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# Ecological management of intensively cropped agro-ecosystems improves soil quality with sustained productivity

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ABSTRACT

Intensively cropped agricultural production systems should be managed to improve soil quality and ecological processes and ultimately strengthen system capacity for sustained biological productivity. We examined the long-term changes (>20 years) in soil quality and productivity with incorporation of ecological management principles in a set of intensively managed row crop systems of the upper Midwest, USA. Replicated experimental treatments include corn (maize)–soybean–wheat cropping systems under four different management regimes: (a) conventional tillage and fertilizer/chemical inputs (*Conventional*), (b) no tillage with conventional fertilizer/chemical inputs (*No-till*), (c) conventional tillage with ~30% of conventional fertilizer/chemical inputs and a leguminous cover crop (*Reduced Input*), and (d) conventional tillage with no fertilizer/chemical input and a leguminous cover crop (*Organic*). Effects of these treatments on soils were compared by developing a soil quality index (SQI) from 19 selected soil health indicators. An old field community maintained in early succession provided a benchmark for comparison. Reduction in tillage or fertilizer (*No-till*, *Reduced Input* and *Organic*) resulted in increased SQI and improved crop production. The *No-till* (SQI = 1.02) and *Reduced Input* (SQI = 1.01) systems outperformed *Conventional* management (SQI = 0.92) in nitrogen availability and use efficiency, soil stability and structure improvement, and microbial nitrogen processing. Improvements in soil quality corresponded with increased primary production and crop yield in these systems, illustrating the value of an ecologically defined SQI for assessing the long-term effects of fertility and tillage management regimes in agricultural production systems.



## 1. Introduction

Food security remains a priority in most of the world (NEPAD, 2001; USDS, 2009; UNDP, 2010) in addition to the newer challenges of climate change, natural resource depletion and environmental degradation. While intensive agricultural management has brought substantial economic and social development, it has also contributed to environmental degradation via increased greenhouse gas emissions, biodiversity loss, and the reduced delivery of many ecosystem services including soil and water conservation (Millennium Ecosystem Assessment, 2005; Kirschenmann, 2010). With the rapid depletion of natural resources upon which today's intensive agriculture depends, there is a growing recognition that alternative agricultural models based on ecologically sound principles are needed to both sustain food production and provide environmental benefits (Gowing and Palmer, 2008; Flora, 2010; UNDP, 2010).

Changes in soil quality and productivity can provide critical signs of environmental degradation and transformation, since soil acts as a source of nutrients and water and a sink for pollutant chemicals. For example, changes in soil aggregation and structure through conventional agricultural management practices aggravate surface runoff and losses of nutrients and soil to water bodies. On the other hand conservation tillage practices help to maintain the soil carbon and nutrient pool, which also promote higher productivity.

Soil quality, which is a complex functional concept (Stocking, 2003), cannot be measured directly but may be assessed from management-induced changes in soil attributes. Assessing soil quality is a challenge because there are no established standards;

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soils vary spatially and temporally and are readily affected by management (Karlen et al., 1994; Stocking, 2003). Traditionally, soil quality research has focused primarily on soil chemical and physical characteristics because simple methods of analysis were available (Larson and Pierce, 1991) and more recently soil biology have been increasingly recognized as an indicator of soil health (Kennedy and Papendick, 1995; Elliott et al., 1996; Ruzek et al., 2004).

Soil quality indicators should also be linked to soil function (Larson and Pierce, 1994; Acton and Gregorich, 1995; Karlen et al., 1996; Doran et al., 1996), which may individually or collectively include serving as a medium for plant growth, as an environmental filter, as a buffer and transformer, and as a habitat for biota (Seybold et al., 1997; Brady and Weil, 2002). Selection of soil quality indicators and their integration into a single index using a valid model could help to provide early indications of soil quality change and thereby guide land and resource management decisions (Granatstein and Bezdicek, 1992; Mandal et al., 2008). Selection of representative soil characteristics that play critical roles in ecological functions is key to effective soil quality assessment (Gregorich et al., 1994; Govaerts et al., 2006; Lee et al., 2006; Mandal et al., 2008).

Quantifying changes in soil quality has been difficult to date, except when assessing changes in individual soil properties. Part of the challenge is site specificity; in some places a single property or subset of properties may be disproportionately important, whereas in other places different properties may matter more. Another challenge is that agricultural management affects all major components – physical, chemical and biological – of a soil system, and evaluation of soil quality thus should ideally involve all. The biggest drawback in this approach is that there are many soil properties that are affected and every property does not have the same degree or even direction of response.

While the assessment of soil quality from individual parameters can be important in specific situations, the development of a multi-parameter index could be more widely applicable for evaluating changes in overall soil health (Larson and Pierce, 1991; Karlen et al., 1996; Andrews et al., 2002; Sharma et al., 2005; Masto et al., 2008; Mandal et al., 2008). This multivariate approach has been tested and found useful by several earlier studies (Sharma et al., 2005; Karlen et al., 2006; Mandal et al., 2008). Integration of multiple soil parameters (Fig. 1) representing soil biology, nutrient recycling and supply, and suitability of physical conditions provide a logical representation of overall soil quality for crop production. Such an index is more effective in measuring overall soil improvement or degradation resulting from different management practices as well as changes in soil quality over time.

Our aim here is to evaluate soil quality changes under intensive agricultural management using an integrated soil quality index. We use a 20-year cropping system experiment with similar crops under a range of different fertilization and tillage management regimes.

## 2. Materials and methods

### 2.1. Study site and experimental layout

We used data from the Main Cropping System Experiment of the Kellogg Biological Station's Long-Term Ecological Research (KBS-LTER) site in southwest Michigan (85°24′W, 42°24′N). The site had been conventionally managed in row-crop agriculture for at least a century before the experiment was established in 1988 (Robertson et al., 1997). Soils at the site developed on glacial outwash and are Typic Hapludalfs (FAO soil order: Luvisols) of the Kalamazoo (fine–loamy, mixed, mesic) and Oshtemo (coarse–loamy, mixed, mesic) series commingled (Mokma and Doolittle, 1993). Climate is temperate with cool, moist winters and warm, humid summers. The area receives approximately 900 mm of annual precipitation, with about half as snow. Mean annual temperature is 9 °C.

We studied a portion of the KBS-LTER Main Cropping System Experiment that includes four annual cropping systems and an *Early Successional* community replicated in 6 blocks of a randomized complete block design (Fig. 2). The annual cropping systems were corn (*Zea mays* L.)–soybean (*Glycine max* [L.] Merr.)–winter wheat (*Triticum aestivum* L.) rotations under different management regimes: (a) conventional tillage and fertilizer/chemical inputs (*Conventional*), (b) no tillage with conventional fertilizer/chemical inputs (*No-till*), (c) conventional tillage with 30% of conventional fertilizer/chemical inputs and a leguminous cover crop (*Reduced Input*), and (d) conventional tillage with no fertilizer/chemical input and a leguminous cover crop (*Organic*). Chisel plowing is conventional tillage for agriculture in this region.

