Biodiversity conservation in the era of biofuels: risks and opportunities

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Growing demand for alternative energy sources has contributed to increased biofuel production, but the effects on biodiversity of land-use change to biofuel crops remain unclear. Using a meta-analysis for crops being used or considered in the US, we find that vertebrate diversity and abundance are generally lower in biofuel crop habitats relative to the non-crop habitats that these crops may replace. Diversity effects are greater for corn than for pine and poplar, and birds of conservation concern experience greater negative effects from corn than species of less concern. Yet conversion of row-crop fields to grasslands dedicated to biofuels could increase local diversity and abundance of birds. To minimize impacts of biofuel crops on biodiversity, we recommend management practices that reduce chemical inputs, increase heterogeneity within fields, and delay harvests until bird breeding has ceased. We encourage research that will move us toward a sustainable biofuels economy, including the use of native plants, development of robust environmental criteria for evaluating biofuel crops, and integrated cost–benefit analysis of potential land-use change.

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Ever-increasing energy demands, volatile petroleum prices, and growing concerns about climate change have spurred worldwide interest in alternatives to fossil fuels. Biofuels, or fuels produced from biomass, have become a major focus of attention, because they represent a potential means of both reducing dependence on fossil fuels and lowering net emissions of atmospheric CO_2 (Fargione *et al*. 2008; Charles 2009). In the US, legislation has stimulated rapid expansion of biofuel production by subsidizing producers and refiners, enacting tariffs on imports, and requiring benchmark production goals (US Congress 2007). To meet these production goals, a substantial shift in land area devoted to the production of biofuel crops is expected (eg Donner and Kucharik 2008; McDonald *et al*. 2009).

Because of the importance of habitat alteration to biodiversity, there is an urgent need for information regarding the potential consequences of increased biofuel production on biodiversity (Robertson *et al*. 2008). Using a quantitative meta-analysis, we evaluate the biodiversity value of different biofuel crops being considered in the US relative to habitats that they could replace. We then discuss the role of management strategies relevant to biofuels production and biodiversity within fields and across production landscapes. Finally, we identify important open questions and research needs, and highlight opportunities for biodiversity conservation associated with increased biofuel production.

In a nutshell:

- Land-use change resulting in increased production of three biofuel crops is expected to decrease local species diversity
- The reduction in diversity caused by increased corn production will likely be greater than that for other biofuel crops, such as *Poplar*
- The consequences to biodiversity of second-generation biofuel crops, such as switchgrass and *Miscanthus*, are largely unstudied
- Opportunities exist to develop biofuel cropping systems that could provide net biodiversity benefits

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Biofuel crops of the present and future

We focus on four major biofuel crops, either currently in cultivation or being considered for production in the US (Walsh *et al*. 2003): corn (*Zea mays*), switchgrass (*Panicum virgatum*), and *Pinus* and *Populus* species. These crops span a land-use gradient from conventional row crops and herbaceous vegetation to managed woodlands, and can be grown throughout much of the US (Figure 1).

Corn is currently North America's predominant biofuel crop. From 2006 to 2007, corn acreage increased 19% in the US (Landis *et al*. 2008), and in 2007 over 7.5 billion gallons of corn ethanol were produced (Donner and Kucharik 2008). Further expansion of corn cultivation is likely, given that the Renewable Fuels Standard (RFS) in the 2007 Energy Independence and Security Act (EISA)

