14 | Synthesis, Interpretation, and Strategies to Enhance Environmental Outcomes

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14.1 Introduction

This report investigates the potential environmental effects associated with select biomass production scenarios across the United States in the *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (*BT16*), volume 1. *BT16* volume 1 (released in July 2016) evaluates potential biomass that could be available for use—at specified prices, assuming a future market for the biomass. *BT16* volume 2 is a first effort to analyze a range of potential environmental effects associated with select near-term and long-term biomass-production scenarios from volume 1. As with volume 1, this report does not assume particular policy conditions. This report takes the broad approach of including environmental indicators that would be of interest to a range of stakeholders. Environmental effects of biomass production that are modeled include effects on soil organic carbon (SOC), greenhouse gas (GHG) emissions, water quality, water quantity, air emissions, and biodiversity. Land-management changes associated with the scenario transitions are also described and discussed.

BT16 volume 2 seeks (1) to advance the discussion and understanding of environmental effects that could result from significant increases in U.S. biomass production and (2) to accelerate progress toward a sustainable bioeconomy by identifying actions and research that could enhance environmental benefits while minimizing negative impacts of biomass production. Therefore, this chapter synthesizes key results from the report, discusses this chapter synthesizes key results from the report, discusses key uncertainties and limitations, and then focuses on strategies to enhance environmental outcomes of commercial-scale biomass production.

This chapter returns to the initial questions from the Introduction (chapter 1):

- What are the land-use change (LUC) implications of the scenarios over time?
- What are the estimated values of environmental indicators and how do those compare among scenarios?
- What are the potential negative environmental effects, and how might they be managed or mitigated?
- What environmental benefits are possible, and under what conditions do they occur?
- Where is more research needed with regard to quantifying effects, enhancing benefits, and preventing negative consequences?
- How sensitive is feedstock productivity to climate?

This chapter describes many strategies to enhance environmental outcomes from biomass production, i.e., to enhance potential benefits and reduce potential adverse effects associated with the specific scenarios as well as biomass production more generally. The strategies include applying constraints that limit where and how biomass can be sourced (such as the constraints employed in modeling biomass in *BT16* volume 1); implementing mitigations for specific potential impacts identified in this volume; using waste (that would otherwise be landfilled or incinerated) for energy; applying best management practices (BMPs) and landscape design principles; and integrating biomass harvesting with other activities (e.g., mineland reclamation and invasive species control). Concepts of ecosystem services and monetary strategies are also introduced. Finally, future research needs are discussed.

14.1.1 Synthesis and Interpretation of Results

The analyses in this report begin to illustrate the environmental effects of biomass that could potentially be available for energy or other purposes in the future, given a market, a $60 price per dry ton of feedstock, available land, and many other assumptions that are described in chapter 2 and embedded in the economic production models used in *BT16* volume 1. Results should be interpreted in the context of *BT16*, which includes factors ranging from specific temporal and spatial resolutions of available data to broad national energy needs. Contextual factors to consider in an assessment of environmental effects typically include the purpose of the assessment, the biomass production and distribution system, end use, policy conditions, stakeholder values, location, temporal influences, spatial scale, baselines, and reference scenarios (Efroymson et al. 2013).

Quantitative results in *BT16* volume 2 are highly dependent upon the particular scenario comparisons that are used, but implications are relevant beyond these scenarios. The temporal aspects of *BT16* volume 2 are selected so that most analyses could focus on near-term harvests of residues and future potential production of energy crops. Comparisons of scenarios containing energy crops (e.g., BC1 2040, HH3 2040) with those that do not (BC1 2017) highlight the potential effects of those energy crops. Miscanthus and biomass sorghum, for example, contribute to gains in soil carbon in the 2040 scenarios. Some scenarios have been designed to facilitate interpretations of how environmental effects are influenced by annual yield increases. Higher-yield scenarios result in lower air emissions for terrestrial biomass on a per-ton basis, as well as a lower consumptive water use for algae. The wide variety of algae scenarios highlight effects of different types of cultivation systems and sources and purity of carbon dioxide (CO_2), which affect water consumption and GHG emissions, respectively.

To further interpret the importance of the environmental effects, they could be compared to effects under alternative land uses and alternative energy production systems. For example, the air emissions analysis (chapter 9) notes that biomass production activities may replace (rather than occur in addition to) current activities and, therefore, may not pose air quality challenges as results might suggest. While a complex business-as-usual scenario is beyond the scope of this report, reference scenarios, an agricultural baseline, and fossil energy comparisons are used in some analyses.

The analyses reflect effects of LUC (land management) transitions associated with simulated biomass production. LUC is important because all social, economic, and environmental indicators of sustainability can be affected by LUC (McBride et al. 2011; Dale et al. 2013). Since 2008, effects of LUC have dominated discussion of bioenergy sustainability because of their implications for GHG emissions, biodiversity, food security, and other aspects of sustainability.

The primary type of LUC associated with *BT16* biomass supply scenarios is the land management practices that accompany transitions of up to 45 million acres of annual crops to perennial cover by 2040. Replacing annual crops with perennial crops has multiple environmental advantages, such as reducing soil erosion, increasing carbon sequestration (chapter 4), improving water quality (chapter 5), and providing higher-value habitat for wildlife (Robertson et al. 2008; Dale et al. 2011). Unlike annual crops, perennial crops can generally be grown with minimal inputs of fertilizer, pesticides, and irrigation (chapter 8) (Chamberlain and Miller 2012; Dale et al. 2011). Management of perennial crops typically involves less-frequent physical disturbance (e.g., tillage, seeding, cultivation), and harvests can be timed to avoid critical life history events for wildlife (Gamble et al. 2015; Roth et al. 2005). Indeed, chapter 10 recommends perennial crop management of this type to mitigate potential habitat quality losses for particular bird populations. In this study, energy crops show favorable performance relative to conventional feedstocks.

Historical land use in different regions is a major element affecting scenario comparisons. For example, an increase in soil carbon (i.e., a carbon sink) is simulated when transitioning from historical cropland to energy crops, whereas a transition from pastureland to energy crops does not always increase soil carbon (except in the case of miscanthus and biomass sorghum). Land management changes on forestland are assumed to be minimal, involving thinnings and harvesting of whole trees and residues but not involving new road building or transitions into or out of forest.