All cropping systems were rotations of corn–soybean–winter wheat. The cover crop of the *Reduced Input* and *Organic* treatments from 1989 to 1993 was hairy vetch (*Vicia villosa* Roth) and from 1994 onward was red clover (*Trifolium pratense* L.). Typically the cover crop prior to corn was frost seeded into wheat in the early spring, and then incorporated into soil in April or May before corn planting. Cover crops also were planted after the corn harvest in the fall and prior to soybean planting in the following spring. There was no cover crop preceding winter wheat. Weed control in the *Organic* and *Reduced Input* treatments, for corn and soybean, was achieved by rotary hoe cultivation as needed from May to early July. For wheat, cultivation was conducted in the fall before planting. An *Early Successional* community that was abandoned from agriculture in 1989 and kept free of trees by burning annually in April–May every year since 1996 served as a reference treatment. The complete site description, experimental design, and management protocols are available at the KBS website (http://lter.kbs.msu.edu).

### 2.2. Soil sampling and analysis

Since the inception of the KBS-LTER project, samples of soil, plants, and soil water have been collected at different temporal intervals and spatial scales. For selection of the minimum data set for soil quality index (SQI) development, we used data from 2006 to 2008 representing conditions after 18–20 years of treatment effects. We additionally used soil carbon and nitrogen concentrations from deep (1 m) core samples collected in 2001, representing 13 years of treatment effects. For biological characteristics, N mineralization and nitrification rates measured over the full growing season in 2002 were used. Microbial C and N were determined in 2008 in soil samples (0–0.30 m depth) collected after corn harvest. For crop productivity we used grain yield and above-ground net primary productivity (ANPP) data from 1993 to 2009. Nineteen physical, chemical, and biological attributes were used for the selection of a minimum dataset and development of the SQI, as described in Fig. 1.

#### 2.2.1. Physical characteristics

Bulk density and soil texture were measured by the core (Blake and Hartge, 1986) and Bouyoucos hydrometer (Gee and Bauder, 1986) methods, respectively. Soil aggregate stability (soil stability ratio; SSR) and volume of drainable pores (VDPs) were determined using the High Energy Moisture Characteristics (HEMCs) method (Pierson and Mulla, 1989; Levy and Miller, 1997; Levy and Mamedov, 2002). Briefly, in this method aggregates are wetted either slowly (20 mm $h^{-1}$) or rapidly (100 mm $h^{-1}$), and moisture characteristic (MC) curves at high energies (i.e., up to 500 mm $H_2O$ tension) provide an index of aggregate stability. For a given wetting rate, a structural index is defined as the ratio of volume of drainable pores (VDPs) to modal suction (Collis-George and Figueroa, 1984).

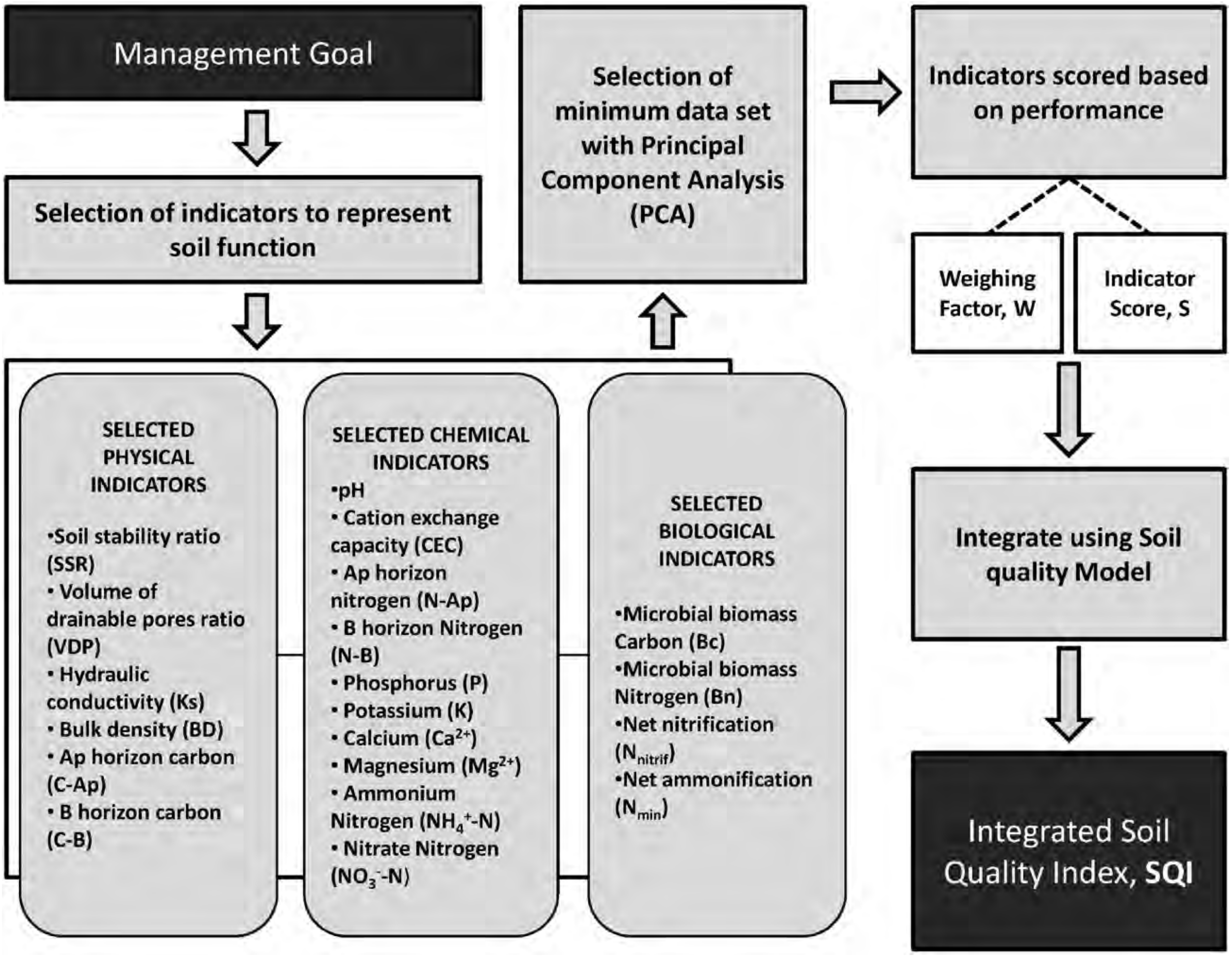


**Fig. 1.** Conceptual framework for soil quality assessment.

Modal suction corresponds to matric potential ($\Psi$, J kg$^{-1}$) at the peak of the specific water capacity curve ($d\theta/d\Psi$), where $\theta$ is the water content (kg kg$^{-1}$). The VDP is defined as the area under the specific water capacity curve and above the baseline. The baseline represents rate of water loss because of aggregate shrinkage rather than pore emptying (Collis-George and Figueroa, 1984). VDP and modal suctions were determined by modeling the MC curves with the modified Van Genuchten model (Pierson and Mulla, 1989). The ratio of fast/slow structural indices, soil stability ratio (SSR), was used to compare the stability of aggregates on a relative scale of zero to one. Details of the method are given in Bhardwaj et al. (2007) and Levy and Mamedov (2002).