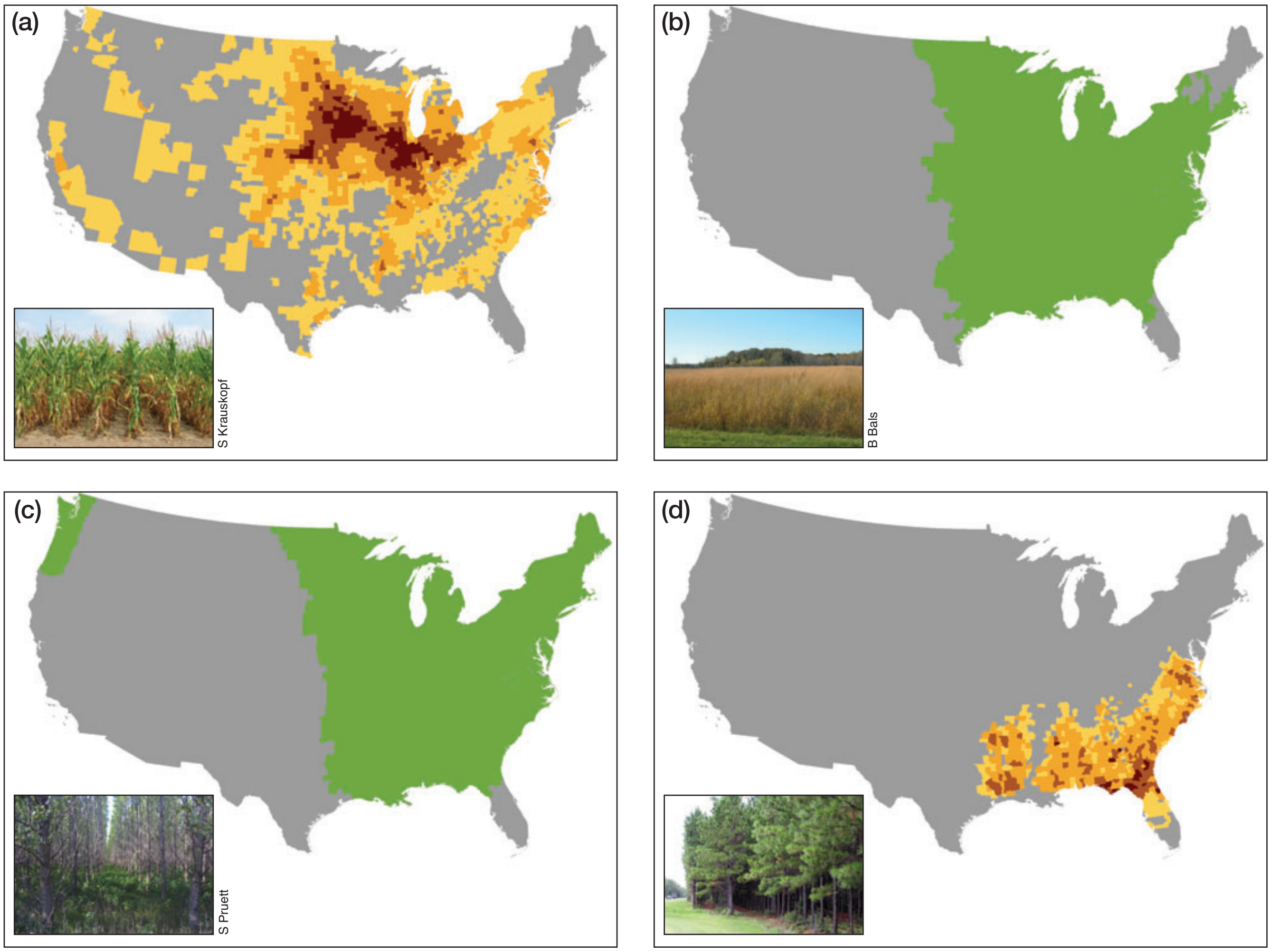

Figure 1. *Geographic distribution of some current and proposed bioenergy crops in the US. (a) Corn is currently a major ethanol crop and is produced throughout much of the US, as shown by the percent of land area per county planted with corn (red areas show greater percentages; from USDA National Agricultural Statistics Service 2007). (b) Switchgrass has been proposed as a major biofuel crop and is thought to be suitable for much of the US (adapted from Graham and Walsh 1999). (c) Hybrid poplar plantations are currently used for pulp and timber production and are being considered for biofuel production. Hybrid poplar could be cultivated throughout much of the eastern and northwestern US (adapted from Walsh* et al. *2003). (d) Pine plantations are also being considered for biofuels. The map shows the relative percentage of land area planted with pine by county (red areas show greater percentages; map courtesy of the US Forest Service Southern Research Station).*

calls for up to 15 billion gallons per year of corn-based ethanol production by 2015. In addition, the potential for the use of corn stover (residues left after grain is harvested) to produce cellulosic ethanol will likely increase production of corn-based ethanol in the future.