The location and type of biomass have also been found to be major factors affecting the direction and magnitude of environmental changes that were estimated. Most counties analyzed in the scenarios show potential for a substantial increase in biomass production to support a growing bioeconomy with minimal or negligible effects on water quality, water quantity, avian diversity (as analyzed in chapter 10), or air pollutant emissions, under the biomass supply constraints assumed in *BT16*. Cellulosic biomass generally shows favorable performance relative to conventional feedstocks for the indicators investigated, with harvest of agricultural and forestry residues generally showing the smallest contributions to changes in certain environmental indicators. However, in some locations and under some biomass scenarios, challenges may arise for maintaining SOC levels, water quality, water availability, biodiversity, and air quality.

The regional context influences the significance of the environmental effects that are estimated in *BT16* volume 2, and it is also important to note that factors besides biomass production affect the environmental indicators investigated here. For example, the air emissions analysis (chapter 9) found that some counties already in nonattainment in 2015 for National Ambient Air Quality Standards could see emissions representing greater than 1% of the National Emissions Inventory for those counties. The chapter notes that the spatial distribution of modeled air emissions, including those not associated with biomass production, would need to be understood before an estimate of local air quality could be made. The water footprint analysis (chapter 8) discusses the importance of considering the context of water withdrawals, such as those from the Ogallala Aquifer, before fulfilling water needs of new activities. Similarly, loadings to waters would need to be placed in the context of local water-quality criteria. The algae chapter (chapter 12) reviews many of the indicators and indices of water quantity that incorporate regional needs, such as environmental flow requirements for fish. Going beyond the environmental effects analysis in this volume is critical to place the indicators in a regional context.

In reality, environmental effects are often cumulative. The analyses of forest water quality, water quantity, and biodiversity focus on the potential environmental responses associated with incremental biomass harvests, without considering effects of total harvests for conventional forest products, as well as residential development. Chapter 11 notes that for some forest species and locations, biomass removal may lower habitat quality such that it reduces local numbers of individuals, thereby increasing vulnerability to other factors affecting the population, such as competition or fragmentation effects.

Most results presented in *BT16* volume 2 represent environmental effects for biomass production and harvesting only (i.e., they do not consider feedstock transportation logistics, biomass conversion, or biofuel combustion). The analyses of logistics in the GHG and air emissions chapters are exceptions; these analyses illustrate the importance of studying environmental effects of later stages of the supply chain for relevant indicators.

A few illustrative cases have been completed to estimate displacement of fossil-derived GHG emissions and energy. Life-cycle GHG intensities for both biomass- and fossil fuel–derived fuel and energy products were applied to specific scenarios based on potential growth in energy, power, and chemical production between now and 2030. These cases illustrate that GHG-emissions reductions (between 4%–9%) and fossil energy consumption reductions could be expected, as compared to a scenario in which all U.S. energy and conventional products are produced from fossil fuels in that year. Results depend on these GHG intensities, the biomass supply, and how the biomass supply is allocated to different end uses.

Other than the illustrative cases showing the potential reductions in GHG emissions and fossil energy consumption, *BT16* volume 2 does not investigate other environmental or socioeconomic effects of displacing fossil feedstock–derived fuel and products. However, determining the net effects of displacing fossil energy and products with biomass-derived energy and products is a critical area for further analysis. Some of the environmental effects of gasoline supply chains are described in Parish et al. (2013) and Dale et al. (2015). For example, environmental effects of gasoline pathways include a shift of carbon from prehistoric times to today's atmosphere, a subterranean dimension of disturbances, and extraction locations in remote and fragile ecosystems that could negatively affect biodiversity.

14.1.2 Uncertainties and Limitations

As stated above and throughout the report, results are limited to particular scenarios, as in all environmental modeling studies. The results must be interpreted in light of the uncertainties in the models used to simulate biomass in *BT16* volume 1 (i.e., POLYSYS and ForSEAM) and models used to simulate environmental indicators in *BT16* volume 2. Volume 2 discusses sources of uncertainty in these analyses, including limited input data for model parameterization and questions about extending models to regions, feedstocks, and time periods for which they have not been calibrated or validated. Some of the uncertainties, such as how fast yields could increase and what conservation practices might be implemented by farmers, are handled through the use of multiple scenarios or cases.

A major assumption in *BT16* is that the agricultural land base and the forest land base do not change between the present and 2040. This assumption has implications for all of the environmental effects analyses, and modifying scenarios to allow transitions between these major land classes could result in environmental changes of different types, magnitudes, or directions than the comparisons presented here.

Model inputs, such as land-cover and land-management classes, are also uncertain, and chapter 3 focuses on those uncertainties. Large uncertainties in basic land-cover classifications are well documented (e.g., Congalton et al. 2014; Kline et al. 2011; Feddema et al. 2005). The classification uncertainties increase when land "use" is inferred from land-cover classes (Lambin et al. 2003), and uncertainties are inherently greater when an analysis attempts to quantify "change" (O'Hare et al. 2010; Dale and Kline 2013). Moreover, crop rotations have not been investigated in this study, even though they are a common land-management strategy.

Uncertainties in environmental models include presumed mechanisms or processes by which environmental indicators respond to changes in land management, as well as uncertainties in the drivers of change on which empirical models are based. Chapter 6 develops empirical relationships between forest harvest area and water quality but notes that if sufficient data and process-based platforms for silvicultural activities were available, a modeling approach that considers soil type, topography, climate, vegetation, and harvest systems involved in estimating water-quality response to biomass harvests could lead to more accurate results. Drivers of environmental change may be different in different regions. For example, the agricultural biodiversity analysis assumes that bird populations change in response to habitat, as reflected in empirical estimates from local studies. However, in a different location, the response may differ; e.g., if major changes in predator populations occurred in one region but not another.

Similarly, decisions about allocation methods can lead to uncertainties in environmental effects results. For example, allocating GHG emissions or irrigation water to corn grain and not to corn residues could affect conclusions about the effects of harvesting those residues on indicators. The importance of allocation method has frequently been identified as an issue that has a major effect on results in life-cycle analyses.

The county-level resolution is an important aspect of *BT16*. Analyses of environmental effects of terrestrial feedstocks require assumptions about how biomass production—estimated at the county level in *BT16* volume 1—is distributed within a county, especially when watershed-level effects are modeled. For example, the water-yield analysis (chapter 7) finds that increased water yields from biomass harvesting in forests would have little additional effect, relative to a 10-year reference. However, if harvest outputs of ForSEAM had been available for particular locations within the county, the effects of increased water yield could have been more important in some locations. Furthermore, biodiversity results depend on the arrangement of feedstocks across the county landscape.

The potential global impacts of an expansion of biomass production in the United States depend on many factors not analyzed under *BT16* scenarios. Reasonable assumptions about increasing biomass production could generate estimates that not only vary widely in terms of magnitude, but also in terms of direction of the effects, particularly with respect to whether forestland is expected to expand or contract in response to policies associated with biomass production (Kline et al. 2009). Potential international effects of future U.S. biomass production scenarios are not considered, including potential indirect LUC.

