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Enhancing agroecosystem performance and resilience through increased diversification of landscapes and cropping systems

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Over the past two decades, ecologists have gained a considerable amount of insight concerning the effects of biological diversity on how ecosystems function. Greater productivity, greater carbon sequestration, greater retention of nutrients, and greater ability to resist and recover from various forms of stress, including herbivorous pests, diseases, droughts, and floods, are among the effects of increased biological diversity noted in a recent review by Cardinale et al. (2012). The latter effect, often called resilience, is particularly important in managed social-ecological systems, including agroecosystems (Walker and Salt, 2006). In addition to being better able to withstand and recover from disturbances due to pests, weather, and other biophysical factors, resilient agroecosystems can be less susceptible to fluctuations in production costs and market prices (National Research Council, 2010; Kremen and Miles, 2012).

In general, the relationship between biological diversity and ecosystem function resembles an asymptotic hyperbola (Cardinale et al., 2012). That is, increases in the number of species present in an ecosystem from a very low level to some intermediate level engender large changes in ecosystem function, whereas increases in species richness above some intermediate, and undetermined, value engender smaller effects.

Another way to look at biodiversity-ecosystem function relationships is through the lens of *losing* species diversity. Professor Shahid Naeem of Columbia University uses the following analogy to examine how many species might be lost from an ecosystem before critical functions are no longer available: Imagine you have a computer on your desk that works well. Now open it, reach in with a needle nose pliers and randomly remove five of the many parts of the motherboard. Do you expect the computer to continue to function well after the loss of those parts?

The development of modern, industrial agriculture has been characterized by large reductions in biological diversity, both across landscapes and within farming systems (DeFries et al., 2004; Vandermeer et al., 2005). This loss of biodiversity is particularly evident in the U.S. Corn Belt. Where species-rich prairie grasslands, wetlands, and oak savannas once grew, corn and soybean now dominate (Klopatek et al., 1979). Farming systems that once contained small grains, hay, and pasture in addition to corn and soybean now contain almost exclusively the latter two crops (Hatfield et al., 2009; Brown and Schulte, 2011; Johnston, 2013). In Iowa, which has lost proportionally more area of its native vegetation than any other U.S. state (Klopatek et al., 1979), corn and soybean now occupy 63% of the state's total land area and 82% of its cropland (National Agricultural Statistics Service, 2014).

Simplification of crop and non-crop vegetation in the Corn Belt has been a strategy pursued through decisions and actions of individual farmers and through federal and state policies, with a goal of producing huge amounts of corn, soybean, chickens, cattle, hogs, ethanol, and farm revenue (Durrenberger and Thu, 1996; Secchi et al., 2009; Nassauer, 2010; McGranahan et al., 2013). It has also been concomitant with simplification of management strategies and increases in scale (Johnston, 2013; McGranahan, 2014). Nonetheless, despite impressive gains in farm productivity and revenue, Corn Belt agricultural systems and the region's residents are threatened by a number of emerging and continuing challenges, including soil erosion, water quality degradation by nutrient and pesticide emissions, greater prevalence of herbicide-resistant weeds, volatility in production costs and crop prices, loss of knowledge and infrastructure to support diverse markets, and declines in rural community vitality (Tegtmeier and Duffy, 2004; Alexander et al., 2008; Sullivan et al., 2009; Brown and Schulte, 2011; Sprague et al., 2011; Mortensen et al., 2012; Heathcote et al., 2013). Perhaps most

Figure 1

Science-based Trials of Rowcrops Integrated with Prairie Strips (STRIPS) experiment at the Neal Smith National Wildlife Refuge, Iowa.

In the STRIPS experiment, small amounts of reconstructed native prairie vegetation have been integrated into row crop fields to improve the performance and increase the resilience of agricultural watersheds. Image credit: Anna MacDonald.

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emblematic of the Corn Belt's environmental effects is the annual discharge of nearly one million metric tons of nitrogen into the Gulf of Mexico from agricultural lands lying upstream in the Mississippi River Basin, leading to a large coastal hypoxic zone (Alexander et al., 2008; Broussard and Turner, 2009).

