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Using biodiversity to link agricultural productivity with environmental quality: Results from three field experiments in Iowa

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Abstract

Agriculture in the US Corn Belt is under increasing pressure to produce greater quantities of food, feed and fuel, while better protecting environmental quality. Key environmental problems in this region include water contamination by nutrients and herbicides emitted from cropland, a lack of non-agricultural habitat to support diverse communities of native plants and animals, and a high level of dependence on petrochemical energy in the dominant cropping systems. In addition, projected changes in climate for this region, which include increases in the proportion of precipitation coming from extreme events could make soil and water conservation in existing cropping systems more difficult. To address these challenges we have conducted three cropping systems projects in central Iowa: the Marsden Farm Cropping Systems experiment, the Science-based Trials of Row-crops Integrated with Prairies (STRIPs) experiment, and the Comparison of Biofuel Systems (COBS) experiment. Results from these experiments indicate that (1) diversification of the dominant corn–soybean rotation with small grains and forage legumes can permit substantial reductions in agrichemical and fossil hydrocarbon use without compromising yields or profitability; (2) conversion of small amounts of cropland to prairie buffer strips can provide disproportionately large improvements in soil and water conservation, nutrient retention, and densities of native plants and birds; and (3) native perennial species can generate large amounts of biofuel feedstocks and offer environmental benefits relative to corn- and soybean-based systems, including greater carbon inputs to soil and large reductions in nitrogen emissions to drainage water. Increasing biodiversity through the strategic integration of perennial plant species can be a viable strategy for reducing reliance on purchased inputs and for increasing agroecosystem health and resilience in the US Corn Belt.

Key words: biodiversity, multifunctionality, conservation, cropping systems

Introduction

The US Corn Belt, spanning from western Ohio to eastern Nebraska and from southern Minnesota to northern Missouri, comprises one of the largest, most productive rain-fed grain regions in the world. Its natural endowment with fertile soils and a favorable climate makes it a major focal point in discussions of how to supply an expanding world population with enough food and plant-derived renewable energy. These discussions increasingly focus not only on the technologies of farming but also on the environmental impacts of farming practices and the resilience of agricultural systems to changes in climate, energy and nutrient availability, and other factors acting at a global scale.

Patterns of agricultural development, land use and environmental quality in Iowa exemplify the directions that conventional agriculture has followed in the Corn Belt during the past half-century. Iowa is now the leading US producer of corn, soybean, hogs, eggs and ethanol, and ranks seventh in cattle production[1,2]. Concomitantly, the state also ranks high nationally in the number of surface waters impaired by excessive concentrations of nutrients, pathogens, pesticides and soil sediment, and its croplands are major sources of nitrogen and phosphorus delivered to the hypoxic zone in the Gulf of Mexico[3–5].

In addition to high levels of water pollution, the development of conventional agricultural systems in the Corn Belt has been accompanied by a major loss of biological diversity. Tall-grass prairie was the dominant land cover in Iowa and much of the central and western Corn Belt prior to Euro-American settlement[6]; smaller areas within the region were occupied by other types of perennial plant communities, including savannas, riparian forests and wetlands. Most of this native vegetation is now gone, having been converted to cropland or pasture by 1900. At present, Iowa ranks last nationally in the amount of pre-settlement vegetation still remaining[7], with the state's prairie communities reduced to <0.1% of their former area[8]. Change has also taken place in recent years where land that had been in perennial cover through enrollment in the Conservation Reserve Program (CRP) has been converted to row crop production. Schilling and Spooner[9] reported that in Iowa's Squaw Creek watershed, 9% of the area that had been in CRP grassland in 1990 was converted to corn and soybean production by 2005. Not surprisingly, given the loss of native plant communities and conservation grasslands, the diversity of Iowa's native flora and fauna has been greatly reduced[10].

A substantial loss of crop diversity has also occurred throughout the central Corn Belt, illustrated by historical changes in land use in Iowa. Although the total amount of cropland in Iowa has remained relatively constant over the past 60 years, there has been a marked shift toward corn and soybean production; these two crops now occupy two-thirds of the state's total land area[11]. Between 1949 and 1997 in Iowa's Raccoon River watershed, the percentage of cropland used for wheat, barley, oat, alfalfa and other hay crops fell from 42 to 3%; in contrast, the proportion in corn and soybean grew from 57 to 97%[12]. Historical changes in crop diversity in the Corn Belt are linked with changes in livestock production in the region. From 1945 to 2000, cattle numbers in the Corn Belt declined by 52% as beef production shifted westward; concomitantly, land used for hay and oat production, used to feed cattle and other livestock, declined by 60 and 97%, respectively[13]. Similarly, in an analysis of landscape change during 1937–2002 in three Iowa townships, Brown and Schulte[14] noted marked reductions in the area of grasslands suitable for pasturing cattle.

Reductions in crop and non-crop diversity have been linked to a variety of forms of environmental degradation and agroecosystem dysfunction; conversely, increases in diversity can be associated with improvements in agroecosystem health and function. For example, Hatfield *et al.*[12] reported that nitrate concentrations in Iowa's Raccoon River have increased since 1970 as land use in adjacent cropland has shifted from diverse cropping systems containing small grains, hay, corn and soybean to simpler corn–soybean systems, which are more prone to nutrient leaching. Reductions in diversity and accompanying reductions in ecosystem functioning have also occurred due to removal of non-crop vegetation. In pursuit of increased field size and greater ease in the use of large agricultural machinery, trees on field borders have been removed in many areas of the Midwestern USA. Yet, fields that lack adjacent shelterbelt trees can be subject to increased wind speeds and greater wind erosion, and have reduced crop water use efficiency and lower yields[15,16]. Non-crop vegetation can also affect pest dynamics. In a comparison of Midwestern US landscapes dominated by corn and soybean fields versus landscapes containing a mix of crop fields and non-crop habitat, Gardiner *et al.*[17] found that soybean aphid (*Aphis glycines*) was subject to less biological control by natural enemies and consequently was more problematic in the less diverse landscapes, whereas greater diversity at a landscape level enhanced predator populations and biological control of the pest.

