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Management intensity – not biodiversity – the driver of ecosystem services in a long-term row crop experiment

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ABSTRACT

A positive role for biodiversity is assumed for managed ecosystems. We conducted a 12-year study of this sustainability principle, through separate manipulation of management intensity and crop diversity. The site was located in southwest Michigan, representative of rain-fed production, with high climate variability and well-drained soils. Provisioning services of grain and protein yield were monitored, simultaneous with supporting services of soil fertility, C and N, and regulating services associated with water quality (N-use efficiency and nitrate-N leached in gravimetric lysimeters). Surprisingly, a strong role for management was shown, and almost nil for crop diversity. Organic management (ORG) sustained soil fertility, augmented soil C (36% increase), enhanced N retention (50% decrease in nitrate-N leaching) and improved N-use efficiency, compared to conventional, integrated (INT) management. Provisioning of grain – quantity, quality and temporal yield stability – was highest in INT continuous maize (monoculture and biculture) with an annual yield of 6.4 Mg ha^{-1}, compared to ORG of 5.1 Mg ha^{-1}. Biodiverse rotational systems (three and six species) produced 25% lower yield, but the grain was of high quality. A focus on ORG management rather than crop diversity is suggested as a means to sequester C, and produced grain in a semi-closed system.

1. Introduction

The growing global population is exerting pressure on the world's agricultural ecosystems to supply food, fiber, and increasingly, fuel. At the same time, the Millennium Ecosystem Assessment (2005) has documented the extent and global scale of the environmental costs associated with intensive agriculture. Degradation of water quality and soil resources are becoming urgent problems and fossil fuel supplies are finite. Organic agriculture is frequently presented as the only currently available 'semi-closed system' that provides a viable alternative to conventional 'open system' management that relies on large doses of agro-chemical inputs (Pearson, 2007). There are, however, few studies that elucidate the ecological principles involved, such as the purported role of biodiversity in closing nutrient and energy flows and enhancing ecosystem services.

Biodiversification is widely considered to be a sustainability principle, and enhanced plant species diversity has been shown to be associated with net primary productivity, nutrient retention and resilience (Tilman et al., 1996). Yet the role of biodiversification in rain-fed cropping systems that feed much of the world remains unknown, as experimentation has focused on systems comparisons of bundled practices associated with different management regimes (Maëder et al., 2002; Pimentel et al., 2005). Diversification of farming involves multiple temporal and spatial scales, at the landscape, community and organism levels (Snapp and Pound, 2008). The focus of this research is on plant species diversity which influences C assimilation, water and nutrient cycling, and soil food web structure and function in agroecosystems.

The Living Field Laboratory (LFL) reported on here is the first study we know of to experimentally manipulate management (organic and conventional) and biodiversity (comparing 1, 2, 3 and 6 plant species) in a factorial design for a row crop production system. We acknowledge that it is challenging to separate out these factors, which involve complex interactions (Drinkwater and Snapp, 2008), and that diversity has been studied explicitly in low management intensity ecosystems (Smith et al., 2008; Tilman et al., 1996).

A simultaneous evaluation of multiple ecosystem services is fundamental to test sustainability principles. Provisioning, supporting and regulating services are ecosystem service categories used for managed lands, along with cultural services which were not the focus of our study (Millennium Ecosystem Assessment, 2005). Economic and agronomic viability of a row crop ecosystem depend on the provisioning service of grain yield. We predicted there would be 'opportunity costs' associated with diversification (Snapp et al., 2005), as systems that optimize the presence of maize,

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a highly ruderal species, tend to be particularly effective at capturing resources for production of grain. These properties have led to maize domination of many rain-fed cropping systems, on a global scale (Smaling and Dixon, 2006). However, maize-based systems are being subjected to increasingly erratic precipitation and temperature and model simulations indicate potential vulnerabilities to climate change (Funk et al., 2008). The interaction of climate, management and biodiversity is complex, and the literature suggests tradeoffs exist among grain yield, soil processes and N loss pathways (Pimentel et al., 2005; McSwiney et al., 2010), which require investigation through long-term experimentation.

We tested the hypothesis that increasing biodiversity rather than management intensity of agro-chemical use would be associated with enhanced N retention, soil C sequestration, soil fertility, crop yield and stability of yield production.

2. Materials and methods

2.1. Site description

The study was located at the W.K. Kellogg Biological Station (KBS), Hickory Corners, MI, USA (42°24′ N, 85°24′ W, elevation 288 m) on sandy loam soils (Haplic Luvisols) developed from glacial outwash. The area receives 87 cm of precipitation annually (30-year average), about half as snow, and the average annual temperature is 9.7 °C. During the study years (1993–2004) annual rainfall ranged from 60 to 103 cm year^{-1}, and was lower than the 30-year average in 1993–1999 and 2002. A full site description is available at http://lter.kbs.msu.edu/Data/LTER, accessed January 6, 2010.

