

Biodiversity Consequences of Increased Biofuel Production

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Introduction

Increased biofuel production, as expected to occur in the coming decades, will have large impacts on biological diversity, defined here as species richness and estimated as number of species of plants, animals and micro-organisms per unit area. Negative impacts on biodiversity will be mostly as a result of habitat loss, increased invasive species, and pollution resulting from the use of fertilizers and herbicides. Increased biofuel production may also have some positive impacts on biodiversity by ameliorating the rate of change of atmospheric composition and global climate. Some biofuels systems may reduce global net carbon emissions; previous chapters discuss the potential for greenhouse gas (GHG) savings across different biofuel systems in greater detail (e.g. Menichetti and Otto 2009; Ravindranath et al. 2009).

This chapter first assesses the effects of habitat loss on biodiversity due to the expansion of agricultural land. We explore the phenomenon, discuss ways of estimating the magnitude of the effects on biodiversity and

assess the relative impact on different biomes and vegetation types. Second, the chapter explores how increased biofuel production will enhance invasion processes from the point of view of focal crops and of the species associated with focal crops. Third, we evaluate the local-scale effects of expanded biofuel production on terrestrial and aquatic ecosystems that receive the nitrogen and phosphorus-rich fertilizers and pesticides used to produce biofuels. We also discuss some examples of small-scale biofuel production systems in which bio-diversity has been maintained, and then comment on how the aforementioned drivers of biodiversity (habitat loss, invasion, and pollution) interact from a qualitative point of view. Finally, the chapter concludes by assessing the positive and negative impacts of biofuels on biodiversity in different regions.

It is important to consider both spatial and temporal scales when assessing the impacts

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of expanded biofuel production on biodiversity. This chapter focuses primarily on the global scale in which there is a finite area of land suitable for cultivation. Temporally, we focus on the window from the present time to the year 2050, which is coincident with the Millennium Assessment scenarios (Carpenter et al. 2005) time scale. During this period of time, biofuel production will increase substantially (IEA 2007) and it is long enough to observe the consequences on biodiversity.

Habitat Loss

Two independent assessments have shown that habitat loss will be the major driver of biodiversity loss in the coming 50 to 100 years (Sala et al. 2000; Sala et al. 2005). The most drastic form of habitat loss occurs when a diverse community of plants, animals and microbes is replaced by a single species crop. For example, habitat loss occurs when a piece of Amazon forest with all its diversity of plants, animals, and microorganisms is logged, burned and planted with a soybean crop. In this example, very little is left of the original species diversity. We recognize that habitat availability is best represented by a gradient of land use from mostly pristine systems to heavily impacted ecosystems.

Available land is finite in and is currently allocated to different land uses as represented in the following equation:

$$(1) \text{ Total land area} = \text{Agriculture land} + \text{Conservation land} + \text{Urban Areas}$$

Recognizing the gradient of land uses and its consequences on conservation, we can then subdivide agriculture land and conservation land into subcategories. For example, agricultural land can vary on a gradient from 'intensive', where single crops are grown with the aid of large agricultural subsidies, to

'extensive', where relatively few subsidies and labor are involved. Whereas intensive agriculture supports low net levels of biodiversity, extensive agriculture often sustains important biodiversity and can play an important conservation role (Daily et al. 2001; Ranganathan et al. 2008). Similarly, the International Union for Conservation of Nature (IUCN) has classified protected areas into six categories ranging from strict nature reserve, wilderness areas, and national parks to protected areas with sustainable use of natural resources (Badman and Bomhard 2008). Subdividing the major categories does not modify the idea of land being a finite resource, and the more intensively a unit of land is used, the less likely it is to support or contribute to the maintenance of high levels of biodiversity.

Biofuel production alters Equation 1, since land needed for biofuel production has to be released from some current land use. The new equation of land allocation looks like the following:

$$(2) \text{ Total land area} = \text{Food production} + \text{Biofuel production} + \text{Conservation} + \text{Urban}$$

Land allocated to biofuel production necessarily competes directly or indirectly in the allocation process with land used either for food production or conservation. Direct competition occurs when biofuels are grown in what previously was conservation land and indirect competition occurs when biofuels displace food crops that in turn displace conservation land (Searchinger et al. 2008).

