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RESEARCH ARTICLE

Spatial land use trade-offs for maintenance of biodiversity, biofuel, and agriculture

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Abstract

Context Expansion of bioenergy production is part of a global effort to reduce greenhouse gas emissions and mitigate climate change. Dedicated biomass crops will compete with other land uses as most high quality arable land is already used for agriculture, urban development, and biodiversity conservation.

Objective First, we explore the trade-offs between converting land enrolled in the U.S. Conservation Reserve Program (CRP) to switchgrass for biofuel production or preserving it for biodiversity. Next, we examine the trade-offs between agriculture, biodiversity, and biofuel across the central and eastern U.S.

Methods We compiled measures of biodiversity, agriculture, and biofuel from land cover classifications, species range maps, and mechanistic model output of switchgrass yield. We used a spatially-explicit optimization algorithm to analyze the impacts of small-to-large scale biomass production by identifying locations that maximize biofuel produced from switchgrass and minimize negative impacts on biodiversity and agriculture.

Results Using CRP land for switchgrass production increases the land area required to meet biomass goals and the species range area altered for birds, amphibians, mammals, and reptiles. When conversion is not limited to CRP, conversion scenarios including biodiversity and agriculture trade-offs require greater than 100 % more area for switchgrass to reach the same production goals. When land conversion scenarios do not include biodiversity, twice the range area for reptiles and amphibians could be altered.

Conclusions Land-use trade-offs between biofuel production, agriculture, and biodiversity exist and alter optimum location of land conversion for low-to-high biofuel levels. This highlights the need for systematic land-use planning for the future.

Keywords Species richness · Ecosystem services · Switchgrass · Spatial optimization · ALMANAC model · *Panicum virgatum* L.

Introduction

Human land-use and land-cover change have been linked to decreases in biodiversity and degradation of many ecosystem services (i.e. air and water quality,

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carbon sequestration, nutrient cycling, etc.) (Foley et al. 2005). Landscapes are continually changing as a result of human activities that convert natural landscapes or change management practices on previously converted land. Human influenced landscapes, cropland and pasture, now cover approximately 40 % of the earth's terrestrial surface (Asner et al. 2004). However, further expansion and intensification of agriculture is still the biggest current threat to biodiversity and ecosystem services (Rockström et al. 2009; Foley et al. 2011).

Development of large-scale biofuel production is predicted to require the largest amount of land-use change since the formation of industrial agriculture (Altieri 2009; Raghu et al. 2011). Most high quality agricultural land is currently used for the production of food, feed, fiber, forestry, nature conservation, and urban development; the addition of bioenergy production will compete with these current land uses (Tilman et al. 2009). If pursued, there are many unintended consequences of biofuel production at a landscape scale (Tilman et al. 2009; Fargione et al. 2010). Concerns have been raised about the quality and quantity of biomass that can be produced and the potential impacts of large-scale biofuel production on biodiversity and the current agricultural industry (Dale et al. 2011; Mitchell et al. 2012). The amount of land dedicated to bioenergy production is projected to increase to 12.0–22.6 million ha for U.S. and Canada, 12.0–17.1 million ha for the European Union, 5.0–11.5 million ha for Asia, and 3.5–5 million ha for Latin America by 2030 (IEA 2006).

A comprehensive understanding of biodiversity patterns and landscape change must consider the impact of agricultural intensification from biofuel production. Modifying the distribution of habitat quality and quantity will impact species diversity and extinction patterns. Changes in species diversity are of paramount concern because these shifts have been linked to changes in the structure and function of entire ecosystems (Chapin et al. 1997; Tilman et al. 1997; Hooper et al. 2005). The quantity and location of land conversion will depend on government policy, society, and economics of biofuel production. To help ensure proper ecosystem function, policy regarding biofuel production should try to understand the potential trade-offs between land-use for conservation of biodiversity and biofuel production.

Current biofuel policy has been put into place as part of a global effort to reduce greenhouse gas (GHG) emissions and consequently global warming (Kyoto Protocol 2009; IEA 2013). Growth of the biofuel industry has been encouraged by an increasing number of governments, which provide tax incentives and subsidies to kick-start the industry. Many countries have also set future production targets. Brazil has set the highest goal to replace 30 % of fossils fuels used for transportation with biofuel by 2030, the European Union and the U.S. aim for 15 %, and China and India 4 % (IEA 2013).

There is concern that conversion of agricultural lands to biofuel production could negatively impact current agricultural infrastructure leading to food shortages and rising food prices (Pimentel et al. 2008). Biofuel is a developing industry and in 2011 biofuel contributed only 2 % to worldwide transportation fuel (IEA 2013). If biofuel production increases along with population size, meeting demands for food and fuel will become more difficult. One proposed solution to avoid potential negative impacts on the current agriculture industry is to plant bioenergy crops on land not used for agricultural production (Perlack et al. 2005). However, non-agricultural lands provide habitat for wildlife and could be critical for the survival of some species that rely on these habitats in highly fragmented landscapes (Reynolds et al. 2006; Herkert 2007; Meehan et al. 2010).

Another option is to plant biomass crops on erodible low quality farmland instead of clearing land or sacrificing prime farmland (U.S. Department of Energy 2011). Several countries have resource conservation and management strategies designed to prevent erosion of agricultural land (Farm Services Agency 2008; Towards a Thematic Strategy on Soil Protection: Communication from the Commission of the Council 2002). For example, in the U.S. farmers enrolled in the Conservation Reserve Program (CRP) are paid to remove highly erodible and environmentally sensitive cropland from annual production agriculture for 10–15 years. The intended benefits are conserving soil and preventing erosion while improving water quality and reducing the loss of wildlife habitat (Johnson and Becker 2008). If biofuel production is pursued on these low quality lands, it is unclear how much biomass can be produced and what the impact would be on the animals that rely on these current plant-diverse communities.