2.2. Experimental design

The study used the integrated conventional (INT) and organic (ORG) management systems in the Living Field Laboratory (LFL) trial established in 1993. The experimental design was a split–split-plot, randomized complete block with 4 blocks (Sanchez et al., 2004). The main plots within blocks were ORG and INT, where a 12-m strip was included around each to meet ORG certification requirements and reduced any potential for cross-contamination between management practices. Management of ORG followed certified, recommended organic practice with dairy-compost and legumes as N sources, tillage for weed control and the absence of agro-chemical inputs. The INT system was managed conventionally following recommended practices, including low-input, integrated management with targeted applications of herbicide (one-third rate compared to common commercial practice), reduced tillage, and stringent accounting of N inputs to minimize N fertilizer requirements (one-half commercial rate) (Table 1). Rotational temporal diversity was evaluated by comparing continuous maize (*Zea mays* L.) to a 4-year rotation of maize–maize–soybean (*Glycine max* L.)–wheat (*Triticum aestivum* L.) with all entry points represented each year for a total of five split-plots (one continuous maize and four rotation entry points) within management systems.

Spatial diversity was introduced through split–split-plot treatments (plot size 15 m × 4.5 m) of winter fallow vs. cover crops (cover crop treatments provided a continuous plant presence through inter-seeding of understory plants in cash crops that continued to grow through the winter after cash crop harvest). Cover crop varied with cash crop. Crimson clover (*Trifolium incarnatum* L.) was inter-seeded in continuous maize (biculture treatment), and in first-year maize of the rotation (six species treatment). Further, in the six species treatment, annual ryegrass (*Lolium multiflorum* Lam.) was inter-seeded into second-year maize and red clover (*Trifolium pratense* L.) into wheat in late March (Sanchez et al., 2004). Thus, continuous maize was grown as a monoculture (winter fallow) or a biculture (winter cover crop of crimson clover), and rotational maize was grown as three species (winter fallow) or six species (winter cover crops of crimson clover, annual rye grass and red clover). The factorial design allowed comparison of primarily temporal crop diversity (one, two, three and six species over a 4-year rotation) within two management systems, ORG and INT.

2.3. Crop management

Following recommended practice (Tri-State Fertilizer Recommendations http://ohioline.osu.edu/e2567/index.html) the INT system received P fertilizer in the form of triple superphosphate at a rate of 50 kg ha^{-1} of P_2O_5 and K fertilizer in the form of K chloride at a rate 84 kg ha^{-1} of K_2O just before planting (late April and early May each year). The ORG system was compost-amended and had sufficient levels of P and K (Table 2). Compost consisted of 4 Mg ha^{-1} (calculated on a dry weight basis) applied annually (22–29 g N kg, 310–360 g C kg; Fortuna et al., 2003) in monoculture

Table 1

Nitrogen source for cropping systems presented and grain yield average over 1993–2004 for continuous maize (monoculture and biculture), and maize, wheat and soybean in rotation systems (triculture and six species) in the Living Field Laboratory trial.

Management/ diversity	Organic N (kg N ha^{-1})	Organic N available[a]	Inorganic N fertilizer	Added soluble N	Maize yield (Mg ha^{-1})	Nitrogen efficiency[b] (kg grain kg^{-1} N)	Wheat yield (Mg ha^{-1})	Soybean yield
Integrated								
Monoculture	0[c]	0	150	150	6.405	42.7	0	0
Biculture	20	0	150	150	6.423	42.8	0	0
Triculture	45	18	120	138	7.642	54.6	3.005	2.228
Six species	105	48	90	138	7.605	58.8	3.004	2.238
Organic								
Monoculture	112	47	0	47	4.995	106	0	0
Biculture	132	50	0	50	5.101	102	0	0
Triculture	157	64	0	64	6.159	96.2	2.609	2.001
Six species	191	77	0	77	7.012	91.1	2.604	2.062

ANOVA	*P*-value			
Management (*M*)	<0.001	<0.0001	<0.001	0.05
Diversity (*D*)	0.03	NS[d]	NS	NS
$M \times D$	NS	NS	NS	NS

[a] Estimated N availability from nitrogen incubation assays (33–45% depending on source).

[b] N-use efficiency determined as a function of maize grain yield, divided by N applied.

[c] No organic nitrogen source in this treatment beyond maize residues present in all treatments.

[d] NS = non-significance.

Table 2
Soil characteristics in April, 2008 for the 0–25 cm depth, and change in soil C status since 1993 (initial soil carbon 2584 g m^{-2}) in the Living Field Laboratory trial at the W.K. Kellogg Biological Station, Hickory Corners, MI, USA.