Given the loss in the Corn Belt of native biodiversity, crop diversity and the ecosystem services that diversity can provide, we ask: Are impoverished biological communities and environmental degradation unavoidable costs of high agricultural productivity or can farming systems be developed to provide both high yields and necessary ecosystem services, including water quality protection, soil conservation and pest control? Schulte *et al.*[18] suggested that the strategic integration of perennial vegetation into agricultural landscapes dominated by annual crops could help reconcile agricultural productivity with environmental quality. Increasing crop and non-crop diversity in agroecosystems with perennial species may be especially important because perennial plants perform many key ecological functions more effectively than annuals, including (1) regulating the flow and storage of water, (2) reducing soil erosion, (3) storing and cycling nutrients and carbon, and (4) providing habitat for natural enemies of crop pests and for native plants and animals of conservation concern[18,19].

Many options exist for diversifying agroecosystems with perennial vegetation, including forage crops that are alternated with row crops in rotation sequences; riparian buffers of trees, shrubs and grasses that separate crop fields from streams; in-field strips of herbaceous species that filter runoff water; trees and shrubs on field margins that reduce wind movement; reconstructed wetlands that receive drainage water from crop fields; agroforestry plantations that supply a variety of economic products; and woody and herbaceous plants that are harvested as biofuel feedstocks[18]. Here, we describe some of the agronomic, economic and environmental consequences of three approaches for increasing diversity in agroecosystems in Iowa: adding perennial legumes to corn–soybean rotations; weaving strips of prairie vegetation into corn and soybean fields to serve as filter strips; and growing prairie vegetation to produce solid or liquid fuel.

Lengthening Rotations to Reduce Agrichemical Use While Maintaining Productivity: The Marsden Farm Cropping Systems Experiment

Conventional corn and soybean production is a chemically intensive activity. Together, corn and soybean receive more herbicide active ingredients and more synthetic fertilizer than any other crops grown in the USA[20,21]. Emissions of herbicides and nitrogen from fields to water in the Corn Belt are roughly proportional to the quantities of those materials applied and the percentage of a watershed occupied by corn and soybean[22–25]. In the case of herbicides, emissions include both runoff and leaching losses; for nitrogen, emissions result from runoff and leaching of fertilizer, as well as losses from mineralized soil organic matter and manure[26]. Unlike deep-rooted perennial forage crops whose root systems are active for many months each year, corn and soybean have relatively shallow root systems that are active for only part of the year, rendering those crops leaky with regard to nitrogen loss during the spring and fall, when rainfall can be abundant and can transport nitrogen through the soil[12,27].

Concentrations of herbicides and nitrate in surface and ground water in the Corn Belt can exceed health-based standards for drinking water quality, raising concerns for impacts on human health, wildlife and fisheries[3,28–30]. Magdoff *et al.*[31] and Dinnes *et al.*[32] noted that reductions in synthetic nitrogen fertilizer use, coupled with greater use of perennial legume crops and judicious use of manure, constitute important components of strategies to conserve nitrogen and protect water from nitrogen contamination. Similarly, reducing herbicide use by increasing reliance on physical weed control practices and diverse crop sequences that challenge weeds with a broad range of stress and mortality factors may be an effective approach for reducing herbicide concentrations in the hydrologic system[3,33,34].

To test the hypothesis that diversifying a simple corn–soybean cropping system could allow for substantial reductions in nitrogen fertilizer and herbicide use without compromising crop productivity and profitability, a 9-ha field experiment was established in 2001 at the Iowa State University Marsden Farm, in Boone Co., IA. The site lies within a region of intensive rain-fed corn and soybean production and is surrounded by farms with high levels of productivity. Soils at the site are fertile Mollisols. In addition to a conventionally managed 2-year rotation (corn–soybean) that receives fertilizers and herbicides at rates comparable to those used on surrounding commercial farms, the experiment includes two more diverse low-external-input (LEI) cropping systems: a 3-year rotation (corn–soybean–small grain + red clover) and a 4-year rotation (corn–soybean–small grain + alfalfa–alfalfa) managed with reduced N fertilizer and herbicide inputs. The 2-year rotation is typical of cash grain farming systems in the region, whereas the 3-year and 4-year rotations are representative of LEI farming systems in the region that include livestock.

The experiment used a randomized complete block design with each crop phase of each rotation system present every year in four replicate blocks. Plots were 0.15 ha and managed with conventional farm machinery. After uniformly cropping the site with oat in 2001 and tuning the three management systems in 2002, intensive data collection began in 2003. Spring triticale was used as the small grain in 2003–2005, whereas oat was used in 2006–2010. During 2003–2010, solid pack manure was applied during the fall preceding corn production in the 3- and 4-year rotations at a mean dry matter rate of 9 Mg ha^{-1}, providing a mean of 120 kg total N ha^{-1}. Corn in the 2-year rotation received 112 kg N ha^{-1} as urea at planting, whereas corn in the 3- and 4-year rotations did not. The late spring nitrate test[35] was used to determine rates for post-emergence side-dress N applications (as urea ammonium nitrate) for corn in all rotation systems. Weed management in the 2-year rotation was based largely on herbicides applied at conventional rates. In the 3- and 4-year systems, herbicides were applied in 38-cm-wide bands over corn and soybean rows rather than broadcast, greater reliance was placed on cultivation, and no herbicides were applied in small grain and forage legume crops. Choices of herbicides used in each system were based on the identities, densities and sizes of weed species observed in the plots. Sampling procedures and other details of farming practices used in the different cropping systems during 2003–2010 are described in Liebman *et al.*[36], Cruse *et al.*[37] and Gómez *et al.*[38].