14.2 Enhancing Environmental Outcomes: Strategies Identified in this Report

Actual environmental effects of future biomass production depend on production practices that will be used. Strategies that can help move toward environmentally sustainable biomass production are described below. As with conventional agricultural and forestry resources, future potential supplies can be estimated, but the environmental effects and sustainability of these future supplies is wholly contingent upon how those supplies are actually produced in the future. Here, environmentally relevant supply constraints are introduced along with other approaches to realize improved environmental outcomes for biomass production.

14.2.1 Supply Constraints in Biomass Resource Assessments

As described in chapters 1 and 2, various supply constraints were assumed in *BT16*, some of which reflected sustainability principles. Though future biomass production practices are not known with certainty, these supply constraints reflect considerations that can be implemented or assumed at large scales. Environmental considerations that may affect biomass resource potential estimates can be implemented in models by:

- Restricting areas on which bioenergy crops may be grown or residues may be collected. For example, some areas in *BT16* were restricted from production to protect biodiversity. Fragile, reserved, protected, and environmentally sensitive forestland was not eligible for biomass harvests. Algae were not produced on agricultural, forest, or other sensitive lands.

- Restricting energy crop choices or forest biomass harvests to particular locations. For example, the Biomass Research and Development Board recommends selecting perennial crops based in part on water requirements and available water (BRDB 2012). Copeland et al. (2012) assert that species selection should consider effects of different crop choices on regional air quality. This type of restriction was not implemented in *BT16*. Instead, energy crops were allocated along with conventional crops at the county level in a way that maximizes profit from the landowners' perspective.
- Implementing management practices that maintain or enhance environmental outcomes (e.g., tillage type, production intensity, harvest frequency, harvest area, residue removal percentage). Many of the supply constraints in *BT16* relate to management practices. Agricultural residue removal coefficients were employed and constrained not to exceed the tolerable soil loss limit of the USDA Natural Resources Conservation Service (NRCS 2016a; 2016b), and not to allow long-term reduction of SOC. Moreover, energy crops were not irrigated. At least 30% of logging residues were left onsite to protect soil, provide habitat, and maintain soil carbon. The use of some BMPs was assumed and included in cost estimates for forests and agriculture. Harvest levels were restricted to ensure that timber growth always exceeds harvest at the state level.
- Implementing targets for environmental indicators (e.g., regulatory levels or thresholds) that can be linked to productivity estimates. Such targets are quantitative goals for an indicator, usually to be achieved at a particular place and time. (The German Advisory Council on Global Change terms these "guard rails," WBGU 2009). An example of the use of environmental targets was the restriction of algae water consumption to no more than 5% of mean annual basin flow.
- Altering farmer or forester choices (in agent-based models) based on incentives, preferences, and established culture. For example, environmental effects of energy crops, such as improved water quality and wildlife habitat have been shown to influence some farmers' motivations for adopting perennial energy crops (Hipple and Duffy 2002). While these feedbacks from environmental effects to feedstock production could be used to constrain supply, such feedbacks were not implemented in *BT16* volume 2.

14.2.2 Mitigation Strategies

While this report was not intended to be prescriptive, some strategies were identified that may be used to enhance the environmental outcomes from biomass production. Strategies to mitigate effects of the *BT16* volume 2 scenarios were identified.

Mitigation strategies were based on environmental analyses that identified drivers of environmental effects in the scenarios. For example, the GHG analysis found that in some counties logistics contributed more than 50% to GHG emissions (excluding soil-carbon change-related emissions). Consumption of fertilizer and agricultural chemicals, as well as nitrous oxide emissions stemming from fertilizer use, were also significant contributors to GHG emissions. Therefore, the energy efficiency of logistics operations and fertilizer efficiency should be improved. Counties with higher yields generally experienced lower GHG emissions intensities. Therefore, increasing yields would be an effective mitigation strategy for GHG emissions. The analysis also found that crop-residue removal (e.g., corn stover or barley straw) can reduce soil carbon levels, but practices such as manure application and cover crop adoption could counteract soil carbon losses and therefore should be pursued as a mitigation strategy (Qin et al. 2015). Planting of deep-rooted species like miscanthus and biomass sorghum could contribute to soil carbon storage.

The agricultural water quality chapter (chapter 5) focused on conservation practices that could reduce loadings of pollutants to surface waters. Large improvements in water quality indicators, on a percentage basis, were achieved without sacrificing production. This was true for landscapes dominated by annual residues and landscapes dominated by a mixture of perennial and annual crops. Results for the Iowa River Basin suggested that four practices (riparian buffer, cover crop, slow-release nitrogen (N) fertilizer, and tile-drain control) could reduce N loading substantially for watersheds planted in corn. In the Arkansas White-Red River Basin, filter strips provided water quality benefits from short-rotation woody crops (SRWCs). Results from the water quality analysis can be used to identify location-specific management practices that can achieve water quality goals and biomass production goals simultaneously. In addition, by choosing perennial feedstocks and implementing conservation practices, biomass production could reduce downstream nutrient loadings to the Gulf of Mexico.

With respect to forests, silvicultural activities have minimal effects on water quality, and potential effects from harvest operations are largely mitigated by the widespread adoption of BMPs, as is discussed below. Furthermore, where forest removals could increase stormflow volume in local areas, forest BMPs such as implementing forest riparian buffers may be effective to mitigate negative harvesting effects on stream hydrodynamics.

The water footprint chapter noted that the National Resources Conservation Service Ogallala Aquifer Initiative aims to reduce water withdrawals and extend the life of the aquifer by implementing multiple conservation measures. One of the strategies is converting operations to dryland farming, which is defined as the non-irrigated cultivation of crops. This strategy is consistent with one of the guiding principles in *BT16*: produce non-irrigated biomass.

The air emissions chapter noted that variability in county-level emissions estimates suggests that certain practices and production locations would result in much lower emissions than others. Higher yields, lower tillage requirements, and lower fertilizer and chemical inputs contribute to lower air emissions intensity. The use of either more efficient equipment or fewer passes would reduce emissions from fuel use and fugitive dust from soil disturbance. The application of emission reduction strategies (e.g., higher yielding seed varieties, energy crops with high nutrient use efficiency, more efficient farm engines, and wider adoption of less intensive tillage practices) could mitigate the potential increase in emissions from *BT16* scenario activities. This analysis illustrates that the long-term feedstock supply logistics system itself could reduce emissions per mile traveled through feedstock densification. In addition, using biomass more locally or using more fuel-efficient long-distance transportation methods (e.g., rail) could potentially decrease emissions from long-distance truck transport.