### 2.2.2. Chemical characteristics

For total soil carbon (C) and nitrogen (N), undisturbed soil cores of 1-m depth and 4.2-cm diameter were collected using a hydraulic core unit (Geoprobe Systems, Salina, KS) (Syswerda et al., 2011). Soil profiles were classified according to soil horizon, and each horizon was measured for length and then split into individual profile segments. Segments were individually weighed and analyzed for soil C and N. Soil segments were first passed through a 4-mm sieve and mixed. A subsample was then oven dried at 60 °C. Duplicate subsamples from each dried sample were then finely ground in a roller mill, 10 mg was weighed into each of three tin foil cups, and then analyzed for C and N using a Carlo Erba NA1500 Series II C N Analyzer (Carlo-Erba Instruments, Milan, Italy). We used Ap horizon (~0–30 cm) soil data for soil quality calculations.

Soil nitrate ($NO_3^-$-N) and ammonium ($NH_4^+$-N) were determined by extraction with 1 M KCl solution (Keeney and Nelson, 1982) followed by analysis on an automated continuous-flow colorimetric analyzer (O.I. Analytical Flow Solution Analyzer, College Station, TX). For other chemical properties including pH, cation exchange capacity (CEC), available phosphorus (P), and exchangeable potassium ($K^+$), calcium ($Ca^{2+}$), and magnesium ($Mg^{2+}$), samples were collected at the end of the growing seasons and were analyzed at Michigan State University's Soil Testing Laboratory. These chemical analyses were also used for annual fertilizer recommendations for each treatment. Determination of P was by extraction using Bray-Kurtz P1 (weak acid) solution, while $K^+$, $Ca^{2+}$ and $Mg^{2+}$ were extracted using 1.0 N neutral ammonium acetate. P concentrations were determined by colorimetry with a spectrophotometer (Olsen et al., 1954), and $K^+$, $Ca^{2+}$ and $Mg^{2+}$ were determined by Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES). Soil pH and electrical conductivity (EC) were measured using a 1:1 soil:water suspension with a pH and EC meter, respectively.

### 2.2.3. Biological characteristics

N mineralization and nitrification were estimated from changes in nitrogen pool sizes in incubated soils. Two methods of estimating mineralization and nitrification rates were used: a short-term in situ buried bag incubation that accounts for daily and seasonal temperature fluctuations, and a long-term laboratory incubation that assesses soil organic matter quality with respect to mineralizable N. Two 100-g fresh weight sub-samples from the composite


**Fig. 2.** Experimental layout of Kellogg Biological Station (KBS)-Long Term Ecological Research (LTER) Main Cropping System Experiment (MCSE). Treatments T1, T2, T3 and T4 were used in the present study along with comparisons for soil quality with T7. *Conventional* T1 = Conventional tillage and fertilizer/chemical inputs, *No-till* T2 = no tillage with conventional fertilizer/chemical inputs, *Reduced Input* T3 = conventional tillage with ~30% of conventional fertilizer/chemical inputs and a leguminous cover crop, *Organic* T4 = conventional tillage with no fertilizer/chemical input and a leguminous cover crop, *Early Successional* T7 = mix of annual and perennial herbaceous plant species on former farmland; burned annually to exclude woody species.

soil sample of each plot were placed in separate polyethylene bags. The composite soil samples were immediately brought to the laboratory and sub-sampled again for inorganic N analysis and soil moisture. The samples in polyethylene bags were then buried in the field in their respective plots. In-field incubations were for 21 days after which time the soil samples were brought to the laboratory, and both samples were composited and subsampled for moisture and inorganic N analysis. Soil nitrate ($NO_3^-$-N) and ammonium ($NH_4^+$-N) were determined as described above. Net mineralization was determined by subtracting the original soil $NH_4^+$ and $NO_3^-$ concentrations from the incubated soil concentrations. Net nitrification was determined by subtracting the initial $NO_3^-$ concentration from incubated $NO_3^-$ concentration.

The chloroform fumigation-incubation method was used to estimate C and N in microbial biomass. Triplicate subsamples from the composite soil sample (0–30 cm depth) for each treatment were incubated for 24 h in a chloroform vapor-saturated atmosphere. At the end of the incubation period samples were placed in quart glass jars and sealed with lids fitted with rubber septa for gas sampling. At the same time, unfumigated soil samples served as control. Evolved $CO_2$ was measured using a TCD gas chromatograph equipped with a Porapak Q column. Microbial biomass C (Bc), was derived from the relationship:

$$\mathrm{Bc} = \frac{\mathrm{Fc}}{\mathrm{Kc}}, \quad (1)$$

where Fc = [($CO_2$-C evolved from fumigated soil during the 10-day incubation) – ($CO_2$-C evolved from the control during the 10-day incubation)], and Kc = 0.41.

Microbial biomass N was estimated by measuring the flush of extractable $NH_4^+$ (2 M KCl) at the end of the 10-day incubation period. Subsamples of the fumigated and unfumigated incubated samples were analyzed for $NH_4$-N and $NO_3$-N. Microbial biomass N (Bn) was derived using the equation:

$$\mathrm{Bn} = \frac{\mathrm{Fn}}{\mathrm{Kn}} \quad (2)$$

where Fn = [(N mineralized by a fumigated soil for the 10-day incubation period) – (N mineralized by the control during the 10-day incubation)] and Kn = [−0.14 ($CO_2$-C evolved from fumigated soil over the 10-day incubation period/N mineralized by the fumigated soil over the 10-day fumigation period) + 0.39].

### 2.3. Crop yields and primary productivity

Above-ground net primary production (ANPP) was estimated as the annual maximum plant biomass accumulation. Plant biomass was measured in the growing season (May–October) by quantifying the peak dry mass of plants per unit area in each treatment. Multiple sampling stations in each treatment were sampled for plant biomass by clipping plants within a 1 $m^2$ area. At clipping, all plants within the sampling area were cut at ground level and stored at 4 °C until species separations were performed. Plants were identified to species based on Gleason and Cronquist (1963), Fernald (1950), and Voss (1972, 1985). The crop plant samples were further separated into seed and stover. The KBS plant reference collection was also used for species identification. Plant biomass was dried at 60 °C for at least 48 h and weighed. Crop yields were determined annually by harvesting each plot using a field combine. Winter wheat was harvested in July, and soybean and corn were harvested in October and November, respectively. Yields are reported on a dry weight basis.

### 2.4. Soil quality assessment

The first step in the soil quality assessment and development of an SQI (Fig. 1) is to define the primary soil function, which in this case is crop productivity. Crop yield and ANPP can be important indicators of soil quality, serving as a plant bioassay of the interacting soil characteristics. However, productivity cannot be considered as the only criterion and should be assessed in light of its interaction with other environmental indicators of soil function and sustainability.

#### 2.4.1. Selection of the minimum data set (MDS)

The second step in development of an SQI is selection of the minimum data set. The data were reduced to a minimum data set through a series of uni- and multivariate statistical methods. Nonparametric statistics (Kruskal–Wallis $\chi^2$) were used to identify indicators with significant treatment differences. Only variables with significant differences among treatments ($P < 0.05$) were chosen for the next step in MDS formation. A standardized principal components analysis was performed for each statistically significant variable (Andrews et al., 2002; Andrews and Carroll, 2001). Principal components (PCs) are defined as linear combinations of variables that account for maximum variance for a data set. Principal components receiving high Eigenvalues and variables with high factor loading best represent system attributes. Therefore, we examined only PCs with Eigenvalues ≥ 1.0 (Brejda et al., 2000). Within each PC only highly weighted factors (i.e., those with absolute values within 10% of the highest weight) were retained for the MDS. To reduce redundancy and to rule out spurious groupings among the highly weighted variables within PCs, Pearson's correlation coefficients were used to determine the strength of the relationships among variables.

