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Vladimir Yakovchenko · Lawrence J. Sikora
Donald D. Kaufman

A biologically based indicator of soil quality

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Abstract Soil quality indices are attempts to classify soil conditions and to compare these conditions to their historical use. From this information it may be possible to determine which uses of soils are better for the long-range goals of agriculture and society. With many factors involved in the profitable production of safe foodstuffs without significant degradation of the environment and soils, an indicator that represents a broad biological perspective of quality is appropriate. Among a group of biological indicators, the ratio of crop N uptake to mineralized N as determined by microbial respiration plus net mineralized N found over a growing season is an useful indicator of soil quality. An evaluation of the 12-year-old Farming Systems Trial at the Rodale Institute Research Center indicated that soils in plots that had been conventionally managed were of lower quality than soil treated with manure or planted with legume-cash grain crops.

Key words Crop productivity · Microbial biomass · Cash grain · Conventional farming · Low-input agriculture · NH uptake

Introduction

The term soil quality is used with increasing frequency in both the popular and scientific press. Larson and Pierce (1991) defined soil quality as the physical, biological and chemical properties that (1) provide a medium for plant growth, (2) regulate and partition water flow in the environment, and (3) serve as an environmental buffer in the formation, attenuation, and degradation of environmentally hazardous compounds. Doran and Parkin (1994) defined soil quality as the capacity of the soil to function within ecosystem boundaries, maintain environmental quality, and promote plant, animal, and human health. Parr et al. (1992) stated that soil quality should serve as an indicator of change in both the soil's ability to produce optimum levels of safe and nutritious food, and its structural and biological integrity, which in turn is related to the status of certain degradative processes and to environmental and biological plant stress.

Soil quality traditionally has focused on, and has been equated with, agricultural system productivity or, more simply, system productivity. Crop yield is an important indicator of system productivity, which is in part dependent upon soil quality. Crop yield can serve as a bioassay for several interacting factors such as soil, water, air, disease, germplasm, and management. However, crop yield alone is an incomplete measure of system productivity. Soil quality can represent system productivity.

Larson and Pierce (1991) proposed that a minimum data set be adopted for assessing the health (quality) of world soils, and that standardized methodologies and procedures be established to assess changes in soil. McDonald et al. (1993) proposed assessing soil quality using the GIS-based evaluation. The basic steps of this assessment include determining inherent quality of soils and speculating which biophysical and anthropogenic properties of soils are susceptible to change. One example of a soil property susceptible to change is depth of topsoil. Rust et al. (1971) suggested that a soil quality index be developed along the concept of additions versus losses. Using soluble N as an example, additions or inputs would be crop residues, mineralization of organic matter, manures, and chemical amendments. Outputs would be crop removal, leaching losses, ammonification, and gaseous losses. The ideal condition would be a zero balance. Smith et al. (1993) suggested that soil quality can be determined by estimating the effects of interacting soil characteristics which define soil quality. This can be accomplished by a non-parametric geostatistics technique called kriging. The only decision to be made is whether the soil characteristics is an indication of good, average, or poor soil quality.

Vladimir Yakovchenko[1] · Lawrence J. Sikora (✉) · Donald D. Kaufman
Soil-Microbial Systems Laboratory, USDA-ARS, Beltsville, MD, USA

[1] Visiting scientist formerly affliated with Rodale Institute Research Center, Emmaus, PA

Soil quality is an integral factor defining agricultural system productivity. The quality of the environment resulting from an agricultural system is, in part, a product of the soil's capability to absorb or eliminate harmful components that are associated with productive agricultural systems. The efficacy of a soil in guarding against accumulation and transfer of toxic materials through roots into the food chain affects the quality of food produced. Although soil quality does not define system productivity, a discussion of soil quality will, in essence, parallel a discussion of system productivity. Improvement in soil quality should lead to an improvement of crop productivity, food safety, or environmental quality. For the purpose of this presentation, soil quality will intrinsically relate to these other factors associated with system productivity, but will not refer directly to them, in order to simplify the discussion.

Numerous quantitative properties can serve as indicators of changes in soil quality: nutrient availability, soil structure, water infiltration, moisture-holding capacity, C and N content, etc. It is unlikely, however, that soil quality can be represented by any single property.