Management/ diversity	Total C (mg kg^{-1})	Total C content[a] (g m^{-2})	C change (g m^{-2} year^{-1})	Total N (g N kg^{-1})	C/N ratio	Phosphorus[b] (mg kg^{-1})	Potassium	Calcium
Integrated								
Monoculture	7.96	2706	9.43	0.85	9.43	29.8	94.4	1228
Biculture	8.11	2757	13.3	0.88	9.22	21.9	79.9	972.0
Triculture	8.30	2822	18.3	0.90	9.27	25.4	64.5	1074
Six species	9.60	3264	52.3	0.94	10.22	28.0	68.1	1126
Organic								
Monoculture	11.53	3920	102.8	1.15	11.09	50.9	94.1	1299
Biculture	11.60	3944	104.6	1.17	9.91	53.4	125.5	1491
Triculture	11.97	4067	114.3	1.20	10.96	44.1	101.5	1395
Six species	11.01	3743	89.2	1.10	11.07	40.7	117.2	1443
ANOVA	*P*-value							
Management (*M*)	<0.0001	<0.0001	<0.0001	<0.0001	<0.003	<0.0001	0.001	0.014
Diversity (*D*)	NS[c]	NS	NS	NS	NS	0.04	NS	NS
$M \times D$	NS	NS	NS	NS	NS	NS	NS	NS

[a] Calculated based on soil bulk density of 1.33 Mg m^{-3} for organic and 1.38 Mg m^{-3} for integrated management.
[b] Phosphorus, potassium and calcium extracted using Mehlich III.
[c] NS = non-significance.

and biculture maize. In rotation systems, 4 Mg ha^{-1} was applied to first-year maize, 8 Mg ha^{-1} to second-year maize, 0 compost to soybean and 4 Mg ha^{-1} to wheat, for a total of 16 Mg ha^{-1} compost applied over 4 years, and thus matched on an annual basis the 4 Mg ha^{-1} applied to monoculture maize. Total N applied, and estimated available N, is shown in Table 1. Nitrogen was applied in INT as a liquid fertilizer (20 kg N ha^{-1}) at planting, and side dressed as ammonium nitrate (70–130 kg N ha^{-1}) in maize where rate depended on organic N inputs (Table 1). Wheat in INT was N fertilized with urea at 80 kg N ha^{-1}. Maize was planted at a population of 81,500 plants ha^{-1}. Soybean was planted at 370,000 seeds ha^{-1} in 76 cm rows and winter wheat was planted at 5,000,000 seeds ha^{-1} (Smeenk, 2003).

Pest management followed recommendations; no chemical inputs in ORG and one-third of commercial rates in INT (Sanchez et al., 2004). Total N applied and estimated available N are shown in Table 1. Weeds were controlled through cultivation in ORG and targeted cultivation combined with banded herbicide in INT. This included *S*-metolachlor at 0.5 kg ha^{-1} a.i. and bromoxynil at 0.1 kg ha^{-1} a.i. in maize and glyphosate at 0.3 kg ha^{-1} a.i. in soybean. Maize insecticide was used as required, following recommended, best management practice for INT. Reduced tillage management was followed for all INT and ORG treatments, relying on a chisel plow and soil finishing equipment, as is common practice in the area.

2.4. Agronomic measurements

Provisioning services were evaluated by measuring grain and protein yield. In maize and soybean a small-scale commercial combine harvested two yield rows per plot 2 weeks after physiological maturity, in late September through early October. Grain weight was reported on a 15% moisture basis, using a DICKEY-john moisture meter to determine moisture and correction factor (Churchill Industries, Minneapolis, MN). We used a consistent 15% moisture content in order to provide a comparable basis for evaluating grain production by system (across species). Wheat grain yields were determined in July by harvesting the center 15.3 m of each plot. Protein yield was calculated by multiplying grain yield produced and protein content (based on N grain measurements conducted in 1998, 1999 and 2006) of maize, soybean and wheat, an average of 98 g kg^{-1}, 370 g kg^{-1} and 150 g kg^{-1}, respectively. An exception was ORG monoculture maize grain which had 16% lower protein content than other treatments, and protein yield was adjusted accordingly. Tissue samples were dried, ground to pass a 1 mm screen in a Christy-Turner Mill (Ipswich, Suffolk, UK) and analyzed for total C and N using a Carlo-Erba NA 1500 CNS (Carlo-Erba, Milan, Italy).

2.5. Soil measurements

Ecosystem supporting services were evaluated by comparing soil properties from a comprehensive sampling of all plots conducted in 1993 (pre-experiment) and 2008. On 2 April 2008 LFL maize plots were sampled (composite of 8 cores 20 mm diameter) to a depth of 0–25 cm, ground (2 mm), and air-dried. Total C and N were determined by dry combustion on a Leco Carbon Analyzer (Leco Corp., St. Joseph, MI) or a Carlo-Erba NA 1500 CNS (Carlo-Erba, Milan, Italy). Soil bulk density was 1.30 Mg m^{-3} in 1993, and in 2000 it was 1.33 Mg m^{-3} for organic and 1.38 Mg m^{-3} for integrated management; these values were used to calculate soil C accumulation (Wilson et al., 2001). Analysis for cation exchange capacity, available phosphorus (P), and potassium (K) were conducted at the A&L Great Lakes Laboratories, Fort Wayne, IN. Available P and exchangeable cations were extracted according to Mehlich III, and analyzed by inductively-coupled plasma spectrometry. Soil inorganic N was determined annually in late April for the 0–25 cm depth using 1 N KCl extraction and a Lachat automated colorimetric analyzer (Lachat Instruments, Milwaukee, WI).