Much of the dysfunction of industrial agriculture in the Corn Belt derives from the low levels of biological diversity now present across landscapes and within farming systems in the region (Broussard and Turner, 2009; Liebman et al., 2013; Asbjornsen et al., 2014). Of particular importance is the fact that shallow-rooted, short-season crops like corn and soybean have replaced native, perennial species whose deep roots and long growth period from early spring to late fall are much more effective in holding soil in place, promoting water infiltration into soil and transpiration into the atmosphere, fostering carbon sequestration and nutrient retention, and providing habitat for pollinators, biological control agents, and a host of other organisms (Asbjornsen et al., 2014). The consequences of this shift in vegetation are illustrated by results from an experiment conducted in Illinois comparing nitrate-N losses to drainage water from two annual crops—corn and soybean—and a reconstructed, multispecies prairie community harvested for biomass. After a two-year establishment period for the perennial prairie species, loss of leached N was 9- to 18-fold greater from the annual crops than from the prairie community (Smith et al., 2013).

The effects of integrating diverse, deep-rooted communities of perennial plants into landscapes and watersheds dominated by row crops are being investigated in experimental watersheds in central Iowa in which strips of reconstructed prairie have been interwoven into corn and soybean fields (Figure 1). As shown in Figure 2, there was a 95% reduction in sediment export, a 90% reduction in total phosphorus export, and an 85% reduction in total nitrogen export from watersheds containing 10% prairie when compared to 100% row-crop watersheds managed without tillage (Helmers et al., 2012; Zhou et al., 2014). Additional benefits

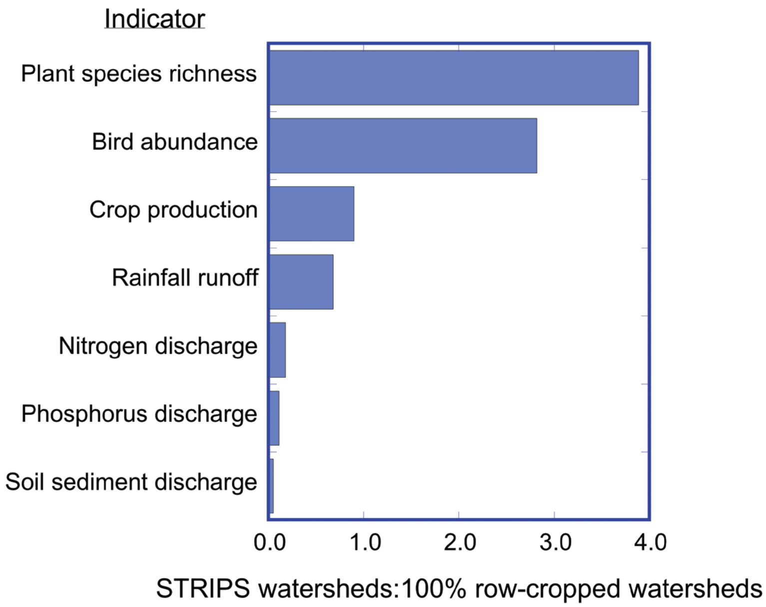

Figure 2

Summary of performance results from the STRIPS experiment.

Ratio of performance indicators in watersheds with prairie strips (10% prairie strips and 90% row-crops) to performance indicators in watersheds without prairie strips (100% row-crops). Soil sediment data are from Helmers et al. (2012); phosphorus, nitrogen, and rainfall runoff data are from Zhou et al. (2014); crop data are unpublished; bird data are from MacDonald (2012); and plant data are from Hirsh et al. (2013). Data were collected during 2008-2012 from three replicate watersheds for each treatment.