The Millennium Ecosystem Assessment predicts under one of its scenarios (Global Orchestration) that by the year 2050 demand for food crops will increase by 3321 million tonnes (Mt) over the current value of 3906 Mt (Alcamo et al. 2005). Demand for cereals alone will increase by 73% and demand for

livestock will increase by 63%. The total area devoted to agriculture, which is our interest here, depends on demand and yield. The latter varies with degree of development and transfer of technology. The most optimistic scenario from this point of view predicts increases in agricultural land of 0.01% per year from 1997 to 2050 and the most pessimistic scenario projects increases of 0.34% per year for the same period of time. This rate of increase means an increase of agricultural land of 137 million hectares (Mha) by 2050.

This analysis suggests that a large increase in the total amount of agricultural land will be required for foodstocks in the future. If the land needed for biofuel feedstock production is in addition to the increased land needed for food production, then a large net loss in the total area remaining in conservation is likely. How do we estimate the effect of habitat loss due to expansion of biofuel production on species richness?

The Millennium Assessment approach (Sala et al. 2005) was based on the species-area relationship (Rosenzweig 1995). The increase in the number of species with increasing land area is a ubiquitous characteristic of most ecological communities. The rate of increase is described by the following equation

$$(3) S = c A^z$$

where S is the number of species, c is the species local density (taxon and region dependent) and z is the slope of the relationship (region dependent; e.g. oceanic islands versus continental areas). The Millennium Assessment (Sala et al. 2005) estimated losses of vascular plant species by 2050 using global estimates of “ c ” (Barthlott et al. 1996), estimates based on published “ z ” values for continents, and changes in area “ A ” based on global ecological and economic model Image 2.2 (Alcamo et al. 1998). It is important to

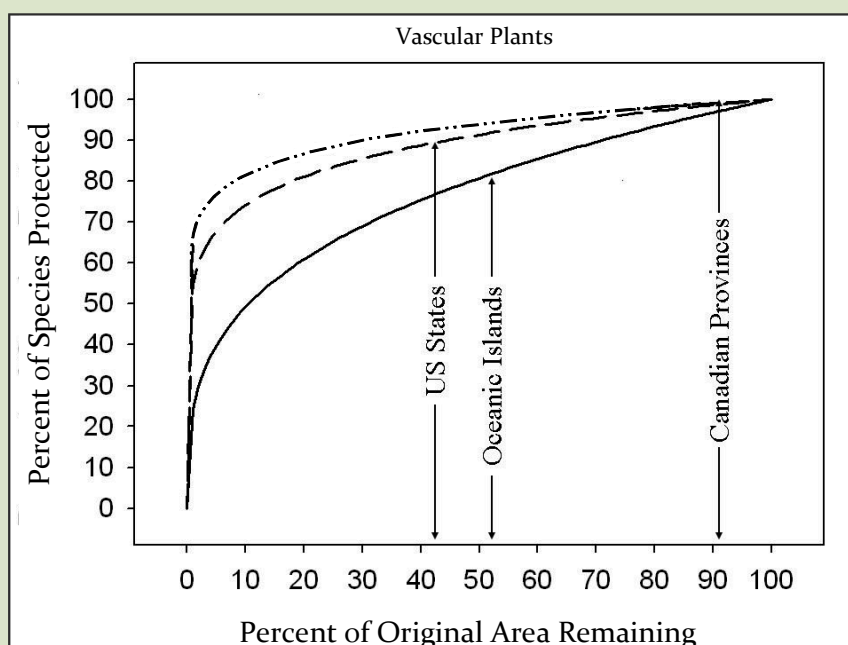
highlight that global extinctions due to reduced habitat do not occur instantly after habitat loss, but that important time lags exist depending on the life history of individual species (Brooks et al. 1999, Tilman et al. 2002).

