The influence of organic transition strategy on chemical and biological soil tests

Carmen M. Ugarte* and Michelle M. Wander

Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign,
1102 S. Goodwin Ave. Urbana, IL 61801, USA.
*Corresponding author: cugarte@illinois.edu

Abstract

Soil testing strategies that include biologically based indicators in organic and alternative farming systems are needed in order to improve recommendations that balance production and environmental goals. In this study, soil samples were collected before and after soils were transitioned from conventional row crop production to organic management using rotations that varied in both their inputs and tillage intensity. Ley-, row crop- and vegetable-based farming systems were implemented using locally specific production practices. Subplots were imposed within each system to allow comparison of farming systems without amendment and with dairy manure- and compost-amendment. Soil analyses included standard chemical tests (0–15 cm) for available phosphorus, exchangeable potassium, calcium, magnesium, pH, total organic carbon (SOC) and total nitrogen (TN). Biological assays (0–15 and 15–30 cm) included particulate organic matter-C and -N (POM-C, POM-N), soil and POM C:N ratios, fluorescein diacetate (FDA) hydrolysis, potentially mineralizable N (PMN) and hydrolysable amino-N + NH_4 (IL-N). Even though cropping and tillage intensity varied among systems (ley < row crop < vegetable), organic matter and nutrient reserves were not statistically different. Nutrient concentrations tested medium to high, even without compost or manure application. Labile fractions of soil organic matter were more enriched in the deeper sampling depth; whereby, POM stocks within the 15–30 cm depth increased by 20% on average compared to roughly 6% in the surface depth. This and observed changes in other properties demonstrate the multiple benefits derived from use of winter annual or perennial crops. Results from our analyses suggested PMN and POM have particular promise as metrics of change in commercial soil testing facilities to assist recommendations for amendments to balance production and environmental goals.

Key words: soil testing, biological indicators, organic farming systems, organic transition, soil organic matter, labile soil organic matter, scoring functions

Introduction

Organic standards emphasize the maintenance or improvement of the soil resource by building soil organic matter and increasing soil biological activity[1]. Organic management practices are intended to satisfy plant nutritional needs without drawing down soil reserves or polluting adjacent air or water resources. Several studies comparing organic and conventional agriculture have suggested that use of organic practices increases soil organic matter, soil biological activity and plant available nutrient stocks[2–8]. Most comparisons have been of conventional-tilled cash-grain systems with more diverse organic rotations amended with compost or animal manures[6,9,10]. Less is known about the ability of organic vegetable-cropped systems or systems that are not amended with animal waste to build soil organic matter

and increase fertility and biological activity. Results from horticultural systems have been mixed and appear to vary with disturbance intensity and amendments applied[11,12]. Systems relying exclusively on plant-based fertility[13] may deplete soils through nutrient removal and lack of input, particularly for P and K. Appropriate testing tools would help growers evaluate the status of their soils and tailor management to maintain soil quality and yield without causing environmental harm[14,15].

To make standard soil tests attractive to organic growers, approaches need to be modified. Standard testing protocols are used to determine whether available nutrient stocks will satisfy crop requirements with the goal of maximizing yield[16,17]. The 'basic soil test' typically measures pH, total soil organic matter, available P, exchangeable K, magnesium (Mg), calcium (Ca) and sulfur (S) in soils collected from the surface depth only

(0–15 cm) and before planting. Additional services frequently include determination of micronutrients if soils are naturally deficient. Accepted measurement techniques vary by region, with soil type and cropping complexity[16]. For example, soil testing methods in Illinois have been adopted following recommendations by the North Central Regional Soil Testing Committee[18] and their interpretation is guided by recent scientific research and delivered through Extension outlets. To serve organic growers, the basic soil test could be broadened to include soil quality measures that have the potential to provide insight into soil functions regulated by organic matter and microbial activity[13]. Some of the most promising candidates for organic soil testing include labile fractions of soil organic matter and N availability[15,19], which are often enriched compared to conventionally managed controls[20–22]. Soil testing for organic systems might also be improved by sampling organic matter and nutrient stocks contained within the full management zone, which extends beyond the current norm for soil testing in the top 15 cm of soil profile.

To develop an interpretive framework to evaluate standard and biologically based indicators within organic systems, upper and lower boundaries related to environmental and production concerns are needed. By establishing clear upper boundaries we can help growers avoid situations where nutrient concentrations are in excess and could degrade adjacent resources, such as water[23], or have negative feedbacks on forage quality[24]. Relationships between multiple desired outcomes and soil test values can be established using non-linear scoring curves[25]. These types of curves (more is better, less-is-better and mid-point optimum) are commonly used for utility functions[26], multi-objective decision making[27] and systems engineering[28]. Efforts to develop and adapt these basic curve shapes for soil applications have relied on literature review with indicator selection being based on statistical reduction and expert opinion[29]. Functional relationships and associated weighting factors have been established using expert judgment based on indicator sensitivity to management, inherent soil properties and climate factors. The scoring curve for soil organic matter, for example, is an ascending logistic *S*-curve, or more-is-better function with a plateau, based on the contributions organic matter makes to fertility, water partitioning and structural stability[29]. It might be appropriate to modify this function and others to include optimum values and associated declines in function with further increases in organic matter to protect the environment and encourage efficiency. For example, organic matter levels are thought to reach a maximum or saturation point that represents a dynamic equilibrium that is soil and system dependent[30]. Setting appropriate maximum threshold values based on this understanding could prevent over-application of manures and composts and prevent unwanted waste or pollution. Similar ideas apply to organic fractions in soils, which cannot accumulate to unlimited levels without

becoming problematic[31]. Reviews by Watson et al.[10] and Nelson and Janke[32] showed how both P and K increased to high levels in organic systems when surplus manure was applied. To avoid depletion or 'mining of nutrients' from soil (e.g., Andrist-Rangel et al.[33]), lower limits need to be established. Studies have shown that both soil P and K test levels decline in some organic cash grain systems[5,34], but it is not clear when and how those levels would limit productivity over time.

The goal of this study was to contribute to the development and application of soil tests for organic farming systems. The research was conducted in a study established at the University of Illinois at Urbana–Champaign with three different farming systems or strategies to transition to organic certification. Field plots managed under a perennial ley, row crop and vegetable system each received three types of organic amendments (cover crops + raw manure, cover crops + composted manure and cover crops only) applied at times and rates appropriate to the system. We expected soil resource status, estimated through conventional soil tests, to decline in the intensive vegetable and row crop-systems that received no manure or compost during transition. Additionally, we expected to detect soil test increases in systems with the lowest disturbance frequency and greatest amount of organic matter addition.