It is almost axiomatic that nearly all agronomically valuable assets of soil are associated with the organic matter content. However, because a direct correlation between organic matter and yield or nutrient status is not always evident, the organic matter content alone may not be an adequate indicator of soil quality. High levels of nutrients can be provided by a rapid biological turnover of organic matter. The same yield with the same amount of fertilizer, however, may be obtained on soils with different organic matter contents. Also, the mineralization rates of soils with a low organic matter content can be higher than those of soils with a high organic matter content. To describe the N regime of soil, it is necessary to use both the organic matter content and the annual organic matter mineralization rate (Yakovchenko 1989).

Microbiological properties can serve as soil quality indicators because soil microorganisms are the second most important (after plants) biological agent in the agricultural ecosystem. Biological activity depends on the complex interaction between physical and chemical components that make a particular soil a unique medium.

Biological properties have received less emphasis than chemical and physical properties in characterizing soil quality because their effects are difficult to measure or predict (Parr et al. 1992). There are many indicators of soil biological properties, i.e., microbiological biomass content, microbial diversity and activity, enzyme activity, etc. We propose that soil microbial activity as measured by CO_2 production coupled with soil microbial biomass N estimates can provide an informative soil quality indicator.

The rate at which N passes from soil organic matter into plants depends primarily on the amount of CO_2 produced or organic matter mineralized during a growing season and the inorganic N resulting from it, and the amount of inorganic N taken up by the soil microbial biomass during the growing season from soil organic matter, green or animal manure mineralization, or directly from fertilizer N. Clearly, plants and microbes can compete for nutrients and the result of this competition is difficult to assess. It is possible to estimate the product of the plant/microorganism interrelationship by monitoring microbial biomass N dynamics during the growing season. Microbial biomass N may change in different ways.

(1) It may remain unaffected during the growing season, with a balanced transfer of N from soil organic matter to the plant through microbial biomass; (2) biomass N may increase during the growing season, portion of mineralized N or fertilizer N being immobilized by microorganisms at the expense of plants; or (3) biomass N may decrease during the growing season as it is mineralized and becomes available to plants or is lost by leaching, denitrification, and/or volatilization.

All of these types of change have been reported in the literature and, as a result, there are differences of opinion, on how far microbial biomass nutrients are a source of nutrients for plants. Bonde et al. (1988) suggested that the microbial biomass is not a major source of plant-available N during a growing season. Granatstein et al. (1987) found little change in the microbial biomass in tilled plots from April to October. Schnürer and Rosswall (1987) reported that in a greenhouse experiment, only 10% on N immobilized by soil microbial biomass was taken up by barley plants during a growing season.

Lynch and Panting (1980) found that the soil biomass increased, then decreased to a plateau during the growth of a wheat crop. McGill et al. (1986) reported that the biomass more than doubled from May to August in the soil surface layer (0–5 cm). Buchanan and King (1992) found a significant microbial biomass peak in the spring for all cropped systems. Singh et al. (1989) found that during the wet season, microbial biomass and nutrient pools declined at the same time that plant growth was most rapid. They concluded that the principal function of the microbial biomass was to accumulate nutrients during the dry season when plant growth was low and to release nutrients rapidly at the onset of the wet season to initiate plant growth.

A test of the hypothesis that microbial activity and N content can indicate soil quality was conducted using the Farming Systems Trial plots at the Rodale Institute Research Center located in Kutztown, Pennsylvania, USA. This trial includes low input–animal, low input–cash grain, and conventional cash grain treatments.

Materials and methods

The study was conducted on the Farming System Trial plot at the Rodale Institute Research Center located in Kutztown, Pennsylvania. This trial includes low input-animal, low input-cash grain, and conventional cash grain treatments. Three cropping systems based on either 3- or 5-year rotations are compared. The low-input/animal system simulates a beef or dairy operation that produces hay, corn silage and grain, wheat, oats, and soybeans. N is provided by animal manure and 3rd-year legume hay crops plowed down just prior to planting corn. The low-input/cash grain system produces cash grain every year including corn, soybeans, oats, winter wheat, and spring barley. N is provided by short-term legume hay and green manure crops. The

conventional cash grain system is a corn–soybean rotation with recommended fertilizers and pesticides. Corn and soybeans are common among the three systems. Every year three of the rotational entry points from each cropping system are represented in the field for a total of nine distinct treatments. The site and design of this study is described in detail elsewhere (Doran et al. 1987; Radke et al. 1988; Liebhardt et al. 1989; Peters et al. 1992).