The agricultural biodiversity chapter echoes suggestions that benefits to birds (and other wildlife) can be attained by implementing wildlife-friendly practices, e.g., timing farm operations prior to avoid nesting periods, using a flushing bar and raising the height of mowing equipment to avoid nests and animals during farm operations; and, simply harvesting from the inside of a field toward the edges, instead of trapping wildlife in the center of a field. Mitigation strategies to protect wildlife biodiversity in forests are more uncertain because of the lack of data relating biomass harvest variables to habitat suitability for various taxa. However, optimal mitigation strategies are expected to be site-specific, for example, protecting species that rely on moist forest floors in lowland hardwood forests or forest systems in temperate rainforests.

As discussed in the chapter on climate sensitivity to feedstock productivity, climate change adaptation is important. Adaptation can be aided by greater focus on the implications of climate change on the long-term strategic selection and production of energy crops across the U.S. landscape.

14.3 Enhancing Environmental Outcomes: Going Beyond Analyses in this Report

The context of land management is a major determinant of environmental effects. Regardless of whether land cover is classified as pasture or energy crop, management that incorporates native species, avoids disturbance during key nesting periods, and increases productivity while reducing the use of pesticides and herbicide applications is likely to improve many environmental indicators compared to management where disturbances are not planned to conserve species, or with higher use of inputs, or minimal control of grazing, or where exotic and invasive species are not controlled. Furthermore, the implications of management practices for additional biomass production in forestlands may result in better control of pests, fires, and invasive species with benefits that extend beyond the managed forest to neighboring parks and reserves (Dale et al. 2015). Thus, real impacts will depend on the prior conditions and actual management practices, which are highly heterogeneous, while impacts estimated through modeling will depend on the assumptions and specifications broadly applied to represent those conditions and management practices. Here, a number of approaches are described that are currently being used or are under development to enhance environmental outcomes for biomass production.

14.3.1 Best Management Practices

BMPs can improve environmental outcomes for realized biomass and future biomass. BMPs are approaches, processes, activities, incentives, or rewards deemed effective at delivering a more favorable outcome than other techniques when applied to particular circumstances. These recommended practices "transform knowledge about local conditions and practices into prescriptions for low-impact operations by specifying methods that reduce negative impacts" (Lattimore et al. 2010). Additional descriptors of BMPs are "useful," "proven," "cost-effective," and "generally accepted" (Texas State Soil and Water Conservation Board 2005). For example, forestry BMPs help to ensure that adequate woody debris remains on site to protect soil and water quality (Evans et al. 2013; Fritts et al. 2014; Cristan et al. 2016). BMPs are sometimes called "conservation" practices, especially in the context of agriculture, as they may be intended to conserve water quality, water quantity, air quality, or other objectives (NRCS 2016). Most BMPs are focused on water quality, and some definitions of BMPs refer exclusively to water quality impacts (Ice 2004). The most useful BMPs are quantitative, reflect targets for environmental indicators, and are associated with detailed advice regarding implementation. As an example BMP, winter cover crops like winter rye (which was modeled in chapter 5) can provide synergistic benefits of soil conservation, water quality, and biomass production with no increased demand for agricultural land (Feyereisen et al. 2013). Chapter 5 and additional studies have shown that the use of cover crops can reduce negative water-quality effects from farming operations (Graham et al. 2007; Mann et al. 2002), while decreasing soil erosion, maintaining land productivity (Kaspar et al. 2001; Snapp et al. 2005; Wyland et al. 1996), and reducing nutrient loadings.

A review of BMPs shows that they are commonly implemented in forestry (Ice et al. 2010), and some BMPs have are commonly employed in agriculture as well. However, additional BMPs could be developed to maintain or improve environmental indicators. Existing BMPs, which often emphasize soil quality and water quality, could be tailored for the purposes of biomass production and harvesting, and additional BMPs could be developed for air quality, biodiversity, and GHG emissions. Moreover, BMPs could be developed for algae biomass production. Adaptive management is an important framework for developing BMPs because it integrates research, planning, management, monitoring, and learning into evolving and improving practices (Lattimore et al. 2010; McAfee et al. 2006; Holling 1978). McAfee et al. (2006) note that the efficacy of recommended management practices in achieving sustainable operations can be limited if monitoring and assessment are not carried out within an adaptive management framework.

14.3.2 Landscape Design

Important improvements in environmental effects can be achieved by within-county spatial allocation of land management for biomass and other purposes, land management to mitigate potential adverse effects, and production area restrictions. The county-level resolution used in *BT16* does not enable environmentally favorable strategies at the field or sub-field scale to be modeled. As some of the chapters in this report illustrate through caveats and sensitivity analyses, county-level biomass estimates lead to substantial uncertainty in environmental indicators if the specific location of the biomass is not defined.

Landscape design principles offer a means to integrate biomass production with other uses of the land while meeting simultaneous environmental, social, and economic goals. A landscape design framework suggested by Dale et al. (2016) involves six steps: (1) establish goals by engaging stakeholders in an open and participatory process that, ideally, facilitates common understanding and agreement on context-specific targets for environmental or other indicators; (2) identify constraints and opportunities, such as impacts to water, soil, or air, as well as the enabling factors that assist in meeting stakeholder goals; (3) identify optimal options for feedstock types, locations, management strategies, and logistics systems; (4) evaluate alternatives and define solutions that are spatially and temporally explicit; (5) monitor and evaluate outcomes over time using mechanisms that are cost-effective, doable, and transparent; and (6) adjust plans based on current information for "continual improvement" and alignment with desired outcomes. By involving diverse stakeholders who are part of the bioenergy supply chain as well as those affected by its development, landscape design can help those involved define appropriate goals, understand tradeoffs, and achieve benefits that would not necessarily be attained through conventional land management approaches (Dale et al. 2016).

Field studies are underway to test landscape design approaches that leverage the ecosystem services provided by second-generation perennial lignocellulosic energy crops. Perennial crops such as SRWCs, switchgrass, miscanthus, and other perennial grasses share traits that differentiate them from annuals like corn and soybeans: a deeper root system, a generally better ability to thrive on less productive soils, a lower dependence on fertilizer inputs, and management options that can be more beneficial to wildlife. When deployed on the landscape in specific locations based on soil and land characteristics and their potential to perform specific functions, perennial bioenergy crops may provide water quality services and patchiness patterns that improve ecological habitats. By working with local producers and stakeholders, bioenergy landscapes can be designed that balance productivity and environmental performance.

