in parentheses.
[d] Total coarse woody debris (material >10 cm diameter and 1 m length).

Table 5
Soil oribatid mite populations in five representative sites in the Coweeta Hydrologic Laboratory basin (After Lamoncha and Crossley, 1998)

Site/rank[a]	N[b]	# spp.[c]	J[d]	H'[e]
OP/3	2237	78	0.752	3.28
MO-L/4	2234	96	0.746	3.41
MO-H/4	2192	92	0.761	3.44
CH/1	570	64	0.876	3.64
NH/2	1454	81	0.793	3.48

[a] Site rank for oribatid mite populations.
[b] Abundance of individuals collected.
[c] Total number of oribatid mite species identified.
[d] Pielow's evenness index.
[e] Shannon–Wiener biodiversity index.

five sites shows that NH ranks highest for forest floor processes with moderate litter decomposition, little accumulation in the Oa horizon and a large pool of CWD (Table 4).

3.3. Fauna populations

All five forest stands contain a high diversity of soil arthropod species. Arthropod sampling using Berlese funnel extraction of soil cores, 5-cm diameter and depth, revealed 135 species of Oribatid mites across the five sites, making Coweeta one of the most diverse forest sites documented. Numbers of microarthropod species (<1.5 mm) varied between sites (Table 5). Abundance (individuals per sample) was lowest in CH; this site also had the lowest ranking for litter decomposition and forest floor characteristics. Diversity indices (H'), however, indicated that all sites had high biodiversity of Oribatid mites, with high dominance, and evenness (J). The measures of arthropod populations, total numbers or community analysis may yield different results. But by any measure, biodiversity of soil arthropods is high in these forest stands. Overall, MO-L and MO-H rank highest among the five sites in the fauna population indicator group.

3.4. Carbon availability

Several variables were examined as indices of soil C availability and its turnover and microbial activity (Table 6). Measurements included microbial biomass carbon (C_{mic}) (μg C (g soil)$^{-1}$) determination using chloroform fumigation, CO_2 flux via dynamic closed-chamber method. C_{mic} values ranked all sites similarly except NH with the greatest amount of C_{mic}. Mean soil CO_2 fluxes were greatest at MO-L and MO-H. Another measure of C turnover and microbial activity is qCO_2. This is the amount of CO_2 evolved from the soil as a function of the microbial biomass (μg CO_2-C h^{-1} (μg C_{mic})$^{-1}$); a lower value suggests greater microbial efficiency. Table 6 shows that OP has the lowest microbial carbon quotient, while NH has the greatest. Microbial quotient (qC_{mic}, μg C_{mic} (g C_{tot})$^{-1}$) is an estimate of organic matter quality. NH has the highest value, suggesting it has the highest quality organic matter. NH ranked highest for overall C availability.

4. Comparison with common measures of site quality

A more traditional view of soil or site quality examines the forest present on a site either in terms

Table 6
Soil carbon (C) availability in five sites in the Coweeta Hydrologic Laboratory basin

Site/rank[a]	CO_2 flux (mg C m^{-2} h^{-1})	C_{mic}[b] (μg C (g soil)$^{-1}$)	qCO_2[c] (mg C_2 h^{-1} (g C_{mic})$^{-1}$)	qC_{mic}[d] (μg C_{mic} (g C_{tot})$^{-1}$)
OP/1	271 (17)	520 (98)	69	21
MO-L/2	310 (17)	801 (160)	52	21
MO-H/2	307 (17)	743 (64)	51	19
CH/2	219 (14)	865 (137)	32	20
NH/3	186 (11)	1673 (375)	20	31

[a] Site rank for soil carbon availability.
[b] Microbial biomass carbon.
[c] Respiratory quotient.
[d] Microbial carbon quotient.

of productivity or composition. Site productivity is a function of climate, soil properties and the biotic potential of the vegetation occupying the site. We examined site productivity in two ways: (1) wood production; and (2) aboveground net primary productivity. Wood production, expressed as overstory net primary productivity (ONPP) in Mg ha^{-1} per year, was calculated from the measurement of all overstory individuals on the LTER plots for three consecutive years. Morris (1997) suggests that total annual litterfall (Mg ha^{-1} per year) is an appropriate index of total aboveground net primary productivity. Litterfall, which includes both overstory and understory species, but excludes herbaceous materials, was collected monthly with ten 1-m^2 littertraps on each site; data represent 2 years of monthly collections (Crossley, unpublished data). Wood production was lowest on MO-L and greatest on MO-H (Table 7). For OP and NH, the sites with the lowest and highest CP ranking, respectively, wood production was equal. Understory vegetation measurements change the outcome. Measurements of total productivity based on annual litterfall rank MO-L and MO-H the highest; these sites had the lowest and highest estimate of wood production, respectively.

