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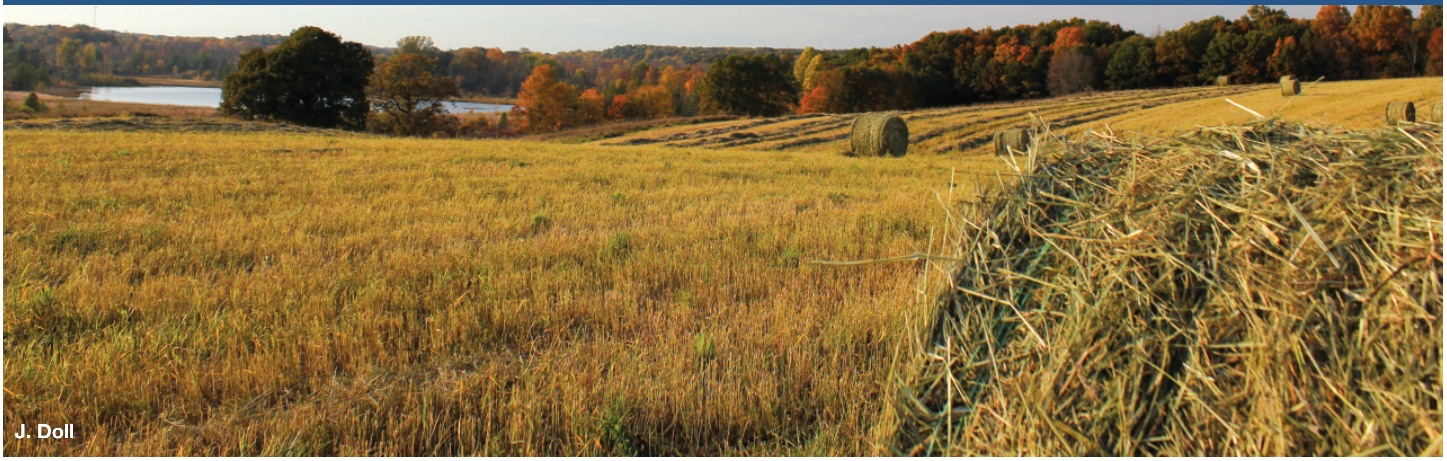
Biodiversity Services and Bioenergy Landscapes



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Growing bioenergy crops will transform agricultural landscapes and affect the services they deliver.

Landscape structure and ecosystem services

The 21st century will challenge agriculture to feed and fuel a growing world while conserving the environment[1,2]. Modern production techniques have facilitated tremendous gains in crop yields, allowing farmers to feed a significant portion of the world. However, these increases in yields have relied heavily on intensive use of fertilizer and pesticides[1], which have polluted some ground and surface waters (**http://water.usgs.gov/nawqa**). At the same time, the footprint of agriculture has expanded to cover nearly 40 percent of the earth's ice-free surface[2]. This simultaneous intensification and expansion of agriculture has caused losses in **biodiversity** and reduced habitat for beneficial organisms like insect pollinators and predators[3,4]. Increasingly, our society is also demanding that farmland produce **bioenergy** as a clean, domestic source of energy. For example, the U.S. Energy Independence and Security Act sets the goal of producing 46 billion gallons of **biofuels** by 2022. This begs the question: How can agriculture produce bioenergy, feed a growing world population and do so in a sustainable way? A key part of the answer may be an increased focus on the full set of **ecosystem services** that agricultural landscapes provide.

A variety of organisms and ecological processes provide ecosystem services on farmland that are critical to crop production and society at large (Table 1)[5]. For example, bees pollinate crop plants, predatory insects and spiders kill crop pests, water flows through the soil to recharge streams and lakes, and game animals and other wildlife are enjoyed by hunters and nature lovers. Most of these organisms and processes move across distances larger than a single parcel of land. For example, insects and birds move between multiple patches of forest and farm fields to make their living, and rain and irrigation water enter groundwater as it flows over miles on its trip to streams, lakes and rivers. Because of this, conserving these services requires a focus that is broader than an individual farm field; it requires a **landscape** perspective.