Regulating services were assessed related to water quality (mitigation of nitrate-N leaching) and N-use efficiency (as an indicator of fossil fuel requirement and greenhouse gas emissions). Intact core lysimeters were installed in the LFL cover crop split–split-plots in 1993, and including a normalization year were monitored for 7 years (data reported here from April 1994 through March 2000). The Ap horizon was set aside and a 61 cm segment of 30.5 cm (ID) PVC pipe was pressed – using hydraulics – through the Bt and subsequent horizons until the leading edge of the core was into the sand-gravel C horizon. Leachate from the 0.8 m depth was collected in a 20-l reservoir, with moveable access tubes that allowed field equipment operations. The reservoirs were sampled monthly, volume determined, and samples frozen for nitrate-N analysis. Nitrate-N leached was summed by leaching year (April–March). Leachate volume averages aggregated over replications and seasons were similar across treatments: 36% of annual precipitation (Smeenk, 2003). Nitrogen-use efficiency was calculated as grain produced, divided by N applied as mineral fertilizer or manure (Table 1), see Tilman et al. (2002).

2.6. Data analysis

We used PROC MIXED in SAS 9.1 to conduct a two-way analysis of variance (ANOVA) to determine the effects of management, cropping system diversity and their interaction on soil properties and nitrate-N leached. Annual leaching nitrate-N sum per year was normalized using a natural log(ln(x)) transformation; means reported were the least square means of the un-transformed data. Grain yield and protein yield analysis by crop and by cropping system were conducted using PROC MIXED for ANOVA, where the factors were year, management, cropping system diversity and their interaction. Temporal variability analysis was conducted by calculating over time the standard deviation of yield divided by average yield to determine the temporal coefficient of variation (CV) for each crop-replicate plot, where plot-level CV was the unit of replication. Ecosystem service indicator values were expressed relative to those measured in INT biculture (the base-line system). Radial graphs were prepared for ORG and INT six species relative to INT biculture, with 100% values equivalent to 22 mg kg^{-1} of P, 8.1 mg kg^{-1} of organic C, 74 kg ha^{-1} of leached nitrate-N, 6.4 Mg ha^{-1} of system grain yield, 640 kg ha^{-1} of system protein yield, and 43 kg grain kg^{-1} N as N efficiency.

3. Results

3.1. Soil fertility and carbon

Soil nutrient and carbon status was evaluated at the beginning of the experiment and after 15 years, to assess supporting services of soil fertility and organic matter (MEA, 2005). Soil in 1993 prior to initiation of the experiment contained 47 mg kg^{-1} of P, 119 mg kg^{-1} of K, and 1610 mg kg^{-1} of calcium (Ca), soil bulk density was 1.3 Mg m^{-3}. Management influenced soil fertility, as soil total N, extractable P, K and Ca status was 29%, 80%, 43% and 28% higher for ORG than for INT, respectively (Table 2). In contrast to management, biodiversity had almost no effect on soil properties. The exception was extractable P which was 13% lower in diverse systems than in monoculture.

Base-line soil C in 1993 was 7.6 g kg^{-1}. By 2008, soil C was 35% higher in ORG (11.5 g kg^{-1}) than in INT (8.5 g kg^{-1}; Table 2). The ORG managed systems accumulated 103 g C m^{-2} year^{-1}, a rate fourfold higher than INT at 23 g m^{-2} year^{-1}. Crop species diversity did not influence soil C.

3.2. Crop yield

We conducted a broad stroke comparison of grain and protein yield by cropping system on a 4-year basis (4-year of continuous maize vs. 4-year rotation M–M–S–W). This system-wide comparison showed strong management and biodiversity effects: cumulative grain in ORG was 20.0 Mg ha^{-1}, 20.4 Mg ha^{-1}, 16.6 Mg ha^{-1} and 17.7 Mg ha^{-1} in monoculture, biculture, three and six species systems, respectively, and in INT was 25.6 Mg ha^{-1}, 25.7 Mg ha^{-1}, 19.5 Mg ha^{-1} and 19.9 Mg ha^{-1}, respectively. The quality of the grain varied as well, as shown by 4-year protein yield, which in ORG was 1.69 Mg ha^{-1}, 1.71 Mg ha^{-1}, 2.28 Mg ha^{-1}, 2.41 Mg ha^{-1} in monoculture, biculture, three and six species systems, respectively, and in INT was 2.56 Mg ha^{-1}, 2.57 Mg ha^{-1}, 2.66 Mg ha^{-1} and 2.71 Mg ha^{-1} respectively. On an individual crop basis, biodiversity enhanced grain yield in maize, but not in soybean or wheat (Table 1). Organic generally produced less grain than INT: 27% less maize (Fig. 1A and B), 10% less soybean (Fig. 1C), and 15% less wheat (Table 1). Soybean production under ORG management was equivalent to INT with the exception of 1995 when the ORG soybean crop failed (Fig. 1).

