

# Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes

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Edited by Peter M. Kareiva, The Nature Conservancy, Seattle, WA, and approved December 11, 2013 (received for review May 23, 2013)

Agriculture is being challenged to provide food, and increasingly fuel, for an expanding global population. Producing bioenergy crops on marginal lands—farmland suboptimal for food crops—could help meet energy goals while minimizing competition with food production. However, the ecological costs and benefits of growing bioenergy feedstocks—primarily annual grain crops—on marginal lands have been questioned. Here we show that perennial bioenergy crops provide an alternative to annual grains that increases biodiversity of multiple taxa and sustain a variety of ecosystem functions, promoting the creation of multifunctional agricultural landscapes. We found that switchgrass and prairie plantings harbored significantly greater plant, methanotrophic bacteria, arthropod, and bird diversity than maize. Although biomass production was greater in maize, all other ecosystem services, including methane consumption, pest suppression, pollination, and conservation of grassland birds, were higher in perennial grasslands. Moreover, we found that the linkage between biodiversity and ecosystem services is dependent not only on the choice of bioenergy crop but also on its location relative to other habitats, with local landscape context as important as crop choice in determining provision of some services. Our study suggests that bioenergy policy that supports coordinated land use can diversify agricultural landscapes and sustain multiple critical ecosystem services.

energy policy | greenhouse gas mitigation

In agricultural landscapes, balancing the provisioning of food and energy with maintenance of biodiversity and ecosystem functions is a global challenge. To avoid impacts on food production, attention is increasingly being focused on the potential for marginal lands to support bioenergy production (1). Marginal lands, those suboptimal for food production, may consist of relatively small areas within generally productive landscapes or larger regions where conditions generally limit crop productivity. However, there is increasing recognition that these lands are already performing a variety of useful functions, and their conversion to bioenergy cropping could reduce these services. For example, in the north central United States, rising commodity prices are predicted to bring marginal croplands—including Conservation Reserve Program lands—into annual crop production with negative impacts on wildlife habitat and water quality (2, 3). With 2013 corn plantings at recent record highs (4) and new reports of grassland and wetland conversion to cropland (5, 6), this may be occurring already.

An alternative to annual cropping is conversion of marginal croplands to perennial, cellulosic crops for bioenergy. Although current US biofuel production centers on grain ethanol derived from annual monocultures of maize (*Zea mays*), this situation

could change with full implementation of the 2007 US Energy Independence and Security Act (7), which calls for increased production of cellulosic biofuels. In the Midwest United States, perennial grasses and forbs grown on marginal lands could provide up to 25% of national targets for cellulosic biofuel, with substantial greenhouse gas (GHG) benefits (8). Moreover, increasing the area of perennial cover on the landscape is predicted to positively affect a diverse array of organisms and ecological functions (9–11), leading to important synergies that have not yet informed the ongoing bioenergy debate. Here we provide the most comprehensive empirical evaluation of this hypothesis to date, reporting data that elucidate the impacts of different bioenergy cropping systems on a wide variety of organisms and the ecosystem functions they perform.

Previous studies have examined the ability of select bioenergy crops to support specific taxa (12) or individual services such as energy production (13) or GHG mitigation (14), without consideration of the tradeoffs or synergies that can arise when considering entire suites of organisms and ecosystem functions. We report on a unique multidisciplinary study of matched sets of organisms and ecosystem services and show that perennial grass energy crops (switchgrass, *Panicum virgatum*, and mixed prairie plantings) synergistically enhance diversity of a variety of

## Significance

Science-based policies are needed to inform sustainable bioenergy landscape design. Our key finding is that the linkage between biodiversity and ecosystem services is dependent not only on the choice of bioenergy crop but also on its location relative to other habitats. The implication is that careful design of bioenergy landscapes has the potential to enhance multiple services in food and energy crops, leading to important synergies that have not yet informed the ongoing bioenergy debate. This study is especially timely as high commodity prices are driving conversion of marginal lands to annual crop production, reducing future flexibility.