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But what is a landscape, and how are different landscapes described? In your travels across Michigan or the greater Midwest, you may have noticed that farmland contains an assortment of habitat types that are constantly repeated but which change from region to region. If you've observed this, you have an intuitive sense of the definition of a landscape. First, a landscape is large; you need to pass multiple farms across many miles to appreciate its character. Second, a landscape contains multiple types of habitats; if asked to describe a farm landscape, you will probably not just mention corn and soybean, but also the farmhouses, barns, pastures, hedgerows and streams. This collection of multiple habitats, repeated across tens of miles, is a landscape[6]. While agricultural landscapes contain typical features, no two landscapes are exactly alike (Figure 1). For example, a greater percentage of farmland in Michigan is covered in forest compared to the prairie region of Iowa. In other words, landscapes vary in **composition**. Further, landscapes with similar composition could still differ. For example, in hilly areas farmers may adopt contour farming, while in flatter areas farmers are more likely to grow crops in large rectangular fields. Both areas may contain similar types of crops (that is, they may be similar in composition), but in different physical **configurations**. Together, landscape composition and configuration describe **landscape structure**.

How and why does landscape structure affect ecosystem services? To answer this question, it is necessary to consider both landscapes and the individual habitats that make them up. At the scale of a farm field, choosing to manage land in a particular way will affect the types of organisms it supports and the services it provides. For example, native grasslands support more bees than cornfields[7]. However, this isn't the whole story, because bees move across multiple habitats to forage for food, find new nest sites and pollinate plants. This means that providing multiple patches of bee habitat across the landscape will benefit bees by allowing them to easily locate nesting and food resources in their travels, while planting one small patch is not enough. Further, it also means that foraging bees are not confined to natural areas, but can pollinate crops to increase and maintain production. Last, it implies that pollination services on farms will not only depend on how farmers manage their individual fields, but also on the actions of neighbors several miles away. Pollination is just one example of an ecosystem service that could change as bioenergy production transforms our agricultural landscapes.

Figure 1. Farmland takes different shapes as humans interact with their surroundings. For example, strips of perennial vegetation can be interspersed with crop fields to reduce erosion (upper left), creating a landscape with narrow crop fields with irregular edges. Alternatively, in regions where water is limiting, crops may be grown using central pivot irrigation, creating large, circular fields (middle left), while in other areas crops may be grown in rectangular tracts of land (right). Finally, little perennial vegetation remains in some farm landscapes (middle left and right), while in other areas annual crop fields are intermingled with grasslands (upper left) and forests (bottom left). Bioenergy production will undoubtedly change the shape of these landscapes to affect ecosystem services, for better or worse.

Biodiversity Services and Bioenergy Landscapes

Landscape change and bioenergy production

Increasingly, our nation is seeking alternatives to fossil fuels, including fuels produced from plant matter. These biofuels could be produced from a variety of herbaceous and woody bioenergy crops, ranging from existing crops like corn, soybean, canola and poplar trees to monocultures or polycultures of perennial grasses and flowers (Figure 2). For example, switchgrass (*Panicum virgatum*) could be grown in monoculture, while mixed prairies (plantings of native grasses and flowers) could also be used to produce fuels. Current evidence suggests that choices between these different bioenergy cropping systems could change landscape structure and affect ecosystem services in positive or negative ways (Table 1). At the scale of a farm field, certain crops

Figure 2. Bioenergy could be produced from many different crops, including, from left to right: corn grain and stover, single-species plantings of native grasses like switchgrass (*Panicum virgatum*), multi-species plantings of native prairie flowers and grasses, the non-native grass *Miscanthus giganteus*, canola, soybean (emerging through corn residue) and poplar. Planting these different crops will change farm landscapes in different ways to affect ecosystem services.

Table 1. Farmland provides a wide variety of ecosystem services to humans that could decrease (–) or increase (+), depending on the types of crops that are grown for bioenergy, how they are managed and how they are deployed on the landscape. Note that many of the benefits of perennial bioenergy crops could diminish with intensive management.