Results of the experiment indicated that corn and soybean yields from the more diverse 3- and 4-year systems were higher than those from the conventional system, despite substantial reductions in the use of synthetic N fertilizer and herbicides[36–38] (Table 1). Fossil energy use decreased with increases in crop diversity due to reductions in the use of fertilizers and pesticides, gas to dry grain, and liquid fuel to power farm machinery[37] (Table 1). Weed suppression was highly effective in each of the three cropping systems as reflected by the very small amounts of weed biomass found in corn and soybean phases of the rotations[36] (Table 1). Although labor requirements were greater in the longer, more diverse rotation systems, net returns to land and management were statistically equivalent in all three cropping systems, with a slight numerical advantage for the 3- and 4-year systems (Table 1).

Biological diversity contributed to the successful functioning of the LEI systems used at the Marsden Farm in multiple ways. For example, though triticale and oat added relatively little revenue themselves to the 3- and 4-year systems[36], they served as effective nurse crops for establishing red clover and alfalfa, thereby minimizing

Table 1. Inputs, yields, weed biomass and net returns for the three cropping systems in the Marsden Farm rotation experiment, Boone Co., IA, 2003–2010. Fossil energy inputs are yearly means for 2003–2008; all other data are yearly means for 2003–2010. Within rows, means followed by different letters are significantly different ($P<0.05$); means not followed by letters are statistically equivalent. Data are from Liebman *et al.*[36], Cruse *et al.*[37] and Gómez *et al.*[38].

	Cropping system		
	2-year rotation: Corn–soybean	**3-year rotation: Corn–soybean–small grain[1]/red clover**	**4-year rotation: Corn–soybean–small grain[1]/alfalfa–alfalfa**
Whole rotation			
Fertilizer N inputs, kg N $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$	76 a	18 b	12 c
Herbicide inputs, kg active ingredients $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$	1.91 a	0.28 b	0.21 c
Fossil energy inputs, GJ $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$	9.1 a	4.9 b	4.3 c
Labor requirements, h $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$	1.8 c	2.8 b	3.5 a
Net returns to land and management[2], \$ $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$	690	705	701
Crop yields			
Corn, Mg ha^{-1}	12.2 b	12.6 a	12.8 a
Soybean, Mg ha^{-1}	3.4 b	3.7 a	3.8 a
Small grain[1], Mg ha^{-1}	–	3.7	3.8
Alfalfa, Mg ha^{-1}	–	–	9.0
Weed biomass			
In corn, kg ha^{-1}	2.0	4.6	3.7
In soybean, kg ha^{-1}	1.5	3.8	3.6

[1] Triticale was grown as the small grain crop in 2003–2005; oat was used in 2006–2010.

[2] Crop subsidy payments were not included as sources of revenue.

erosion and reducing weed growth in the absence of herbicides.

Although forage legumes were less profitable than corn[36], their inclusion within the diversified rotation systems allowed substantial reductions in nitrogen fertilizer use for corn production[39,40] (Table 1). Harvest of alfalfa hay and concentrated feeds allowed integration with livestock production and fostered nutrient return to cropland through the application of manure[36], further reducing production costs and fossil energy consumption[37]. In studies conducted by Randall *et al.*[27] and Drinkwater *et al.*[41], leaching losses of nitrogen from deep-rooted perennial forage crops, and from corn–soybean systems diversified with forage legumes and small grains were lower than from corn and soybean. Although we did not measure nitrogen losses in our study, those results suggest that nitrogen losses from the diverse LEI systems in the Marsden Farm experiment are likely to have been lower than from the simpler conventional system.

As in our study, other research has shown that lengthening rotations beyond 2 years can increase soybean yields[42,43]. In addition, both corn and soybean yields have been shown to respond positively to manure application even when the nutrient requirements of those crops are met with other fertility sources[44–46]. In 2010, the incidence and severity of sudden death syndrome of soybean, caused by the pathogen *Fusarium virguliforme*, and subsequent losses of soybean yield were much lower in the 3- and 4-year rotation systems than in the 2-year rotation, though the mechanisms for these effects are not yet clear (L.F. Leandro, pers. comm.).

Finally, diversifying the corn–soybean system with small grain and forage crops increased the diversity of habitats available to insects and rodents that preyed upon weed seeds[47–49], which is likely to have stabilized seed predator populations and increased their effectiveness in suppressing weed population growth under conditions of reduced herbicide inputs[50].

The rotation systems and management practices used in the Marsden Farm experiment are well suited to investigations of crop performance, weed dynamics, and economic and energetic costs and returns, but they should not be construed to represent optimal systems. The experiment has not addressed the need for market development for diverse crops to be viable at a larger scale, nor has the experiment provided direct data concerning the impact of the contrasting cropping systems on nutrient and pesticide emissions. Nonetheless, results from the experiment indicate diversified LEI systems for agronomic crops in the US Corn Belt can be highly productive and economically viable, and that further research into their refinement and environmental impacts is warranted. Research focused on the social and economic conditions that help to maintain the dominance of simple cropping systems and that discourage farmers from exploring and adopting more diverse LEI systems would be a useful complement to investigations targeting biophysical characteristics of contrasting cropping systems.