The primary goal of this study is to analyze the three-way interaction between land use for maintenance of biodiversity, agriculture (including cropland, pasture/hay, and forestry), and lignocellulosic biofuel production from switchgrass, *Panicum virgatum* L. We analyze trade-offs using machine-learning optimization and generate optimal land allocation scenarios that maximize simulated switchgrass biomass production while simultaneously minimizing impacts on biodiversity or agriculture (Ciarleglio et al. 2009). First, we determine the quantity of land-use change needed to meet a wide range of biomass production levels while considering these trade-offs. Next, the proportion of species range area altered by biofuel production from all terrestrial amphibians, birds, mammals, and reptiles are analyzed. Third, the land area removed from farmland (land used for cropping and pasture/hay) and forested land is analyzed. Lastly, we identify locations where switchgrass cultivation minimizes these impacts.

Materials and methods

Spatial data sources

To develop these trade-off scenarios, we defined spatially continuous measures of biodiversity, agriculture, and biofuel from land cover classifications, species range maps, and mechanistic model outputs. The spatial extent of the analyses was limited to the central and eastern U.S where rainfall is adequate to support native tallgrass species. Each data source was aggregated to a 0.25° grid cell (approximately 27.5 × 27.5 km) using ArcGIS 10.0. A 0.25° grid cell was chosen to be small enough to capture the effect of local variation in climatic conditions and large enough to incorporate uncertainty in location and variation of soil type on switchgrass yields (Behrman et al. 2013).

Biodiversity data

For this study, we limit our use of the term “biodiversity” to reflect species diversity or alpha diversity for four major taxon groups (amphibians, birds, mammals, and reptiles). Because of the large spatial extent and coarse resolution (0.25°) of our analysis, terrestrial species range maps were chosen to represent the each species’ potential habitat area. Each biodiversity surface was estimated by counting the number of terrestrial species range maps in each taxon group that overlap each cell (BirdLife International, NatureServe 2012; IUNC 2012) (Fig. S1). Species that are exotic and invasive were excluded from the analysis. Migratory, breeding, and wintering bird ranges were included in the analysis but only counted once for each species.

Land use data

We define agricultural lands as those primarily used for current food, feed, fiber, and forestry. For classification of agricultural land types, we chose the 2011 National Land Cover Database (NLCD) because it is the most recent and comprehensive classification at a fine spatial resolution of 30 meters (Homer et al. 2015). Three agricultural surfaces are calculated as the proportion of land classified by the NLCD as cultivated crops and pasture/hay, forest (deciduous, mixed, and evergreen), and urban development in each cell (Fig. S2). For each surface, the proportion of area inside each 0.25° cell was calculated using ArcGIS 10.0. Farmland was calculated as the proportional area classified as cultivated cropland and lands used for the pasture/hay production. Forested lands were defined as the proportional area classified as deciduous, evergreen, and mixed forest. Urban/impervious lands were calculated as the proportional area classified as open space development, low intensity development, medium intensity development, high intensity development, and barren land. The contribution of urban and imperious land is included to avoid the optimization algorithm mistakenly choosing these areas for biomass production because they have low proportion of agriculture and biodiversity. Since switchgrass cannot be grown on urban or impervious land, this contribution is removed from all reported estimates of potential biomass production and land conversion. In addition, cells that contained greater than 75 percent of the area classified as national parks, state parks, reserves, and Indian reservations were excluded from the optimization analysis to avoid the optimization algorithm choosing cells that will most likely never be converted to biofuel production (see electronic supplementary material, Fig. S1, black dots).

Switchgrass biomass data

We define lignocellulosic biofuel production potential as the spatially explicit switchgrass yield reported by Behrman et al. (2013) for the central and eastern U.S. where switchgrass is native. Yield values were estimated by the ALMANAC model, an extensively validated process-oriented crop growth model, parameterized for local adapted switchgrass ecotypes (Fig. S3). A 0.25° grid cell was chosen to be small enough to capture local variation in climatic conditions and large enough to incorporate uncertainty in location and variation of soil type. The biomass potential estimated for each grid cell is the yearly average biomass production of 20 randomly distributed fields that capture local variation in soil type and climate. For each field, ALMANAC was run on a daily time step for 10 years of simulated post establishment growth and harvesting. ALMANAC contains a built in daily weather generator parameterized for the average monthly conditions of 975 weather and wind stations using daily data from the National Climatic Data Center. The soil type at each field location and the corresponding soil properties were from the USDA-NRCS Soil Survey and Geographic database (SSURGO). A unified management schedule with no irrigation and adequate N and P fertilizer was applied to all areas to allow for a more direct comparison of environmental heterogeneity. The modeled yield estimates show the highest switchgrass production along the Gulf Coast, southern Atlantic Coast, and in the East North Central Midwest (IA, IL, IN, and OH). CRP biofuel production is defined as the switchgrass biomass that can be produced on all active CRP lands within each cell. This was calculated by multiplying the land area enrolled in the Conservation Reserve Program through 2013 by the corresponding switchgrass yield for each cell (Farm Services Agency 2012).