#### 2.4.2. Data normalization

After determining the variables for the MDS, every observation of each MDS indicator was normalized for inclusion in the SQI (Liebig et al., 2001). The normalized values of the indicator, called the 'indicator scores' (*S*), were calculated as follows. Indicators were ranked in ascending or descending order depending on whether a higher value was considered 'beneficial' or 'detrimental' to primary soil function. For 'higher is better' indicators, each observation value was divided by the highest observed value such that the highest observed value received a score of 1. For 'lower is better' indicators, the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received a score of 1. For those indicators where neither higher is better nor lower is better, observations are scored as 'higher is better' up to a threshold value and then scored as 'lower is better' above the threshold value (Liebig et al., 2001).

#### 2.4.3. Integrated soil quality index (SQI)

Once normalized, the MDS variables for each observation were weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage, divided by the total percentage of variation explained by all PCs with Eigenvectors > 1.0, provided the weighted factor for variables chosen under a given PC. The SQI was determined as

$$\mathrm{SQI} = \sum_{i=1}^{n} (W_i \times S_i) \quad (3)$$

where $W_i$ is the PC weighting factor and $S_i$ is the indicator score for variable *i*. In the model, higher index scores indicate better soil quality or greater performance of soil function.

### 2.5. Statistical analysis

The selection of MDS and the PCA for SQI development were performed using SPSS (1998). Yield and productivity were analyzed statistically using SAS (2004). All parameters were tested using a one-way analysis of variance (ANOVA) and separation of means was subjected to Tukey's honestly significant difference test (Steel and Torrie, 1960). Correlation analysis was conducted to identify relationships between the measured parameters. All tests were performed at the 0.05 significance level.

## 3. Results

### 3.1. Fertilizer and tillage effects on soil characteristics

Most of the measured physical, chemical and biological properties were affected by treatment (i.e., management regime). Among the four different types of management systems compared in the present study, highest soil C concentrations in the Ap horizon were found in *Reduced Input* followed by *Organic*, *No-till* and *Conventional*, though soil C in each of these treatments was significantly lower than in the *Early Successional* community (Table 1). Compared to the *Early Successional* community that we chose as benchmark for soil quality, the Ap soil carbon concentration was 13.4–25.2% lower in all of the agricultural treatments. Variation in bulk density does not account for these differences.

Soil pH showed a greater reduction in *Conventional* and *Organic* systems compared to *No-till* and *Reduced Input* as well as to the *Early Successional* reference, which had the pH closest to neutral

**Table 1**
Soil chemical properties used for the minimum data set (MDS) selection process for different treatments.

| Treatment[a] | pH | C-Ap | N-Ap | C-B | N-B | $NH_4^+$-N | $NO_3^-$-N | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | P | CEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conventional | 6.23$^B$ | 10.0$^B$ | 1.07$^A$ | 4.10$^A$ | 0.60$^A$ | 3.10$^{AB}$ | 2.44$^{BC}$ | 1685$^A$ | 333$^B$ | 264$^A$ | 98.4$^A$ | 6.66$^A$ |
| No-till | 6.34$^B$ | 10.8$^B$ | 1.14$^A$ | 4.17$^A$ | 0.63$^A$ | 3.38$^A$ | 2.72$^{BC}$ | 1907$^A$ | 404$^A$ | 268$^A$ | 83.6$^A$ | 7.50$^A$ |
| Reduced input | 6.28$^B$ | 11.6$^{AB}$ | 1.17$^A$ | 3.88$^A$ | 0.56$^A$ | 2.74$^{AB}$ | 2.99$^B$ | 1784$^A$ | 365$^{AB}$ | 248$^A$ | 80.5$^A$ | 7.06$^A$ |
| Organic | 6.17$^B$ | 11.5$^B$ | 1.11$^A$ | 4.32$^A$ | 0.52$^A$ | 2.21$^B$ | 2.09$^C$ | 1858$^A$ | 343$^{AB}$ | 200$^A$ | 60.8$^A$ | 7.29$^A$ |
| Early successional | 6.57$^A$ | 13.4$^A$ | 1.22$^A$ | 4.51$^A$ | 0.55$^A$ | 0.79$^C$ | 4.74$^A$ | 1856$^A$ | 376$^{AB}$ | 269$^A$ | 89.3$^A$ | 7.66$^A$ |
| $P<\alpha$[b] | <0.001 | <0.001 | 0.274 | 0.914 | 0.624 | <0.001 | <0.001 | 0.253 | 0.030 | 0.263 | 0.210 | 0.395 |

C-Ap, total carbon in Ap horizon (g kg$^{-1}$); N-Ap, total nitrogen in Ap horizon (g kg$^{-1}$); C-B, total carbon in B horizon (g kg$^{-1}$); N-B, total nitrogen in Ap horizon (g kg$^{-1}$), $NH_4^+$-N, ammonium nitrogen (mg kg$^{-1}$); $NO_3^-$-N, nitrate nitrogen (mg kg$^{-1}$); $Ca^{2+}$, Calcium (kg ha$^{-1}$); $Mg^{2+}$, magnesium (kg ha$^{-1}$); $K^+$, exchangeable potassium (kg ha$^{-1}$); P, available phosphorus (kg ha$^{-1}$); CEC, cation exchange capacity [meq (100 g)$^{-1}$].

[a] Conventional = conventional tillage (chisel plow) with recommended fertilizer and chemical inputs; No-Till = no tillage with conventional fertilizer and chemical inputs; Reduced Input = conventionally tilled (chisel plow) with 50% of the recommended fertilizer/chemical input; Organic = conventionally tilled organic system with winter leguminous cover crop with no fertilizer and chemical inputs.

[b] $\alpha$ level of significance of Kruskal–Wallis test for differences in means among treatments.

**Table 2**
Soil physical and microbiological properties that were used for the minimum data set (MDS) selection process for the different treatments.

| Treatment[a] | BD | VDP | SSR | Bc | Bn | $N_{nitrif}$ | $N_{min}$ |
|---|---|---|---|---|---|---|---|
| Conventional | 1.62$^A$ | 0.65$^D$ | 0.66$^D$ | 186$^A$ | 18.9$^A$ | 0.39$^{AB}$ | -0.07$^{AB}$ |
| No-till | 1.59$^{AB}$ | 0.85$^B$ | 0.82$^B$ | 115$^A$ | 20.7$^A$ | 0.51$^A$ | -0.07$^{AB}$ |
| Reduced input | 1.60$^A$ | 0.95$^A$ | 0.94$^A$ | 223$^A$ | 23.6$^A$ | 0.51$^A$ | -0.13$^B$ |
| Organic | 1.54$^{AB}$ | 0.76$^C$ | 0.73$^C$ | 169$^A$ | 18.7$^A$ | 0.31$^{AB}$ | -0.08$^{AB}$ |
| Early successional | 1.50$^B$ | 0.97$^A$ | 0.95$^A$ | 230$^A$ | 34.1$^A$ | 0.18$^B$ | -0.01$^A$ |
| $P<\alpha$[b] | 0.008 | <0.001 | <0.001 | 0.475 | 0.122 | 0.007 | 0.002 |

BD, bulk density (Mg m$^{-3}$); VDPs, volume of drainable pores ratio; SSR, soil stability ratio; Bc, microbial biomass Carbon (mg kg$^{-1}$), Bn, microbial biomass Nitrogen (mg kg$^{-1}$); $N_{nitrif}$, net nitrification (mg kg$^{-1}$ day$^{-1}$); $N_{min}$, net mineralization (mg kg$^{-1}$ day$^{-1}$).