A case study being conducted by Argonne National Laboratory (ANL) and centered in the Agricultural Midwest illustrates a promising opportunity to enhance aspects of the environmental outcomes from producing biomass for energy. Ongoing field research shows that a willow contour buffer on a sub-productive portion of a field can intercept nitrate from subsurface soil and provide important reductions in nitrate losses through plant uptake (fig. 14.1), confirming modeled results (Ssegane et al. 2015). To scale this concept up to a 50,000-acre tile-drained agricultural watershed in Illinois in the Mississippi River basin (as described in (Hamada et al. 2015), researchers are targeting production of bioenergy crops in "marginal agricultural subfield areas" identified using seven soil-based environmental criteria (susceptibility to nitrate and pesticide leaching, soil drainage, frequency of surface water ponding, frequency of flooding, soil erosion, and crop productivity).

Figure 14.1 | A field site in Fairbury, Illinois, is providing primary data on the effectiveness of a willow contour buffer in reusing the nitrate lost by the adjacent corn. In the picture, willow plots in the foreground and background are shown after corn harvest in their 2nd year of growth.

Using a calibrated SWAT model, ANL simulated the effects of growing switchgrass, willow, and big bluestem in these targeted subfield areas on annual yields of both energy crops and predominant corn and soybeans, nitrate-N and sediment exports, and water yields (Ssegane and Negri 2016). Results show that water quality benefits can be obtained by converting underproductive and environmentally marginal portions of fields to energy crops, with the production of biomass more than compensating for the loss in output of commodity crops from the landscape. The introduction of perennial energy crops using the same water-quality-focused watershed design may help create additional ecosystem services in terms of pollinator habitat, based on bioenergy crop type, landscape configuration, and energy crop area (fig. 14.2) (Graham, Nassauer, W. S. Currie, et al. 2016). ANL compared the cost of this practice per unit of N removed, including production and logistics costs to delivery at a depot, to other conservation practices (fig. 14.3) and found, for example, that a willow buffer would be close in cost to the adoption of practices such as wetlands or denitrifying bioreactors, and cheaper than a cover crop (Ssegane et al. 2016).

Finally, ANL calculated a comprehensive value for the water-quality based ecosystem services provided for potential future trading markets, including services derived from improvements to reservoir, navigation, recreation, irrigation, fisheries and other categories. The values obtained show the potential for supporting the production of perennial energy crops, should these markets be established. Through targeted workshops, conversations with farmer stakeholders jointly reviewed the proposed landscape designs and discussed solutions that advance societal goals while being feasible and acceptable by those who will implement them (Graham, Nassauer, and, et al. 2016).

Figure 14.2 | Modeling of the same watershed has shown that increasing the amount of land transitioning from corn/soybean rotations to perennial energy crops has the potential to increase pollinator nesting indices, with differences attributable to type of crop, area extent, and landscape configuration. The figure shows percent change in wild bee abundance when comparing current land use with two willow cropping scenarios: (a) 11% of the land in willow, and (b) 22% of the land in willow. (Graham, Nassauer, W. S. Currie, et al. 2016).

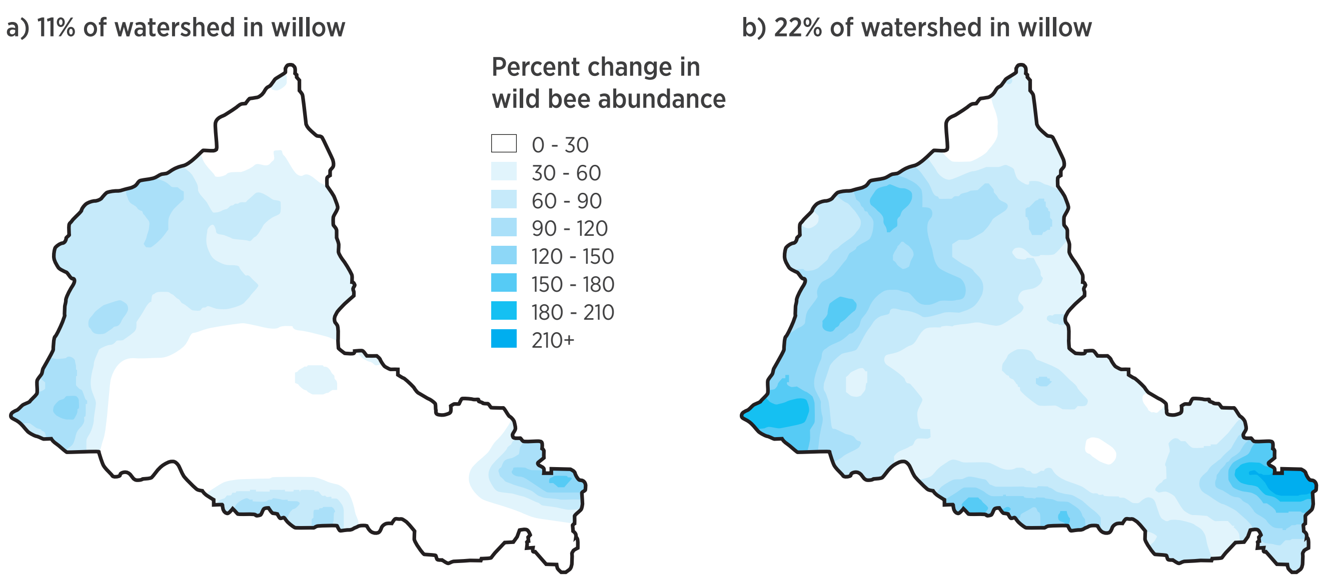
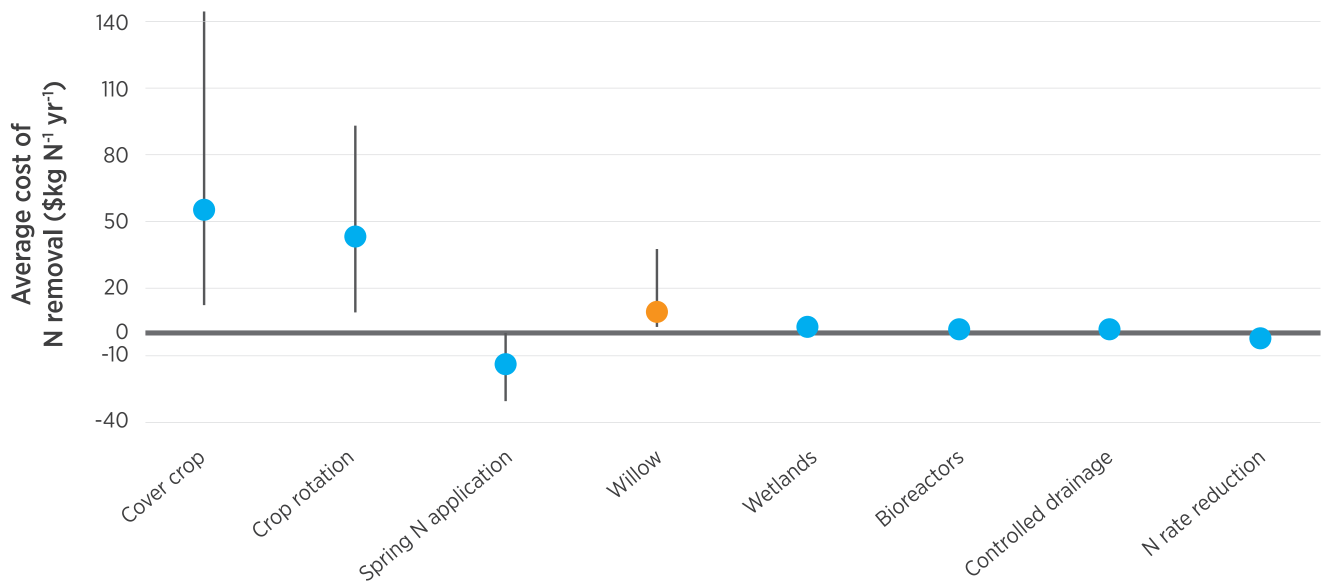