Our specific objectives were to evaluate: (1) changes in soil nutrient status and organic matter resulting from three distinct farming systems used in transition to organic production; (2) changes in soil properties expressed at two soil depths and (3) the commercial potential of biologically based test methods. Finally, we wanted to outline a framework for test interpretation and application to organic farming systems using a scoring curve approach. This method was selected because it was considered well suited to growers seeking to balance economic and environmental performance[24,35,36].

Materials and Methods

Site and treatment description

The Windsor Organic Research Trial occupies a 2.5 ha site on Catlin silt loam (moderately well drained, fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls) and Drummer silty clay loam (poorly drained, fine silty, mixed, superactive, mesic Typic Endoaquolls) soils located at the University of Illinois at Urbana-Champaign campus. During the 4 years preceding the start of this study, the areas had been used for conventional soybean (*Glycine max* (L.) Merr.) production with inputs based on soil tests. In the spring of 2003, 36 experimental plots (33 × 13 m) were established to begin a 3-year transition period to meet the certification criteria for the National Organic Standards[1,37]. Treatments were arranged in a split-plot design randomized in four blocks, in which farming systems were randomized to whole plots

Table 1. Crop rotation and field management summary at the Windsor Organic Research Trial during the three-year transition period.

Farming system	Rotation	Amendment	Amendment incorporation	Tillage[1]
Ley	Alfalfa, red clover, timothy, orchardgrass, alsike clover	• Compost (NPK equivalent to 622, 504 and 352 kg ha^{-1}) • Manure (NPK equivalent to 780, 259 and 461 kg ha^{-1}) • Cover crops only	Spring 2004, Fall 2005 Spring 2004, Fall 2005	Moldboard plough (20 cm, May)[2], Disk (15 cm May), seeding pasture mix, 2 mowings for weed control—compost and manure application (June), 4 mowings for weed control—mowing for weed control, manure and compost application (November)
Row crop	Soybean-winter wheat-hairy vetch-corn, winter rye	• Compost (NPK equivalent to 578, 480 and 444 kg ha^{-1}) • Manure (NPK equivalent to 324, 115 and 217 kg ha^{-1}) • Cover crops only	Fall 2003, Fall 2005 Fall 2003, Fall 2005	Moldboard plough (20 cm, May), Disk (15 cm May), soybean planting, 2 passes of cultivator for weed control (10 cm, June and July), compost and manure application (October), seeding winter wheat (October)—wheat harvest and straw raked and removed (July), hairy vetch drilled (September)—mowing and incorporation of hairy vetch (15 cm, May), disk/harrow for seed bed preparation (15 cm, May), corn planting (June), cultivator for weed control (10 cm, June and July), manure and compost application (November)
Vegetable	Tomato, Austrian peas-broccoli, wheat/hairy vetch-winter squash, winter rye	• Compost (NPK equivalent to 324, 115 and 217 kg ha^{-1}) • Manure (NPK equivalent to 323, 114 and 189 kg ha^{-1}) • Cover crops only	Spring 2004, Fall 2005 Spring 2004, Fall 2005	Moldboard plough (20 cm, May), Disk (15 cm May), and seed bed preparation for tomato transplanting (May), disk/harrow for residue incorporation (15 cm, October), disking and Austrian winter pea seeding (15 cm, October)—mowing and incorporation of cover crops (10 cm, March), seed bed preparation and broccoli transplanting (15 cm, June), cultivation for weed control (10 cm, July), manual weeding, disk/harrow (15 cm, October), winter wheat/hairy vetch seeding (October)—disk/harrow for cover crop incorporation (15 cm, May), row preparation for squash transplanting (10 cm, May), cultivator for weed control (10 cm, June), manual weeding, manure and compost application (November), winter rye broadcast (November)

[1] Growing seasons are separated by em dashes.
[2] Indicates the depth and month of cultural practice.

and organic matter amendments were randomized to split plots. The experiment compared three transitional farming systems used by growers in the US Midwest, varying in their need for inputs and cash flows. These farming system treatments were selected after consultation with an advisory board comprised of Illinois growers who had been farming organically for a decade or more. The treatments were: (1) ley fallow (low intensity); (2) row crop (intermediate intensity) and (3) vegetable (high intensity) systems. Organic matter inputs were: (A) cover crops + composted dairy manure; (B) cover crops + raw dairy manure, and (C) cover crops only. Each split plot was 372 m^2. Applications of organic amendments were made on a system basis to satisfy N requirements, and timed to reflect practices commonly used by producers. Details on management practices are summarized in Table 1. Inclusion of a 'conventional control' that continued the previous practice for purposes of comparison

was not appropriate for an organic transition study for several reasons, including restrictions by the granting agency and certification requirements that prohibit exposure to agrichemicals.

The entire experimental area was disked once and winter rye (*Secale cereale* L.) was seeded in the fall of 2002 before treatments were initiated in the spring of 2003. At that time, the plots assigned to the ley system were planted with a hay and pasture mix (untreated non-organic): alfalfa (*Medicago sativa* L. 'Big Sky'; 29.5%), red clover (*Trifolium pratense* L. 'Arlington'; 19.9%), timothy (*Phleum pratense* L. 'Climax'; 19.9%), orchard-grass (*Dactylis glomerata* var. 'Potomac', 19.5%) and Alsike clover (*Trifolium hybridum* L.; 9.9%). This mixture was consistent with the transition and rotation strategies used by our collaborating farmers who were not limited by land availability. To prevent the establishment of perennial weeds, these plots were mowed to 15 cm two times in 2003, four times in 2004 and once in 2005 and all residues were left in place. A similar effect would have been achieved had we harvested the forage as hay. The row crop system was seeded to soybeans, followed by winter wheat (*Triticum aestivum* L., Gleason Grains, Bridport, Vermont) in 2003. When wheat was harvested in the following year (2004), straw was baled and removed from the field plots. After a brief fallow period, plots were planted with a hairy vetch (*Vicia villosa* Roth) green manure cover crop, which was followed in 2005 with corn (*Zea mays* L.) and winter rye. The vegetable system was planted in 2003 with tomato (*Lycopersicon esculentum* Miller) on raised beds. After harvest crop residues were incorporated and no winter cover crop was used. In the late winter of 2004 plots were disked and seeded with Austrian winter peas (*Pisum sativum* spp. *arvense* (L.) Poir.) as a green manure that was followed by broccoli (*Brassica oleraceae* L. 'Gypsy'). After harvest, plant residues were flail mowed and incorporated before planting a mixture of winter wheat/hairy vetch cover crop followed by winter squash (*Cucurbita maxima* Duchesne ssp. *andreana* (Naudin) Filov) in the last year of transition. After harvest, winter rye cover crop was seeded.