Ecosystem service	Value of service to humans	Impacts of bioenergy
Provision of food, fuel and fiber	• Grains, fruits and vegetables are harvested from farmland for food and animal feed. • Fibers from plants are used to produce paper or lumber. • Plant matter can be converted to liquid fuels or combusted for energy.	– Bioenergy crops could compete with food crops for productive land. + Bioenergy crops could be grown on marginal cropland to produce fuel and minimize impacts on food production.
Water purification	• Wetlands, forests and grasslands remove contaminants from water before it enters rivers, streams and groundwater.	– Bioenergy crops that require intensive fertilizer and pesticide use will decrease water quality. – Cultivation of forests, wetlands and grasslands with annual crops could reduce natural water purification. + Perennial bioenergy crops (for example, native grasses) could be used to buffer stream edges and reduce surface runoff.
Erosion regulation	• Hedgerows, forests and deep-rooted, perennial crops reduce wind erosion and stabilize soils.	– Bioenergy could be produced from conventionally tilled, annual crops susceptible to erosion. + Woody bioenergy crops and perennial grasses could help to stabilize soils and decrease erosion. + Cover crops could be incorporated into no-till bioenergy cropping systems to reduce erosion.

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Table 1. (continued) Farmland provides a wide variety of ecosystem services to humans that could decrease (–) or increase (+), depending on the types of crops that are grown for bioenergy, how they are managed and how they are deployed on the landscape. Note that many of the benefits of perennial bioenergy crops could diminish with intensive management.

Ecosystem service	Value of service to humans	Impacts of bioenergy
Climate regulation	• Agricultural soils produce and capture greenhouse gases. • Crops sequester greenhouse gases by capturing carbon dioxide (CO2).	– Bioenergy crops could be heavily fertilized, increasing release of greenhouse gases from soils. + Perennial crops may support diverse communities of soil bacteria that capture more greenhouse gases than annual crops. + Deep-rooted, perennial bioenergy crops could sequester carbon and store it over the long term.
Pollination and pest regulation	• Insect pollination is required for production of a variety of food crops. • Predatory insects, spiders and birds, eat and kill insect pests of crops, reducing crop damage.	– Landscapes dominated by low-diversity, annual bioenergy crops will provide little habitat for pollinators and predators. + Planting diverse, perennial crops on farmland could provide nesting and food resources for pollinators and predators.
Soil nutrient cycling	• Soil bacteria and fungi decompose dead plant matter and make nutrients available to plants. • Plants with symbiotic fungi and bacteria can fix nitrogen.	– Conventional tillage of annual bioenergy crops could reduce soil organic matter. + Perennial grasses and woody crops could increase soil organic matter. + Legumes could be incorporated into perennial or annual bioenergy crops to add nitrogen to the soil.
Biodiversity conservation	• Farmland is composed of multiple types of habitat that support many different species, some of which are threatened with extinction.	– Cultivating perennial habitats with annual crops could reduce farmland biodiversity. + Diverse, perennial bioenergy crops could add diversity to agricultural landscapes and provide key habitat, providing opportunities for recreation and conservation of rare species.

may provide better habitat for species that are of conservation concern or provide key services. For example, mixed prairies support breeding populations of several threatened grassland birds[8], provide stopover habitat as they migrate south in the fall[9], support flowers that promote reproduction of pollinators[7], and contain diverse plant communities that provide habitat for predatory insects and spiders that attack crop pests[10]. In contrast, evidence suggests crops like corn, which are intensively managed and contain a low diversity of plants, are poorer habitat for all these organisms.