Using Native Perennial Vegetation to Improve Conservation in Annual Cropland: The Science-based Trials of Row-crops Integrated with Prairies (STRIPs) Experiment

Soil and water conservation are critical components of any cropping system, yet, existing rates of erosion within the US Corn Belt indicate that despite high levels of crop productivity, substantial conservation challenges need to be addressed[51,52]. Conservation practices that have proven useful in restricting the movement of soil sediment within and out of crop fields include buffers and filter strips composed of herbaceous plants, typically perennial grasses. An extensive review by Dosskey *et al.*[53] found that sediment trapping efficiencies of buffers generally range between 40 and 85% for buffers that are as small as 2.5% of the source area. Modeling results predict a relatively rapid increase in sediment trapping efficiency as the percentage of buffer area to source area increases from 0 to 10%, with trapping efficiency leveling off as the percentage increases above 10%[53]. Distributing perennial cover across several contour strips within a watershed in addition to buffers at the bases of catchments may enhance sediment and runoff trapping efficiency since most sediment deposition occurs in the first few meters of the up-slope edge of buffers[54].

In addition to the amount of vegetation cover, the composition of herbaceous vegetation used for conservation buffers can affect their function. Cool season exotic grasses, such as smooth brome (*Bromus inermis*) and Kentucky bluegrass (*Poa pratensis*), are widely used to provide ground cover in agricultural areas of the US Corn Belt, but are relatively weak-stemmed and prone to lying flat under heavy rain. In contrast, native tallgrass prairie communities are typically dominated by stiff-stemmed warm season grasses, such as Indiangrass (*Sorghastrum nutans*), big bluestem (*Andropogon gerardii*) and switchgrass (*Panicum virgatum*), and a wide range of erect forbs, including species in the genera *Solidago*, *Aster*, *Rudbeckia*, *Ratibida*, *Silphium*, *Helianthus* and *Monarda*[55], which are less prone to collapse under heavy rain, and which are more effective in providing resistance to water flow and sediment movement[56,57].

In addition to reducing water runoff and soil erosion from crop fields, strips and patches of perennial native plants in and around agricultural areas can provide habitat to support native animal populations, including species of conservation concern[58–63]. Many bird species respond positively to agricultural conservation practices such as grassed waterways[64,65], field borders[66,67], and riparian buffer strips[62,68]; the general trend among these studies is increased bird presence, abundance and richness where those small habitats are present adjacent to row crops. Compared with monocultures of cool-season grasses, diverse prairie communities are expected to provide higher quality bird habitat and harbor more bird species[65,69,70].

Beginning in 2004, 12 experimental watersheds (0.5–3.2 ha each) were established within the Neal Smith National Wildlife Refuge (NSNWR), in Jasper Co., IA, to test the hydrologic and biodiversity effects of integrating prairie conservation buffers with row-crop production. The four treatments in the experiment consisted of varying proportions and different configurations of reconstructed native prairie species within corn and soybean fields. For the 100% crop treatment, each replicate watershed was used entirely for corn and soybean production, with the different crops grown in alternate years. There were two 10% prairie/90% crop treatments, one with prairie vegetation concentrated at the toe slope position and a second in which prairie vegetation is distributed in contour strips along the slope, including at the toe slope. In addition, there was a 20% prairie/80% crop treatment that also had prairie vegetation distributed in contour strips and at the toe slope. The experiment used a balanced incomplete block design with three replicates of the four treatments in four blocks. Soils in the experimental watersheds are Alfisols and Mollisols. Analysis of pretreatment data indicated that the watersheds had similar slopes, soil textures, and soil C and N concentrations.

Prior to the start of the experiment, exotic cool-season forage grasses, primarily smooth brome, dominated each of the watersheds. After tillage in the fall of 2006 to kill sod and level the soil, crop production in all watersheds was conducted using continuous no-tillage techniques; soil disturbance occurred only during corn and soybean planting and injection of anhydrous ammonia for corn production. Soybean was grown in 2007 and 2009 and corn was grown in 2008 and 2010 using conventional fertilizer and herbicide practices. Native prairie species were seeded in toe slope and strip positions in July 2007. The strips of prairie species had a minimum width of 4 m and were spaced at a minimum distance of 36 m to accommodate agricultural machinery operations.

Each watershed had a distinct surface flow outlet point where an H-flume was installed to monitor volume and rate of surface runoff. Each of these locations was also instrumented with an automated water sampler to obtain flow measurements and discrete water samples based on flow intervals. In addition, belowground water quality was monitored with a network of suction lysimeters and groundwater wells. Surface and ground water measurements were conducted in 2007–2010. Vegetation surveys were conducted between July and August in 2008, 2009 and 2010 to estimate species richness and determine plant cover using sampling quadrats along transects within the prairie and cropped areas of the watersheds. From 2007 to 2010, all watersheds were visited 9–12 times during spring and summer months and surveyed for birds using spot