[a] Conventional = conventional tillage (chisel plow) with recommended fertilizer and chemical inputs; No-Till = no tillage with conventional fertilizer and chemical inputs; Reduced Input = conventionally tilled (chisel plow) with 50% of the recommended fertilizer/chemical input; Organic = conventionally tilled organic system with winter leguminous cover crop with no fertilizer and chemical inputs.

[b] $\alpha$ level of significance of Kruskal–Wallis test for differences in means among treatments.

(Table 1). No significant differences were found among tested treatments for soil C in the B horizon, soil N in the Ap and B horizons, or soil $Ca^{2+}$, $K^+$, P and CEC (Table 1). Though there were no differences in total soil N, there were significant differences in available $NH_4^+$ and $NO_3^-$. Significantly higher available $NH_4^+$ concentrations were measured in the *No-till* followed by *Conventional* and *Reduced Input* systems compared to the *Organic* system and *Early Successional* community. On the other hand *No-till*, *Reduced Input*, and *Conventional* systems maintained higher levels of soil $NO_3^-$ compared to the *Organic* system though the levels were significantly lower than the *Early Successional* community. The *Early Successional* community had the lowest average soil $NH_4^+$ levels while having the highest average soil $NO_3^-$ levels. Significantly lower levels of $Mg^{2+}$ were measured in the *Conventional* system compared to all other management systems, though $Mg^{2+}$ has not been reported as a limiting nutrient at the levels found in any of the treatments.

All of the physical parameters used for soil quality evaluation – Bulk Density (BD), SSR and VDP – were significantly affected by management regime (Table 2). In all the agricultural treatments, the BD was higher than in the *Early Successional* community. Comparatively higher aggregate soil stability ratio (SSR) was observed in *Reduced Input* and *Early Successional* followed by *No-till*, *Organic* and *Conventional* treatments (Fig. 3). On the other hand higher VDP was found in the *Early Successional* and *Reduced Input* systems, followed by *No-till*, *Organic* and *Conventional* systems.

### 3.2. Selection of minimum data set

The nonparametric test of treatment means revealed that of 19 soil variables, 9 did not show significant differences among treatments. Cation exchange capacity (CEC), total N in the Ap and B horizons, total C in the B horizon, $Ca^{2+}$, $K^+$, available P, $B_c$ and $B_n$ showed no significant differences among treatments at the $\alpha = 0.05$ level (Tables 1 and 2). These 9 variables were therefore dropped and the remaining 10 variables having significant differences among treatments were selected for PCA (Table 3). In the PCA using these 10 variables, four PCs had Eigenvalues >1 and explained 76% of the variance in the data (Table 3 and Fig. 4). Highly weighted variables under PC1, defined as those within 10% of the highest weight of factor loading, included soil $NH_4^+$-N and $Mg^{2+}$. The variable with highest correlation sum ($NO_3^-$-N) was chosen for the MDS, while the one with lowest correlation sum ($Mg^{2+}$) was dropped. In PC2, SSR showed highest weighted value (Table 3). We consider SSR to be an important soil quality parameter because of its effects on erosion as well as soil hydraulic characteristics. Bulk density and pH had highest weighted values in PC3 and were retained in the MDS. In PC4, $N_{nitrif}$ had the highest weighted value and therefore

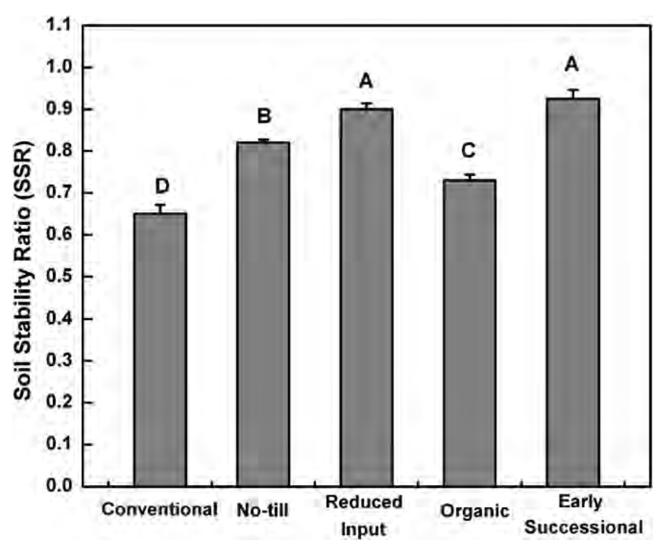


**Fig. 3.** Effect of crop management on the soil stability ratio (SSR) of the tested treatments. Error bars denote ±1 SD. Treatments are described in Fig. 2 legend.

**Table 3**
Results of principal components analysis (PCA) of statistically significant soil quality indicators.

| | PC1 | PC2 | PC3 | PC4 |
|---|---|---|---|---|
| Statistical parameter | | | | |
| Eigenvalue | 2.690 | 2.142 | 1.729 | 1.037 |
| % of variance | 26.90 | 21.42 | 17.29 | 10.37 |
| Cumulative percent | 26.90 | 48.33 | 65.62 | 75.99 |
| Factor loading/eigenvector | | | | |
| Soil parameter[d] | | | | |
| SSR | 0.187 | 0.835[a] | 0.223 | 0.244 |
| C-Ap | −0.183 | 0.678 | −0.391 | 0.107 |
| BD | −0.230 | −0.180 | 0.863[a] | 0.250 |
| VDP | −0.580 | 0.353 | −0.455 | −0.399 |
| pH | 0.025 | 0.220 | 0.793[a] | −0.166 |
| $NH_4^+$-N | 0.880[b] | −0.129 | −0.182 | 0.267 |
| $NO_3^-$-N | 0.580[a] | 0.427 | 0.192 | 0.300 |
| $Mg^{2+}$ | 0.791[a c] | 0.301 | −0.137 | −0.254 |
| $N_{nitrif}$ | 0.122 | 0.146 | −0.008 | 0.898[a] |
| $N_{min}$ | −0.089 | −0.691 | −0.018 | 0.092 |

[a] Factor loadings are considered highly weighted when within 10% of variation of the absolute values of the highest factor loading in each PC.
[b] Highest Pearson's correlation sum.
[c] Lowest Pearson's correlation sum.
[d] SSR, soil stability ratio; C-Ap, total carbon in plow zone; BD, bulk density; VDP, volume of drainable pores; NH4+-N, Ammonium nitrogen; NO3−-N, Nitrate nitrogen; $Mg^{2+}$, Magnesium; $N_{nitrif}$, net nitrification; $N_{min}$, net mineralization.