At the landscape scale, deployment of these different crops could alter landscape structure to affect ecosystem services across multiple landholdings. For example, energy policy (the Energy Independence and Security Act of 2007) initially favored ethanol derived from corn. This increased the demand and price for corn, causing farmers to shift crop acreages to corn. Researchers found evidence that this decreased the suitability of landscapes for beneficial insects that attack soybean aphid, reduced natural pest control and caused losses estimated at $58 million in four Midwestern states[11]. Researchers also estimate that increasing corn acreage to meet the goals of our energy policy could increase dissolved inorganic nitrogen export to the Gulf of Mexico by 10 to 34 percent[12]. This additional nitrogen could worsen existing problems with algal blooms that reduce oxygen availability and create "dead zones" where fisheries are depressed. However, this problem could be partially mitigated by improving nitrogen management in annual crops like corn. For example, the 2005–2009 average total nitrogen load is 16 percent less than the baseline, indicating that improved nitrogen management in corn production is helping[13]. As an alternative to corn, woody or herbaceous perennials could be planted on **marginal land** to produce bioenergy. Evidence suggests that planting marginal cropland with perennial habitats could increase bird diversity[14], provide habitat for predators of crop pests, reduce pest problems and create riparian buffers that remove nutrients from runoff[15]. All this suggests that bioenergy production will profoundly affect ecosystem services. These effects could be positive or negative, depending on the types of crops that are grown, how they are managed and the resulting structure of the landscape.

Emerging principles for design of bioenergy landscapes

Farmers can enhance biodiversity and ecosystem services by managing bioenergy crops to promote stability and plant diversity. If well-coordinated, these efforts could feedback to increase biodiversity and services across entire landscapes. Below we provide some scientific findings (below and in Table 1) that could be used by farmers to manage bioenergy crop fields and by policymakers to create incentives that promote landscapes that support ecosystem services.

Habitat stability and perenniality matter. Conventional, annual cropping systems disrupt communities of soil microbes and beneficial insects through yearly tillage and use of nutrients and pesticides, reducing the ability of these organisms to cycle nutrients, remove greenhouse gases from the atmosphere and suppress pests. Stability and perenniality could be included in biofuel landscapes in two ways. First, farmers could grow annual bioenergy crops using reduced or no-tillage and lower nutrient and pesticide application to create more stable conditions that favor increased biodiversity and ecosystem services[16,17]. Second, farmers could plant perennial bioenergy crops such as switchgrass, prairie or fast-growing tree species. These habitats are more stable than annual crops because they are planted with vegetation that persists for multiple years.

Plant diversity matters. Habitats with multiple plant species support greater biodiversity and ecosystem services compared to habitats dominated by a single plant. Bioenergy producers could incorporate plant diversity into annual crops through the use of diverse crop rotations and **cover crops**[18]. Alternatively, biofuels could be produced from diverse grasslands (for example, mixed prairie) that incorporate a variety of plant species.

Landscape perenniality and diversity matter. Agricultural landscapes that contain a mix of annual crop and perennial habitats will support more species and greater rates of many ecosystem services compared to landscapes dominated by one or a few annual crops. Planting perennial biofuel crops could increase the area of perennial habitats on landscapes. Because these habitats are rare in some agricultural landscapes, planting them could increase **landscape diversity**, which is important because different organisms may have different needs. Such diverse landscapes may support more types of organisms, ensuring that a decline in one species is offset by the presence of another that can fill in to provide a service. In addition, any given species may meet their different needs by using different habitats (for example, some predatory beetles feed within wheat fields but shelter in grassy margins in the winter[19]); diverse landscapes could provide for these needs.

Strategic implementation of bioenergy crops. The benefits of a given cropping system for ecosystem services will be context dependent[15]. This argues for the strategic design of bioenergy landscapes in which specific habitats are located where they will produce the most value. For example, strips of grassland and forest can be planted to intercept runoff from crops. All else being equal, these strips will provide the greatest benefits for water quality when they are planted on hillsides or along streams[15]. Similarly, connecting existing natural areas with strips of perennial habitat may increase the movement of pollinators, predators and wildlife across the landscape by providing corridors[6]. In contrast, planting an isolated patch of perennial habitat may do little good if organisms from existing natural areas cannot reach it. Experience with programs such as the Conservation Reserve Program demonstrates that effective policy and incentive programs can reward farmers for deploying crops in locations where they will provide the most good for water quality and wildlife[20], allowing them to produce commodities like biofuels while being paid for enhancing ecosystem services.