Switchgrass, a sod-forming, perennial, warm-season grass native to the North American tallgrass prairie, was selected as a model energy crop by the US Department of Energy (McLaughlin and Walsh 1998) because it maintains soil stability, has high yield and high nutrient use efficiency, and requires relatively low inputs of energy, water, and agrochemicals. Switchgrass is often grown by farmers as a means of protecting erodible cropland from depletion by agricultural production, in compliance with the Conservation Reserve Program (CRP).

Pine and poplar are already planted (plantations hereafter) for wood fiber, wood products, and supplementary fuel for coal-fired power plants, and are candidate species for new cellulosic biofuel crops (Walsh *et al*. 2003; Evans and Cohen 2009). Though these trees may be cultivated outside of their historical ranges, both genera are native to North America.

Land-use change and biodiversity

We used a meta-analysis to examine the biodiversity consequences of potential land-use conversions from natural habitats (sensu Brockerhoff *et al.* 2008; Danielsen *et al.* 2009) to biofuel crops. We focused on vertebrate abundance and diversity because information on vertebrate habitat use at the scale of biofuel production (on the order of hectares rather than square meters) is more extensive than that for other taxa, and because many vertebrates are highly mobile, which facilitates identifying short-term responses to land-use change.

Building and analyzing the dataset

We searched for published articles by way of ISI Web of Science (search date: June 2008), using relevant keywords associated with bioenergy, land-cover types (eg corn, pine plantation, etc), and biodiversity. We supplemented this search with other articles and reports cited from relevant articles. Of the 433 articles identified, we selected studies for meta-analyses that contrasted at least one potential biofuel crop with a "reference" habitat, consisting of a natural (eg coniferous forest) or low-intensity (eg pasture) land use. We note here that we pooled variation in crop management (eg pine plantation ages) and that some investigations, while addressing crops being considered for biofuels, did not consider land currently being used for biofuel production.

We contrasted estimates of animal abundance/density and diversity (eg species richness, Shannon's Index) between crop and reference habitats. We used the ratio of estimates in biofuel crops to reference habitats ($\ln[X_{biofuel}/X_{reference}]$) as our measure of effect size (Hedges *et al.* 1999). We further considered abundance effect sizes for bird species as a function of regional conservation importance, based on Partners in Flight (PIF) scores (Carter *et al.* 2000). PIF uses a set of rules regarding species population size, distribution, trends, potential threats, and regional abundance to rank the conservation importance score of species in "bird conservation regions" throughout the US. Scores range from 5 to 25, with larger values signifying species of greater conservation concern.

We used random-effects models to estimate differences in animal abundance and diversity in biofuel crops relative to reference habitats and whether effects differed with crop type (Raudenbush 1994). When a single investigation reported >1 effect size for a response variable (abundance or diversity), we treated reported effect sizes as correlated observations by multiplying the weight (var^{-1}) by the reciprocal of the number of effect sizes reported within the study (Bender *et al.* 1998). After weighting by the sampling variance, the relative contribution of each study was equal (Bender *et al.* 1998). To address species abundance as a function of conservation status, we used the average PIF regional scores for each species (96 responses from 23 species), accounting for >1 effect size per species by multiplying the weight by the reciprocal of the number of effect sizes/species (Bender *et al.* 1998). Considering effect sizes as independent or adding investigation as a random effect to account for correlations gave similar results. We generated estimates and bias-corrected, bootstrapped confidence intervals for each crop type and used resampling tests to infer significance (Adams *et al.* 1997).