Spatial optimization

Spatial optimizations using these surfaces were obtained using CONSNET, which employs a tabu search algorithm (Ciarleglio et al. 2009). CONSET was developed to select optimum conservation reserve placement from continuous estimates of the probability of occurrence for many species. The software selects a set of land parcels that maximize or minimize a trade-off function within user-specified bounds. This is novel use of the CONSET for biofuel applications. CONSET was chosen because it has an advanced search algorithm that can quickly search alternative solutions across a large spatial extent. A general weighted constraint was used to minimize the cost to all layers grouped as agriculture and biodiversity while maximizing biofuel production (see Table S1 for the weights). Each optimization was run for 500,000 iterations to ensure the optimum solution was found. All optimizations were started with both all cells and no cells selected. The scenarios analyzed each differentially weight the relative importance of biodiversity, biofuel production, and agriculture. For each scenario, 72 optimizations were run encompassing low-to-high switchgrass biomass production targets.

We analyze two different sets of trade-off scenarios. The first set of trade-offs termed, T1, assumes that land available for biofuel production is limited to land enrolled in the U.S. Conservation Reserve Program (CRP). The spatial extent of the T1 analysis is limited to grid cells that contained land enrolled in the CRP and the only trade-off is between biodiversity and the quantity of biomass production on CRP lands. The second set of trade-offs, termed T2 assumes that all land in the central and eastern U.S. is available for biofuel production except areas that contain greater than 75 % national parks, state parks, reserves, and Indian reservations. We analyze the trade-offs between all three entities: biodiversity, agriculture, and biofuel production. For each trade-off analysis, we specify a scenario or a set of relative weights to maximize biofuel production while simultaneously

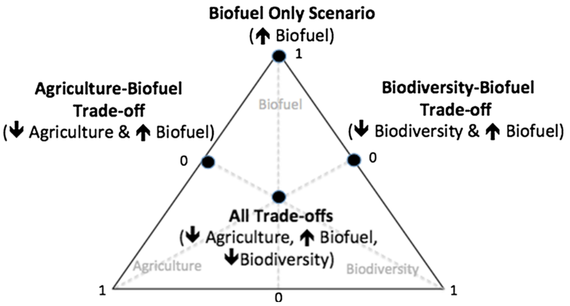

Fig. 1 A graphical representation showing the relatives weights of the four T2 scenarios in parameter space ("all trade-offs", "agriculture-biofuel trade-off", "biodiversity-agriculture trade-off", "biofuel only")

minimizing the cost to biodiversity and agriculture (Fig. 1). Next for each scenario, a biomass production target is set and the optimization algorithm is run until a stable solution is found. The optimum solutions identified for three scenarios and three biomass production targets are shown in Fig. 2.

A key consideration in any analysis of trade-offs is the relative weights given to each cost-benefit category, in our case: biodiversity, agriculture, and biofuel production (or CRP biofuel production). In practice, this decision will depend on stakeholder objectives or policy-related incentives, mandates, and regulations. For example, a stakeholder concerned with the maintenance of biodiversity may claim that the conservation of species range habitat is twice as important as the production of biofuel and food. Still others may argue that the growing global population necessitates more focus on food production. Whereas, those concerned with rising GHG emissions may contend that biofuel production is more important than the conservation of biodiversity and food production. Because weighting schemes may vary, we analyze the full range of optimization functions for T2 by continuously varying the weights applied to each category (agriculture, biodiversity, and biofuel) (Fig. S4). We repeat this analysis for three biomass production targets sufficient to offset 10, 20, and 30 % of current petroleum usage (Perlack et al. 2005). While the magnitude of costs to agriculture and biodiversity increased with biomass production, the general trade-offs patterns remained the same for all three biomass targets (Fig. S4).

For the following results, we focus on two scenarios describing T1 and four scenarios describing T2 (Table S1; Fig. 1). Focusing on select scenarios makes it possible to analyze the potential impacts of biofuel production across a wide range of possible future biomass production levels. For T1: “biodiversity-CRP biofuel trade-off” is the scenario in which the production of biofuel on CRP lands and the