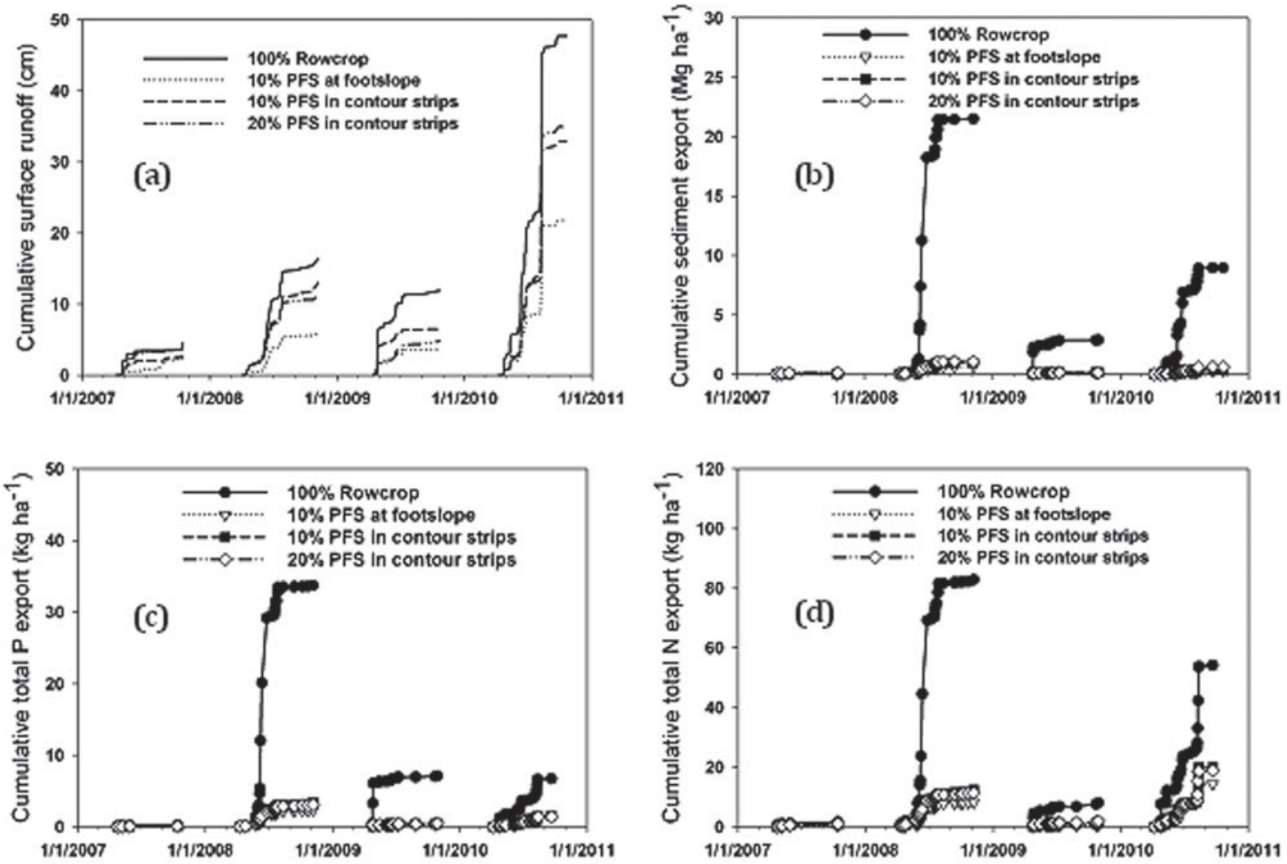

Figure 1. Cumulative (a) surface runoff[72], (b) export of sediment[73], (c) total phosphorus export (Helmers *et al.*, unpublished data), and (d) total nitrogen export (Helmers *et al.*, unpublished data). Measurements were made when soil was not frozen. PFS, prairie filter strips.

mapping techniques[71]; nest searching and monitoring were added in 2010.

Results of the experiment indicated that prairie buffers had disproportionately large effects on water movement, soil loss and nutrient loss, relative to the amount of annual cropland converted to perennial cover. During 2008, 2009 and 2010, greater water runoff occurred in the 100% crop watersheds than in the mixed perennial-annual watersheds (Fig 1a). Concomitantly, soil sediment loss from 100% crop watersheds was at least 10 times greater than from watersheds with 10 or 20% perennial cover (Fig. 1b). Losses of phosphorus (Fig. 1c) and nitrogen (Fig. 1d) in surface runoff were also markedly higher in the 100% crop watersheds. It is notable that no-tillage production techniques, generally viewed as important for soil conservation, failed to prevent large amounts of soil erosion in the 100% crop watersheds, especially in 2008, a year of intense rainfall during late May and early June.

Although differences in plant species richness and cover were not observed among the three treatments that contained prairie vegetation, plant species richness and cover by native perennial species increased with time in the prairie strips. Dominant native perennial species included Canada goldenrod (*Solidago canadensis*), pinnate prairie coneflower (*Ratibida pinnata*), wild bergamot (*Monarda fistulosa*), smooth ox-eye (*Heliopsis helianthoides*), Indiangrass (*S. nutans*) and big bluestem (*A. gerardii*). By 2010, prairie strips contained an average of 51 plant species in a total sample area of 6 m^2, of which 35 were native. In contrast, cropped portions of the watersheds (corn in 2010) contained only 15 plant species other than corn, of which 6 were native. Thus, by 2010, conversion of 10–20% of cropland area to reconstructed prairie gave, on average, a 240% increase in overall plant species richness and a 480% increase in native species richness. Transects within cropped areas indicated that the presence of prairie strips did not increase weed infestation in adjacent crops relative to 100% crop watersheds.