Author contributions: B.P.W., R.I., C.G., K.L.G., C.M.M., T.D.M., B.A.R., G.P.R., T.M.S., and D.A.L. designed research; B.P.W., H.G., C.G., T.D.M., L.R., B.A.R., A.C.S., T.K.T., and J.K.W. performed research; B.P.W., T.L.D., C.M.M., L.R., B.A.R., and T.K.T. analyzed data; and B.P.W., T.L.D., R.I., H.G., C.G., K.L.G., H.L., C.M.M., T.D.M., L.R., B.A.R., G.P.R., T.M.S., T.K.T., J.K.W., and D.A.L. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

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This article contains supporting information online at [www.pnas.org/lookup/suppl/doi:10.1073/pnas.1309492111/-DCSupplemental](http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1309492111/-DCSupplemental).

organisms and levels of the services they provide. We further quantify the importance of landscape context on service provisioning, suggesting that policy supporting intentional design of bioenergy landscapes could increase sustainability of both food and energy production.

## Results

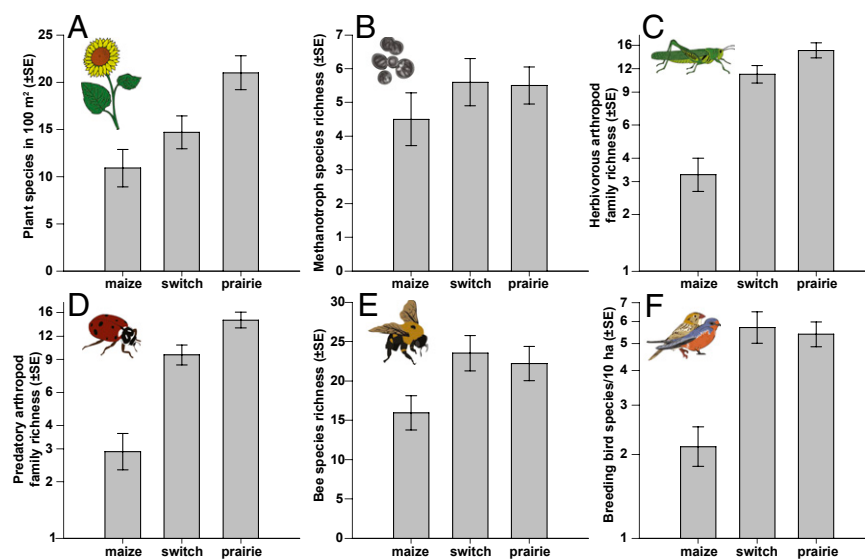
We compared biodiversity and key ecological processes among maize, switchgrass, and prairie, three plant communities representing distinct alternatives for use of marginal lands that vary in management intensity, perenniality, and sown diversity (Fig. S1). To accomplish this, we identified and sampled 115 maize, switchgrass, and prairie fields across the major agricultural production regions of Michigan and Wisconsin (Fig. S1 and Tables S1–S3). Maize was grown as an annual monoculture and managed for high yields using herbicides and fertilizers (Table S2). Switchgrass and prairie sites were planted as perennial monocultures and polycultures, respectively, and managed using prescribed burns or mowing on 2–5 y cycles. Supplemental analyses found no evidence that recent burning or mowing negatively affected response variables (Text S2, Figs. S2 and S3, and Table S4).

Biodiversity was quantified by measuring the taxonomic richness of plants, methane-consuming soil bacteria (methanotrophs), predatory and herbivorous arthropods, bees, and breeding birds using sampling methods and measures of richness appropriate for each group. As expected, maize fields contained a low-diversity plant community dominated by the crop itself (99% of biomass; Figs. 1A and 2A). Although planted as monocultures, switchgrass stands were more diverse, with biomass typically composed of 20% opportunistic forbs and grasses. Prairies were most diverse in both plant species and biomass composition. Diversity of herbivorous and predatory arthropods showed a stairstep increase from maize to prairie that mirrored trends in plant diversity (Fig. 1C and D), whereas methanotroph, bee, and breeding-bird diversity was equally high in the two perennial grasslands compared with maize (Fig. 1B, E, and F). Effect statistics (Hedge's *D*) were used to standardize differences and test for statistical significance (15). Compared with maize, perennial grass plantings had positive effects on diversity of all taxa, which were statistically significant for all but methanotrophs (Fig. 3A). Differences in richness between the two perennial grass systems were either smaller (plant

and predatory arthropod richness) or near zero (all other organisms; Fig. 3B).