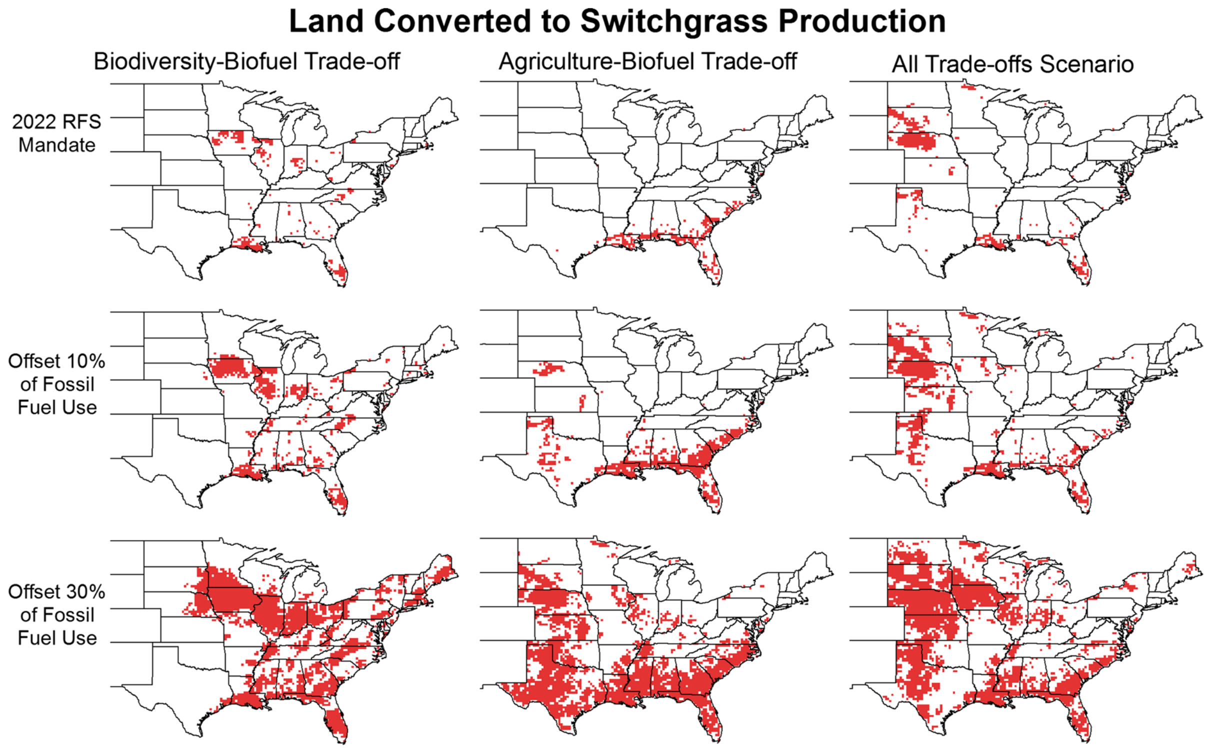

Fig. 2 Maps of the optimum solution determined for three biomass production targets (RFS mandate for cellulosic biofuel production set for 2022 assuming a conversion rate of 0.38 kg l^{-1} of ethanol (Renewable and Application Energy Laboratory 2007; U.S. Congress 2007), biomass need to offset 10 % of current petroleum use, and biomass needed to offset 30 % of current petroleum use) and three T2 trade-off scenarios (“all trade-offs”, “agriculture-biofuel trade-off”, “biodiversity-biofuel trade-off”)

maintenance of species biodiversity are weighted equally, and “CRP biofuel only” allocates land area based on CRP biofuel production potential irrespective of either agricultural land use or biodiversity. For T2, “all trade-offs” is the scenario in which all three entities (biodiversity, agriculture, and biofuel) are included and weighted as equally important, “biodiversity-biofuel trade-off” is the scenario in which the production of biofuel and the maintenance of species biodiversity are weighted equally, “agriculture-biofuel trade-off” is the scenario in which the production of biofuel and the maintenance of agriculture are given equal weight, and “biofuel only” is where land conversion is solely based on simulated biofuel production potential irrespective of either agricultural land use or biodiversity.

Biomass production guidelines

To provide a reference point for comparing these trade-off scenarios across a wide range of biofuel production levels, three biomass production levels relevant to U.S. biofuel policy are explicitly compared. These thresholds are guidelines to understand how the magnitude of biomass production for ethanol will contribute to offsetting fossil fuels use in the U.S. We did not specifically frame our analysis based on these recommendations and this comparison is not meant to imply that switchgrass should be or is the only biomass crop in this region that will contribute to filling these production goals.

The first production goal is the U.S. Energy Independence Security Act of 2007’s renewable fuel standard (RFS), which mandates production of 60 billion liters of lignocellulosic ethanol per year by 2022 (Renewable and Application Energy Laboratory 2007). Assuming a biomass to ethanol conversion rate of $0.38\ \mathrm{l\ kg^{-1}}$ of ethanol, that is equivalent to 159 million Mg of biomass production per year (U.S. Congress 2007). In the second RFS (RFS2), the environmental protection agency (EPA) further qualifies that biomass cultivation must be on land that is actively managed, fallow, and non-forested prior to December 19, 2007 (US Environmental Protection Agency 2010). This includes cropland, pasture/hay, and land enrolled in the CRP. The NLCD is a spectral classification product and it may not have the ability to capture subtle changes between all managed land types as specified by the RFS2. Because of this uncertainty and to allow for analysis of the T2 scenarios across a wide range of biomass production levels, we did not limit our scenario development to only actively managed, fallow, and non-forested land as specified by the RFS2. However to relate our scenarios directly to the RSF2, we did additionally calculate the land area necessary to meet the 2022 biomass production goal if only land classified as cropland or pasture by the NLCD is allowed to be converted to biomass production.

The second and the third biomass production goals are both related to the future estimates made by the Billion-Ton Study (BTS) of potential biomass available mid-century when large-scale biofuel refineries may exist (Perlack et al. 2005; U.S. Department of Energy 2011). This biomass will come from forest biomass, agricultural biomass, waste resources, and bioenergy crops. The second biomass production goal is 393 million Mg, which was estimated as the biomass production necessary to offset 10 percent of U.S. fossil fuel use (Perlack et al. 2005). The third production goal is 1179 million Mg of biomass to offset 30 % of U.S. fossil fuel use.

Results

Total area requirements

Minimizing biodiversity impacts (“diversity-CRP biofuel trade-off”) does not increase the land area required compared to the “CRP biofuel only” scenario (Fig. 3), possibly reflecting a relatively homogeneous distribution of taxon species diversity in CRP lands. If all current CRP land (6.7 million ha) in the central and eastern U.S. is converted to switchgrass production, an estimated 62.4 million Mg of biomass could be produced each year. Although commercial-scale biofuel production from switchgrass has not yet been achieved, assuming a biomass to ethanol conversion rate of $0.38\ \mathrm{l\ kg^{-1}}$ of ethanol, at most CRP land conversion could produce 39 % of the biomass needed to meet the 2022 RFS2 goal. However, if biofuel production is not limited to CRP land (T2 scenarios), then substantially less land area is needed to meet the same biomass production levels for all four trade-off scenarios (Fig. 3, left panel).