Soil sampling and analyses

Soil samples were taken using soil testing protocols that are common in the North Central region. Soil samples taken in Spring 2003 before treatments were established were used as the baseline against which post-transition samples taken in Spring 2006 were compared to evaluate whether use of organic practices improved soil quality as is required by the National Organic Program standards[1]. To avoid edge effects, soil samples were collected from the center region of each split plot (11 m length) by avoiding 11 m along the outside length and 3 m along the width of each sampling area. Two cores (5 cm in diameter) were taken and divided in two depths (0–15 and

15–30 cm). The use of a larger core than the standard (2 cm in diameter) for soil testing was expected to reduce variability. In preliminary work (unpublished data), we have been able to achieve similar estimates of nutrient and labile fraction concentrations within plots by pooling two large cores (5 cm) as with six to eight small-sized 2.25 cm cores.

Samples from each depth were combined for use as a composite sample. In the laboratory, field moist samples were passed through a 25 mm sieve, then air-dried and ground to pass through a 2 mm sieve. A subsample was analyzed for P, K, Ca and Mg, total organic carbon (SOC), total nitrogen (TN) and pH by the Iowa State University Soil and Plant Analysis Laboratory. Phosphorus, K, Ca and Mg were determined for samples from the top 15 cm of depth as recommended on standard soil testing protocols. For P determination, Bray-1 P solution extractant was used[38]. Exchangeable K, Ca and Mg were extracted with an ammonium acetate solution. Soil pH was measured in a solution with a 1:1 soil to water ratio. SOC, TN and pH were determined for the 0–15 and 15–30 cm depths. SOC and N were evaluated by dry combustion analysis in a Costech ECS 4010 Elemental Combustion System.

Particulate organic matter C (POM-C), fluorescein diacetate (FDA) hydrolysis (a measure of soil hetero-trophic activity), potentially mineralizable N (PMN) and hydrolysable amino N + NH_4 (IL-N) were determined in samples from 0 to 15 and 15 to 30 cm depths in the University of Illinois Soil Ecology Laboratory. For POM fractionation, we modified the method described in Marriott and Wander[7]. Briefly, 10 g air-dried soil was weighed into a 30 ml Nalgene plastic bottle. To the sample, 30 ml 10% (w/v) sodium hexametaphosphate solution was added and allowed to sit overnight to facilitate dispersion. The mouth of the 30 ml bottle was then covered with a 53-μm-mesh fabric and placed into a 250 ml Nalgene centrifuge bottle to which an additional 120 ml sodium hexametaphosphate solution was added. Samples were then shaken in a reciprocal shaker to allow separation of the mineral fraction from POM. After 1 h, the fine particles and sodium hexametaphosphate were discarded, and 150 ml tap water was added. Samples were shaken for 10 min to rinse the excess sodium hexameta-phosphate and fine particles smaller than 53 μm. This rinsing procedure was repeated five times. The sample remaining in the 53 μm mesh fabric was considered POM. Using tap water, the POM was transferred to another piece of 53-μm-mesh fabric and oven dried at 50°C for 24 h. Dried samples were ground in a disk mill and analyzed for their C and N content (dry combustion analysis in a Costech ECS 4010 Elemental Combustion System).

Microbial enzymatic activity was evaluated with a modified version of the FDA hydrolysis method described by Schnurer and Rosswall[39] as improved by others[40,41] and optimized in our laboratory to achieve maximum

color development for our soils. Briefly, 1 g air-dried soil (ground <2 mm) was placed in a 50 ml Nalgene centrifuge tube. Twenty milliliters of sodium phosphate buffer (60 mmol l^{-1}, pH 7.6) were added, followed by 0.50 ml FDA stock solution (4.8 mmol l^{-1}). Bottles were tightly capped and shaken in an orbital shaker for 5 h at 200 rpm and 20°C. Then, 20 ml acetone was added and swirled to stop the reaction before the solution was vacuum-filtered through Whatman No. 4 filter paper. Controls were prepared for each soil type in the experiment following the same procedure as for FDA hydrolysis except that 0.50 ml acetone was added instead of 0.50 ml FDA stock solution. Blanks containing only the solutions were used to adjust the absorption curve for color development not associated with the soil samples. The concentration of FDA was estimated based on spectrophotometric readings of absorbance at 650 nm.

PMN was determined by anaerobic incubation with the method described by Drinkwater et al.[42] with small modifications. Two sets of 5 g samples of air-dried soil (ground <2 mm) were placed in 50 ml centrifuge tubes. Fifty milliliters 2 mol l^{-1} KCl were added to the first set to quantify the amount of NH_4^+ originally present in the soil. Samples were shaken for 1 h on a reciprocal shaker and vacuum-filtered through Whatman No. 42 filter paper. To the second set, 10 ml deionized water were added and incubated for 7 days at 40°C. After 1 week, samples were mixed with 40 ml 2.5 mol l^{-1} KCl solution, shaken, and the solution filtered in the same manner as the first set of samples. Ammonium concentrations in both sets were colorimetrically determined[43].

Hydrolysable amino N + NH4 was estimated using the Illinois-N (IL-N) procedure described by Khan et al.[44]. Air-dried soils (ground <2 mm) were treated with 2 mol l^{-1} NaOH in a tight glass jar and heated to 48 to 50°C for a 5-h period to liberate NH_4^+ and amino sugar-N as NH_3. Ammonia was collected in a 4% H_3BO_3 solution and its concentration was determined by semi-automated titration with 0.01 mol l^{-1} H_2SO_4 solution.

Statistical analysis and interpretation

Results from this experiment were analyzed in a split-split plot arrangement with farming systems as the main plot and the organic amendment and time in transition as the split plots using the PROC MIXED procedure[45]. A split–split–split plot design was used to evaluate the effect of depth (0–15 and 15–30 cm). The influence of soil variability was captured using four blocks that were treated as random effects. Variables that did not meet the assumptions of normality and homogeneity of variances were transformed prior to analysis. Potassium, Ca, Mg, pH, SOC, POM-N and POM C:N were log-transformed whereas TN, POM-C, FDA and PMN were square-root transformed. Two- and three-way interaction terms with P values >0.25 were dropped from the model and were not reported. Significant mean effects were separated with a

least-squared means post hoc test adjusted with the Tukey adjustment to control type I error ($\alpha = 0.1$). Means of transformed variables were back-transformed for presentation. A CV was generated for each variable based on field replicates among experimental units. To evaluate the power of the analysis, we evaluated the minimum detectable difference as proposed by Yang et al.[46] and Stroup[47].