The Millennium Assessment approach can be used to estimate losses of species of vascular plants due to expansion of biofuel production. Major unknown variables include the land area and the location of areas that would be put into biofuel cultivation. Such an assessment will yield results on number of species locally extinct, number of species committed to global extinction because of habitat loss, and a ranking of the most vulnerable vegetation types.

A quantitative study of the effects of biofuels on species diversity has not yet been done. However, authors have attempted to make predictions based on first principles. De Vries et al. (2007) suggest that grasslands would be the primary target for biofuel expansion. The locations of future biofuel crops will vary depending on the region of the world under consideration. In the developed world, where most of the potential agricultural land has already been converted, we expect that biofuels will be located in either abandoned agricultural land (de Vries et al. 2007) or marginal lands that are not suitable for food production (Hill et al. 2006). On the contrary, there are large areas of forest, grasslands, shrublands, and savannas in the developing world that have not been converted into agriculture, mostly because of infrastructure limitations, but these areas would be suitable for biofuel production. These areas are currently under some sort of formal or informal protected status. In areas such as the Amazon forest, agriculture expansion has been limited in part by biophysical constraints, road availability as well

Figure 7.1 Species-area relationships for vascular plant species on oceanic islands (solid line), the lower-48 US States (dashed line), and Canadian Provinces and Territories (short-dashed line) predict species extinctions expected to occur in each region with loss of area (species data: Sax and Gaines 2008, NatureServe 2008). Arrows indicate the amount of area in each region that has been converted to urban area, cropland, and pastureland in the lower-48 US states, on Hawaii, as a proxy for other oceanic islands, and in Canadian provinces and territories (land-use data: (Anonymous 1996, Lubowski et al. 2006).

Additional land conversion is predicted to have disproportionate effects on species extinctions in these regions. Future species loss should be influenced by 1) the inherent shape of region-specific species-area relationships and 2) the point along the species-area curve that exists prior to additional land use conversion. For example, additional area loss of an equal amount should lead to proportionally more species extinctions on oceanic islands than in Canadian provinces.



as legal protection. The latter two constraints may change under a scenario of high global demand for biofuels.

Two generalizations can be drawn regarding the relative impact of land-use change on species diversity using the species-area relationship depicted in equation 3. First, because of the curvilinear relationship between species richness and area, a similar

amount of land converted from a protected area into a biofuel production will have different consequences depending on the losses that have already occurred in that community. Regions that have experienced large protected land losses would be located in the steep region of the species-area relationship and further area losses will have enormous species extinction consequences.

In contrast, vegetation types that have lost only small amounts of area will withstand increased biofuel production with relatively small biodiversity cost. This principle is illustrated in Figure 7.1, which shows that future losses of area equal in proportion to the areas of the respective regions will have disproportionate effects on species loss due to differences in the shape of region-specific species-area curves and differences in the amount of area that have already been lost from each region.

The second generalization is related to differences in species density of different regions, which varies broadly across vegetation types (Barthlott et al. 1996). Because some regions are much more diverse than others, equal proportional losses of area will result in dissimilar total losses of species; for example, equal proportional loss of area in temperate and tropical North America would result in greater total loss of species in the tropics, since the density of species is higher there. Consequently, conversion of protected areas into biofuel production will generally have much more negative impact on biodiversity in areas with a high species density.

Predicting total future species losses is a scale-dependent process, and generalizations that apply at broad spatial scales may not apply at smaller scales. To estimate biodiversity losses within a region experiencing increased biofuel production, it is necessary to compare the species-area relationships of the vegetation or habitat types of concern. So, for example, one might examine the species-area relationships in riparian habitats, grasslands, and scrublands within a given region, examine the amount of habitat loss each has sustained, and then estimate the impacts of future habitat-specific losses.

Results can then be compared with those of analyses from larger scales (e.g. as in Figure 7.1) to examine differences across spatial scales. More work is needed to better evaluate the qualities of species-area relationships in predicting future species losses (Sax and Gaines 2008), but these approaches provide a starting point for evaluating the relative threat of biodiversity loss.