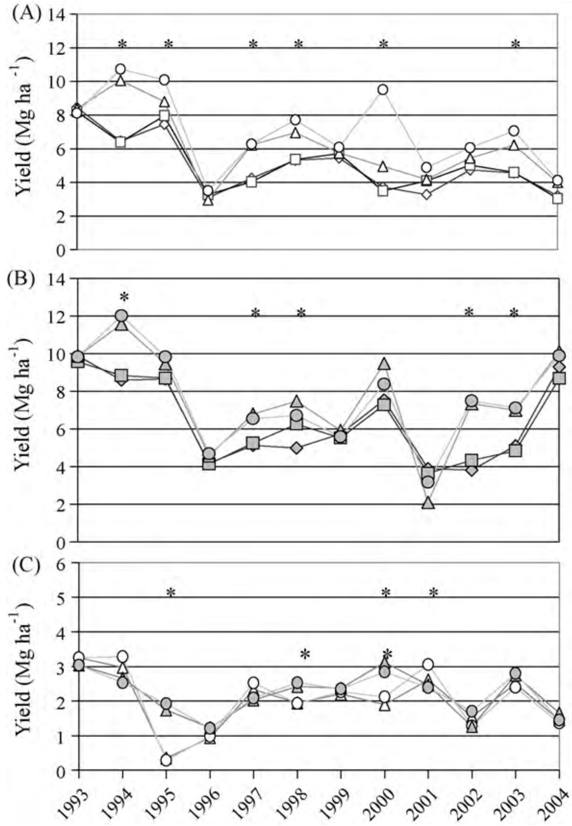

Fig. 1. Maize grain yield in (A) ORG and (B) INT systems, (C) soybean yield in the LFL trial at the Kellogg Biological Station, Hickory Corners, MI. * Significantly different within a panel. ◇ = monoculture, □ = biculture, △ = triculture, ○ = six species ORG management, ◆ = monoculture, ■ = biculture, ▲ = triculture, ● = six species INT management.

To evaluate response to climate variability, the temporal CV was assessed for grain yield, and found to be 36% for maize, 34% for wheat and 40% for soybean (Fig. 2). Management did not affect maize yield variability, but ORG was associated with enhanced variability in soybean ($P < 0.001$) and reduced variability in wheat ($P = 0.02$). Interestingly, yield patterns over time differed for each crop (Fig. 1). In 1999 there was a 45% reduction in precipitation from the 30-year average. Across management systems, maize yield in 1999 was reduced to 5.7 Mg ha^{-1}, a 12% decline (Fig. 1A and B). In contrast, soybean yield in 1999 was increased by 7% to 2.3 Mg ha^{-1}, above the average of 2.1 Mg ha^{-1} (Fig. 1C), and wheat yield in 1999 was the long-term average, 2.8 Mg ha^{-1} (data not shown).

3.3. Reactive nitrogen loss

Nitrate-N leaching in the LFL was investigated from 1994 to 2000, as a major N loss pathway and indicator of agroecosystem impact on water quality. The annual pattern of nitrate-N leached indicated loss was highest in the spring (Fig. 3). Management had a marked effect on nitrate-N leached, as ORG practices were associated with annual leaching losses of 37 kg nitrate-N ha^{-1}, about half that of INT at 70 kg nitrate-N ha^{-1}. Nitrate-N losses were on average 26% of organic N inputs at 112–191 kg N ha^{-1}, and 48% of inorganic N inputs at 138–150 kg N ha^{-1}. We monitored nitrate-N loss in treatments with winter annual cover crops, so only biculture vs. six species systems could be compared and no influence of diversity was observed for this subset of treatment (Fig. 3).