A total of 45 bird species were recorded in the watersheds, including several grassland bird species on Iowa's list of species of greatest conservation need[10]: common yellowthroat (*Geothlypis trichas*), dickcissel (*Spiza americana*), grasshopper sparrow (*Ammodramus savannarum*), lark sparrow (*Chondestes grammacus*), field sparrow (*Spizella pusilla*) and eastern meadowlark (*Sturnella magna*). Bird species richness was higher after prairie establishment (2008–2010) than during establishment (2007), and tended to be highest in watersheds containing 20% prairie in strips (Fig. 2). Individual bird

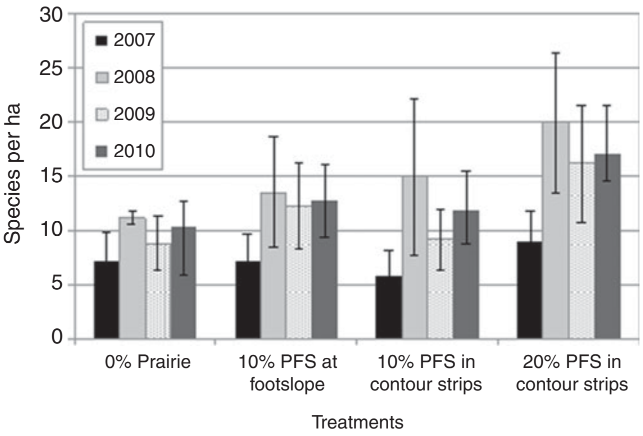

Figure 2. Mean bird species richness in the different experimental treatments, 2007–2010 (Schulte *et al.*, unpublished data). Lines represent one standard error. PFS, prairie filter strips.

species' responses to prairie within the watersheds varied among no response, avoidance, disproportionate use, or dependence on prairie habitat. Many bird species used both prairie and crop vegetation, but with a greater frequency of observations in prairie than expected given the extent of the habitat within a watershed (G-values 138–419; $P<0.0001$). In 2010, 17 nests from four bird species were located and monitored, five of which fledged successfully. Although we do not have enough data to robustly assess nest success, success rates for two grassland bird species, dickcissels and vesper sparrows (*Pooecetes gramineus*), are within the range of those observed in other studies[74,75]. Placement of the STRIPs study within the NSNWR may have had some influence on these results, but they are supported by results of a recent study by Walk *et al.*[63], who documented that small patches (1–142 ha) of grassland habitat located within cropland matrices in Illinois could contribute to the nesting success of dickcissels and eastern meadowlarks. In this case, croplands dominated the surrounding landscape (∼80% of land cover); furthermore, the investigators did not find a strong influence of patch size on nest success[63].

Taken together, these results provide substantial support for the hypothesis that diversifying small areas of annual cropland through the incorporation of perennial prairie vegetation can have disproportionately large beneficial effects on soil, water and biodiversity conservation. Such effects are especially important because projected climate changes in the US Corn Belt are expected to make farming more challenging. The amount of precipitation from heavy and extreme events is expected to increase in this region during the 21st century[76], with concomitant increases in crop damage[77] and erosion potential[78]. Biodiversity conservation is also expected to become more challenging as rising crop prices encourage producers to convert conservation grasslands to row-crop production[79,81]. In a review of climate change impacts on crop production, Hatfield *et al.*[81] emphasized the need for quantifying how cropping systems can be made more resilient to stress. As shown by results from the STRIPS experiment, strategic targeting to place prairie buffers in landscapes and watersheds dominated by row-crops is likely to be a valuable strategy for pursuing long-term agricultural productivity and environmental quality.

Identifying Trade-offs Among Agroecosystem Performance Indicators: The Comparison of Biofuel Systems (COBS) Experiment

Over the past decade, the USA has had a rapid expansion of interest and investment in transportation fuels derived from plant materials (biofuels), driven in part by concerns over the future availability and costs of fossil energy, and by recognition of the environmental effects of extracting and using fossil energy, including damage from petroleum spills and greenhouse gas emissions. To date, the biofuel boom in the USA has relied almost exclusively on corn grain for ethanol production[82,83]. However, heavy reliance on corn has led to a range of environmental and conservation concerns, including increases in nitrogen and phosphorus contamination of water[84,85], higher rates of soil erosion[86], greater greenhouse gas emissions due to land conversion[87,88], reductions in wildlife habitat and wildlife populations[89,90], and declines in biological control of crop pests[91].

Various forms of perennial vegetation have been proposed as alternatives to corn grain for use as biofuel feedstocks, including trees, certain grasses and mixtures of multiple prairie species[92–94]. These perennials would serve as sources of lignocellulose, rather than starch substrates for fuel production, and might confer a greater degree of environmental protection compared with corn-based systems[95,96]. Previous studies have shown that, in comparison with corn-based systems, perennial plants used as biofuel feedstocks may result in lower nitrate emissions to drainage water[97]; improved soil physical characteristics that can reduce water runoff, soil erosion and phosphorus transport[98]; greater root growth and below-ground carbon storage[98,99]; lower greenhouse gas emissions[100,101]; and better habitat for supporting pollinators, natural enemies of crop insect pests, and other wildlife populations[17,80,87,102].

The wide range of environmental as well as agronomic indicators that can be used to assess biofuel production systems calls attention to the multiple goods (e.g., fuel) and ecosystem services (e.g., water quality protection, carbon sequestration and wildlife conservation) that agricultural systems can provide. The multifunctionality of food and feed production systems in Iowa and Minnesota has previously been investigated by Santelmann *et al.*[103] and Boody *et al.*[104]. It is clear from those studies that no one approach for agricultural production is likely to score highest for all performance indicators. Similarly, the use of perennial species in lieu of corn for biofuel production may also involve trade-offs among key indicators of system performance.

The COBS experiment was initiated in 2008 at the Iowa State University South Reynoldson Farm in Boone Co., IA, to investigate the productivity characteristics and environmental impacts of corn- and prairie-based biofuel production systems. The 9-ha experimental site was on Mollisols with a relatively flat landscape (largely <1% slope, with some small areas of 2–3% slope), and was used for corn and soybean production prior to the start of the COBS experiment.