It is possible to develop small-scale systems that produce feedstocks for biofuels and maintain relatively high levels of native biodiversity. For example, Ranganathan et al. (2008) describe an ancient agricultural system in India that is compatible with high levels of bird diversity. Similarly, Tilman et al. (2006) has advocated the use of high diversity grasslands as source of a biofuel feedstock that can maintain biodiversity and minimize competition with food production. However, currently, most biofuels are produced using traditional agricultural practices that compete with the other land uses described in equation 2. It is unlikely that solutions that produce biofuels while maintaining biodiversity can be implemented at the scale necessary to meet current biofuel demand. Consequently, expanded biofuel production will continue to compete with conservation land use and negatively affect biodiversity.

Invasion

Taxa that invade or are introduced to areas outside their historic ranges often have large, negative impacts on native biodiversity. Non-native taxa (species and genotypes) have facilitated native species extinction (particularly of island taxa), altered the composition of ecological communities (in many habitats world-wide), changed patterns of disturbance (e.g. periodicity of fire cycles), and altered ecosystem processes such as

water filtration or nutrient cycling (Vitousek et al. 1987, Mack and D'Antonio 1998, Wilkinson 2004, Elliott et al. 2008, Sax and Gaines 2008). While not the focus of this chapter, non-native taxa can also pose direct threats to human health (as introduced pathogens) and cause economic losses – estimated in the billions of USD annually (Pimentel et al. 2000).

Biofuel production is likely to increase the risks and costs associated with non-native taxa. These increased risks can occur as a consequence of the species and genotypes used to produce biofuels, but also as a consequence of other taxa that are fostered in some way by biofuel production.

Taxa used for biofuel production. A large and growing number of species are candidates for biofuel production (Zah et al. 2007). Many of the species are known to be invaders outside of their native range (Barney and DiTomaso 2008). For example, giant reed *Arundo donax*, a problematic invader in many parts of North America, is currently being considered for use in biofuel production in the US state of Florida (Barney and DiTomaso 2008). The dangers posed by species grown and cultivated for biofuel production includes all of the dangers typically associated with invasive species (as cited above). These dangers are relatively small if the biofuel crop is one that has typically been grown as a human food-crop (such as corn), because these species have been selected to be heavily dependent on large nutrient subsidies and consequently are unlikely to escape cultivation to become aggressive invaders (Barney and DiTomaso 2008). However, many species currently being considered for the next generation of biofuel production require few subsidies and are capable, once planted, of growing without human assistance (GISP 2008). In fact, the characteristics desirable in a biofuel crop

(perennial lifecycle, few known pests or diseases, high water-use efficiency, long canopy duration, etc.) are often the same characteristics associated with taxa that are invasive (Raghu et al. 2006).

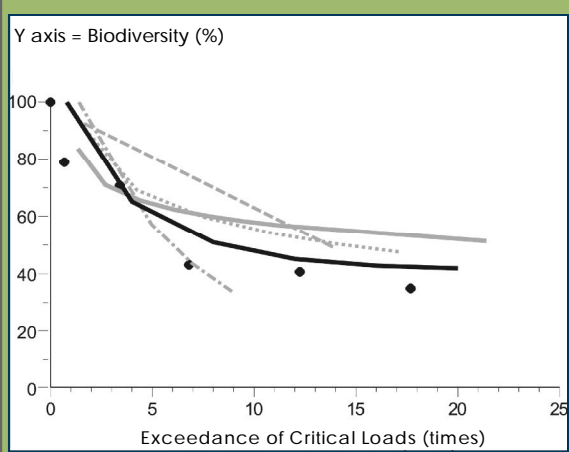
It is not just species *per se* that may pose invasion risks, but also genotypes. One of the most problematic invaders in North America is common reed *Phragmites australis*, whose introduced genotype has spread widely and often forms dense monocultures (Tulbure et al. 2007). Candidates for biofuel production (e.g., switchgrass *Panicum virgatum*) have often experienced decades of artificial selection for traits that make them more likely to tolerate infertile soil, grow in dense stands, and reproduce from vegetative plant fragments – all traits that increase their likelihood of becoming invaders (Barney and DiTomaso 2008). Consequently, even species that are planted within their native range could have varieties, subspecies or other genotypic variants that become invasive.