When all land is considered available for conversion, optimizations minimizing the cost to both

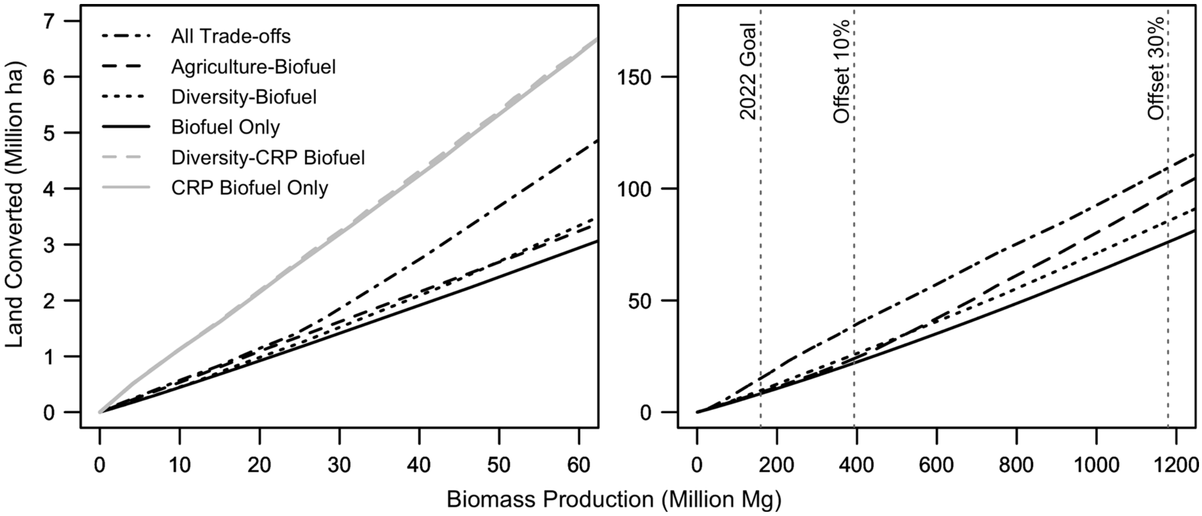

Fig. 3 The land area needed to meet small (*right panel*) and large (*left panel*) biomass production levels for the two T1 ("CRP biofuel only trade-off"—*solid gray line* and "biodiversity-CRP biofuel trade-off"—*dashed gray line*) and four T2 ("all trade-offs"—*dotted and dashed black line*, "agriculture-biofuel trade-off"—*dashed black line*, "biodiversity-biofuel trade-off"—*dotted black line*, and "biofuel only"—*solid black line*) scenarios of land-use change. The *gray dashed lines* highlight three biomass production goals (RFS mandate for cellulosic biofuel production set for 2022 assuming a conversion rate of 0.38 kg l^{-1} of ethanol (Renewable and Application Energy Laboratory 2007; U.S. Congress 2007), biomass need to offset 10 % of current petroleum use, biomass needed to offset 30 % of current petroleum use)

biodiversity and agriculture require more land area conversion for all biomass production levels (Figs. 2, 3). At low biomass production goals (<20 million Mg per year) the amount of land conversion for the "biofuel only" and "biodiversity-biofuel trade-off" scenario is approximately the same (Fig. 3, left panel). Scenarios with multiple constraints ('all trade-offs", "agriculture-biofuel trade-off", "biodiversity-biofuel trade-off") require more land conversion as biomass production levels increase (>20 million Mg per year) compared to the "biofuel only" scenario because areas with lower switchgrass productivity are chosen to avoid areas of high productivity that also contain high levels of biodiversity or agricultural production (Fig. 3, right panel). To meet the 2022 goal, a minimum of 8.3 million ha of land will be needed to produce switchgrass biomass, and this increases up to 15.1 million ha (82 % more land) when trade-offs with both biodiversity and agriculture are considered ("all trade-offs" scenario) (Fig. 3; Table 1). When land conversion is limited to land classified as cropland or pasture/hay by the NLCD to emulate the guidelines specified by the RFS2, then 9.5–15.6 million ha of land will be required to meet the 2022 goal (Table 1, parentheses).

However if cellulosic biofuel from switchgrass expands to offset 30 % of current petroleum use, a minimum of 79.1 million ha of land will be required for biomass production, and this increases to 99.1, 99.2, and 109.1 million ha if land management decisions incorporating trade-offs with both agriculture, biodiversity, and both agriculture and biodiversity are considered (Figs. 2, 3). By sacrificing one of the three classifications ("biodiversity-biofuel scenario" or "agriculture-biofuel scenario"), the land area required to meet the 30 % goal can be reduced (Table 1).