On five dates during the 1992 growing season, samples were taken from each of the three points within one of the eight repetitions in the Farming Systems Trial. Samples were taken from plots that had supported corn in the previous season. Samples were taken from depths of 0–10 and 10–20 cm, sieved (<2 mm), and stored at field moisture content for 1–2 days at 4°C before use.

Soil respiration and microbial biomass N were determined on field-moist soil. Respiration analyses were conducted in biometer flasks at 25°C for 14 days as described by Jordan et al. (1982). CO_2 was collected in 0.1 *M* NaOH and was measured by back-titrating with 0.1 *N* H_2SO_4 to the phenolphthalein end-point after precipitating the carbonates with saturated $BaCl_2$.

Microbial biomass N was estimated by the rehydration technique (Blagodatskyi and Panikov 1989; Blagodatskyi et al. 1989; Endokimov et al. 1991; Sikora et al. 1994). This method is based on the release of microbial cell components into the aqueous phase during the rehydration of dried (24 h at 65–70°C) soils. An alternative method is to remoisten the soil to 20% water-holding capacity, incubate it for 7 days, and determine the NH_4^+ content which is equated to biomass N. Biomass N is calculated from the same formula and *K* factor except that N_d and N_c are the NH_4^+ content in extracts of soil after drying and incubation and undried soil, respectively (Sikora et al. 1994). We used the 7-day incubation method. Quantities of NH_4^+ and NO_3^- in K_2SO_4 extracts were measured using an automated laboratory analysis (American Public Health Association 1979). The N (N generated by biomass turnover) was calculated from the total CO_2-C for 200 days (equalling the growing season) divided by the average biomass C, assuming a C:N ratio of 8.

All concentrations were expressed in terms of kilograms per hectare, using an average bulk density of 1.25 Mg m^{-3} for 0–24 cm. Since this soil has an average gravel (>2 mm) content of 18.5% we adjusted the weight of the soil in the plow horizon to 2445 Mg ha^{-1}.

Results and discussion

A soil quality indicator based on N uptake was proposed and tested. This index encompasses biological, physical, and chemical parameters because N mineralization in soil and N uptake by plants are affected by all three. Moisture and temperature (physical factors; Cassman and Munns 1980), pesticides and salts (chemical factors; Marsh and Davies 1981; Laura 1976), and biomass content and activity (biological parameters; Bonde et al. 1988) affect N mineralization. Clay layers and crusting (physical factors; Devitt et al. 1976), heavy metals (chemical parameters; Chaney and Giordano 1977), and pathogens (biological parameter; Futrell and Kilgare 1969), affect N uptake. Therefore, monitoring the potential N mineralization in soils and N uptake by plants can provide information about soil quality, the effect of farming practices on soil quality, and the pollution potential from the inefficient use of mineral N.

The more efficient a soil system or farm practice is, i.e., the higher the percentage of mineralizable N taken up by the crop, the better the soil quality and the higher the soil quality indicator. In the present work this calculation is based on the following measurements: (1) Annual N uptake by the corn plant from 1986 to 1990; (2) available N from all organic sources, based on CO_2-C respiration from samples taken during the growing season of 1992; and (3) net changes in water-soluble NH_4^+ and NO_3^- and biomass N from the start to the end of the 1992 growing season.

Annual yields and manure N additions were averaged over 1986 to 1990 (Peters et al. 1992). The sources of mineral N available to the plant are soil organic matter, manure, plant residue, and microbial biomass. The calculated N mineralization of these organic sources was based on published C:N ratios, shoot:root ratios, grain:straw ratios, and percent N concentration in plant parts (Table 1). Mineralized N from all organic sources was based on respiration data and the assumptions listed in Table 1. CO_2 not associated with the decomposition of manure or plant residues was assumed to be from soil organic matter. Most of the CO_2 in the conventional treatment was from soil organic matter, which has a lower C:N ratio than manures or plant residues. As a result more N was mineralized per unit CO_2 and the total mineral N from soil was highest in the conventional treatment even though the respiration was lowest.