Figure 14.3 | Comparison between the calculated costs (per unit of nitrogen removed) of a willow buffer (orange dot) to intercept nitrate from a corn field and other conservation practices (blue dots). (Data from other conservation practices are from Christianson et al. 2013)



14.3.3 Precision Agriculture

Technological innovations and precision agriculture can also help enhance environmental outcomes (Muth et al. 2012). The biomass feedstocks from *BT16* volume 1 and those evaluated in volume 2 are quantified at the county level. However, sub-county and even subfield variability challenges the farmer's ability to sustainably produce and collect cellulosic biomass. *BT16* volume 1 includes assumptions regarding the operational availability of crop residues and how that availability may increase over time, given the potential of precision agronomics to enhance biomass availability in the future. Innovations in advanced logistics systems and precision agriculture enhance environmental outcomes by increasing biomass availability, practicality, and profitability while improving water quality through subfield stover removal decisions and associated variable harvesting technology.

Using the Landscape Environmental Assessment Framework (LEAF), a simulated supply shed (i.e., an area supplying feedstock to a biorefinery) in central Iowa was assessed for corn stover availability (fig. 14.4). To ensure that residues were being collected in a practical manner that also protected soil quality, water quality, and profitability, the analysis assumed that the entirety of individual fields must be managed to permit residue collection that meets environmental objectives. In other words, if a portion of a field could not support residue collection that met soil quality and water quality targets, the entire field was ineligible and contributed no biomass to the supply area total. This constraint results in a significant reduction in biomass availability compared with the future potential biomass supplies estimated an earlier Billion-Ton report (U.S. Department of Energy 2011), but it fairly represents the challenges and limitations of conventional field-level residue management (fig. 14.6). This ongoing research is described in Bonner, Cafferty, et al. (2014) and Bonner et al. (2016).

If the full potential of a billion-ton bioeconomy is to be realized, alternative management practices must be implemented to overcome the challenges of practicality and maintaining soil and water quality targets.

Figure 14.4 | Modeled feedstock supply shed relative to two pioneer lignocellulosic facilities

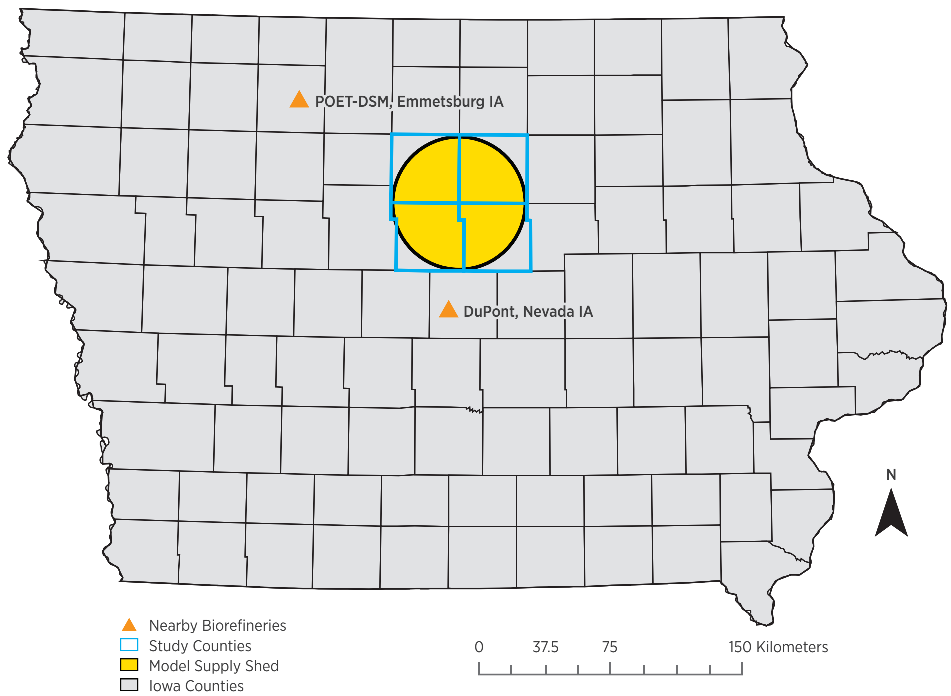
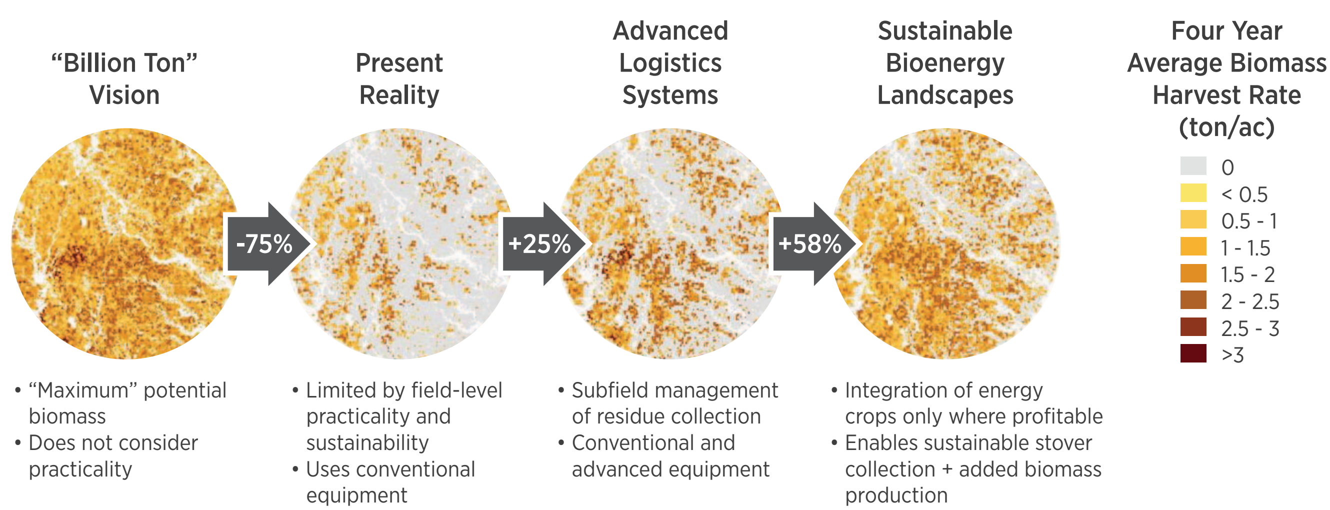