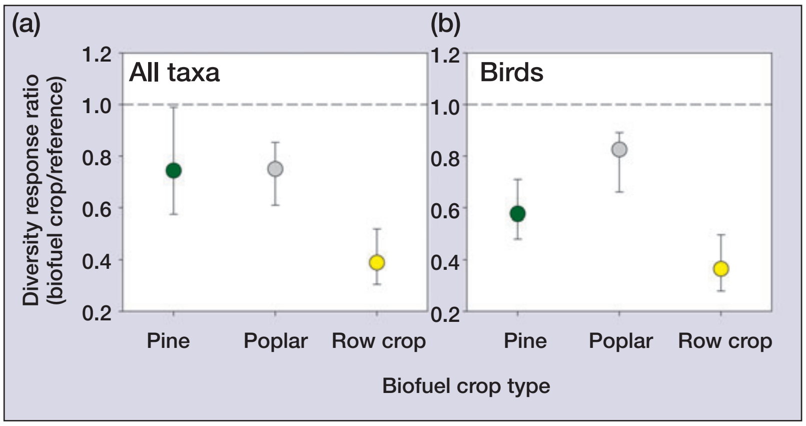

Figure 2. *Effect sizes (response ratios ± 95% confidence intervals) of metrics of diversity for each biofuel land use for (a) all taxa combined and (b) birds only. Responses are considered significant if confidence intervals do not overlap with the dashed lines.*

Composition of the dataset

Only 15 articles provided data appropriate for meta-analyses (see WebTable 1). Although more work is clearly needed, these articles reported 215 responses in abundance and 57 in diversity. More investigations have focused on row crops (seven articles) than on other potential biofuel crops. All studies on row crops except two – Jobin *et al.* (1998) and Olson and Brewer (2003) – pooled corn and soybean row crops (presumably because they are often rotated annually; Donner and Kucharik 2008), and compared row crops with other grassland habitats (eg CRP, hay, pasture, prairie). We found no investigations comparing switchgrass with other relevant land uses (eg row crops, prairies). Investigations of pine contrasted pine plantations of various ages to old-growth coniferous forests, deciduous/mixed forests, or pasture (Repenning and Labisky 1985). Studies of poplar contrasted plantations with other deciduous forests (Hanowski *et al.* 1997).

Insights from the literature

Overall, row crops as well as pine and poplar plantations generally had lower measures of diversity than reference habitats (Figure 2). However, the effects of potential biofuel crops on diversity were different among biofuel-crop types for all taxa combined ($Q_{2,54}$ = 20.53, P = 0.005), with greater negative effects of row crops than of plantation forests, which were more variable potentially as a result of variations in management (see below). Similar effects occurred for birds ($Q_{2,41}$ = 45.73, P = 0.001), although there were insufficient data for mammals.

The effects of biofuel crops on abundance were generally negative (Figure 3), although effects on abundance were not substantially different between crop types (all