Taxa fostered by biofuel production. Habitat changes associated with biofuel production are likely to increase the risk of invasions by non-native taxa. This should occur within cropland, within areas where other types of vegetation are harvested for biofuels, and within areas that provide infrastructure for these activities.

Intensive agriculture is a common source of introduction and source area of invasions. For example, the seeds of unwanted 'weedy' species may be unintentionally mixed with seeds of an agricultural crop, and thus introduced during sowing (Novak and Mack 2005). Also, croplands serve as breeding grounds for unwanted animal pest species (see examples in Lever 1985). Increases in total cropland area, newly introduced

Figure 7.2 Nitrogen deposition leads to declines in plant-species diversity. Critical load refers to the level at which ecosystem effects are assumed to be detected based on previous studies.

The distinct lines refer to different experimental tests of the effect of N loading on terrestrial plant communities. (Adapted from Sala et al. 2005, Figure 10.15.)



cropland, or use of new species in intensive agriculture increase the risk of exacerbating existing invasions and fostering invasions of previously non-invasive species.

In the future, large-scale biofuel production will likely occur in natural or semi-natural landscapes, particularly on land that is marginal for intensive agriculture. This might involve, for example, the harvesting of plant material from grasslands, woodlands or forests. Whether these habitats are clear-cut in large patches, small patches, or selectively harvested for particular species will each bring its own invasion risks. Each case poses a risk, however, in that disturbances that free resources may provide a potential foothold for invasions by non-native taxa (Davis et al. 2000). Over the longer term, harvesting at particular frequencies or of particular taxa could create conditions favorable to non-native species, particularly if the conditions created do not mimic those previously

experienced by native species in the region (Sax and Brown 2000).

Pollution

Pollution from fertilizers and pesticides associated with biofuel production is anticipated to be another major source of impact on terrestrial and aquatic biodiversity. On land, atmospheric deposition of nitrogen associated with biofuel production, as well as with other agricultural and industrial activities, can lead to changes in species composition and decreased species richness (Figure 7.2; Pitcairn 1994 cited in Sala et al. 2005). Increases in phosphorus and nitrogen loading due to runoff of fertilizer applied to biofuel crops can impact aquatic ecosystems by decreasing species richness, water quality and aesthetic value, as well as contributing to increased frequency and magnitude of harmful algal blooms (Carpenter et al. 1998). Moreover, eutrophication caused by nutrient pollution often leads to changes in biogenic habitats (e.g. coral reefs and seagrass beds) and ecosystem functioning of aquatic ecosystems (Carpenter et al. 1998). Herbicides (e.g., atrazine, glyphosate) used to increase biofuel crop yields and other agricultural contaminants have also been shown to negatively impact aquatic organisms and ecosystems in both laboratory and field settings (Pratt et al. 1997, Fleeger et al. 2003).

Given that corn is a particularly fertilizer- and pesticide-intensive crop (Hill et al. 2006), increased production of corn-based ethanol could be particularly damaging to aquatic ecosystems. This point is illustrated by a recent analysis focused on the impacts of corn production in the Mississippi-Atchafalaya River system. The current level of corn production in the region (and the fertilizers that it requires) is driving hypoxia, or the 'dead zone', in the northern Gulf of

Mexico (Rabalais et al. 2002). Increasing corn cultivation to a level recommended by the US Senate would lead to an increase of 10-34% in the annual average flux of dissolved inorganic nitrogen (DIN) to the Mississippi and Atchafalaya Rivers (Donner and Kucharik 2008). This increase in nitrogen export would make targeted reductions of nutrient pollution in the Gulf difficult to realize, exacerbating the extent and impact of the dead zone. While other candidate biofuel species are notable for not requiring much nutrient addition, Donner and Kucharik (2008) suggest that, to maximize production, crops like switchgrass will also require 'moderate to high levels' of fertilizer.