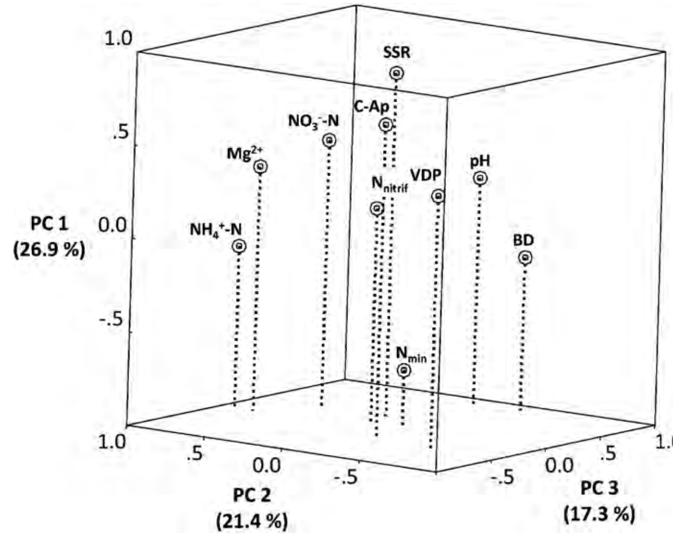


**Fig. 4.** Principal component (PC) scores of all parameters in the first three PC's used for soil quality index (SQI) development. Percentage of total variance accounted for by each PC is indicated in brackets. BD, bulk density; SSR, soil stability ratio; VDP, volume of drainable pores; C-Ap, total carbon in Ap horizon, $NH_4^+$-N, Ammonium nitrogen; $NO_3^-$-N, Nitrate nitrogen; $Mg^{2+}$, Magnesium; $N_{nitrif}$, net nitrification, $N_{min}$, net mineralization.

was also selected. The final MDS was thus composed of SSR, BD, pH, $NH_4^+$-N, $NO_3^-$-N and $N_{nitrif}$. Pearson's correlation coefficients for the highly weighted variables under different PCs were determined separately to reduce the redundancy among the variables (Table 4).

### 3.3. Soil quality index (SQI)

The 6 selected variables for the MDS were transformed using linear scoring functions. BD was considered as 'lower is better' and SSR was considered as 'higher is better'. For pH, neutral (7.0) was considered desirable and therefore it was taken as 'higher is better' because all values were less than 7. For soil pH and SSR the values for the *Early Successional* community were highest and therefore received a score of 1; values for other treatments were divided by this observed value for *Early Successional* to normalize them. For BD, the lowest value, which was also observed in *Early Successional*, was divided by the values of other treatments to obtain their respective linear scores. The values for rest of the selected parameters – soil $NH_4^+$, $NO_3^-$ and $N_{nitrif}$ – were transformed similarly. The coefficient of 'weighting factor' derived from the PCA was determined by the percent of variation in the data set explained by the PC that contributed towards the indicated variable divided by the total percentage of variation explained by all PCs with Eigenvector >1. The weighting factor for the variables in PC1 ($NH_4^+$-N and $NO_3^-$-N) was 0.353; for PC2 (SSR) the weighting factor was 0.281; for PC3 (BD and pH) the weighting factor was 0.227, and for PC4 ($N_{nitrif}$) the weighting factor was 0.136.

The SQI was highest for *No-till* (1.02 ± 0.02, mean ± s.e.m.) and *Reduced Input* (1.01 ± 0.03) followed by the *Early Successional* (0.96 ± 0.02), *Conventional* (0.92 ± 0.04) and *Organic* (0.85 ± 0.05) systems (Fig. 5). Inorganic nitrogen ($NH_4^+$-N and $NO_3^-$-N) made the greatest contribution to SQI. The highest soil quality index in *No-till* and *Reduced Input* was largely due to a positive change in the soil structure (aggregate stability and porosity) as well as soil nutrient pool (available N and pH) due to management.

### 3.4. Agricultural management effects on crop production

The average (1993–2008) aboveground net primary productivity (ANPP) of the three crops in rotation (corn, soybean and wheat) was not significantly affected by tillage and fertility management practices in the different treatments, except for the wheat crop where there was reduction in ANPP in the *Organic* treatment (Fig. 6).

**Table 4**
Pearson's correlation matrix and correlation sums for highly weighted variables with high factor loading under the principal components.

| Variables[a] | BD | SSR | VDP | C-Ap | pH | $NH_4^+$-N | $NO_3^-$-N | $Mg^{2+}$ | $N_{nitrif}$ | $N_{min}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| BD | 1.000 | | | | | | | | | |
| SSR | −0.242* | 1.000 | | | | | | | | |
| VDP | −0.604 | 0.442 | 1.000 | | | | | | | |
| C-Ap | −0.588 | 0.580 | 0.637 | 1.000 | | | | | | |
| pH | −0.070* | 0.568 | 0.400 | 0.456 | 1.000 | | | | | |
| $NH_4^+$-N | 0.254* | −0.415 | −0.767 | −0.515 | −0.575 | 1.000 | | | | |
| $NO_3^-$-N | −0.476 | 0.707 | 0.477 | 0.598 | 0.654 | −0.573 | 1.000 | | | |
| $Mg^{2+}$ | −0.507 | 0.217* | 0.182* | 0.162* | 0.060* | 0.085* | 0.148* | 1.000 | | |
| $N_{nitrif}$ | 0.350 | −0.032* | −0.525 | −0.262* | −0.370 | 0.597 | −0.383 | −0.234* | 1.000 | |
| $N_{min}$ | −0.251* | 0.018* | 0.324 | 0.114* | 0.373 | −0.413 | 0.457 | −0.070* | −0.330 | 1.000 |
| Correlation sum | 4.3421 | 4.221 | 5.358 | 4.912 | 5.164 | 5.194 | 5.473 | 2.665 | 4.083 | 3.601 |

[a] BD, bulk density; SSR, soil stability ratio; VDPs, volume of drainable pores; C-Ap, total carbon in plow zone; $NH_4^+$-N, Ammonium nitrogen; $NO_3^-$-N, Nitrate nitrogen; $Mg^{2+}$, Magnesium; $N_{nitrif}$, net nitrification; $N_{min}$, net mineralization.
* No significant difference at $P = 0.05$.

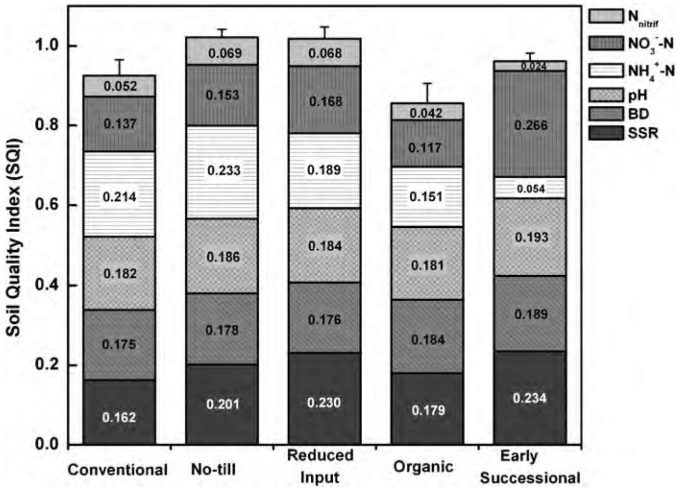


**Fig. 5.** Effect of fertilization and tillage management on the soil quality index (SQI) in the tested treatments. Stacked bars represent the individual contribution of the variables in the SQI for the tested treatments. BD, bulk density; SSR, soil stability ratio; $NH_4^+$-N, Ammonium nitrogen; $NO_3^-$-N, Nitrate nitrogen; $N_{nitrif}$, net nitrification, $N_{min}$, net mineralization. Treatments are described in Fig. 2 legend.