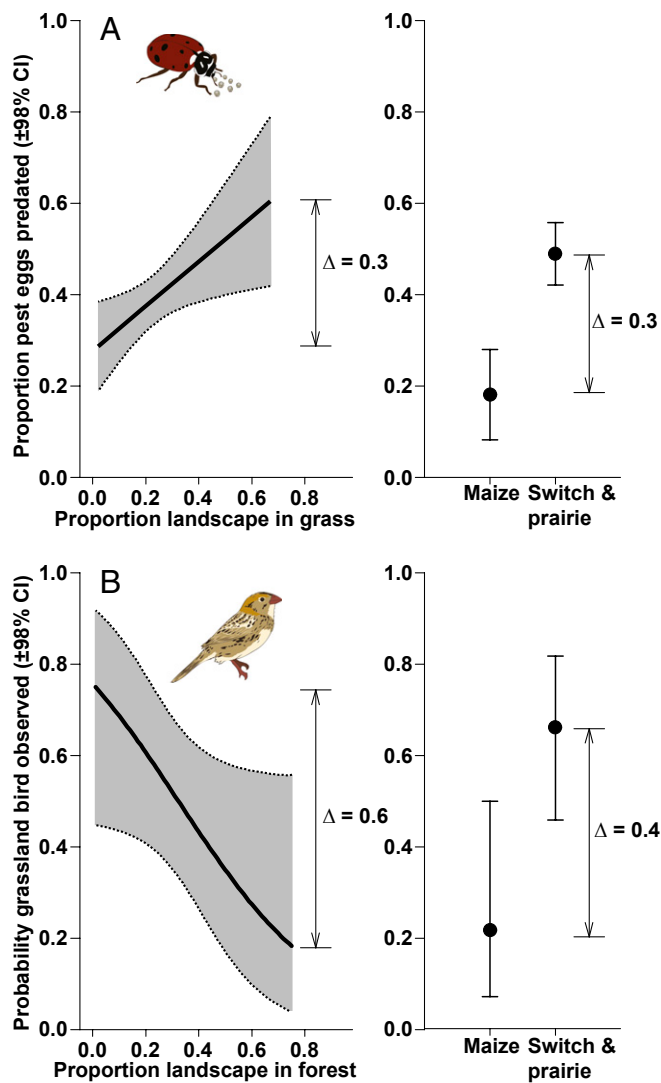
We also quantified ecological processes involving each focal group, including plant primary productivity, consumption of methane by soil bacteria, consumption of insect pest eggs by arthropod natural enemies, pollination, colonization by pest aphids, and habitat use of grassland birds. Although maize fields produced an order of magnitude more aboveground biomass than the two perennial grass systems, all other beneficial processes measured were greater in grasslands (Fig. 2). In grasslands, rates of methane consumption were an order of magnitude higher, predation of pest eggs by beneficial insects increased by a factor of two, and grassland birds—a nationally imperiled group (16)—were observed twice as frequently (Fig. 2A–D). In addition, pollination of sentinel sunflowers almost doubled adjacent to prairie, and pressure of pest aphids was ~50% lower in prairie compared with maize (Fig. 2E and F). Effect statistics likewise identified substantial differences between maize and perennial grass plantings, which were statistically significant for all processes except pollination (Fig. 3C). In contrast, differences between prairie and switchgrass were near zero (Fig. 3D).

Multiple regression models that incorporated landscape influences on pest suppression (17) and bird prevalence (16) showed that landscape composition—the identity and extent of nearby vegetation types—can have as strong an impact on service provisioning as the nature of the planting itself (Fig. 4). After accounting for differences in crop types, our model predicted that rates of predation of pest eggs by beneficial insects increased by 30% as the extent of grassland within 1.5 km of a focal field increased to maximum observed values (Fig. 4A). This was comparable in size to the difference in within-field service provisioning between maize and perennial grass plantings. Likewise, our model of landscape influence on grassland birds predicted a 60% increase in occupancy of patches as surrounding landscapes became less forested at the 1.5-km scale (Fig. 4B), an increase that was again comparable to differences between planting types. Land use patterns at these scales are typically influenced by multiple landowners, suggesting a role for regional planning to maximize provisioning of ecosystem services in agricultural landscapes.