Potential biodiversity impact

When land conversion is limited to land enrolled in the CRP, both the "CRP biofuel only scenario" and "biodiversity-CRP biofuel trade-off" scenario have nearly the same proportion of range alternation for all four diversity groups across production levels ranging from 0 to 62.8 million Mg per year (Fig. S6). This indicates that even though CRP lands harbor many species, there is little variation in total taxon species diversity in these areas and therefore a relatively consistent cost to species diversity will always be

Table 1 Total land, farmland, and forested land area converted to switchgrass production to meet three biomass production goals (RFS mandate for cellulosic biofuel production set for 2022 assuming a conversion rate of 0.38 kg l^{-1} (Renewable and Application Energy Laboratory 2007; U.S. Congress 2007), biomass need to offset 10 % of current petroleum use, and biomass needed to offset 30 % of current petroleum use) for the four T2 scenarios. Land area in parenthesis is for conversion of only agricultural land to meet 2022 RFS2 mandate

	Agriculture-biofuel trade-off	Diversity-biofuel trade-off	Alia trade-offs	Biofuel only scenario
2022 RFS mandate (159 million Mg)				
Total and area (million ha)	8.9 (10.5)	9.7 (11.1)	15.1 (15.6)	8.3 (9.5)
Farmland (million ha)	1.3	4.3	1.6	1.6
Forested land (million ha)	2.1	1.2	0.5	2.7
Offset 10 % of fossil fuel (393 million Mg)				
Total and area (million ha)	24.0	25.8	38.4	22.0
Farmland (million ha)	4.0	13.0	6.2	4.5
Forested land (million ha)	5.7	4.1	2.3	7.4
Offset 30 % of fossil fuel (1179 million Mg)				
Total and area (million ha)	98.1	85.5	109.2	76.1
Farmland (million ha)	17.2	40.6	33.2	23.4
Forested land (million ha)	18.1	19.6	12.0	27.4

acquired when converting CRP land to switchgrass monocultures. Furthermore, the proportion of potential range area altered for all taxon groups decreases when land conversion is not confined to CRP land (Fig. S6).

For the four T2 scenarios, there are clear trade-offs between biodiversity and biofuel. The "biodiversity-biofuel trade-off" scenario removes the smallest cumulative proportion of species range area for all taxon groups, and the proportion of range area altered to offset 10 % of current petroleum production is close to 5 % for all taxon groups (Table 2; Fig. S7). The "biofuel only" and "biodiversity-biofuel trade-off" scenarios require similar proportions of range area removal for mammals and birds. The "all trade-offs" scenario removes the most mammal and bird range area. Reptiles and amphibians will have the largest proportion of their range area altered when species diversity is ignored ("agriculture-biofuel trade-off" and "biofuel only" scenario) in our optimization of biofuel field placement (Fig. S7). The "agriculture-biofuel trade-off" scenario has the largest impact on reptiles when production levels are high (>700 million Mg per year).

Potential impact to agriculture

The amount of farmland, area classified as cultivated crops or pasture/hay, removed from agricultural production and replaced by perennial switchgrass monocultures is the highest in the "biodiversity-biofuel trade-off" scenario (Table 1; Fig. S5). At lower production targets (<160 million Mg per year), optimization including agriculture ("agriculture-biofuel trade-off" scenario) does not lead to a substantial decrease in the proportion of farmland (<0.2 million ha difference). However at higher biomass production goals (>400 million Mg per year), optimization including agriculture reduces farmland conversion to biofuel production (Fig. S5).

Avoiding regions with high species diversity ("biodiversity-biofuel trade-off" scenario) reduces the amount of forested land converted to biofuel production and increases the amount of agricultural land converted to biofuel production (Table 1; Fig. S5). Minimizing the impact to both agriculture and diversity ("all trade-offs" scenario) requires conversion of the least amount of forested land to biofuel production. When the negative impacts on biodiversity and

Table 2 Percentage of species range area in the central and eastern U.S. converted to biofuel production for the four T2 scenarios to meet three biomass production goals (RFS mandate for cellulosic biofuel production set for 2022 assuming a conversion rate of 0.38 kg l^{-1} (Renewable and Application Energy Laboratory 2007; U.S. Congress 2007), biomass need to offset 10 % of current petroleum use, and biomass needed to offset 30 % of current petroleum use)

	Agriculture-biofuel trade-off	Diversity-biofuel trade-off	All trade-offs	Biofuel only scenario
2022 RFS mandate (159 million Mg)				
Amphibian range area (%)	3.2	2.0	2.3	3.6
Bird range area (%)	2.1	2.1	3.2	2.2
Reptile range area (%)	3.3	2.0	2.7	3.5
Mammal range area (%)	1.8	1.9	3.1	2.1
Offset 10 % of fossil fuel (393 million Mg)				
Amphibian range area (%)	8.2	5.5	6.0	9.3
Bird range area (%)	5.4	5.6	8.2	5.9
Reptile range area (%)	8.7	5.1	7.6	9.4
Mammal range area (%)	4.7	5.1	8.2	5.3
Offset 30 % of fossil fuel (1179 million Mg)				
Amphibian range area (%)	24.7	19.5	19.5	27.9
Bird range area (%)	21.2	18.4	23.0	18.7
Reptile range area (%)	31.7	17.2	23.6	26.7
Mammal range area (%)	20.7	17.1	23.1	17.5

agriculture are ignored ("biofuel only" scenario) the amount of forested land converted to biofuel substantially increases.

Spatial land use trade-offs

To analyze the spatial location of the optimum solution, 72 optimizations were run for each scenario from low to high biomass production levels to create a "frequency" surface (Fig. 4). Frequency refers to the proportion of times that each location was chosen as part of a stable optimum solution. Locations with high frequency are consistently chosen as optimum solutions for both low and high biomass production levels. Whereas, low frequency locations are only chosen when biomass production levels are high.