Mineralization of manure was based on the manure applications and a 50% mineralization rate. The legume residue estimate was based on sample hay yields and a mineralization rate of 70%. Because the corn yields were similar in all treatments (Peters et al. 1992) no account was taken of the N from corn residues and roots.

Hypothetically, if all mineralized N is taken up by the plant, a soil quality indicator of 1 is obtained. Excess fertilizer application without a concomitant increase in yield may result in a loss or inefficient use of N and a soil quality indicator of less than 1. The N not taken up by plants is termed "unproductive" N. Poor soil physical conditions, excess salts, or a decline in microbial activity could result in inefficient use of mineral N and a soil quality indicator of less than 1. In comparing treatments in the Farming Systems Trial, low-input systems used N more efficiently and had lower contents of "unproductive" N, i.e., the low-input systems had higher soil quality indicator values (Table 1). A statistical evaluation of soil quality indicator values was not possible because yields were averaged over 5 years while potential mineralizeable N estimates were based on 1992 data only. This difference, coupled with the use of several assumptions on the crop N content and mineralization rate, although equal across all treatments, precluded any practical use of statistics.

The fate of "unproductive" N is not clear. This N may be associated with stable soil organic matter, fixed to clay, or lost by leaching or volatilization. The amount of N fixed by clay increases with increasing NH_4^+ and a decreasing K^+:NH_4^+ ratio in the amendment (Cameron and Haynes 1986). Data from the Farming Systems Trial collected by Peters et al. (1992) indicated that the K^+:NH_4^+ ratios for applied manure, legume, and fertilizer from 1986 to 1990 were 0.5, 0.5, and 0.06, respectively. These data suggest that more fixation may have occurred in the conventional system than in the low-input systems.

Leaching of inorganic N may be a major pathway of soil N loss (Allison 1966). There are limited data from

Table 1 Soil quality indicator calculations based on corn yield for the Farming Systems Trial at the Rodale Institute Research Center, Emmaus, Penn. N uptake was calculated for corn yield averaged over 1986–1991 (Peters et al. 1992): assumptions used were %N in tops = 1.3 (Peterburgskii 1979); %N in roots = 0.7 (Bisovetsky et al. 1966); grain : straw ratio = 1.0 (Larson et al. 1978); grain : root ratio = 1.0 (Bisovetsky et al. 1966). Manure N application was an average over 1986–1990 (Peters et al. 1992): assumption in calculating legume N applications was 50% of red clover and alfalfa hay yields; shoot : root ratios 3.0 and 1.8 for red clover and alfalfa, respectively (Bowren et al. 1969); C : N ratios 17.8 and 12.4 for red clover and alfalfa, respectively (Millar et al. 1936). Mineralization of manure was assumed to be 50% (Kolenbrander 1974) and legume 70% (Ladd et al. 1981) during the first year, the C : N ratio of manure 11.5, and of soil organic matter 7.0 (Doran et al. 1987). Estimates of soil organic matter mineralization were obtained by subtracting residue and manure mineralization estimates from total CO_2. Because of its C : N ratio, soil organic matter mineralized more N per unit C, resulting in higher mineral N in the conventional system. Net cumulative mineral N represents mineral N plus biomass N at the start minus mineral N plus biomass N at end of 200 days

Parameters measured in soil samples or calculated from published data	Farming system			Notes
	Low-input animal	Low-input legume cash grain	Conventional cash grain	
A Average N uptake (kg ha^{-1})	237	218	234	Calculated from 1986–1990 yields
Average N applied (kg ha^{-1})	300	119	146	Calculated from amend rates and legume yields
CO_2-C, 200 days (kg ha^{-1})	3370	2880	1960	Calculated from respiration
Estimated N from manure, legume, or fertilizer	150	84	146	Estimated from mineral %
Estimated N from soil (by respiration difference)	236	233	279	Remaining CO_2-C divided by C : N ratio of 7
B Total estimated N from organic C mineralized	386	317	425	Total = amend/legume N + soil mineral N
C Net cumulative mineral N, 200 days (kg ha^{-1})	7	9	16	Laboratory analysis
Unproductive N $(B+C)-A$	156	108	207	Calculation
Soil quality estimate $A/(B+C)$	0.6	0.67	0.53	Calculation

studies comparing the leaching of N from manure-, legume-, and conventional fertilizer-amended plots. N from manure, plant residues, and soil organic matter, however, may be considered slow-release in comparison to conventional fertilizer, and Swoboda (1977) demonstrated that 53% less N was lost from slow-release fertilizer than from soluble sources of N.