**Fig. 1.** Compared with maize, perennial grasslands supported a greater diversity of organisms ranging from plants to vertebrates. Graphs show variation between maize, switchgrass, and prairie in richness of plants (A), methanotrophic soil bacteria (B), herbivorous arthropods (C), predatory and parasitic arthropods (D), bees (E), and breeding birds (F). Error bars are  $\pm 1$  SE. Note logarithmic axes in C, D, and F.





**Fig. 4.** Multiple-regression models indicated that habitats surrounding bioenergy crops can have as large an effect on ecosystem services as the crop itself. Predation of pest eggs (A) increased by 30% as the proportional area of grasslands within 1.5 km of sites increased, an effect as large as differences between maize and the two grasslands. The probability of observing a grassland-dependent bird species (B) declined by 60% as forest land cover increased within 1.5 km of sites, an effect larger than differences between maize and grasslands.

crops on marginal lands could maintain or enhance these functions, complementing and even feeding back to benefit commodity production on prime agricultural land (10). In this respect, these perennial systems provide a means to support bioenergy goals, broaden the portfolio of services supported by agricultural landscapes, and support their long-term functioning (19).

Site-level management decisions are likely to alter ecosystem services provided by bioenergy crops. For example, incorporating features of perennial systems into maize, through practices like cover cropping, could enhance services such as greenhouse gas mitigation (20). Alternatively, intensifying grassland management by fertilization may increase biomass production but reduce other services. For example, fertilization will likely reduce plant diversity (21), particularly of forbs, and so likely also reduce pollination and pest suppression services (17). Our landscape analyses—in which grasslands were broadly defined to include lands such as pastures and hayfields which are managed for agricultural production—have

detected positive effects of grasslands on services (Fig. 4A) (9, 10). This suggests that it is possible to actively manage grasslands for biomass while maintaining their positive contribution to other ecosystem services.

For agricultural landscapes to be sustainable, production of food, energy, and biodiversity need to coexist (22). Using policy to encourage thoughtful placement of energy crops in the landscape could allow agriculture to take advantage of ecosystem service synergies (23). Highly intensified annual crop landscapes might be strategically diversified with perennial grassland bioenergy crops, increasing biodiversity (9) and pest suppression in annual crops (10) while reducing water pollution (11), GHG fluxes (14), and reliance on pesticides (24, 25). Our ability to design sustainable agroenergy landscapes that producers will implement requires additional understanding of the costs of potential ecosystem service tradeoffs (25), elucidation of “bundles” of ecosystem services that could be jointly produced (26), and understanding society’s perception of the value of these services (27). Finally, realizing the benefits of such landscape design will require policies that encourage landowners to make informed and coordinated decisions at the landscape scale. Prior work on biodiversity conservation at landscape scales suggests that the benefits of such coordinated land use decisions are substantial (28) and that spatially explicit incentives show promise as a voluntary tool for achieving desired landscape configurations (29, 30). Applying such lessons to the development of agricultural landscapes for sustainable bioenergy production is a logical next step.

## Materials and Methods

**Sample Sites.** We collaborated with farmers, private landowners, and state land managers to locate 115 maize, switchgrass, and prairie plantings across the major crop production regions of Michigan and Wisconsin (Fig. S1 and Table S3). Management of these plantings is described in Table S2. Sampling at each site was conducted in four plots spaced 50 m apart at the corners of a 50 × 50 m square, with two plots located 50 m from the habitat edge and two located 100 m away. For more narrow sites, plots were arranged in a linear transect down the center of each patch with the first plot 50 m from the edge and remaining stations spaced 50 m apart. Departures from this design are noted below.