The locations targeted for the T1 and T2 trade-off scenarios are mostly disjunct (Fig. 4). The regions targeted for switchgrass biomass production under the single T1 trade-off scenario ("biodiversity-CRP biofuel trade-off") are in regions with a high density of CRP land (Fig. 4, top left, and Fig. S8). The only regions frequently targeted for switchgrass biomass production under all three T2 trade-off scenarios (agriculture, biodiversity and all trade-offs) are the highly productive lowland regions of southern gulf coast and southern FL. This is because switchgrass productivity is predicted to be the highest in this region. The regions that minimize the quantity of agriculture land displaced while maximizing switchgrass yields ("agriculture-biofuel trade-off") are along the gulf coast of LA, GA, MS, AL and FL, and the Atlantic coast in GA, SC, and NC (Fig. 4, bottom left). The regions that minimize the cost to biodiversity ("biodiversity-biofuel trade-off") are primarily located in the Corn Belt (IA, IL, and IN), Gulf Coast of LA, and southern FL (Fig. 4, top right). When both the removal of land from traditional agriculture and biodiversity is minimized ("all trade-offs"), the regions most frequently chosen as optimal for conversion to switchgrass cropping systems are in LA along the gulf coast, southern FL, and central NE (Fig. 4, bottom right).

Discussion

Laud use change for biofuel production is already occurring and is expected to continue (Altieri 2009; Raghu et al. 2011). These changes will have contending

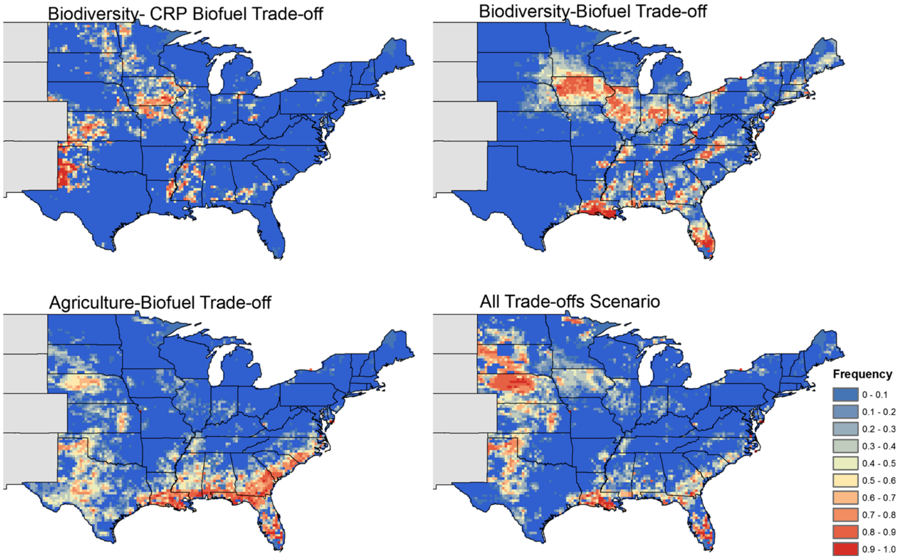

Fig. 4 A heat map showing the frequency of land conversion or (the proportion of times each cell was chosen as part of an optimum solution) for the one T1 trade-off scenario (“biodiversity-CRP biofuel trade-off”—*top left*) and three T2 trade-off scenarios (“all trade-offs”—*bottom right*, “agriculture-biofuel trade-off”—*bottom left*, “biodiversity-biofuel trade-off”—*top right*). Cells that are *bright red* or close to one were chosen for almost all production levels. Cells that are bright blue or close to zero were never chosen or only chosen when the production level was large

impacts on agriculture and biodiversity (Tilman et al. 2009). The patterns of land use change will be driven by the values given to these competing aspects by stakeholders. Government regulations may direct some of these changes, but further planning with a clear understanding of value and trade-offs is needed to make informed decisions. Here we utilize a spatially explicit optimization technique to formally explore trade-offs between biofuel, biodiversity and agriculture under two sets of trade-off scenarios.

The plant material needed to produce lignocellulosic biofuel can come from a variety of resources, such as cellulosic waste, forest residues and thinning, annual crop residues, perennial energy crops, and short-rotation woody crops (Perlack et al. 2005). Here we present a macro-ecological analysis of one potential feedstock, switchgrass, to allow for a more direct comparison of impacts across landscape scale land use patterns. Switchgrass is a leading second-generation biofuel crops because it is adapted to a large range of climatic conditions, can produce reasonable yields on marginal lands without irrigation, and requires lower agrochemical inputs (Sanderson et al. 1996; Casler et al. 2004; Perlack et al. 2005; McLaughlin et al. 2006; Schmer et al. 2008; U.S. Department of Energy 2011). Perennial grasses take 3 years to reach full yield potential therefore commitment to biofuel production is considered long-term compared to annual cropping systems. The goal of this study is identify potential trade-offs for one potential feedstock that can be grown throughout a large portion of the U.S. However, we are not implying that one feedstock will supply all the biomass to meet U.S. biofuel production needs. From a practical standpoint if large-scale biofuel production is pursued, biomass for biofuels will likely come from a broad set of regionally adapted plant material. The inclusion of other species or even improved varieties of switchgrass will alter the yields and the associated trade-offs explored here.