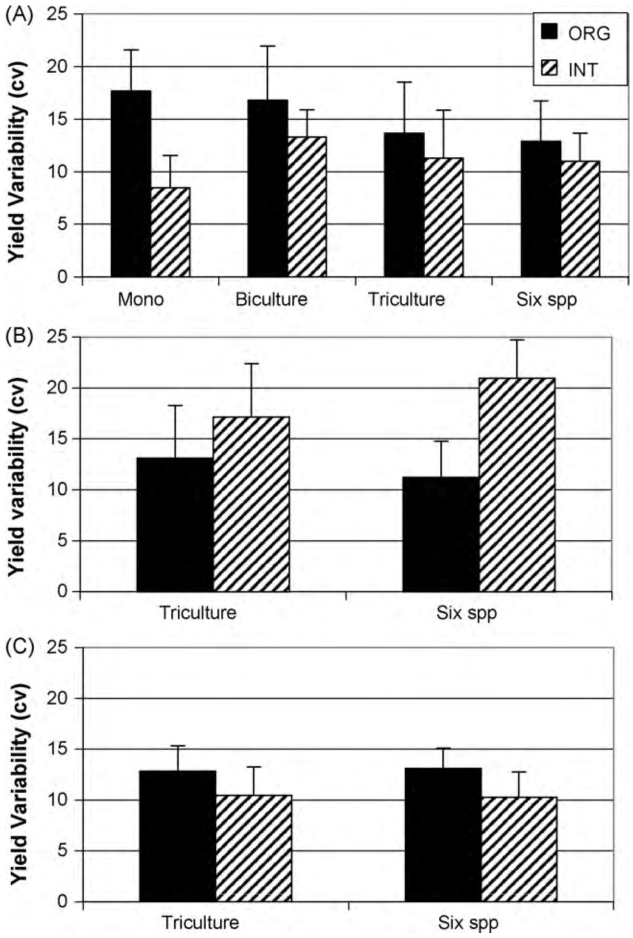

Fig. 2. Temporal variability (coefficient of variation on a crop-replicate plot basis shown with standard deviation bars) over 12 years in (A) maize, (B) soybean, and (C) wheat in the LFL trial at the Kellogg Biological Station, Hickory Corners, MI.

3.4. Ecosystem service tradeoffs

Ecosystem services were evaluated relative to a base-line system of INT biculture (Fig. 4). The provisioning service of grain was highest in INT biculture, 25–30% higher than diversified INT and ORG managed systems. Provisioning of high quality grain on the other hand was maintained at the same level in all systems studied, as shown by protein yield (Fig. 4). Supporting and regulating services were markedly high in ORG, with a 50% mitigation of nitrate-N leaching and a 54% increase in soil C, relative to INT biculture. Diversification of INT biculture to six species had limited benefits, including a slight reduction in nitrate-N leached and greater soil C accumulated (Fig. 4). Assessing tradeoffs in systems trials is a complex issue, but a comparison of grain produced and N retained in the biculture system under ORG and INT management is illustrative. As shown in Table 1, the average maize grain yield in ORG biculture was 5101 kg ha^{-1}, and in INT biculture was 6423 kg ha^{-1}. Nitrate-N leached in ORG biculture was 32 kg ha^{-1} and in INT biculture was 74 kg ha^{-1} (Fig. 3). This is suggestive that there is a ‘cost’ of 31 kg grain ha^{-1} per kg of N ha^{-1} retained, i.e., not leached.

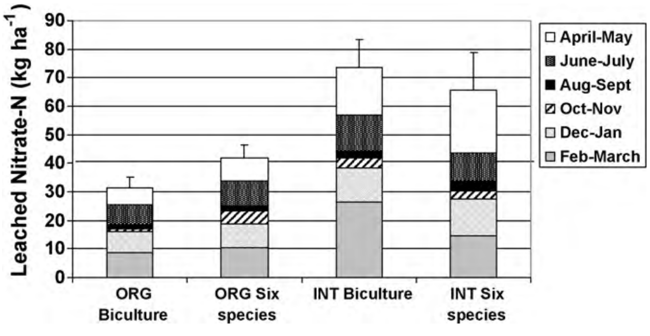

Fig. 3. Annual leached nitrate-N for 2-month time periods averaged over 6 years 1994–2000, standard deviation bars based on annual values. Management by ORG and INT for biculture and six species row crop systems in the LFL at Kellogg Biological Station, Hickory Corners, MI.

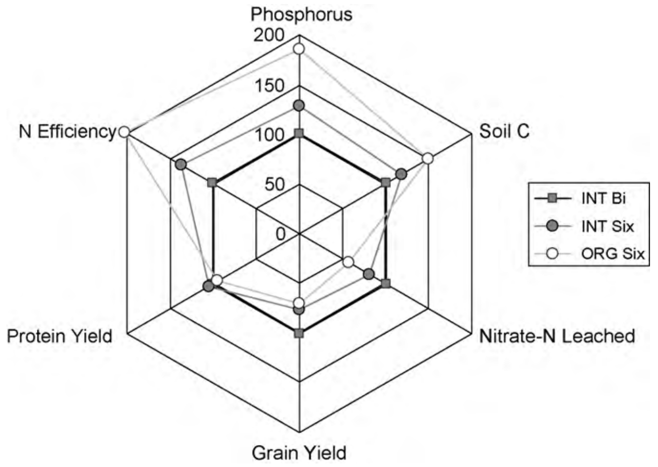

Fig. 4. Ecosystem services from LFL cropping systems. Results are presented as % relative to INT biculture ■ in a radial graph, INT six species ● and ORG six species ○. INT biculture 100% values equivalent to 22 mg kg^{-1} of P, 8.1 mg kg^{-1} of organic C, 74 kg ha^{-1} of leached nitrate-N, 6.4 Mg ha^{-1} of system grain yield, 640 kg ha^{-1} of system protein yield, and 43 kg grain kg^{-1} N as N efficiency.