Differences in mineral N among treatments may be associated with differences in N flux. This parameter is generally defined as the N cycled through the microbial biomass over a specific time period. Jenkinson and Parry (1989) developed an N-flux model which followed plant-root exudates through the microbial biomass into the inorganic N pool. Srivastava and Singh (1991) defined the N flux as the biomass N content divided by turnover time. McGill et al. (1986) calculated flux as the total biomass loss over a growing season divided by the average biomass, which gives a minimum turnover and N flux. Blagodatskyi et al. (1989) measured CO_2 production and the biomass N content in soils in order to calculate the N flux. This latter method was used to calculate the N flux for the Farming Systems Trial over the growing season.

A microbial biomass turnover occurred five to seven times in 200 days and the N flux equalled 165–282 kg ha^{-1} (Table 2). Smith and Paul (1990) reported a turnover time for biomass C ranging from 0.2 to 0.6 years, corresponding to two to five times per year. Coleman et al. (1983) believed that microbial populations may be cycling, i.e., being consumed or dying as other populations take up nutrients, perhaps as many as eight to ten times a year in field situations.

Paul and Voroney (1984) estimated the N flux by dividing microbial biomass N by turnover time for different plant-soil systems. The flux ranged between 34 and 350 kg N ha^{-1} $year^{-1}$. Paustian et al. (1990) estimated a microbial production of between 400 and 1750 kg C ha^{-1} $year^{-1}$ for different cropping systems. Using a C:N ratio of 8, they estimated a microbial biomass N production of 50–220 kg N ha^{-1} $year^{-1}$.

Our data indicate that the microbial biomass N flux was lowest for the conventional system (approximately 165 kg N ha^{-1}). The lower N flux in treatments with an equal organic matter content suggests that at any point in time microorganisms have less immobilized N, resulting in

Table 2 N flux (mean ± SD) through the microbial biomass in treatments of the Farming Systems Trial at Rodale Institute Research Center. N flux = biomass $N \times \mu \times T$ where biomass N is an average for growing season, μ is the specific growth rate, and T is the growing season in days (Blagodatskyi et al. 1989; Paustian et al. 1990); $\mu = CO_2$–C day^{-1} biomass C^{-1} *Y*, where *Y* is a formation coefficient of biomass per unit of oxidized C; *Y* equals biomass C (biomass $C+CO_2)^{-1}$ and for these calculations, 0.40 was assumed (Schimel 1988; Paustian et al. 1990; Anderson and Domsch 1986). Biomass C was calculated from biomass N using a C : N ratio of 8, an average of the range cited by Jenkinson (1987)

Farming system	N-flux through biomass (kg ha^{-1} 200 $days^{-1}$)	Biomass N turnover per 200 days
Low-input animal	282 ± 28	6
Low-input legume	243 ± 27	7
Conventional	165 ± 28	5

more taken up by crops, immobilized into soil organic matter, accumulated as mineral N, or lost from the root zone. There were, however, no significant differences in N uptake by corn (Table 1) or inorganic N in soil during the growing season. The conclusion, therefore, is that the N is lost from the root zone.

A greater loss of N might be expected in conventional farming systems as proposed by Radke et al. (1988) and Andrews et al. (1990). They suggested that the main difference between organic and conventional farming systems is an increase in N cycling within the organic systems as a result of increased activity of the soil organic matter fraction following cropping with legumes or the application of animal manure. Decomposition of the residues increases the labile pool of soil organic matter. In the conventional cropping systems with large inputs of fertilizer N, much of this N is lost from the plant-soil system and relatively little is maintained in the soil.