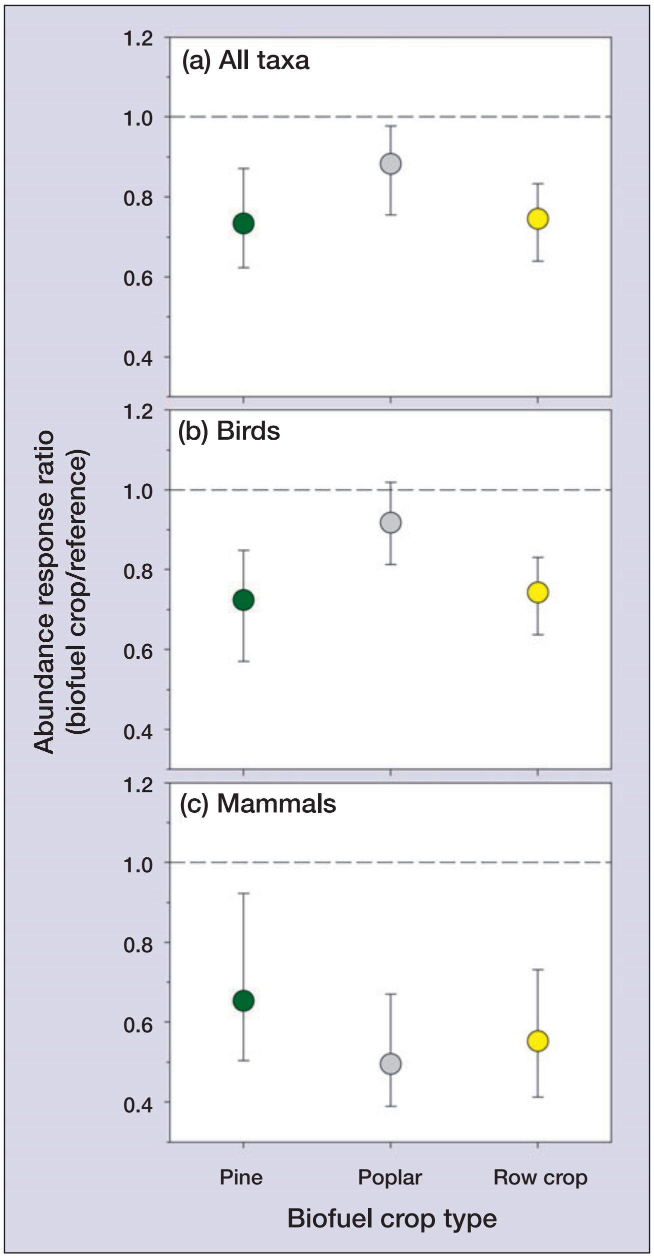

Figure 3. *Effect sizes (response ratios ± 95% confidence intervals) of metrics of abundance for each biofuel land use for (a) all taxa combined, (b) birds, and (c) mammals. Responses are considered significant if confidence intervals do not overlap with the dashed lines.*

taxa: $Q_{2,212}$ = 3.52, *P* = 0.30), with similar patterns for birds ($Q_{2,130}$ = 4.04, *P* = 0.12) and mammals ($Q_{2,79}$ = 0.98, *P* = 0.79). For bird species considered in row crops (insufficient data for other crop types; see WebTable 2), there was a significant, negative correlation between abundance and species' PIF scores ($Q_{1,63}$ = 4.12, *P* = 0.042; Figure 4), suggesting that species of conservation concern may suffer greater impacts as a result of increases in corn-based ethanol than other species.

These observed effects on biodiversity are not surprising, given that many of the investigations found that biofuel crops tend to have less structural and compositional heterogeneity than reference habitats (Hanowski *et al.* 1997; Olson and Brewer 2003). Heterogeneity also differs among these crop types, with little structure and heterogeneity for row-crop fields, whereas plantations can be more variable (Hanowski *et al.* 1997), depending on local management (see below). For example, corn provides little structure for breeding birds and, as a result, the only species that typically breed in corn fields are ground-nesting birds that require little cover (Best *et al.* 1997). By contrast, ground-, canopy-, and cavity-nesting birds may all occur in pine plantations (Repenning and Labisky 1985).

■ Local management practices for biodiversity

Increased biofuel production may cause changes in management practices rather than land-cover change, as quantified in our meta-analysis. Two major issues regarding potential changes in local management that may influence the magnitude and direction of effects of biofuel crops on biodiversity include increases in chemical applications and changes in harvesting techniques.