Challenges to overcome

Implementing a diverse landscape is challenging. Multiple farmers will need to work together to shape the landscape. At the same time, these farmers will need to balance crop productivity, economics, market access, availability and cost of equipment and a whole suite of other factors when deciding which crops to plant. Tradeoffs between ecosystem services and crop productivity will challenge the ability of farmers to grow crops that are productive and support ecosystem services. In particular, bioenergy crops with the greatest potential to increase ecosystem services have the biggest disadvantage in yields and are not economically competitive with corn across a range of prices[21]. Perennial crops may also require farmers to invest in new harvesting equipment and produce delayed returns. For example, woody crops like hybrid poplars require different harvesting equipment than other crops and are harvested every 3

The Great Lakes Bioenergy Research Center plots at Kellogg Biological Station in Hickory Corners, MI.

to 6 years, which could cause cash flow issues for farmers because they will incur establishment costs up front but receive income at longer intervals. Finally, a general lack of experience may cause some farmers to choose familiar crops rather than novel perennials that promote ecosystem services. These considerations suggest that society will have to place a value on ecosystem services and create policies and markets that reward farmers for providing them.

Bioenergy production for multiple services

Bioenergy production provides an opportunity for society to create multi-functional landscapes that produce food and energy while supporting other ecosystem services. For example, buffers of fast-growing trees and perennial grasslands could be planted along waterways. These buffers could reduce runoff into streams, increase water quality (improving fish habitat) and provide corridors that allow wildlife to move between patches of forest. Rows of bioenergy crop trees could also be planted in open areas to reduce wind erosion and provide habitat for predators of crop pests. Conventional tillage could be replaced with no-till systems and cover crops could be used more extensively, supporting predatory insects and spiders that control pests, reducing erosion and improving soil quality. And suboptimal farmland (for example, dry corners of center pivot fields or marginal soils) could be planted with perennial grasslands to increase soil organic matter and provide habitat for bees, birds and predatory insects. In the long term, creating these landscapes could increase the productivity of agriculture by supporting crop pollination and natural pest control in addition to supporting a variety of other services that have value beyond production. In conclusion, bioenergy production provides a chance to shape agricultural landscapes to provide food and fuel while promoting a variety of services.

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Websites for further reference:

Biomass Crop Assistance Program:

www.apfo.usda.gov/FSA/webapp?area=home&subject=ener&topic=bcap

Cover cropping in annual crops:

Michigan State University Kellogg Biological Station
www.covercrops.msu.edu

Ecosystem services:

Ecological Society of America
www.actionbioscience.org/environment/esa.html

GreenFacts Scientific Board
www.greenfacts.org/en/ecosystems/index.htm

General information on bioenergy:

U. S. Department of Agriculture Economic Research Service
www.ers.usda.gov/features/bioenergy/

Glossary of terms used in text

Biodiversity – The variety of organisms that inhabits a given place (number of species, varieties or genetic strains)

Bioenergy – Energy derived from contemporary biological materials (fossil fuels are derived from ancient biological material)

Biofuels – Liquid and solid fuels derived from contemporary biological materials that can be combusted to produce energy

Cover Crop – A crop planted to maintain vegetation cover on the soil to suppress weeds, add nutrients and reduce erosion during periods when cropland is idle (for example, late fall, winter and early spring)

Ecosystem services – The benefits that humans obtain from ecosystems including food, fuel, fiber, clean water, recreation and less tangible things such as a sense of place and natural beauty, sometimes called "nature's benefits"

Landscape – A landscape is an area of land made up of multiple types of habitats that are repeated across a large scale (for example, tens of miles)

Landscape composition – The types of habitats that make up a landscape, best described by the area of each habitat (e.g., acres of corn, acres of grassland, acres of forest)

Landscape configuration – How habitats are arranged across landscapes, described by the size and shape of habitat patches and how they interconnect with other habitats

Landscape diversity – Diverse landscapes contain a variety of habitat types that are intermingled; you will see more types of habitats (and more transitions between different types) per mile traveled in a diverse landscape

Landscape structure – The composition (what habitats are present) and configuration (how habitats are arranged in space) of the landscape

Marginal land – Active or abandoned farmland with soils (for example, rocky or low fertility) and other conditions producing suboptimal yields of food crops

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