4. Discussion

4.1. Supporting services—soil resource

The soil resource at this site is typical of intensively cropped, well-drained Alfisols. One of the most important soil orders for agricultural lands, Alfisols typically have low to moderate soil C stocks and are becoming increasingly nutrient deficient (Palm et al., 2007). Organic management enhanced soil fertility (Table 2). Compost applications in ORG may have contributed to nutrient availability through indirect as well as direct processes, including soil structure improvement and complex interactions with soil biogeochemistry (Ohnoa et al., 2005). The moderate soil fertility status in the INT system – which followed recommended conventional management – may have been related to N fertilization which has been associated with declines in exchangeable cations in other long-term studies (Liu et al., 1997). Diversity was associated with a slight decline in soil P, and had no effect on cations, soil N or C. This despite the increased presence of legumes in the diverse systems, which are generally associated with soil N accumulation (Russell et al., 2009), but this was not the case in our study.

Adjacent late successional ecosystems indicate the potential to increase soil C by ~twofold in Alfisols managed agriculturally (Grandy and Robertson, 2007). The ORG management system dramatically increased soil C, to levels that were 50% higher than those observed at the initiation of the study. Integrated management on the other hand had limited effects on soil C (Table 2). An earlier report showed a similar pattern of response: Sanchez et al. (2004) found that soil C increased by 30% in ORG in the seventh year of this study, but no change was observed in INT. Soil C accumulation has been observed previously with organic management, in similar legume and compost-diversified cropping systems (Grandy and Robertson, 2007; Maëder et al., 2002). Interestingly, C accumulation in the LFL does not appear to be closely related to C inputs: Residue C inputs in continuous maize INT were 22–29% greater than C inputs in diversified maize INT for this experiment (Fortuna et al., 2003), yet this was not reflected in soil C (Table 2). It is probable that other factors such as N fertilizer and decomposition processes need to be considered (Russell et al., 2009); LFL investigations on these questions are not yet complete.

4.2. Provisioning services—yield

Diversity and management profoundly influenced crop yield in the LFL. Crop grain yields were consistently lower in ORG compared to INT; however, this was not readily apparent until the last third of experiment, in years 9–12 (Fig. 1). On the other hand, protein yield was maintained in diverse systems across management (Fig. 4). Moderate to severe grain yield reductions have been reported previously for ORG management (Cavigelli et al., 2008; Maëder et al., 2002; Smith et al., 2007), but not in all cases (Pimentel et al., 2005). Soybean yields were generally maintained with ORG, except for 1 year of almost complete crop loss (Fig. 1C). Occasional failure of an organic soybean crop has been observed previously (Cavigelli et al., 2008; Pimentel et al., 2005). Planting date is often delayed in ORG to permit control of weeds through cultivation of early season weeds, but this reliance on bio-physical processes can lead to crop failure if late planting is followed by erratic rainfall. Another source of risk in organic systems may be moderate levels of soil inorganic N, and the requirement to delay planting until sufficient mineralization and decomposition processes are underway, which competes with the need for timely planting of summer annuals (Cavigelli et al., 2008; Snapp et al., 2005). Substituting biologically-based management for agro-chemical inputs thus can introduce risk in organic systems, which could be of greater concern in the future with anthropogenic-forcing of erratic rainfall.

If response is considered on an individual crop-year basis, then diversification was associated with higher grain yield in maize, but not wheat or soybean (Table 1). Continuous maize yield was lower than first-year rotated maize in almost every year, under both management treatments. This growth-promoting diversity effect is consistent with other studies (Berzseny et al., 2000; Pimentel et al., 2005; Smith et al., 2008). Quality of crop yield is important, as well as quantity. Grain protein content was consistently low in ORG continuous maize; however, diversity maintained total protein yield across all systems (Fig. 4).

Temporal stability of crop yields was also assessed, but no discernable effect of biodiversity was observed (Fig. 3). In a nearby study, Smith et al. (2007) reported that temporal yield variability of a corn–soybean–wheat sequence was similarly not reduced in a treatment with enhanced biodiversity from growing winter cover crops, although other changes in management practices were also implemented. Large yield variability is not surprising at this site, given that annual precipitation ranged from 61 cm to 103 cm per year, and precipitation was below the 30-year mean (86 cm) in 7 of the 12 years studied. Based on research in natural systems, biodiversity might have been expected to stabilize productivity over time (Gunderson, 2000), as was shown over two decades for maize and wheat in a Hungary cropping systems trial (Berzseny et al., 2000).

4.3. Regulating services—reactive N and water quality

Agriculture is profoundly linked to society and the environment through reactive N, which influences productivity, water quality, and climate change through direct and indirect processes (Drinkwater and Snapp, 2008). In our study N requirements were markedly influenced by cropping system diversity. The winter annual wheat and N-fixing soybean required soluble fertilizer inputs of 80 kg N ha^{-1} and 0, respectively, while maize required 150 kg N ha^{-1}, 120 kg N ha^{-1} and 90 kg N ha^{-1}, depending on organic N sources (Table 1), and higher N inputs are common practice in commercial production. Overall, maize monoculture and biculture received 600 kg N ha^{-1} every 4 years, whereas the triculture received 320 kg N ha^{-1}, and six species received 280 kg N ha^{-1} over the same period. Soluble N in fertilizer form was not applied to ORG crops, but similar total N inputs were applied in ORG compared to INT (Table 1).