Expansion of biofuel production may entail increased use of chemical applications to maximize yields. In particular, fertilizer represents the single largest input for US corn production (Hill *et al.* 2006). With the additional harvesting of corn stover for biomass, corn yields may decrease, leading to a greater need for fertilizer applications (Varvel *et al.* 2008). While switchgrass may not require fertilizer in many areas, a variety of fertilizer application methods have been considered in experimental trials (Fike *et al.* 2006; Varvel *et al.* 2008), as has also been the case in plantation forests (Scott and Tiarks 2008). Although few studies have measured the impacts of fertilizer use on vertebrate biodiversity in biofuel crops, the intensity of use has been correlated with biodiversity loss on a global scale (Mozumdera and Berrens 2007).

Increased biomass production may also cause changes in harvest techniques, which are likely to have profound consequences for biodiversity. For example, summer harvests of switchgrass (Fike *et al.* 2006) could result in the destruction and abandonment of nests by birds, analogous to tilling effects in corn fields (Best 1986). In contrast, rotational winter harvesting strategies for switchgrass fields may have positive impacts on biodiversity by increasing structural heterogeneity (Murray and Best 2003). Increased biofuel production in plantation forests may require harvesting smaller diameter trees (Scott and Tiarks 2008), which could have beneficial impacts on biodiversity by increasing structural heterogeneity within stands (Hanowski *et al.* 1997; Hartley 2002). However, if plantation forests move toward shorter rotations without increases in heterogeneity, negative effects on biodiversity may arise (Repenning and Labisky 1985). Thus, differences in silvicultural systems for producing biofuels may have strikingly different effects on biodiversity.

■ Biofuels and biodiversity in production landscapes

Across the US, it is expected that the land area devoted to biofuel production will increase substantially in the next decade (Donner and Kucharik 2008). The EISA mandates that 15 billion gallons of corn-based ethanol be produced per year by 2015, which could require an increase of 9 million acres planted in corn (Donner and Kucharik 2008). In addition, EISA mandates that the remaining 21 billion gallons per year called for by the 2022 RFS will be comprised of cellulosic ethanol and other "advanced" biofuels, most of which are not yet in large-scale commercial production.

The composition and configuration of this future land portfolio will be key to interpreting effects on biodiversity. For example, avian diversity declines with increasing field sizes of corn (Best *et al.* 1990), but increases in switchgrass fields (B Robertson unpublished data). If an expansion in biofuel crops across landscapes alters the diversity of land uses, regional biodiversity will likely be altered as well (Firbank 2008; Landis *et al.* 2008). Strategic placement of some biofuel crops has the potential to buffer disturbance regimes and edge effects in remnant patches (Brockerhoff *et al.* 2008), and biofuel crops may also influence the connectivity of natural habitats for animal populations (Hanowski *et al.* 1997; Firbank 2008). Yet, because of transportation costs for delivering biomass to ethanol production facilities, the spatial configuration of biofuel crops will likely be aggregated around existing or future ethanol plants (Graham *et al.* 2000). Current policies also suggest that land area needed for biofuels will disproportionately reduce the extent of some habitats more than others (eg temperate grasslands; McDonald *et al.* 2009), thereby increasing the vulnerability of species that currently rely on these land-cover types.