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Table 1. Inputs, aquatic toxicity, yields, weed biomass, and net returns for the three cropping systems in the Marsden Farm rotation experiment, Boone Co., IA, 2006–2011[a]

	Cropping system		
Metrics:	**2-year rotation: Corn-soybean**	**3-year rotation: Corn-soybean-oat + red clover**	**4-year rotation: Corn-soybean-oat + alfalfa-alfalfa**
Whole rotation:			
Mineral N fertilizer inputs, kg N ha^{-1} yr^{-1}	80 a	9 b	7 b
Herbicide inputs, kg active ingredients ha^{-1} yr^{-1}	1.78 a	0.07 b	0.05 b
Herbicide aquatic toxicity, comparative toxic units	21973 a	74 b	56 b
Fossil energy inputs, GJ ha^{-1} yr^{-1}	8.9 a	4.0 b	4.1 b
Labor requirements, hr ha^{-1} yr^{-1}	1.7 c	2.8 b	3.6 a
Net returns to land and management[b], \$ ha^{-1} yr^{-1}	954	965	913
Crop yields:			
Corn, Mg ha^{-1}	12.3 b	12.6 a	12.9 a
Soybean, Mg ha^{-1}	3.4 b	3.7 a	3.8 a
Oat, Mg ha^{-1}	—	3.5 b	3.6 a
Alfalfa, Mg ha^{-1}	—	—	8.9
Weed biomass:			
In corn, kg ha^{-1}	2.9	6.2	5.5
In soybean, kg ha^{-1}	0.8	2.4	2.1

[a] Within rows, means followed by different letters are significantly different ($P < 0.05$); means not followed by letters are statistically equivalent. Data are from Davis et al. (2012).

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

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for biodiversity conservation of plants and birds have been documented in these experimental watersheds (Figure 2; Hirsh et al., 2013; Liebman et al., 2013). The average annual cost of treating a farm field with prairie conservation strips ranges from \$60 to \$85 per treated hectare, making it one of the least expensive conservation practices available to landowners and farmers (Tyndall et al., 2013).

Results from the prairie strips study emphasize that biodiversity-ecosystem function relationships can be highly non-linear: small changes in the proportion of land area used for prairie rather than row crops gave disproportionately large conservation benefits. Such benefits may be increasingly important as a shift in the region's climate regime toward a greater frequency of high intensity rainfall events threatens agroecosystem resilience by increasing soil erosion and crop damage, even in zero-tillage systems (Rosenzweig et al., 2002; Angel et al., 2005; Pryor et al., 2014). On the other hand, though yields of corn and soybean per cropped hectare were unaffected by the presence of the prairie conservation strips, total production of corn and soybean were reduced 10% due to the substitution of prairie vegetation for crops. Thus, increases in soil, water, and nature conservation involved a trade-off with crop production. While the prairie strips study compares row-crop fields containing diverse, native, perennial vegetation with crop fields without diverse prairie communities, other studies have shown that compared with annual crops, monocultures of perennial species can also confer substantial environmental benefits; the type and level of benefit varies with plant species and management (Asbjornsen et al., 2014).

The degree of diversification *within* cropping systems can have important effects on crop productivity. A recent review by Bennett et al. (2012) found yield reductions from 3 to 57% for major crops grown in short rotation sequences and monocultures relative to yields in extended rotation sequences that included multiple crop species. Lower productivity in less diverse rotations was attributed to numerous interactive factors, including increased prevalence and greater damage from insect pests and weeds, deleterious interactions with soil microbes and nematodes, soil compaction, nutrient depletion, self-inhibition due to toxic compounds from plant exudates, and reduced soil water availability. Alternatively, cropping system diversification through the use of multispecies crop rotations can maintain soil fertility and productivity, suppress pests, and increase yields even in situations where substantial amounts of fertilizers and pesticides are applied (Karlen et al., 1994). Rotation systems foster diversity not only in time, but also in space, since different crops within the rotation sequence are typically grown in different fields on a farm in the same year. Diversification through crop rotation can be an especially useful strategy in farming systems that integrate crop and livestock production, through the production of perennial forage crops and the application of manure on crop fields (Russelle et al., 2007).