**Taxonomic Richness.** We measured the taxonomic richness of plants, microbes, and animals present in each habitat, sampling different subsets of our total pool of sites for each experiment (Text S1 and Table S3). Plant species richness was measured by recording all species (planted and naturally colonizing) present in four 100-m<sup>2</sup> circular plots at 10 maize, 13 switchgrass, and 12 prairie sites between 2008 and 2010. Methanotroph richness was measured by taking soil samples (10 cm deep × 2.5 cm diameter) from four maize, five switchgrass, and eight prairie plantings during 2009–2011 and quantifying the total number of genetically distinct strains [operational taxonomic units (OTUs)] present at each site. Two cores were taken at each of the four plots and aggregated at the site level and transported to the laboratory on ice, where they were sieved to 4 mm and then stored at –80 °C for genetic analysis (Text S1). For insects and spiders (“arthropods”), we separately measured richness of herbivores, predators, and bees. Richness of herbivorous and predatory arthropods was measured by taking 100 sweeps with a sweep net at 19 maize, 20 switchgrass, and 20 prairie sites in June and July of 2008 and 2009 and determining the number of families in each of these two groups; methods are detailed elsewhere (31). Bee species richness was measured by trapping bees in arrays of white, yellow, and blue 29-mL soufflé cups filled with soapy water. Traps were deployed for 48 h in June, July, and August on platforms (Text S1) at four plots in 20 maize, 20 switchgrass, and 20 prairie sites in 2009. Before analysis, one observation was removed from both the predatory arthropod and bee richness datasets; these observations were sixfold and fivefold greater than median values of predatory arthropod and bee richness, respectively, and were the largest outliers across all datasets. Finally, breeding bird richness was measured by visually or aurally identifying all species perching, feeding, or singing during whole-field searches at 20 sites of each habitat during 2008 and 2009; see published methods (16). All data are available in Dataset S1.