Cross-scale interactions and landscape connectivity will be important considerations in developing quantitative scenarios of the range of impacts of air and water-borne pollution on biodiversity. Many of the eutrophication and contaminant effects associated with biofuels will be observed in downstream freshwater, estuarine, and marine ecosystems (Diaz and Rosenberg 2008), rather than on the terrestrial ecosystems where biofuels are actually grown or processed. This implies that a regional or global analysis aimed at assessing where biofuel production is least likely to negatively impact local biodiversity (and perhaps even yield positive effects due to land restoration or conservation in native species) must incorporate information on connectivity among the atmospheric, terrestrial and aquatic components of the ecosystem of interest.

Interactions among drivers

We have assessed in previous sections the independent effects of expanded biofuel production on biodiversity via changes in habitat, invasions, and fertilizer and pesticide

pollution. We know that all these changes are going to occur simultaneously and therefore it is critical to understand how the effects of these drivers will interact in order to predict the final outcome of expanded biofuel production on biodiversity. Multiple drivers can affect biodiversity in an additive, synergistic, or antagonistic fashion (Sala et al. 2000). We do not know the exact form these interactions will take, but below we identify examples of the three types of interactions.

Additive interactions may occur when the effects of drivers occur in different locations and at different scales. Expansion, for example, of corn-based ethanol may result in increased nutrient runoff and the consequent loss of aquatic diversity down stream in addition to local habitat loss, which may independently reduce diversity of terrestrial species.

Synergistic interactions will likely occur when drivers operate at similar scales, in nearby or adjacent areas. For example, use of marginal land for biofuels may directly impact native biodiversity, while simultaneously fostering source populations for invasive species that then spill over to impact land that has been conserved.

Finally, examples of antagonistic interaction occur when one of the drivers has very a high magnitude and overwhelms the effects of the other drivers. For example, the effect of logging and burning a patch of tropical forest on local biodiversity would not be exacerbated by invasion of alien species since most of the local biodiversity would be lost already.

Conclusions

We predict heterogeneous effects of expanded biofuel production on biodiversity, mostly dependent on the biodiversity characteristics of the region under consideration, the type of

biofuel production, and interactions among drivers. Assuming equivalent levels of diversity, areas of the world and vegetation types that have already experienced large losses of biodiversity would be most vulnerable in comparison to areas that have not been affected to a large extent by biodiversity loss already. In already heavily impacted areas, we anticipate that a modest expansion of biofuel production would have large, negative effects on biodiversity. Similarly, communities with high species density may lose more species than that experienced in species-poor communities with an equal level of disturbance. The degree of intensification of biofuel production will have a direct impact on biodiversity with larger losses scaling positively with increasing intensification. For example, we expect a larger impact on biodiversity if we use corn rather than natural grasslands as a source for ethanol production.

Negative and positive effects of biofuels on biodiversity operate differently across spatial and temporal scales. Negative effects occur at all scales from local to regional and global. We have described above how conversion of protected land into biofuel production may result in local extinctions, loss of aquatic species in distant habitats (regional effect) and in global extinctions depending on the magnitude of the sum of local extinctions. In contrast, positive effects occur primarily at the global scale by potentially ameliorating climate change – although these effects should scale down to local-scales by reducing the extent of local impacts of climate change. These benefits at local scales, however, will only be realized after a long lag time (decades to centuries) because of the inertial properties and lag times inherent in climate systems. This is in contrast to many of the negative effects of biofuel production on native biodiversity, which will be realized

instantaneously or after a short period of time (years to decades). Consequently, simple qualitative analysis is not adequate to assess the final outcome of expanded biofuel production on biodiversity. Instead, it is necessary to develop quantitative models of biofuel production that take into account local, site-specific threats to biodiversity, regional impacts, and potential longer-term benefits for biodiversity.

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