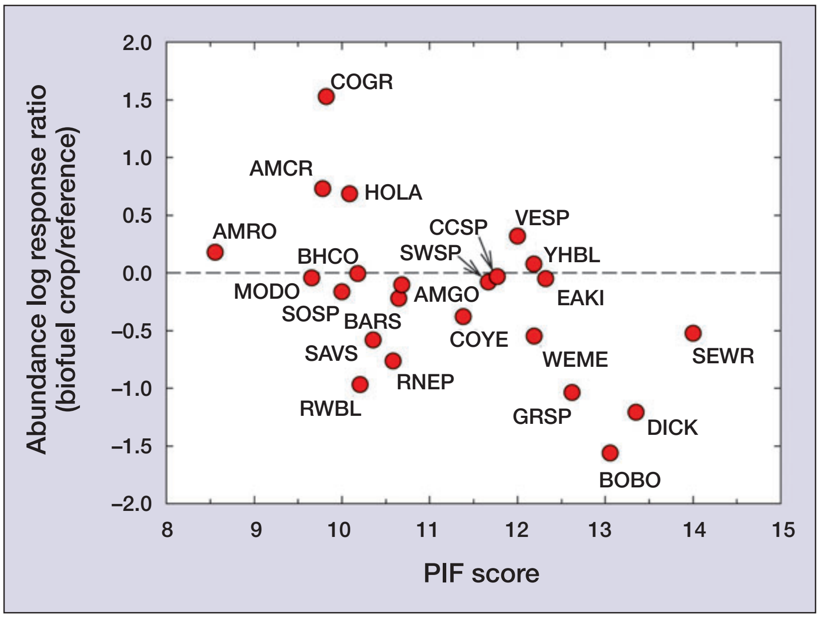

Figure 4. *Average effect sizes (log response ratios) for abundances of 23 bird species in row crops relative to reference sites (grasslands) as a function of Partners in Flight (PIF) regional scores of conservation concern. Four-letter species codes are defined in WebTable 2.*

To achieve federal mandates, tradeoffs could arise in terms of high-intensity production on small areas of the landscape relative to lower-intensity production across larger areas. For example, Heaton *et al.* (2008) argued that by using perennial grasses, such as *Miscanthus*, we can achieve our energy goals using less land because of its relatively high yields per unit area, whereas Tilman *et al.* (2006) suggests that using low-input, high-diversity grassland biomass on existing degraded lands would have net environmental benefits. Consequently, identifying if and how such production tradeoffs may influence biodiversity will be useful for sound decision making.

■ The path forward: gaps and opportunities

Will expansion of biofuel production be detrimental or beneficial for biodiversity? Answering this question will depend largely on the type of crop used, if it was converted from a natural plant community or from another crop, whether management is altered for existing crops to produce biofuels, and on the application of policies that mandate ecological sustainability. Here, we identify several current gaps and opportunities that should be considered in the development of a sustainable biofuel economy.

(1) We still know remarkably little about the biodiversity associated with current biofuel crops and we know even less about next-generation crops, such as *Miscanthus*, or succulents of the genus *Jatropha*. The lack of information on switchgrass with regard to land-use change is particularly troubling, considering its prominent place in the development of second-generation biofuels (McLaughlin and Walsh 1998). Understanding the potential for non-native biofuel crops to become invasive will also be crucial, and even native species may pose risks when introduced beyond their historical range (eg switchgrass in California; Raghu *et al.* 2006; Barney and DiTomaso 2008).

(2) If next-generation biofuel crops are genetically engineered for pesticide or herbicide resistance, there may be substantial impacts on ecological communities. Although the effects of genetically modified (GM) organisms on biodiversity are currently limited (Dale *et al.* 2002; but see Firbank *et al.* 2006), data relevant to biofuel crops are needed.

(3) We need to consider how the interplay between social, economic, and ecological factors may affect biodiversity. For example, increased biofuel production has the potential to accelerate global warming and reduce freshwater supplies (Fargione *et al.* 2008; Evans and Cohen 2009), and increased corn production in the American Midwest may result in higher global soybean prices, which may impact land-use change in other geographic regions (Firbank 2008). Thus, criteria for evaluating the

Figure 5. *Some grassland species of conservation interest requiring large tracts of grassland, such as (a) the greater prairie chicken (*Tympanicus cupido*) and (b) bison (*Bison bison*; Niemuth 2000; Freese* et al. *2007), could benefit from the conversion of row crops to native prairies for next-generation biofuels production.*

ecological sustainability of biofuel crops must also incorporate social and economic consequences (Landis *et al.* 2008). Existing risk assessments for GM crops provide a potential template for interpreting management effects resulting from biofuel production, although land-cover change issues and other environmental effects associated with biofuels pose unique challenges (Firbank 2008).