In general, over the 20-year period, for corn there was no significant difference in grain yields among the *Conventional*, *No-till* and *Reduced Input* systems, but lower yields in the *Organic* system (Fig. 7). On the other hand, there were no significant differences in the soybean grain yields among any of these treatments. In the wheat crop, although there were no differences in the yield among the *Conventional*, *No-till* and *Reduced Input* systems, there were significantly lower yields in the *Organic* system. The least inter-annual variability in yields was observed for soybeans, followed by corn and wheat.

The total inorganic N in the soil (0–25 cm) and the grain yield from all the crops from 1993 to 2008 under different management systems showed significant interactions. There was a highly significant increase in grain yield with an increase in total soil inorganic N in the *Reduced Input* ($P < 0.0001$; $n = 18$) and *Organic* ($P < 0.0001$; $n = 18$) systems (Fig. 8).

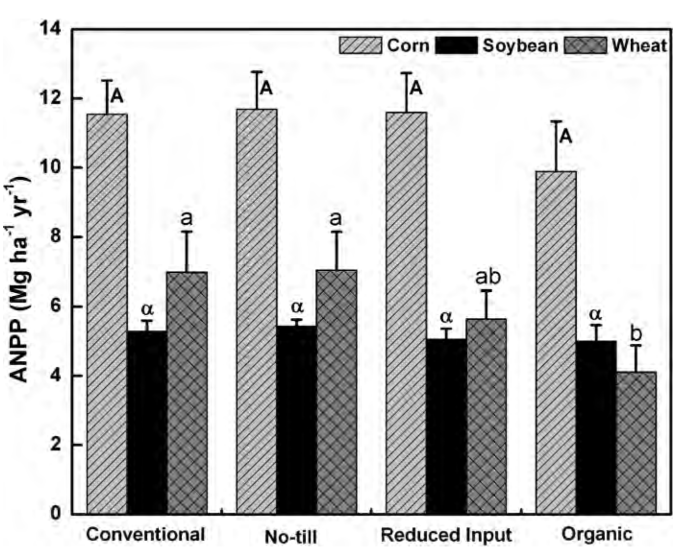


**Fig. 6.** Fertilization and tillage treatment effects on aboveground net primary productivity (ANPP) of corn, soybeans, and wheat crops from 1993 to 2008. For a given crop, treatments marked with the same letters do not differ significantly ($P < 0.05$). Error bars denote ±1 SD. Treatments are described in Fig. 2 legend.

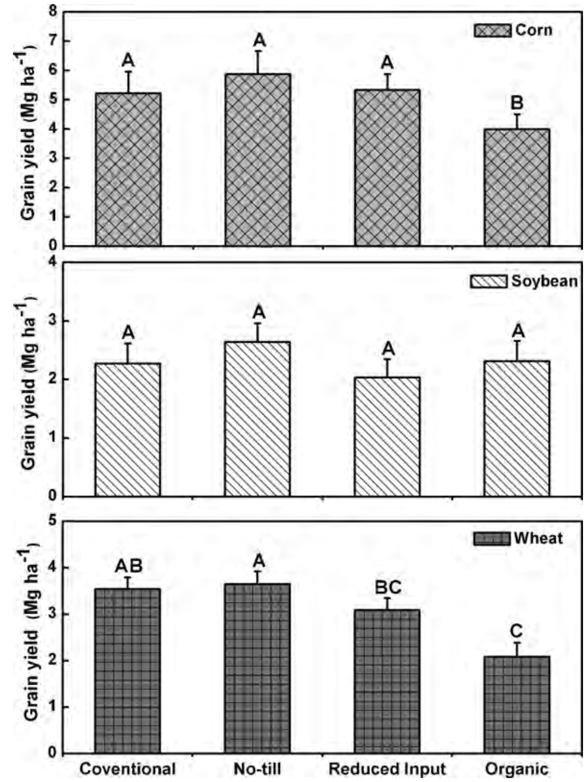


**Fig. 7.** Treatment effects on the grain yields of corn, soybeans and wheat crops, from 1993 to 2008. For a given crop, treatments followed by same letters do not differ significantly at ($P < 0.05$). Error bars denote ±1 SD. Treatments are described in Fig. 2 legend.

## 4. Discussion

Overall, our results suggest that there were significant changes in soil quality due to tillage and fertilizer management in the various treatments (Fig. 5). These changes in relation to productivity were more evident in corn and wheat grain yields (Figs. 6 and 7), probably due to very significant effects of treatments on microbial nitrogen transformations ($N_{nitrif}$, $N_{min}$). The *No-till* and *Reduced Input* systems, albeit with higher SQI than *Conventional*, showed no significant gains or losses in the grain yield or ANPP. The *Organic* system led to decreased yields in wheat and corn, which corresponded with lower soil quality (SQI) compared to other treatments.

### *4.1. Soil quality assessment for food production systems*

Among the numerous soil properties considered important for crop production as well as for other ecosystem services, selection of the most significant ones, and their integration into a single index, help to interpret the performance and sustainability of different management systems. We found that our soil quality index (SQI) is useful for identifying potential tradeoffs in soil conditions that might result from management choices, as well as for demonstrating how improved management practices yield environmental benefits. For example, the *No-till* and *Reduced Input* treatments had a higher SQI value than *Conventional* management, even though the yields were statistically comparable in all the three systems. These changes are not trivial, considering the two most significant constraints for crop production in the region: nutrient leaching losses and poor water holding capacity, both exacerbated by coarser soil textures.