Davis et al. (2012) found that diversification of simple corn-soybean cropping systems with small grain crops and perennial forages can be a viable strategy for reducing reliance on mineral fertilizers, pesticides, and fossil fuel inputs, while maintaining or improving crop yields, profitability, pest suppression, and environmental quality (Table 1). Compared with a conventionally managed corn-soybean system, more diverse rotation systems (corn-soybean-oat/red clover and corn-soybean-oat/alfalfa-alfalfa) treated periodically with cattle manure used 90% less mineral nitrogen fertilizer, 97% less herbicide, and 54% less fossil energy, while producing corn yields that were 4% higher, and soybean yields that were 10% higher. Weed suppression was effective in all systems, but herbicide-related aquatic toxicity was two orders of magnitude lower in the more diverse systems. When calculated over all crop phases, net returns to land and management were equivalent for each system, though labor requirements were greater for the more diverse systems.

Biological diversity contributed in multiple ways to the successful functioning of the more diverse rotation systems examined in this experiment. For example, though oat added relatively little revenue to the more diverse systems (Liebman et al., 2008), it served as an effective companion crop for establishing red clover and alfalfa, thereby minimizing erosion and reducing weed growth in the absence of herbicides. Forage crops were generally less profitable than corn (Liebman et al., 2008), but their inclusion in the more diverse systems allowed substantial reductions in the amount of mineral nitrogen fertilizer used for corn production (Fox and Piekielek, 1988; Morris et al., 1993) and contributed to greater nitrogen retention (Drinkwater et al., 1998; Tomer and Liebman, 2014). Integration with livestock, through forage harvest and manure return, fostered nutrient balance and further reduced production costs (Davis et al., 2012). 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, which is likely to have stabilized seed predator populations and increased their effectiveness in suppressing weed population growth under conditions of reduced herbicide inputs (Westerman et al., 2005; Heggenstaller et al., 2006; O'Rourke et al., 2006; Williams et al., 2009). Spreading the burden of weed control over multiple tactics through diverse rotation systems and their attendant management practices is a key strategy for retarding the evolution of herbicide resistance in weeds, and is particularly relevant to the management of glyphosate-resistant weed species, which are increasingly prevalent in the Corn Belt and which present a clear example of a human-induced challenge to agroecosystem resilience (Mortensen et al., 2012).

Although we have presented just two case studies of how diversification might be used to enhance agroecosystem performance and resilience in the U.S. Corn Belt, studies conducted in other regions also support diversification as a key principle underpinning the design of multifunctional agroecosystems that provide a wide range of goods and services while protecting environmental quality (Altieri, 1995; Kremen and Miles, 2012; Asbjornsen et al., 2014). Additional options for diversifying landscapes and cropping systems include the use of mixed species pastures for dairy and beef production (Sulc and Tracy, 2007); perennial grains for food and feed production (Cox et al., 2006); cover crops to fill otherwise unoccupied temporal niches (Snapp et al., 2005); dedicated perennial grasses and native mixed-species communities for biofuel feedstock production (Heaton et al., 2013); herbaceous and woody species for reconstructing wetlands (Zedler, 2003) and riparian corridors (Schultz et al., 2004); and trees for agroforestry plantations (Jose et al., 2012).

Given the broad portfolio of diversification options that are, or soon could be, technically feasible, how might greater diversification be implemented? Currently, weak markets and a lack of marketing infrastructure impede the production of 'alternative' crops in areas dominated by only one or two commodity crops. Thus, in addition to the need to supply farmers with necessary technical information and inputs for producing non-traditional crops, planning for generating a critical mass of producers and the development of expedited paths to markets are needed. This is particularly true in the case of 'second-generation' bioenergy crops, for which new biomass collection strategies and processing facilities are needed (Heaton et al., 2013).

Failure to recognize and prevent the costs of environmental degradation incurred by current patterns of agricultural land use penalizes citizens downwind and downstream of regions of intensive commodity production, as well as those in future generations dependent upon unpolluted air, clean and abundant freshwater resources, productive soils, abundant pollinators, and other components of resilient ecosystems. Diversification of agricultural landscapes and cropping systems offers one of the best and most accessible strategies for resolving the seemingly intractable tension between agricultural production and environmental quality (Boody et al., 2005; Jordan and Warner, 2010; Liebman et al., 2013; Asbjornsen et al., 2014; McGranahan, 2014).