Over the 12 years of the study, N-use efficiency for maize was ∼40 kg grain kg N^{-1} in INT and ∼90 kg grain kg N^{-1} in ORG (Table 1). This indicates that significant gains in use efficiency can be achieved over current levels of ∼30 kg maize grain kg N^{-1} in the upper Midwest (Cassman et al., 2002). Higher efficiency is generally associated with low N inputs, and this may explain in part the gains observed in the ORG systems, as soluble N was low in these cropping systems (Cassman et al., 2002; Table 1). However, total N applied was high with ORG management (Table 1), so the explanation for higher N-use efficiency may involve other processes, such as shifts in synchrony of N availability in relationship to plant demand.

Research on N efficiency has been conducted previously within 2- to 3-year time frames (Tonitto et al., 2006), which do not take into account equilibrium shifts that may have occurred in our study with the coupled carbon-N sources in the ORG treatment. Monitoring nitrate-N loss through gravimetric lysimeters indicated that 26% (ORG) and 48% (INT) of N applied was lost through leaching (Fig. 3). A Pennsylvania study reported similar leaching losses, equivalent to 24–55% of N applied (Jemison and Fox, 1994). In our study we measured leaching in systems with cover crops and moderate N application rates, yet N losses were still significant. Nitrogen exports would be expected to be low in the presence of winter annuals that increase transpiration and scavenge residual nitrate-N. Diversity in this case was also associated with lower N fertilizer additions, yet N losses were only reduced by 8 kg N ha^{-1} in six species compared to two species INT (Fig. 3). Management was a more effective means to reduce N loss than diversity. The organic managed systems leached half as much nitrate-N as INT. Total N inputs in ORG were in some cases higher than INT, although soluble N was lower, and soil N accumulated over time in ORG. This confirms findings by Pimentel et al. (2005) that N is retained under organic management, and is consistent with the strategy of enhancing temporary immobilization as a means to reduce N loss from row crops (McSwiney et al., 2010).

High nitrate-N leaching loss was observed in our study from February through July, while relatively minimal loss (<9%) occurred from August through November (Fig. 3). This illustrates the importance of managing soil inorganic N turnover and pool size in the spring. If temporary N immobilization could be promoted during this leaching period, then environmentally-damaging N loss would be markedly reduced. This temporal pattern requires study in other environments, but it suggests that close attention be paid to soil N processes early in the growing season to support synchrony of N availability and plant demand, while minimizing the soluble pool.

4.4. Ecosystem service tradeoffs

Ours is the first report we know of testing diversity as a factor separate from management in long-term agroecosystem experimentation. On a single-crop basis, maize yield responded positively to biodiversity (Table 1), but overall INT continuous maize produced the largest amounts of grain and, surprisingly, this simplified system was not associated with high temporal yield variability. The productivity associated with INT management requires chemical inputs in the form of fertilizer and herbicides, and was associated with almost twofold higher nitrate-N leaching than ORG (Fig. 3).

ORG management – but not biodiversity – supported soil C assimilation, N retention and high N-use efficiency (Fig. 4). This supports earlier findings that ORG production has high environmental benefits (Maëder et al., 2002; Pimentel et al., 2005); however, we extended these findings and documented the extent of agronomic tradeoffs, which were substantial. Maize yield was consistently reduced by ~20% under ORG management, and the ORG soybean crop failed in 1 out of 12 years. A tradeoff was apparent, as nitrate-N leaching was reduced in the ORG biculture to a moderate level of 32 kg ha^{-1}, but this was in concert with reduced yield potential. Overall, an estimated loss of 30 kg ha^{-1} of grain occurred per kg nitrate-N retained annually in ORG managed bicultures compared to INT.

5. Conclusions

For a diverse cropping system to be economically sustainable, grain must be of higher value to overcome the lower quantity of grain produced than by continuous maize. Either that, or incentives must be put in place that support farming for ecosystem services, such as subsidies based on N preserved or C sequestered. Taken together, over a decade of experimentation indicated that it was not sufficient to only vigilantly manage agricultural inputs and promote cropping system diversity, the strategy followed in INT six species. The temporal cropping system diversification (crop and cover crop rotation sequences) studied here was not closely associated with supporting or regulating ecosystem services. All treatments were amended with moderate levels of N inputs and this may have attenuated response to biodiversity. Organic practice in our study included reliance on compost as a nutrient source rather than soluble N, and the absence of agro-chemical inputs; these practices deserve closer study for their role in mitigating nitrate-N loss, soil C storage, soil fertility maintenance, and N-use efficiency.

The successful reduction of ecosystem disservices through organic management should be a source of encouragement to managers of coarse-textured soils around the globe. There are implications for climate change mitigation, as these soil types provide a vast reservoir for sequestering C. However, yield reductions indicate that economic incentives are required if broader adoption is to be promoted.

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