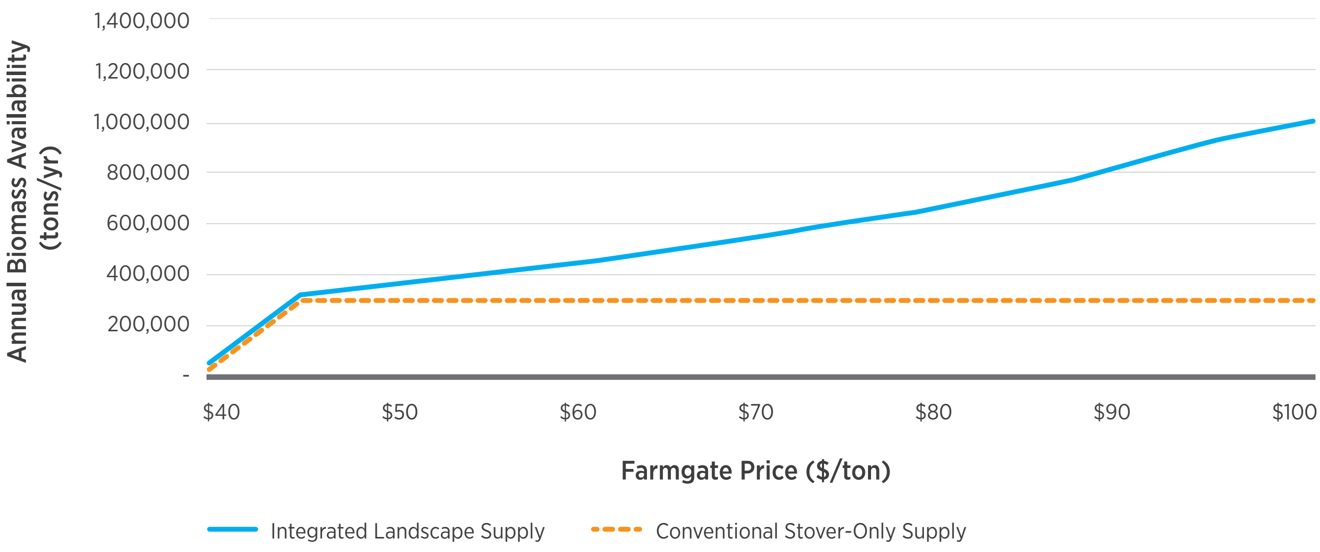
Figure 14.5 | Depiction of the reduction in biomass availability when practicality constraints are applied at the field level, and how biomass resources are mobilized and increased as a result of advanced logistics and conservation of soil carbon. Sustainability refers to soil quality and water quality.



Advanced logistics systems offer great potential, with one such alternative being a simple "binary" harvest where precision agronomics are used to avoid residue collection on sensitive portions of fields. Precision management plans constructed at the subfield level can then be used in conjunction with conventional equipment and Global Positioning System (GPS) guidance technology to direct harvesting equipment operation to where residue collection is permitted. This concept may be further expanded into variable-rate collection techniques whereby specialized equipment is used to apply real-time calculation of residue removal constraints during grain harvest and residue management (Karkee et al. 2012; Muth and Bryden 2012). For the case study supply shed modeled here, such advancements in logistics would permit nearly half of the fields to participate in sustainable residue collection, so that 50% of the available biomass that meets soil and water quality targets becomes practically available (fig. 14.5).

Although these results show a promising alternative for achieving greater biomass yields while maintaining soil quality, further improvements in land management will be required if all biomass from subfields that meet the soil and water quality targets is to be accessed in a practical manner. Such methods could be simple alterations of existing practices, such as reducing tillage intensity, or adoption of conservation practices like cover crops or vegetative barriers (Bonner, Muth, et al. 2014). Alternatively, the incorporation of dedicated bioenergy crops into the supply shed presents a valuable opportunity to increase biomass resources, sustainability, and profitability for growers. By better utilizing under-performing portions of row-crop-producing fields, energy crops can be introduced in a manner that is cost-competitive and beneficial for the environment (Bonner, Cafferty, et al. 2014; Bonner et al. 2016). For example, the integration of switchgrass into subfield locations within the modeled supply shed can be done in such a manner that field-level revenue is increased, additional biomass is produced, and the collection of corn stover is enabled on over 90% of fields (fig. 14.6). Through the combination of advanced logistics and subfield precision agriculture, a pathway to achieving the agricultural residues and biomass crop supplies discussed in *BT16* volume 1, while maintaining or improving environmental outcomes, becomes tangible.

Figure 14.6 | Comparison of feedstock availability between a conventional corn stover system limited by practicality and an integrated landscape in which switchgrass is used to increase biomass production and enable additional corn stover collection



14.3.4 Multipurpose Biomass Production and Removal

Strategies to produce and use biomass resources in ways that enhance environmental outcomes and provide multiple environmental benefits are being evaluated. These strategies include waste or "opportunistic resources" that, if used, provide benefits beyond biomass products. For example, biomass production can offer environmental benefits through phytoremediation, mineland reclamation, and wastewater remediation. Bioenergy can be a coproduct in many of these applications. Another example is the production of algae using waste CO_2 in flue gas that would otherwise be emitted directly to air.