Indicators of biologically based fertility (SOC, TN, C:N ratio, POM-C, POM-N, POM C:N ratio, FDA, PMN and IL-N) were evaluated for their suitability for routine soil testing. We considered the time required for processing, costs for required laboratory equipment and the environmental/health risks associated with analyses. Evironmental/health risk assessment was based on the toxicity specifications for handling and disposal of chemical supplies[48].

To support indicator interpretation we adapted existing scoring functions for pH, available P, SOC and PMN from Andrews et al.[29] which are described by the following equations:

For pH:

$$y = \frac{a \times \exp[-(pH - b)^2]}{2 \times c^2} \qquad (1)$$

where $a = 1.0$ and $b, c = \int (crop)$

For available P:

If $P \leqslant \max$ (for crop and method) $\Rightarrow$

$$y = \frac{(a \times b + c \times P^d)}{b + P^d} \qquad (2)$$

If $P > \max$ (for slope and method) $\Rightarrow$

$$y = a - b \exp(-c \times P^d) \qquad (3)$$

Else $y = 1$, where $a = 9.26 = 10^6$; $c = 1.0$; $d = 3.06$ and $b = \int (crop, SOC, texture, method)$

For SOC:

$$y = \frac{a}{1 + b \times \exp(-c \times SOC)} \qquad (4)$$

where y is the indicator score, $a = 1$; $b = 50.1$ and $c = \int (iOM, texture, climate)$

For PMN:

$$y = \frac{a}{1 + b \times \exp(-c \times PMN)} \qquad (5)$$

where $a = 1$; $b = 50.1$ and $c = \int (iOM, texture, climate)$

We set agronomic thresholds using recommendations for horticultural and agronomic crops grown within our region[49]. Environmental thresholds were based on the scoring functions suggested by Andrews et al.[29], where the indicator concentration was transformed to a unitless scale from 0 to 1. A value closer to zero indicates that the system is functioning at lowest capacity, whereas values

Table 2. The influence of management system, organic amendment, depth of sampling and time under transition on soil attributes used for soil testing and soil organic matter. In the table are *P* values for main effects and interaction terms in an analysis of variance (ANOVA).

Factor/dependent variable[1]	P	K	Ca	Mg	pH	SOC	TN	C:N ratio
P values								
System	0.55	0.58	0.55	0.59	0.44	0.63	0.55	0.99
Amendment	0.80	0.98	0.36	0.77	0.10	0.78	0.52	0.66
Transition	0.04	<0.001	<0.001	<0.001	0.69	0.08	<0.001	0.001
Depth	ND[3]	ND	ND	ND	<0.001	<0.001	<0.001	<0.001
System × amendment	D[2]	D	D	D	0.1512	D	D	D
System × transition	D	D	D	D	D	D	0.18	D
Amendment × transition	D	D	D	D	D	D	0.06	D
System × depth	ND	ND	ND	ND	D	D	D	D
Amendment × depth	ND	ND	ND	ND	D	D	0.23	D
Transition × depth	ND	ND	ND	ND	0.09	0.26	D	0.02
System × amendment × transition	D	D	D	D	D	D	D	D

[1] P, = available P; K, exchangeable K; Ca, calcium; Mg, Magnesium; SOC, total organic C and TN, total N.
[2] Interaction terms with *P* value >0.25 were dropped (D) from the model.
[3] P, K, Ca and Mg were only determined in the 0–15 cm depth.

Table 3. Changes in standard test values of available P, exchangeable K, Ca, Mg and pH during the three-year transition period toward organic certification. Values represent means across all systems and amendment types (*n* = 4). Samples were collected at the Windsor Organic Research Trial in the spring of 2003 and 2006.

Soil property	Depth (cm)[1]	2003	2006	% CV
Available P (Bray-P) (mg kg^{-1} soil)	0–15	53b[2]	62a	30
Exchangeable K (mg kg^{-1} soil)	0–15	162b	247a	40
Ca (mg kg^{-1} soil)	0–15	2186b	3041a	23
Mg (mg kg^{-1} soil)	0–15	233b	311a	33
pH[3]	0–15	6.76	6.81	55[4]
	15–30	6.64	6.55	

[1] Samples were analyzed at the 0–15 cm depth for P, K, Ca and Mg. In the case of pH it was quantified at the 0–15 and 15–30 cm of depth.
[2] Means followed by different letters in the same row are significantly different at α = 0.1.
[3] Time by depth (transition × depth) interaction was not significantly different at α = 0.1.
[4] Coefficient of variation for the concentration of hydrogen ions [H$^+$].

closer to one approach the system's maximum capacity. In addition, we compiled reports from the scientific literature for soils managed using organic and, when necessary, conventional cropping practices. Our literature survey was limited to studies conducted on silt and clay loam soils in regions with temperate climates.

Results and Discussion

Management effects on soil test values and indicators of biologically based fertility

Our prediction that soil quality would be most improved where disturbance was low and organic additions were high was not met. Furthermore, no significant differences were detected among systems, but significant increases were detected in the concentrations of all nutrients and labile organic matter fractions after the 3-year transition (Tables 2 and 3). Even though the vegetable-based system was tilled 6 times more frequently than the ley-based

system and 1.5 times more frequently than the row crop system, there was no evidence of significant difference in soil quality among systems. This may have been due to the lack of power in our statistical design to detect significance. Cumulative compost and manure additions (which on average contained 545, 448 and 364 kg of N, P and K ha^{-1}, and 476, 163 and 289 kg N, P and K ha^{-1}, respectively) did not significantly increase soil reserves over those found in the untreated plots, which relied on N derived from N fixation and on P and K recycling from residues or captured/remobilized by roots. Based on estimates of nutrients removed in harvested crops, which were ranked row-crop > vegetable > ley, reductions in K (and to a lesser extent P) concentrations in unfertilized plots had been expected. Instead, the average concentrations of available P, K, Ca and Mg in baseline (pre-transition) samples were 51, 162, 2186 and 233 mg kg^{-1} soil, respectively. After transition, nutrient concentrations in the 0–15 cm depth had increased to 62, 247, 3041 and 311 mg kg^{-1} soil, respectively. Soil pH (0–15 cm) did not

Table 4. The influence of management system, organic amendment, depth of sampling, and time under transition on attributes of labile soil organic matter. In the table are *P* values for main effects and interaction terms in an analysis of variance (ANOVA).