(4) Interdisciplinary approaches are needed to aid in the development of policies that encourage the adoption of land-use patterns that have net benefits for biodiversity, or minimize costs, across landscapes (Holzkamper and Seppelt 2007). Better communication between policy makers, land managers, and scientists is needed to implement national and regional policies that are robust to changing economic and environmental circumstances.

(5) Although caution about the new biofuel economy is warranted, these products could also provide conservation opportunities. For example, replacing annual, grain-based crops with native perennial communities could have positive impacts on biogeochemical integrity and biodiversity, which are two of the major environmental costs of today's agriculture (Robertson *et al.* 2008). Developing cellulosic technology could open the possibility that mixed-species feedstocks, such as native grasslands, could become a source of biofuels (Tilman *et al.* 2006), which might, in turn, lead to substantial ecological benefits (Fargione *et al.* 2009). The grasslands of the American Midwest are among the most converted biomes on the planet (Hoekstra *et al.* 2005). Restoration and management of prairies for biofuels could provide substantial benefits for species of conservation concern that require large tracts of grassland (Figure 5). While new legislation will be needed, existing policies, such as various forest certification programs (Cashore *et al.* 2005) and the CRP, already provide opportunities for biofuels production to affect biodiversity. From our meta-analysis, four articles addressed biodiversity in CRP relative to row crops (54 responses). Although additional research is necessary, these studies suggest that abundance and diversity of birds and mammals are generally greater in CRP than in row crops (Figure 6), providing evidence that CRP land managed for biofuels could provide net biodiversity benefits.

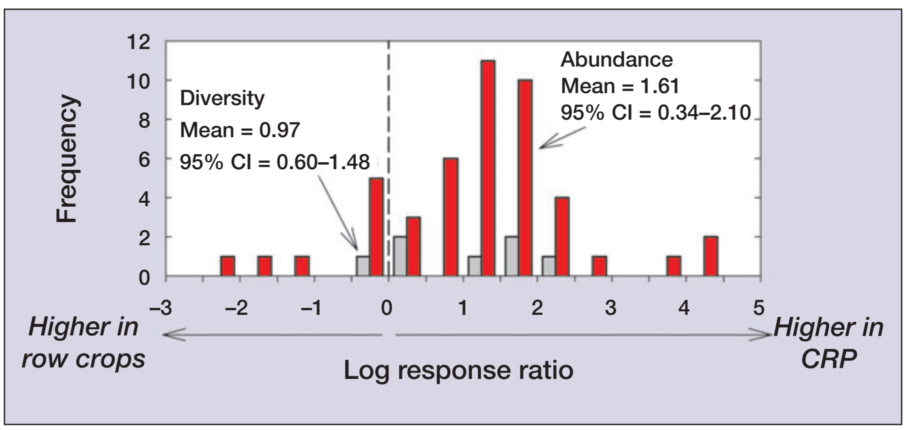

Figure 6. *Frequency of effect sizes (log response ratios) and 95% confidence intervals for abundance (red bars) and diversity (gray bars) estimates for all taxa combined in Conservation Reserve Program (CRP) fields relative to row crops, showing that conversion of row crops to mixed grasslands for cellulosic biofuels production could benefit biodiversity.*

Conclusions

Government mandates and increasing energy demands make the expansion of biofuels production in North America a virtual certainty. Although many questions remain, the results of our meta-analysis suggest that land-use change from nonproduction habitats into land dedicated to major biofuels crops may have negative impacts on biodiversity in the US. While an increase in corn-based ethanol production could have greater negative environmental effects than those of other biofuel crops being considered, land-use change from corn to native herbaceous perennials or forest plantations may have net biodiversity benefits (Hill *et al*. 2006; Fargione *et al*. 2008; Charles 2009). Crop management practices aimed at increasing yields and/or minimizing ecological costs will further influence the role biofuels play on biodiversity. Ultimately, the path forward to a successful, new biofuel economy will require finding solutions for both the long-term economic goals and the ecological sustainability of the underlying production systems.

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