1. Dauber J, et al. (2012) Bioenergy from “surplus” land: Environmental and socio-economic implications. *BioRisk* 7:5–50.
2. Langpap C, Wu J (2011) Potential environmental impacts of increased reliance on corn-based bioenergy. *Environ Resour Econ* 49(2):147–171.
3. Secchi S, Gassman PW, Williams JR, Babcock BA (2009) Corn-based ethanol production and environmental quality: A case of Iowa and the conservation reserve program. *Environ Manage* 44(4):732–744.
4. USDA-NASS (2012) *Acreage* (USDA-NASS, Washington, DC). Available at [www.usda.gov/nass/PUBS/TODAYRPT/acrg0613.pdf](http://www.usda.gov/nass/PUBS/TODAYRPT/acrg0613.pdf). Accessed October 30, 2013.
5. Faber S, Rundquist S, Male T (2012) *Plowed Under: How Crop Subsidies Contribute to Massive Habitat Losses* (Environmental Working Group, Washington, DC). Available at [http://static.ewg.org/pdf/plowed\\_under.pdf](http://static.ewg.org/pdf/plowed_under.pdf). Accessed April 21, 2013.
6. Wright CK, Wimberly MC (2013) Recent land use change in the Western Corn Belt threatens grasslands and wetlands. *Proc Natl Acad Sci USA* 110(10):4134–4139.
7. Energy Independence and Security Act of 2007 (2007) H.R.6. 110<sup>th</sup> Congress of the United States of America, 1<sup>st</sup> Session.
8. Gelfand I, et al. (2013) Sustainable bioenergy production from marginal lands in the US Midwest. *Nature* 493(7433):514–517.
9. Meehan TD, Hurlbert AH, Gratton C (2010) Bird communities in future bioenergy landscapes of the Upper Midwest. *Proc Natl Acad Sci USA* 107(43):18533–18538.
10. Meehan TD, Werling BP, Landis DA, Gratton C (2012) Pest-suppression potential of midwestern landscapes under contrasting bioenergy scenarios. *PLoS ONE* 7(7):e41728.
11. Parish ES, et al. (2012) Multimetric spatial optimization of switchgrass plantings across a watershed. *Biofuels Bioprod Biorefin* 6(1):58–72.
12. Dauber J, Jones MB, Stout JC (2010) The impact of biomass crop cultivation on temperate biodiversity. *GCB Bioenergy* 2(6):289–309.
13. Gelfand I, Snapp SS, Robertson GP (2010) Energy efficiency of conventional, organic, and alternative cropping systems for food and fuel at a site in the U.S. Midwest. *Environ Sci Technol* 44(10):4006–4011.
14. Robertson GP, Hamilton SK, Del Grosso SJ, Parton WJ (2011) The biogeochemistry of bioenergy landscapes: Carbon, nitrogen, and water considerations. *Ecol Appl* 21(4):1055–1067.
15. Nakagawa S, Cuthill IC (2007) Effect size, confidence interval and statistical significance: A practical guide for biologists. *Biol Rev Camb Philos Soc* 82(4):591–605.
16. Robertson BA, Doran PJ, Loomis LR, Robertson JR, Schemske DW (2011) Perennial biomass feedstocks enhance avian diversity. *GCB Bioenergy* 3(3):235–246.
17. Werling BP, Meehan TD, Robertson BA, Gratton C, Landis DA (2011) Biocontrol potential varies with changes in biofuel-crop plant communities and landscape perenniality. *GCB Bioenergy* 3(5):347–359.
18. James LK, Swinton SM, Thelen KD (2010) Profitability analysis of cellulosic energy crops compared with corn. *Agron J* 102(2):675–687.
19. Atwell RC, Schulte LA, Westphal LM (2010) How to build multifunctional agricultural landscapes in the US Corn Belt: Add perennials and partnerships. *Land Use Policy* 27(4):1082–1090.
20. Robertson GP, Paul EA, Harwood RR (2000) Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. *Science* 289(5486):1922–1925.
21. DiTommaso A, Aarssen LW (1989) Resource manipulations in natural vegetation: A review. *Plant Ecol* 84(1):9–29.
22. Tilman D, et al. (2009) Energy. Beneficial biofuels—The food, energy, and environment trilemma. *Science* 325(5938):270–271.
23. Power AG (2010) Ecosystem services and agriculture: Tradeoffs and synergies. *Philos Trans R Soc Lond B Biol Sci* 365(1554):2959–2971.
24. Meehan TD, Werling BP, Landis DA, Gratton C (2011) Agricultural landscape simplification and insecticide use in the Midwestern United States. *Proc Natl Acad Sci USA* 108(28):11500–11505.
25. Zhang W, Ricketts TH, Kremen C, Carney K, Swinton SM (2007) Ecosystem services and dis-services to agriculture. *Ecol Econ* 64(2):253–260.
26. Raudsepp-Hearne C, Peterson GD, Bennett EM (2010) Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proc Natl Acad Sci USA* 107(11):5242–5247.
27. Martín-López B, et al. (2012) Uncovering ecosystem service bundles through social preferences. *PLoS ONE* 7(6):e38970.
28. Polasky S, et al. (2008) Where to put things? Spatial land management to sustain biodiversity and economic returns. *Biol Conserv* 141(6):1505–1524.
29. Parkhurst GM, Shogren JF (2007) Spatial incentives to coordinate contiguous habitat. *Ecol Econ* 64(2):344–355.
30. Parkhurst GM, et al. (2002) Agglomeration bonus: An incentive mechanism to reunite fragmented habitat for biodiversity conservation. *Ecol Econ* 41(2):305–328.
31. Robertson BA, Porter C, Landis DA, Schemske DW (2012) Agroenergy crops influence the diversity, biomass, and guild structure of terrestrial arthropod communities. *BioEnergy Res* 5(1):179–188.
32. Chao A (1984) Non-parametric estimation of the number of classes in a population. *Scand J Stat* 11(4):265–270.
33. Zuur AF, Ieno EN, Walker N, Saveliev AA, Smith GM (2009) *Mixed Effects Models and Extensions in Ecology with R* (Springer, New York).
34. R Core Development Team (2006) *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, Vienna). Available at [www.R-project.org](http://www.R-project.org). Accessed April 21, 2013.
35. Fox J (2003) Effect displays in R for generalised linear models. *J Stat Software* 8(15):1–27.