Factor/dependent variable[1]	POM-C	POM-N	POM C:N ratio	FDA	IL-N	PMN
P values						
System	0.34	0.90	0.36	0.90	0.81	0.61
Amendment	0.63	0.62	0.04	0.64	0.91	0.80
Transition	0.03	<0.001	0.10	<0.001	0.003	<0.001
Depth	<0.001	<0.001	0.20	<0.001	<0.001	<0.001
System × amendment	D[2]	D	D	D	D	D
System × transition	D	0.24	D	D	D	D
Amendment × transition	D	0.12	D	D	D	D
System × depth	D	D	D	D	D	0.23
Amendment × depth	D	0.17	0.15	0.16	D	D
Transition × depth	0.24	D	0.22	0.04	D	0.04
System × amendment × transition	D	D	D	0.12	D	D

[1] POM-C, particulate organic matter C; POM-N, particulate organic matter N; FDA, fluorescein diacetate hydrolysis; IL-N, Illinois N test and PMN, potentially mineralizable N.
[2] Interaction terms with *P* value >0.25 were dropped (D) from the model.

change significantly during transition but trended upward even though no lime was applied (Tables 2 and 3). All test values excluding pH, were in the 'very high' soil test range on both sampling dates[50]. Concentrations were similar to those reported by Delate and Cambardella[51] in a four-year-old organic row crop system that was also conducted on an inherently productive prairie soil. Their work, and that of Clark et al.[52], which was conducted on vegetable-based systems, reported increased nutrient contents in soils after organic transition in systems amended with compost or manure and reductions when amendments were not applied. Declining test values have also been reported in several European studies when systems did not include application of manure or compost[5,34,53]. Smukler et al.[54] reported slight reductions in P and K test values during a 3-year transition period in systems amended annually with compost and manure. That study considered a more intensive rotation that allowed for at least two crop harvests per growing season. We attribute our results to intensive nutrient recycling and active rooting by cover crops that increased nutrient availability and recovered nutrients from the subsoil to enrich the surface. This kind of increase in availability in the rhizosphere or where organic amendments are applied has been widely observed[55,56]. Root-based nutrient concentration has been observed by others, including Thorup-Kristensen et al.[57,58] who found that by adding cover crops to a wheat system they were able to capture and recover enough nutrients to offset losses from crop removal. Several reports of root-based concentration of nutrients within the soil surface appear in studies conducted on inherently fertile soils[59,60].

Although SOC increased slightly over time ($P<0.1$), increases were not significantly different when the interaction effects with system, amendment regime or depth were taken into consideration (Table 2). Despite the lack of statistical significance, the overall increase (see Table 5) is consistent with other works showing gains in organic matter under organic management[7,51,52,54,61]. Increased concentration in TN was most pronounced in the deeper soil depth and contributed to a reduced post-transition soil C:N ratio (Tables 2 and 5). This change in soil C:N ratio suggests N addition to the subsurface, rather than solely organic matter decay, and may reflect inputs from leguminous species with more readily decomposable substrates[7].

The similarity among soils transitioned under different organic production systems was surprising given that the more dynamic properties are known to be quite responsive to manure and compost additions. The statistical separation between pre- and post-transition soils was greater for labile soil organic matter fractions than for total SOC (Tables 4 and 5). This illustrates why these assays are used as indicators of change and is consistent with other works showing that statistically significant differences will emerge more rapidly within labile soil organic matter fractions than in whole soil C or N stocks[3,62,63]. Sensitivity of indicators will be discussed later. The magnitude of increase in POM concentrations observed was comparable to those seen in other US organic systems[7]. In a comparison of organic and conventional systems, Marriot and Wander[7] found that POM-C contents were similar in manure- and legume-based systems and low in conventional systems. We found POM C:N ratios varied only slightly after transition ($P=0.1$), and were similar in the compost amended and cover cropped plots (22) but greater than POM C:N ratios observed in plots amended with manure (20). In general, POM C:N ratios exceeding 20 reflect inputs from carbonaceous plant residues and indicate use of soil-building practices; ratios approaching 15 are commonly associated with an abundance of decayed organic matter but can briefly occur after incorporation of fresh legume-derived residues[3,63]. To evaluate the relationship between management practices and POM one must consider both the quantity and quality of the fraction.

Table 5. Changes in SOC, TN, C:N ratio and measures of biologically based fertility (POM-C, POM-N, POMC:N ratio, FDA, IL-N and PMN) as affected by time of organic management and sampling depth ($n = 4$). Samples were collected at the Windsor Organic Research Trial at two sampling depths.

Soil property	Depth (cm)[1]	2003	2006	% CV	% change
Mean estimates					
SOC (g C kg^{-1} soil)[3]	0–15	21.9	23.4	20	7
	15–30	18.9	19.6	22	4
TN (g N kg^{-1} soil)[3]	0–15	1.7	1.8	16	6
	15–30	1.5	1.6	19	9
C:N ratio	0–15	12.7a[2]	12.7a	7	(<0.1)[4]
	15–30	12.2a	11.8b	12	(3)
POM-C (g C kg^{-1} soil)[3]	0–15	2.9	3.1	24	6
	15–30	1.2	1.4	37	20
POM-N (g N kg^{-1} soil)[3]	0–15	0.1	0.1	26	8
	15–30	0.05	0.06	33	20
POM C:N ratio[2]	0–15	21.9	22.2	11	1
	15–30	20.7	22.1	19	7
FDA (ug FDA g^{-1} soil h^{-1})	0–15	29.6b	51.6a	47	74
	15–30	14.4d	25.0c	59	74
IL-N (mg NH$_4$-N kg^{-1} soil)[3]	0–15	268.1	259.6	13	(3)
	15–30	253.2	238.9	17	(6)
PMN (mg NH$_4$-N kg^{-1} soil week^{-1})	0–15	34.8a	40.2a	47	15
	15–30	20.1b	33.0a	51	64

[1] Samples were collected at the 0–15 and 15–30 cm of soil profile.
[2] Means followed by different lower case letters within the same variable are significantly different at $\alpha = 0.1$.
[3] Time × depth (transition × depth) interaction was not significantly different at $\alpha = 0.1$
[4] Numbers in parentheses mean a negative change over time.