The experiment contained five cropping systems: continuous corn grown for grain and stover removal; the same corn-based system, but with rye used as a winter cover crop; a corn–soybean system from which only grain was removed; reconstructed multispecies prairie grown for whole-plant removal, without fertilizer; and the same diverse mixture of prairie species grown for whole-plant removal with fertilizer. The experimental plots were 0.17 ha each and arranged in a randomized complete block design with four replicates. All treatments were managed with no tillage. Planting, fertilization, crop protection and harvest operations were conducted with conventional farm machinery. Both prairie treatments were sown in 2008 with a mixture of 31 species native to Boone Co. or adjacent counties, including cool-season and warm-season grasses, legumes and other forbs. All corn treatments received 84 kg N ha^{-1} at planting, with additional nitrogen applied as a side dressing during early growth, based on treatment-specific soil test results[35]. In 2010, total nitrogen application rates for corn were 105 kg N ha^{-1} in the corn–soybean rotation, 123 kg N ha^{-1} in the continuous corn treatment and 169 kg N ha^{-1} in the continuous corn plus cover crop treatment. The fertilized prairie treatment received 84 kg N ha^{-1} in 2010; no N fertilizer was applied to unfertilized prairie or soybean plots. Weeds were suppressed in corn and soybean plots with post-emergence herbicides; no herbicides were applied to the prairie treatments.

The intent of the COBS experiment was to investigate a wide range of performance indicators. Here, we discuss measurements and calculations made in 2010 related to liquid fuel production, nitrogen loss through leaching, and root growth. Corn and soybean seeds, corn stover and prairie biomass were harvested in late September and October, and potential energy yield per unit of field area (GJ ha^{-1}) was calculated for grain-based ethanol, biodiesel and lignocellulosic ethanol, based on measured yields and conversion data given by Shapouri and Gallagher[105], Conley and Tao[106], Hill *et al.*[107], and Tilman *et al.*[92]. Leaching losses of nitrate–N (kg NO_3–N ha^{-1}) from the different treatments were determined using tile drains installed through the center of each plot at a depth of 1.1 m. Tile lines installed on the borders of each plot were used to prevent subsurface drainage from entering adjacent plots laterally. Flow of water out of central tile lines was metered and flow-proportioned water samples were drawn to monitor nitrate–N concentrations in each plot. After crops were harvested, root biomass (Mg ha^{-1}) was determined using soil cores (80 or 224 cm^2 plot^{-1}, depending on soil stratum) taken to a depth of 1.0 m, which were subsequently washed in an elutriator to remove soil particles. Remaining materials were then subjected to flotation and inspection under a dissecting microscope, and recovered roots were dried and weighed.

To facilitate comparisons of the relative performance of the different cropping system treatments, means of each treatment were divided by the highest mean value for each of the three performance indicators: energy production, nitrate–N loss and root mass. Results for 2010, shown in Fig. 3, clearly indicated the existence of trade-offs among different facets of cropping system performance. Energy production (unadjusted for fossil energy used in producing and harvesting crop materials) was greatest from the continuous corn systems, least in the unfertilized prairie system, and intermediate in the fertilized prairie and corn–soybean rotation systems. Nitrate–N loss was greatest from the corn–soybean system, almost nil from both the fertilized and unfertilized prairie systems, and intermediate from the continuous corn systems. The unfertilized prairie system produced more roots than all other systems, including the fertilized prairie system. Root mass of the annual crop systems was ≤14% of the root mass of the unfertilized prairie.

One of the striking features of these results was that the fertilized prairie treatment performed well compared with the conventional corn–soybean system for all three indicators: its estimated fuel yield was similar, it lost less nitrate–N in drainage water and it produced more root mass. Tilman *et al.*[108,109] have shown that above-ground productivity, N retention and root mass can increase with increasing species diversity in prairie communities, due to complementary patterns of resource use among species. High root mass in the prairie treatments of the COBS experiment may have been a consequence of including warm-season (C_4) grasses within the diverse communities, since warm-season grasses can produce more root mass than cool-season (C_3) grasses and legumes[110]. Economic performance indicators obviously need to be considered in any holistic assessment of biofuel feedstock production systems and their potential for adoption. Nonetheless, the potential for prairie-based biofuel systems as ways to address production and environmental challenges merits further investigation.

Using Biodiversity to Link Agricultural Productivity with Environmental Quality at a Landscape Scale

After a half-century of substantial increases in yield and labor efficiency, agriculture in the US Corn Belt has

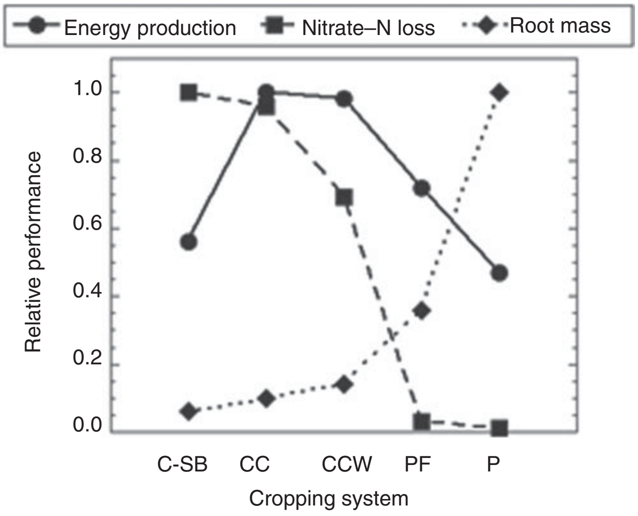

Figure 3. Relative performance of different cropping systems in the COBS experiment in 2010 with respect to liquid fuel production (GJ ha^{-1}), nitrogen loss in drainage water (kg NO_3–N ha^{-1}) and root mass (Mg ha^{-1}). Data for the C-SB treatment represent the average of the corn and soybean phases of the rotation sequence. C-SB, corn–soybean in rotation; CC, continuous corn; CCW, continuous corn with a rye cover crop; PF, fertilized prairie; P, unfertilized prairie. Data used for the calculations are unpublished and are from M. Jarchow, M. Helmers and R. Dietzel.

entered a new and increasingly challenging era. In addition to increasing demands for food, fiber and biofuels, agriculture is now being asked to provide cleaner water, healthier soil, better wildlife habitat, and a range of other environmental goods and services[111].