Another value of forests in the southern Appalachians is their high biodiversity. Biodiversity results from competition among species for coexistence on a site (Huston, 1993). High biodiversity of an ecosystem implies its resilience — an ability to recover and respond to stress or change (Franklin et al., 1989). The Shannon–Wiener biodiversity index (H') was calculated for each site using the overstory basal area measured in 1996. All sites had approximately equal diversity of overstory tree species (Table 7).

Table 7
Overstory net primary productivity (ONPP), annual litterfall and overstory biodiversity on five sites in the Coweeta Hydrologic Laboratory basin

Site	ONPP[a] (Mg ha^{-1} per year)	Annual litterfall[a] (Mg ha^{-1} per year)	H'[b]
OP	4.0	3.2	2.25
MO-L	2.8	*3.8*	1.96
MO-H	*5.0*[c]	*3.8*	2.14
CH	3.8	2.8	2.04
NH	4.0	2.6	1.93

[a] ONPP and litterfall significant difference 15%.
[b] Shannon–Wiener biodiversity index.
[c] Values in italic print rank highest for that indicator.

In order to compare sites and estimate overall soil/site quality, we ranked the five sites using the soil indicators discussed here, biological and chemical or physical quality and the aboveground indices — wood production, net primary productivity and biodiversity. Overall, soil biological quality was highest for OP and MO-L, with the highest scores in N availability, C availability, and fauna population groups of indicators. Based solely on soil chemical and physical properties, NH ranks highest with the greatest cation, C and N concentration and lowest bulk density. When we examine the overstory indicators of site quality again we see that the highest quality site is dependent on the goal set for that site. In terms of wood production, MO-H is the highest quality site. The two mixed oak sites (MO-L and MO-H) have the highest productivity using the total litterfall index. However, if site goals were to maximize biodiversity then all sites are high quality sites.

An important component of site quality that is not included in soil or overstory quality indices but weighted heavily when policy decisions are made is the value humans put on a site. For example, an old growth site has generally high N_{loss} rates due to leakage of N to the surrounding streams, depletion of soil nutrients by aboveground sequestration, and rather low overstory productivity. However, people place a high value on these few remaining sites that are therefore, considered to be of very high quality. Another example is the xeric oak–pine vegetation type which is in severe decline in the southern Appalachians. Several years of drought (1985–1988) followed by southern pine beetle infestation reduced the land coverage of this ecosystem within the Coweeta basin from 40 ha in 1971 to 0.9 ha in 1988 (Smith, 1991). This resulted in experimentation and treatment of these highly degraded sites to regenerate this community type through the use of cutting and prescribed burning using various methods (Clinton et al., 1993) to maintain the high biodiversity of the region.

5. Conclusions

Setting and monitoring soil quality indicators is important to ensure that soil function is maintained,

not only for the current land use, but also for potential future uses. The difficulty in determining appropriate indicators and their values for multiple use sites increases in complexity as we try to combine soil chemical, physical and biological variables. This case study example shows that using soil chemical, physical and biological indicators to rank soil quality is difficult, even over a small spatial scale. Ranking the soil quality indicators to conduct an unbiased comparison of a given number of sites allows the synthesis of many diverse soil and vegetation variables. However, the resultant ranking of soil or site quality is dependent on the objective or goal for that specific site. Attempting to determine the quality of a soil or a site, removed from the larger ecosystem in which it exists is inappropriate. Determining overall site quality is complex and must consider soil, vegetation and the surrounding ecosystem as well as potential changes in land use and societal needs. If soil and site quality indicators are going to be useful to land managers and decision-makers more integrated work is needed to develop appropriate indicators and their values.

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