Increases in FDA hydrolysis rates and PMN concentrations paralleled those of POM and were positively related. The increase in FDA activity after transition (74%) was more pronounced than for POM or PMN (13 and 40%, respectively) (Table 5). Drinkwater et al.[4] also found FDA to be positively related to measures of available N and argued that this showed how organic practices increase N supply by promoting microbial activity. Unlike PMN, the IL-N, which is a biochemically based method used to estimate mineralizable N, declined during transition. In their multi-site study of organic systems, Marriott and Wander[7] found that the IL-N was not as sensitive to different organic management practices as POM-N and was more closely related to clay content than these other estimates of mineralizable N. That result agrees with the findings of Spargo et al.[64] who found that the IL-N was closely related to TN. In this work, IL-N declined with time, whereas TN increased, suggesting that the proportion of N in the hydrolysable fraction was reduced during transition but converted to another, possibly more resistant form. According to Kwon et al.[65], the IL-N test detects N in only some components of the microbial biomass. They showed that the IL-N recovered 95% of monomeric amino sugars contained in bacterial cell walls and 55% of amides abundant in fungi and concluded that the assay did not recover alpha amino acids or chitin. Further, they showed that the IL-N test was more sensitive to changes in bacterial amino sugars than to fungal amides

and noted that this would complicate interpretation in systems that promote fungal biomass. This might suggest that the proportion of N in amides increased with transition and provided indirect evidence of an increased importance of fungal biomass in these post-transition soils.

Significant depth-by-date interactions revealed important changes in soil quality (Tables 4 and 5). As expected, all variables were more concentrated in the surface than subsurface depths; however, the degree of stratification for most indicators of biologically based fertility (SOC, POM-C, POM-N and PMN) decreased during transition (Table 5). Stratification by depth was less pronounced for pH than for other variables (Table 3). The depth distribution of soil organic matter in the ley system was similar to that found in the tilled row crop- and vegetable-based systems even though it was not tilled after seeding; that occurred within a month of our baseline sample collection. Other works have shown that use of perennial mixtures or cover crops and manure increase the depth of soil organic matter enrichment[66,67]. We attribute study-wide reductions in soil organic matter stratification to active C additions principally associated with diversification of the crop rotation. According to Kong and Six[68], it is likely that the presence of active roots in the systems is more important for soil organic matter accumulation than the incorporation of above-ground residue and/or organic amendments. These results suggest organic farmers should sample more deeply than the current

Table 6. Estimates of labor and cost of laboratory equipment needed to process soil samples for SOC, TN, C:N ratio, POM-C, POM-N, POM C:N ratio, FDA, IL-N and PMN.

Variables	Labor (h/sample)	Equipment ($ approximate cost)	Materials
SOC + TN + C:N ratio	0.22	Analytical balance ($ 4500), grinder ($10,000), CHN analyzer ($ 26,000)	Acetanilide standard (1)[5], chromium oxide (2), cobaltic oxide (3), magnesium perchlorate (1), cupper wire (1), helium (2)
POM-C + POM-N + POM C:N ratio	0.32[1]	Analytical balance ($ 4500), reciprocal shaker ($ 2200), grinder ($ 10,000), CHN analyzer ($ 26,200)	Sodium metaphosphate (2), acetanilide standard (1), chromium oxide (2), cobaltic oxide (3), magnesium perchlorate (1), cupper wire (1), helium (2)
FDA	0.11[2]	Analytical balance ($ 4500),orbital shaker ($ 2200), microplate reader ($ 5600)	Sodium phosphate tribasic (2), acetone (2) and FDA (1)
IL-N	0.25[3]	Analytical balance ($ 4500), hot plate apparatus ($ 900), titrator ($ 5300)	Sodium hydroxide (4), boric acid (2), sulfuric acid (4)
PMN	0.12[4]	Analytical balance ($ 4500),reciprocal shaker ($ 2200), microplate reader ($ 5600)	Potassium chloride (2), 2-hydroxibiphenyl sodium (3), sodium nitroprusside (3), trisodium citrate (1)

[1] Labor estimates assuming samples were processed in sets of 30 for POM fractionation and sets of 35 for CN analysis.
[2] Labor estimates assuming samples were processed in sets of 80.
[3] Labor estimates assuming samples were processed in sets of 33.
[4] Labor estimates assuming samples were processed in sets of 50.
[5] Numbers in parenthesis refer to the health risk hazard from the material safety data sheets for each compound. Being 1, slight; 2, moderate; 3, severe and 4, extreme.

norm (0–15 cm), at least in Mollisols in Illinois, to allow them to better manage the active rooting zone.

Sensitivity of soil organic matter attributes to changes in soil resource condition

The relative utility of the indicators of biologically based fertility depends on each measure's responsiveness to management, inherent variability, costs and environmental risks associated with each method. We assessed indicator sensitivity by considering the relative change in soil organic matter fractions with respect to baseline samples (control samples collected before any organic management was established). Soil FDA, PMN, POM-N and POM-C contents were the variables with the greatest percent change observed during transition (Table 5). The consistency of each soil organic matter fraction was assessed using its variability and represented by the coefficient of variation (CV, %). Coefficients of variation for FDA, PMN and POM fractions observed in both depths ranked FDA > PMN > POM-C and POM-N. The lowest CVs were found for SOC, TN, IL-N and the POM and soil C:N ratios (SOC > TN > IL-N > POM C:N ratio > soil C:N ratio). Even though FDA, and hence heterotrophic activity, was quite responsive to management, this parameter was also highly variable and this decreased the power of the test to around 20% for the farming system by transition interaction. Based on FDA's variability we would have needed to collect ten composite samples per management system in order to detect treatment differences with a 90% confidence level. Clearly, this is impractical given the limited amount of resources devoted to establishment of replicated field experiments, sampling and testing. The POM fraction and SOC were less variable than FDA and so would have required about six and eight replicate samples to be taken per treatment to document differences at the 90% confidence level. The variability of soil organic matter fractions in both depths was similar to that observed for chemical test variables in the 0–15 cm depth. This suggests that testing regimes that incorporated indicators of biologically based fertility would not need to modify sampling intensity even if they were altered to increase sampling depth. Further work is needed to explore indicator variability in other soils and organic cropping systems.