In this paper, we have reviewed results from three experiments indicating that strategic timing and placement of perennial crop and non-crop species in agroecosystems dominated by annual crops can have large beneficial effects on agroecosystem functioning. In the Marsden Farm cropping systems experiment, lengthening a simple corn–soybean rotation with small grain and forage crops and recycling nutrients and carbon in the form of manure allowed for 76–84% reductions in the use of synthetic N fertilizer, 85–89% reductions in the use of herbicides and 41–56% reductions in the use of fossil energy, while increasing corn yield 3–5%, increasing soybean yield 9–12%, and maintaining equivalent returns to land and management on a whole rotation basis (Table 1). Results of the STRIPs experiment indicate that diversifying a simple corn–soybean system with small strips and patches of reconstructed prairie vegetation reduced soil and nutrient loss from watershed catchments by >90% (Fig. 1), while also increasing the diversity of native plants and birds (Fig. 2). In the COBS experiment, a fertilized prairie community was found to be capable of producing amounts of liquid fuel comparable to amounts produced by a corn–soybean systems, but with six-fold greater additions to the root C pool and with 97% less nitrate–N released to drainage water (Fig. 3). In addition to the perennial forage crops, prairie buffer strips and prairie biofuel feedstocks we have discussed here, other vegetation types and practices exist within the 'perennial portfolio' for restoring agroecosystem health and function, including riparian buffers, agroforestry plantations and constructed wetlands[18,19]. Site-specific use of the full range of such practices would lead to a patchwork mosaic of diverse crops and non-crop vegetation interwoven on landscape and watershed scales[112,113].

In a world in which rising population and greater affluence have created increased demands for commodity crops such as corn and soybean, should arable land be used differently to achieve adequate levels of food, feed, fuel and fiber production? We believe that it should be. Our argument for increasing biodiversity by moving beyond a narrow base of commodity crops has three parts.

The first part relates to the need to re-couple crop and livestock production. Systems in which livestock are concentrated at high densities and isolated from the land base producing the crops that feed them are often characterized by high levels of pollution[114]. In contrast, integrated crop–livestock systems, including the diversification of cereal-based rotations with forage crops, the local application of manure, and pasture-based production, are likely to play an important role in reducing water contamination, soil erosion and fossil fuel dependence in agroecosystems, while maintaining high levels of productivity and profitability[13,37,114–116]. With appropriate forms of crop diversity and integrated management systems, livestock products might be generated in a manner that permits food security to coexist with ecosystem integrity. Results of the Marsden Farm Cropping Systems experiment provide support for the crop portion of this hypothesis, and indicate that diversification and integration can be important ways to reduce reliance on fossil energy and agrichemicals that can become environmental contaminants.

The second part of the argument relates to the need for resilience in the face of climate change. The currently dominant cropping systems in the US Corn Belt were developed in a climate regime different from the one that is beginning to express itself in the region. The types of high intensity rainfall events that are predicted to occur with increasing frequency are exemplified by the storms and flooding that took place in Iowa in May and June of 2008[117]. These events created severe erosion (defined as loss of ≥45 Mg of soil ha^{-1}) on about 930,000 ha, representing 10% of the state's arable cropland[118]. Existing soil conservation practices helped to prevent more damage, but were inadequate for full protection. If agricultural productivity is to be maintained or improved in the future, new conservation practices, such as the small areas of prairie vegetation used in the STRIPs project, need to be developed, refined and implemented. Patches of perennial vegetation might be used to provide biofuel feedstocks, as in the COBS project, allowing farmers to harvest a crop with use or market value, while still achieving conservation goals[95,119]. A key research question that needs to be addressed is: how small a proportion of arable land might be converted to perennial cover for various conservation benefits, and how does this proportion vary with site-specific conditions and specific conservation goals?

Our final point relates to the cost and value of increased biodiversity. Currently, agroecosystems are valued almost exclusively for their provisioning services, i.e., their ability to generate food and income. Their ability to conserve soil, protect water quality, provide wildlife habitat and recreational opportunities, and offer other supporting and regulating services is largely overlooked in the marketplace and, in most cases, farmers receive little or no financial compensation for providing these services[120]. The development of markets for organic and grass-based crop and livestock products that command price premiums indicates one approach for compensating farmers for ecosystem services that are linked to particular sets of production practices. Nonetheless, most agricultural land in the USA is used for commodity crops, rather than organic and grass-based production. Between 1995 and 2010, US farmers received $167 billion in federal crop subsidies for a narrow group of commodity crops, compared with $35 billion in federal conservation payments[121]. Shifting commodity crop subsidies toward conservation and ecosystem services payments could provide strong financial incentives for farmers to increase crop and non-crop diversity at targeted locations within agricultural landscapes, while maintaining farm income. Moreover, a shift of support from commodity subsidies to payments for ecosystem services could generate substantial benefits for society as a whole, including a more stable food supply, cleaner water and improved outdoor recreational experiences. Moving in this direction requires an explicit recognition of the multifunctional nature of agroecosystems and the need for a balance among different functions. Politically, such a move may be difficult. Ecologically, we feel it is necessary to insure that agroecosystems are both agronomically and environmentally sustainable.

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