Of particular importance is the fact that substantial numbers of agricultural stakeholders are interested in reconfigurations of landscapes and cropping systems in ways that enhance resource conservation and biodiversity. Nassauer et al. (2011) examined the attitudes of Iowa farmers and farmland investors toward alternative land management systems ranging from maintenance of status quo patterns of corn and soybean production to a shift toward greater perennial cover, either as a part of rotational grazing systems or through greater use of conservation buffer strips. Under the assumption that all scenarios were equally profitable, less than 25% of the farmers and fewer than 10% of the investors ranked the status quo scenario most preferable. Boody et al. (2005) conducted a statewide survey in Minnesota to determine how much residents were willing to pay to reduce environmental impacts of agriculture in a manner consistent with the effects of greater planting of small grains and forages in corn and soybean-based cropping systems, and including more pastureland and more perennial conservation buffers in the overall landscape. Respondents indicated that they would be willing to pay an average of $201 per household annually to achieve reductions in soil erosion, nutrient runoff, flooding, and greenhouse gas emissions from Minnesota farmland, while gaining increases in wildlife habitat.

Often forgotten in the discourse over alternative paths in U.S. agriculture is the fact that there is already substantial public investment in maintaining the status quo of land use and commodity crop production. That investment could be shifted toward the types of diversification practices named here. Between 1995 and 2012, U.S. farmers received $231 billion in federal crop subsidies, supported by tax dollars, for a narrow group of commodity crops and insurance that promoted production of those crops, compared with $39 billion in federal conservation payments (Environmental Working Group, 2014). Shifting commodity crop and insurance subsidies toward conservation and ecosystem service 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. Diversification's documented effects on natural resource conservation and protection indicate it could benefit both farmers and society at large by enhancing the resilience of cropping systems to climate change and other large-scale environmental stresses (Kremen and Miles, 2012). Moreover, a shift of support from commodity and insurance subsidies to payments for agricultural conservation programs, farm-derived ecosystem services, new and expanded market opportunities, and reoriented research and extension activities could generate additional benefits, including a more stable and secure food supply, cleaner air and water, larger wildlife populations, and improved outdoor recreational experiences (Iles and Marsh, 2012).

Though understanding of the effects of diversification in agroecosystems has expanded considerably in recent years, substantial knowledge gaps remain, especially with regard to questions of scale, appropriate domains of inference, and the impacts of social and economic factors. Questions we feel especially important to address include the following:

- What functional roles do particular species play in improving agroecosystem performance and resilience, and how can this information be used to design agroecosystems that will promote high yields and conserve resources over the long term?
- To what extent do the plot-level studies (i.e., <0.5 ha) that have dominated agroecological research to date reflect the effects of biodiversity on ecological function and resilience at farm, landscape, and regional scales?
- To what extent are the research results from one region transferrable to others?
- What is the value of an agroecological approach to agriculture, such as increased crop and non-crop diversity, in comparison to other approaches?
- What kinds of policies, informal governance structures, and educational activities support the adoption by farmers of low-external-input, diversified agroecological approaches in different settings around the world?
- What strategies can be employed to garner greater cooperation between scientists, farmers, and other stakeholders in answering these questions at farm, landscape, and regional scales?

We welcome submissions to this forum addressing these and other salient questions on how diversification and other agroecological approaches can enhance farm and landscape performance and resilience.

Returning to Professor Naeem's analogy, there is widespread recognition that computers play an important role in our everyday lives. What we tend to forget is that healthy food, farms, and farm landscapes are far more important, garnering benefits at individual to global scales and for present and future generations. While the challenge of sustaining highly functional, resilient agroecosystems cannot be reduced to protecting a motherboard from damage, it is not intractable. Indeed, tangible and practical approaches are already in hand. Concerted effort to build upon current agroecological foundations, especially the importance of enhancing biological diversity, is likely to yield a highly desirable future for all.

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- Both co-authors contributed to the writing and revision of this article, and both approve the submitted version for publication.

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Competing interests

The authors declare no competing interests.

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