The potential for commercial use of biologically based indicators was assessed using the costs associated with labor and equipment and the health-risk-hazard of chemical use. All measurements considered in this study were affordable (< 0.5 h of labor per sample) and so deemed suitable for use in commercial soil testing laboratories. Determination of indicators like FDA, IL-N and PMN does not require specialized equipment. Labor requirement was 0.1–0.3 h per sample (Table 6) assuming that sets of multiple samples could be processed simultaneously. Soil FDA hydrolysis rate was the least— and POM was the most—labor-intensive methods described here. We note that methodological improvements could reduce time required to recover the POM fraction. These labor requirements are similar to those needed for determination of conventional chemical soil tests (G. Steffen, Illinois Soil Testing Association, pers. comm., 2008). The chemical supplies used during processing

Table 7. Reference values for indicators of soil organic matter found in the organic literature.

Soil property	Management	(No. of sites)	Median	Concentration (Min–Max)	Citations
g kg^{-1} SOC (g C kg^{-1} soil)	Organic	13	16.7	10.0–28.0	Drinkwater et al.[4]; Marriott and Wander[7]; Khan et al.[44]; Delate and Cambardella[51]; Wander et al.[61]; Teasdale et al.[66]; Wander et al.[67]; Wander and Bollero[83]; Needelman et al.[84]; Poudel et al.[85]; Maughan et al.[86]; Varvel and Wilhelm[87].
	Conventional	14	16.2	9.0–26.0	
TN (g N kg^{-1} soil)	Organic	9	1.5	0.9–2.4	Drinkwater et al.[4]; Marriott and Wander[7]; Khan et al.[44]; Delate and Cambardella,[51]; Wander et al.[61]; Teasdale et al.[66]; Wander et al.[67]; Wander and Bollero[83]; Needelman et al.[84]; Poudel et al.[85]; Maughan et al.[86]
	Conventional	13	1.2	0.9–1.9	
POM-C (g C kg^{-1} soil)	Organic	7	2.9	2.0–5.8	Marriott and Wander[7]; Wander et al.[67]; Maughan et al.[86]; Mirsky et al.[88]; Coulter et al.[89]; Hernandez-Ramirez et al.[90]
	Conventional	7	2.2	1.8–2.5	
POM-N (g N kg^{-1} soil)	Organic	2	0.2	0.2–0.2	Marriott and Wander[7]; Maughan et al.[86]; Coulter et al.[89]; Hernandez-Ramirez et al.[90]
	Conventional	5	0.1	0.1–0.2	
POM C:N ratio	Organic	2	19.0	15.0–23.0	Marriott and Wander[7]; Maughan et al.[86]; Coulter et al.[89]; Hernandez-Ramirez et al.[90]
	Conventional	5	18.0	15.0–18.0	
FDA (µg FDA g^{-1} dry soil h^{-1})	Organic	4	23.0	18.0–66.0	Drinkwater et al.[4]; Workneh and van Bruggen[91]; van Bruggen[92]; Mendes et al.[93]; Darby et al.[94]
	Conventional	5	20.0	12.0–149.0	
IL-N (mg NH$_4$-N kg^{-1} soil)	Organic	2	334.0	165.0–503.0	Marriott and Wander[7]; Khan et al.[44]; Spargo et al.[64]; Wander et al.[67]; Ruffo et al.[95]
	Conventional	18	224.0	98.0–465.0	
PMN (mg NH$_4$-N kg^{-1} soil week^{-1})	Organic	8	6.4	4.5–29.4	Drinkwater et al.[4]; Needelman et al.[84]; Clark et al.[96]; Liebig and Doran[97]; Idowu et al.[98]
	Conventional	10	4.7	4.3–22.0	

would fall into the moderate health rating hazard[49]. Concentrations of those compounds that rank under the high health risk hazard were used in very small quantities and very low concentrations; thus, safety would not be a concern with the use of normal laboratory precautions for protection and handling and with proper disposal.

Interpretation of soil testing values

To evaluate the influence of organic transition on soil quality at our site we used conventional testing and then sought to adapt interpretation guides developed for conventional agriculture and included appropriate scoring functions. Currently, there are no critical values or proposed methodologies of interpretation for most indicators of biologically based fertility with exceptions for SOC[29], PMN[29] and IL-N[44].

Table 7 includes a summary of the median, maximum, and minimum values for variables found in the relevant literature. These values describe the general range of concentrations one could expect to find in medium- to fine-textured soils under organic and conventional management practices. Data from organic systems represent a wider range of tillage and fertilization practices applied in cash grain and vegetable production systems; this probably accounts for the wider range of values found for SOC, TN, POM and PMN fractions. The small number of

reports for FDA and IL-N in organic systems explains the relatively narrower range. In general, concentrations of indicators used in our study approached the upper limit for reported values. As previously noted, standard soil test values were also in the high-to-very-high range. This suggests that nutrients and probably energy reserves were abundant or in surplus at this site. Concentrations of PMN (40 mg NH$_4$–N kg^{-1} soil week^{-1}) were significantly higher than those reported in the literature and our mean IL-N was above the value (235 mg NH$_4$–N kg^{-1}) Khan et al.[44] found to be a critical limit beyond which corn would not respond to additional N fertilization. The IL-N critical limit should be relevant to other N-demanding crops such as tomato or broccoli[49].