The soil quality indicator was compared to other proposed quality indices such as the soil microbial biomass, total CO_2 evolution, the ratio of CO_2-C to microbial biomass C or of microbial C to organic C, and total soil organic matter in the same Farming Systems Trial plots (Table 3). Soil microbial biomass, the CO_2-C to microbial biomass C ratio, and total CO_2 evolution were significantly greater for low-input versus conventional systems. The microbial C:organic C ratio was significantly greater in the animal treatment than the conventional treatment. Differences in some of these indicators in the Farming Systems Trial have been reported previously (Doran et al. 1987; Werner and Dindal 1990), although there was no consensus on how these indicators related to soil productivity and quality. There was no significant difference in total organic matter content between low-input and conventional systems. This was not surprising when the amount of organic C applied to the low-input systems and the age of the trial were calculated. The average amount of organic C added from 1981 to 1990 as manure and legume as calculated from N data (Liebhardt et al. 1989; Peters et al. 1992) was 2820 and 2730 kg C ha^{-1} $year^{-1}$, respectively. Both manure and legume were applied twice (average for all entry points) during a 5-year cycle for a total organic C application of 11300 and 10900 kg C ha^{-1}, respectively, since the start of the trial in 1981. Newly formed soil organic matter (humus, not plant residues) can reach 20–30% of the weight of the added organic matter but is more likely to be 10% (Kononova 1984). Assuming a humification coefficient of 20%, approximately 2260 and 2180 kg C ha^{-1} of soil organic matter would form from the applied manure and legumes, respectively. These calculations represent 5.1 and 4.8% increases in the total soil organic matter or a 0.09% increase by weight of soil. Despite the extrapolations from these calculations, the amount of newly formed organic matter is small and probably difficult to detect. The spatial variability of soil alone can result in considerable differences between measurements made in replicated field plots. To detect a significant increase, at least a 12–15% increase in soil organic matter content is required, on the basis of additions to the Farming Systems Trial. To achieve this difference in the trial system would take approximately 15–20 years.

It is not clear whether the microbial biomass can act as an indicator of soil quality. Campbell et al. (1991) suggest that an increase in biomass N does not necessarily denote an improvement in soil quality. McGill et al. (1986) reported a highly significant correlation between average biomass C and total crop yields over 5 years (R=0.80, P<0.001). Biederbeck et al. (1984) found more biomass C and N in continuous wheat grown without fertilizer compared to continuous wheat grown with fertilizer N. They suggested that there was a larger but less active microbial population in the poorly fertilized system. Nor are CO_2 evolution and the microbial respiration:biomass C ratio necessarily correlated with soil productivity. Dinwoodie and Juma (1988) reported that more C was lost (during a 10-day incubation) by microbial respiration from less productive than more productive soils. The CO_2-C released was up to twofold greater when expressed on an area basis (mg m^{-2}) and two- to fivefold greater when expressed as mg g^{-1} microbial C ratio. Chien et al. (1964), on the contrary, reported that the respiratory capacity increased with an improvement in soil fertility.

The present data show no correlations between crop yield (which was the same for all farming systems for 1986–1990, after the 5-year transition period) and the microbial biomass concentration, microbial C:total C ratio, total CO_2 evolution, CO_2-C:microbial biomass C ratio, or the soil quality indicator. These data demonstrate that crop yield and soil quality may not be correlated while soil microbial indicators and soil quality are related.

Soil quality indices are attempts to classify soil conditions and to compare these conditions to their historical use. One indicator is probably insufficient to make a sole judgement on quality. With a large number of factors involved in the profitable production of safe foodstuffs without significant degradation to the environment and soils,

Table 3 Means ± SEM for parameters often associated with soil quality or activity

Treatment	Biomass C (mg kg^{-1})	CO_2-C (mg kg^{-1} 24 h^{-1})	Ratio CO_2-C to biomass C (mg kg^{-1} 24 h^{-1}) (mg kg^{-1})	Ratio biomass C to total C (%)	Total organic C (%)
Low-input animal	157.7±14.5	7.63±0.84	0.051±0.005	0.896±0.089	1.78±0.08
Low-input legume	114.8±9.4	6.04±0.44	0.055±0.004	0.613±0.049	1.87±0.08
Conventional	96.3±7.8	3.72±0.24	0.041±0.003	0.544±0.044	1.77±0.02

an index that represents a broad biological perspective of quality seems appropriate. Among a group of biological indicators, the ratio of crop N uptake to potentially mineralized N as determined by microbial respiration plus mineral N found over a growing season provides an informative soil quality indicator. An evaluation of this index in the 12-year-old Farming Systems Trial at the Rodale Institute Research Center indicated that soils in plots that had been conventionally managed were of lower quality than soils treated with manure or planted with legume-cash grain crops. Microbial N-flux determinations corroborated these results and could be used as a soil quality indicator without the need for crop yield data.

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