Land-use change has been documented as the primary cause of biodiversity loss and is predicted to be the leading cause of biodiversity loss in 2100 (Sala et al. 2000). If only CRP land is used for biofuel production from switchgrass, the proportion of biodiversity range area altered increases due to an increase in the amount of land area needed to meet biomass production levels. However, CRP land alone can provide 40 percent of the biomass needed to meet the 2022 RFS2. The land-use conversion of 8.3–15.6 million ha of agricultural land to switchgrass production will be needed to meet the RSF2. These estimates are with in the range of agricultural land conversion values for 2022, 5.3–17.8 million ha, reported for perennial grasses for a range of prices assuming high crop yield growth (U.S. Department of Energy 2011).

When all land uses are available for conversion, minimizing conversion of high diversity areas (“biodiversity-biofuel trade-off” scenario) greatly reduces the proportion of reptile and amphibian range area altered. Birds and mammals however do not benefit greatly from optimization, as the proportion of range area altered is similar under both the “biodiversity-biofuel trade-off” and “biofuel only” scenarios. A likely explanation is that lower diversity of birds and mammals in the high-productivity agricultural landscapes are favored by our optimizations.

Minimizing the amount of agricultural land removed from production (“all trade-offs” or “agriculture-biofuel trade-off” scenario) reduces the quantity of forested land cleared for biofuel production and the quantity of GHGs emitted from direct land conversion (Danielsen et al. 2008; Fargione et al. 2008; Searchinger et al. 2008). Increases in GHG levels have been linked to global warming and consequently the extinction or shifts in many species’ ranges (Thomas et al. 2004; Parmesan 2006). At low biomass production goals (<400 million Mg year^{-1}) minimizing the conversion of agricultural land does not reduce farmland conversion. This is because the areas that have the highest predicted switchgrass productivity are on prime farmland. Conversely at high biomass production goals (>1.2 billion Mg per year) the quantity of farmland and forested land removed from production can be cut in half under the “agriculture-biofuel trade-off” scenario. Therefore segregating biofuel production away from agricultural land may be necessary to maintain stable food production and prices and reduce GHG emissions under high biofuel production levels.

The impacts of large-scale biofuel production can be considered from many different perspectives. Our study presents one in which the impact of land-use change is measured as the area removed from agriculture or the species range area altered and replaced by switchgrass monocultures for biofuel production. The consequences are assumed to be the loss of biodiversity in that area and the potential economic consequences of replacing food, fiber, or feed production with biofuel. Other environmental impacts of land-use conversion to biofuel cropping include the release of GHGs, soil erosion, water quality, soil organic carbon, nitrate leaching, etc. (Renewable Fuels Agency 2008; Davis et al. 2010; Robertson et al. 2011c). These indirect effects are often assumed to be small because switchgrass is a perennial grass with low fertilizer and pesticide requirements (McLaughlin and Walsh 1998). However, management plays a big role in this assumption and a variety of different management practices should be extensively evaluated before large-scale biofuel production from switchgrass is implemented (Wang et al. 2010).

We defined the impact to biodiversity as the cumulative species range area altered from each taxon group. This measure of biodiversity is not sensitive to the loss of an individual species and does not identify a species that may become threatened or endangered due to land-use change. There are many other measures of biodiversity that may provide a different set of solutions than the ones presented here (Brooks et al. 2009). For example, a large area in the Central Great Plains was chosen as the optimum solution for the “all trade-offs scenario”. This area contains a high number of endangered birds (Dobson et al. 1997). If biodiversity was defined by endangered species instead of total species diversity the biodiversity value assigned and the corresponding solution for each scenario would be altered.

Species diversity is a fairly conservative measure of biodiversity because all land-use change is assumed to have an equal negative impact on biodiversity. It is possible that planting switchgrass could have a positive effect on biodiversity, but may be specific to the type of land conversion and species of interest. Specifically, perennial grasses provide an increase in post breeding and migratory stop over habitat compared to traditional row crops resulting in increased bird diversity (Robertson et al. 2011a, b). In addition, land enrolled in the CRP has been documented to increase the abundance of many declining bird species and it is unclear if clearing and planting switchgrass monocultures will negatively affect these species (Reynolds et al. 2006; Herkert 2007). We also assume that the magnitude of all land conversion is equal. That is, converting pasture to switchgrass is the same as converting row crops to switchgrass. In an area with high land-use heterogeneity, species range maps may not capture these fine-scale changes in community composition between these different land uses.

Because of the relatively large spatial resolution of our analysis we did not impose spatial constraints influencing compactness or connectivity on the optimization algorithm. That means a single cell has the same probability of being selected as a group of cells. Assuming a biomass productivity of 10 Mg ha^{-1} each cell has the capacity to fuel a 190 million liter ethanol plant using only 70 % of the area (U.S. Department of Energy 2011). In reality, there will be costs associated with transportation of biomass that will depend on refinery locations and the network configuration of roads and railways. Incorporating GHG emissions and fuel cost associated with transportation to and from biofuel refineries and related spatial constraints may alter the perceived costs and benefits of land conversion. Considering biomass transportation will be an important next step in modeling land use trade-offs.

Land area for biomass production will be the factor limiting large-scale biofuel production from switchgrass. However, future research efforts focused on improving conversion efficiency and enhancing biomass production through genetic breeding and advancements in agronomic management may reduce the amount of land area needed for conversion. Reducing land-use change will alleviate some of the negative impacts on biodiversity and the agricultural industry identified by our trade-off analysis.

Negative effects of biofuel expansion have already been documented and the biofuel industry is still in its infancy (Wang et al. 2010). Many difficult decisions will need to be made to meet biofuel production goals. Any efforts to assess risks of land-conversion strategies can provide valuable input to potentially mitigate or lessen the severity of these negative impacts on biodiversity.

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