Figure 1 presents some of our data using the soil scoring curves proposed by Andrews et al.[29]. Both pre- and post-transition observations fell on the asymptote of the scoring functions for pH, available P and PMN and on the ascending portion of the SOC curve. Based on standard interpretations, the high scores suggest that these soils were functioning near their maximum capacity for productivity. It may be appropriate, however, to reduce the level of the plateau used in the functions when applied within organic systems or to apply an optimum-shaped function, which declines past some maximum because the presence of high levels of available nutrients could suppress plant–microbe associations contributing
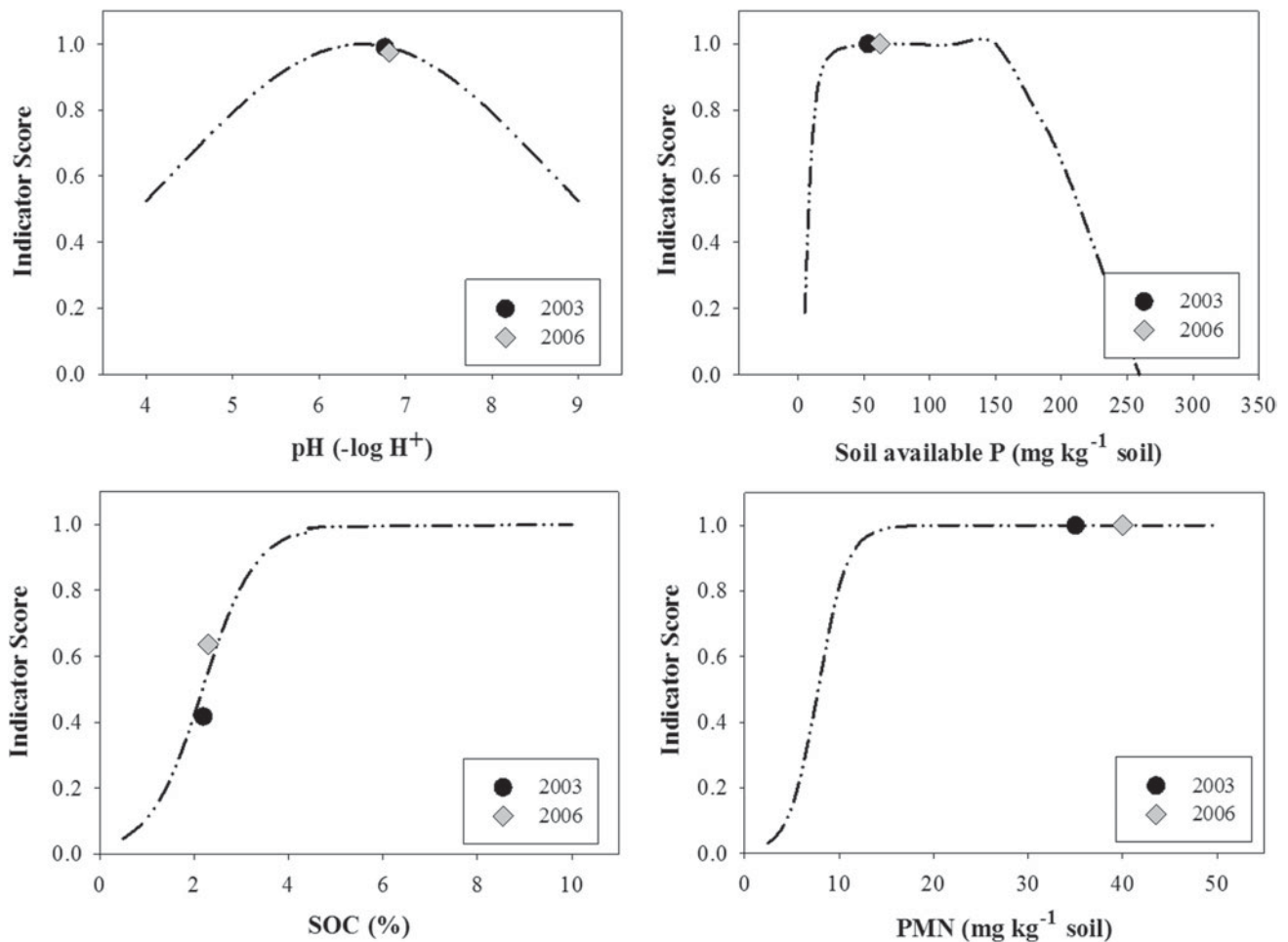
Figure 1. Scoring functions illustrating the change in scores affected by organic transition. Dotted lines represent the expected values for soils classified as Catlin silt loam and Drummer silty clay loam in Champaign, IL using the algorithms presented in Andrews et al.[29]. Symbols within the curve represent the mean average scores for each indicator computed in our study on soils collected pre- and post-transition. Black circles are the means for samples collected in 2003 before organic transition started; gray diamonds are the means for samples collected in 2006 after organic transition ended. Indicators were: pH, available P, SOC and PMN at the Windsor Organic Research Trial. Scores for PMN and SOC assume a more-is-better relationship, with no reduction for environmental concerns after they reach a plateau. Soil pH is an optimum function that depends on the crop in place.

to tight nutrient cycling[69,70]. The shape of the P curve already takes environmental excess into account and reduces scores when threats to water quality emerge. It is not clear whether this is an appropriate model for available N, which in our study is in the high-to-very-high range for both PMN and IL-N compared to other published works. Organic matter stocks were low compared to the site's potential as a result of the history of cultivation[71]. Values on the ascending section of the SOC curve suggest that further increases in SOC would enhance soil function by enhancing soil physical properties and nutrient availability but further increases in the concentration of labile N, estimated by PMN or IL-N would not be desirable from an environmental perspective. There is not a simple linear relationship between C inputs and SOC accumulation[72], and soil N status can alter decay dynamics[67,73]. Ideally our soils could continue to accumulate organic C and with it, N in forms less prone

to undergo nitrification and subsequent loss, but these forms would be difficult to separate and quantify[74]. The small increase observed in the concentrations of POM-C, which was from 7.5 to 13% of SOC, could be due to positive priming of C caused by high levels of available N[75]. Limitation of SOC accrual has been observed in systems where liberal or chronic applications of N are made in the form of manure[67,76] or inorganic fertilizers (e.g., Shen and Bartha[77], Gerzabek et al.[78], Bol et al.[79], Van Lauwe et al.[80] and Blagodatsky et al.[81] as reviewed by Kuzyakov et al.[75] and Khan et al.[82]). This is why we propose changing the plateau function to an optimal scoring function for PMN with reductions in scores occurring when levels exceed an optimum. To account for the microbial contribution to N availability, the scoring function should consider both C and N status. If we are correct in our theory that reductions in IL-N accompanied by increases in PMN signal a shift in microbial N

explained by increased fungal importance, then we have moved left along the curve toward a more optimal condition. This ability to decline or maintain available N even while total N increases might indicate greater potential for the IL-N or other amino-sugar-based assays to be used as indicators. It is doubtful that PMN would fall unless SOC and TN levels fell too.

Conclusions

In general, organic management increased standard and biological soil test values observed in soils under organic perennial ley-, row crop- and vegetable-based production. Regardless of management intensity, organic practices improved/maintained soil resource condition in the plow layer. Increases in resource abundance in the 15–30 cm depth were notable and suggest that deeper sampling might be needed to better track changes in the soil resource caused by organic practices.

Data were used to demonstrate how indicators of biologically based fertility could have practical and therefore commercial application, and outline a strategy to use scoring functions to create an interpretive framework for assessment of performance in organic cropping systems. By revising established norms and values published in the literature, we concluded that soil nutrient stocks were at or beyond optimum agronomic levels and may be too high from an environmental perspective. Intermediate scores for SOC and modest rates of SOC and POM-C accrual suggest that reductions in labile N may be needed. The results suggest that scoring functions for biologically based indicators of soil quality should be optimum functions and seek to account for feedbacks influencing biotic interactions.

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