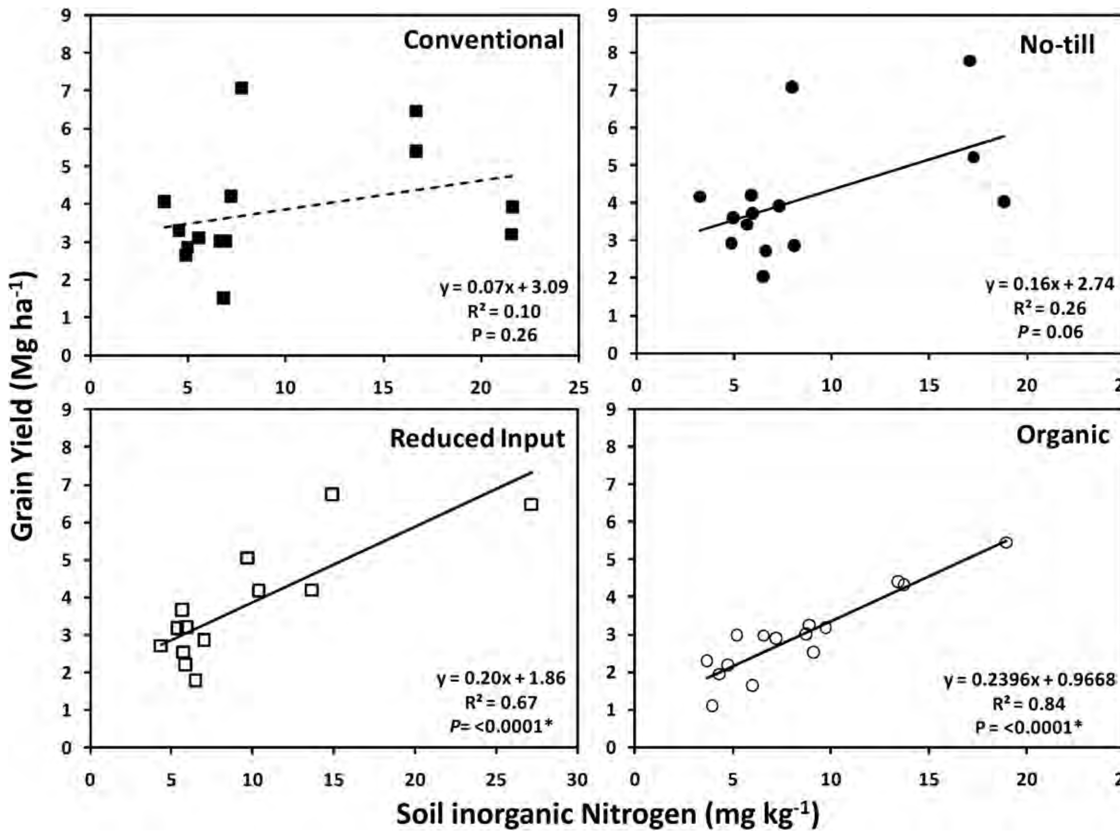


**Fig. 8.** Variation in grain yields for corn, soybean and wheat crops as function of available soil nitrogen ($NH_4^+$-N and $NO_3^-$-N) over the growing season, from 1993 to 2008. Treatments are described in Fig. 2 legend.

### 4.2. Soil quality relevance for food security and ecosystem services

The rationale for conventional tillage and fertilizer application in crop production is to ameliorate problems of decreased N availability, compaction, and competition with weeds (Mehdi et al., 1999; Vetsch and Randall, 2002). Our evaluation of soil quality, together with crop yields and productivity which serve as important bioassays of soil quality, indicated significant improvement in soil quality under alternative management regimes (Figs. 6 and 7). For *No-till* and *Reduced Input* systems, improvement in soil quality did not correspond to significant increase in yields, though there was a reduction in yield with *Organic* treatment which corresponded with lower SQI.

Highly significant relationships were observed between grain yield and soil inorganic nitrogen in the Reduced Input and Organic treatments, and a marginally significant ($p = 0.06$) relationship was observed in the No-Till treatment (Fig. 8). An increasing slope of the regression lines among these treatments (*Conventional* = 0.07 but not significantly different from zero, *No-till* = 0.16, *Reduced Input* = 0.20, *Organic* = 0.24) suggest a monotonically increasing response to available soil nitrogen as fertilizer inputs were lowered. A stronger yield response to available soil nitrogen in the alternative management practices suggests increasing nitrogen use efficiency, which has large implications for environmental quality (Robertson and Vitousek, 2009) since N is one of the most important pollutants of surface water and ground water, and excess N in the environment results in higher nitrous oxide emission to the atmosphere, contributing to climate change. Maintenance of equal or higher yields in the *No-till* and *Reduced Input* treatments corresponded with an improvement in overall soil quality. Though soil quality changes did not correspond strongly with the grain or biomass yield, over a more extended time period these changes might show effects in terms of productivity. The changes in soil quality do concord with observations of nitrogen leaching from these treatments, which diminished in the order *Conventional* > *No-till* > *Reduced Input* > *Organic* management (Syswerda, 2009). Thus as the yield responses to available nitrogen increased in these treatments and the nitrogen losses to ground water decreased. Analysis of annual yields (Grandy et al., 2006) indicated significantly higher yields for *No-till* compared to *Conventional* management for some years, but the effects were not significant in other years. However there is a possibility of a treatment × year interaction that is masked by our yield averages.

The role of reduced but strategic nutrient inputs using practices such as cover crops, 2–3-year rotations and minimum but timely inputs of N-fertilizer also likely contributed to equal or greater yields in the less intensively managed (*No-till* and *Reduced Input*) systems. N limitation may not be as great when corn is grown in rotation with other crops with differing N requirements (Martens, 2001). Increased aggregation and soil C content suggest that, over a longer time period, *No-till* might have attained higher crop yields. Increased soil stability will improve aeration and drainage, and make the system more resilient to compaction. Increased soil C concentrations will improve soil structure and potentially increase the N mineralization potential during the growing season when soils are sufficiently warm to support active decomposition. The observation that average yields in the *No-till* and *Reduced Input* management systems can be as high as those in the *Conventional* systems supports earlier work showing that intensive chemical and mechanical management is not always necessary to maintain high yields (Eghball et al., 1995; Pimentel et al., 2005; Smith and Gross, 2006; Mallory and Porter, 2007).

Several factors might have contributed to the yield responses in the alternative management regimes studied here. In a previous study conducted at the same site, the *No-till* system was shown to have higher organic matter and improved soil quality in the top 5 cm relative to the *Conventional* system (Grandy et al., 2006). For the same soils, Senthilkumar et al. (2009) observed that the 'conservation management' practices of the *No-till* and *Organic* treatments appeared to have resisted soil C losses, over 16-year period, compared to the *Conventional* tillage and fertilized systems. Other studies have also reported yield differences between *Conventional* and *No-till* management systems due to soil quality changes (Hammel, 1995; Diaz-Zorita et al., 2004).

Several management practices differed between the *Conventional* and *Reduced Input* systems. The *Reduced Input* system received substantially fewer chemical inputs, but was over-seeded with a legume cover crop that provided supplemental N, improved soil quality, and might have also contributed to weed suppression (Snapp et al., 2005). Row spacing and cultivation frequency also differed between the *Reduced Input* and *Conventional* treatments, and these practices have been shown to affect row crop yields in earlier studies (Zhang et al., 1996; Pedersen and Lauer, 2003). Unlike the *No-till* and *Reduced Input* systems, the *Organic* system received no chemical inputs and had the lowest yields for both the corn and winter wheat phases of the rotation. These results agree with Smith and Gross (2006) who reported lower corn yields in a similar rotation under O*rganic* compared to *Conventional* management. In contrast, Pimentel et al. (2005) found that crop yields in manured organic systems were similar to those in *Conventional* systems. Differences in the response of the organic systems observed in these studies suggest that site attributes, crop management practices, or differences in the use of organic amendments may play a role determining the relative performance of organic vs. *Conventional* systems (Mallory and Porter, 2007).

## 5. Conclusions

We conclude that:

1. The use of multivariate approach for soil quality evaluation can be more effective than single parameter assessment. The approach can be used to compare soil quality under different management systems and can be repeated easily to monitor changes over time.
2. The principal components analysis for soil quality parameter selection can indicate the relative importance of soil properties in the soils and climatic conditions specific to the region. The most significant characteristics that contributed towards changes in soil quality were soil inorganic nitrogen, soil C, pH, bulk density, and aggregate stability. The positive association between soil inorganic N and grain yields in the *Reduced Input*, *No-till* and *Organic* treatments suggest increased N use efficiency under these systems, and consequently lower losses of nitrogen compared to *Conventional* management.
3. A ranking of the four management systems based on both soil quality and long-term yields suggests that in comparison with the *Conventional* system, the *Reduced Input* as well as *No-till* systems may provide equal or higher crop yields with lower environmental impacts in the upper Midwest US region. The success of the *No-till* and *Reduced Input* systems observed in this study may be due to their impact on soil quality, which may have ameliorated yield responses to environmental fluctuations relative to the tilled systems (Lotter et al., 2003).

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