Waste biomass is a category of biomass that is estimated in *BT16* volume 1, and potential benefits of waste use are discussed here. The multiple benefits to utilizing waste products for energy vary depending on the waste resource and include: displacing fossil fuels (thus reducing GHG emissions and reducing imports), reducing demand on disposal facilities (e.g., landfills, waste treatment facilities), odor control (from manure), protection of water quality, improved air quality (reduction in field burning of residues, reduced emissions from raw manure), conservation of natural resources by producing useful products from wastes, and a reduction in forest fire risk (from thinnings and use of standing dead wood).

Waste biomass is the most diverse category of feedstocks estimated in *BT16* volume 1. That volume includes twenty-four waste resources: agriculture (cotton gin trash, cotton field residues, grain dust and chaff, orchard and vineyard prunings, rice hulls, rice straw, sugar cane bagasse, sugar cane trash, soybean hulls, animal fats, yellow grease, animal manure, and the garbage fraction of municipal solid wastes (MSW)), forestry (other residue removals, treatment thinnings from other forestland, unused primary and secondary mill residues, urban wood wastes – construction and demolition, and urban wood wastes from MSW), and other resources (biosolids, brown trap grease, food wastes (industrial, institutional, and commercial), landfill gas, and utility tree trimmings). In the aggregate, waste resources in 2040 total 155 million dry ton at $60 per dry ton and 229 billion ft3 of additional landfill gas.

The use of waste resources for energy represents a substantial opportunity if the economics are favorable. The three largest categories of waste resources are the garbage fraction of MSW (i.e., paper and paperboard, plastics, rubber and leather, textiles, food waste, yard trimmings, and other, but excluding wood wastes) (55 million dry tons in 2040 at $60 per dry ton in *BT16* volume 1), animal manures (18 million dry tons in 2040 at $40 per dry ton, about half of agricultural waste resources), and construction and demolition (C&D) wastes (25 million dry tons in 2040 at $60 per dry ton). Major issues with MSW include (1) finding landfill space for disposal and (2) methane emissions from landfills. (If methane is captured and burned in a controlled situation it produces CO_2 and water, while methane has approximately 21 times the greenhouse warming potential of CO_2. A reduction in GHG emissions is a major benefit of capturing and combusting methane.) Utilization of MSW for energy purposes reduces the need for landfill space and capturing methane generated by existing landfills reduces GHG emissions and displaces other forms of energy.

The utilization of manures via anaerobic digestion to produce biogas has a number of environmental benefits that include protecting water quality by destroying potentially pathogenic bacteria and reducing biological oxygen demand, which can improve water quality and protect aquatic biodiversity; and reducing GHGs from methane produced from manure by capturing and utilizing the methane. In addition to these environmental benefits, the utilization of captured methane also displaces fossil fuels. EPA estimates that for dairy and swine (hog) farms with more than 500 and 2000 head, respectively, anaerobic digester systems to capture biogas could be economically feasible (U.S. Environmental Protection Agency 2011).

Another example of opportunistic resources is residues from forest thinnings, for which harvesting may reduce fire risk. At the time of this writing, forest fires are inflicting as-yet uncalculated damage in the Great Smoky Mountains National Park and nearby Gatlinburg, Tennessee, as well as other areas in the southeastern and western United States. Wildfires cost lives and over a billion dollars annually in the United States (Mosley et al. 2013). Biomass harvests in the wildland-urban interface, though likely not the cheapest source of biomass, can provide critical value in the form of fuel load removal and wildfire risk reduction (Staudhammer et al. 2011). These fuel load reduction treatments can provide biomass beyond the supplies reported in *BT16* volume 1.

Similarly, biomass removals for control of invasive species can provide win-win biomass use benefits. Ecosystem restoration efforts may benefit from the removal of kudzu, melaleuca, cogongrass, leuceana, castor bean, and other species. Powerline right-of-ways and other areas that require maintenance can also be used to produce biomass while providing co-benefits of vegetation-control.

Mineland reclamation and phytoremediation represent synergistic opportunities to produce biomass while providing other environmental benefits. These strategies may be preferred to conventional remediation technologies, which can be expensive and environmentally harsh. Through its "Re-Powering America's land" initiative, the USEPA encourages the development of renewable energy on potentially contaminated land, landfills and mine sites (U.S. Environmental Protection Agency 2016).

Phytoremediation uses green plants to remove contaminants from soil or water (Negri and Hinchman 1996) presenting dual-purpose opportunities for phytoremediation and biomass production (e.g., Rockwood et al. 2004). Phytoremediation can involve extraction of contaminants, stimulation of biological degradation, and sequestration in situ through the establishment of a functional ground cover. Phytoremediation has been proposed as a viable alternative to costlier remediation solutions in cases of large expanses of land contaminated with low levels of pollutants, or as a "gentle" remediation technique with more favorable lifecycle environmental impacts where harsher interventions would compromise other important ecological functions. In these cases, the potential to defray costs through the production of biomass is considered an attractive opportunity. A number of the same crops that are proposed for bioenergy have been used in phytoremediation, which typically share required traits of fast growth, deep root systems and the ability to grow in suboptimal conditions. In the US, 1,200 contaminated sites are listed in the National Priority List for remediation (U.S. Environmental Protection Agency 2011), with an estimated 2,600,000 hectares contaminated with trace elements alone.

Sites such as mine land, landfills and brownfields could be used to produce biomass while under a long-term reclamation/remediation process. Biomass production for mineland reclamation has been evaluated for applications in the Appalachian coal mines (Burger 2011; Akala and Lal 2000), phosphate and titanium mined lands in Florida, (Brown et al. 1992; Segal et al. 2001; Tamang et al. 2005; Rockwood et al. 2006; Langholtz et al. 2007; Proctor 2002), and elsewhere. Production of biomass from low opportunity cost lands can provide multiple environmental benefits while being publicly favorable and contributing to regional mine land reclamation goals.

Algae can be co-located with CO_2 or other waste nutrients. Co-location of algae biomass production facilities with CO_2 to produce energy or food (see chapter 7 in *BT16* volume 1) is a beneficial use of waste. Wastewater has nutrients that can be used by algae or, if reclaimed, taken up by irrigated crops. Algae biomass production can be co-located with wastewater treatment facilities that provide nutrients. The relative economic benefits of treating wastewater and producing algal biofuel as a coproduct versus producing algal biofuel as the main product and treating wastewater as a coproduct are discussed in Lundquist et al. (2010). Fast-growing terrestrial feedstocks can also absorb nutrients from reclaimed wastewater, providing a tertiary treatment while producing biomass ((Alker et al. 2002; Langholtz et al. 2005).

The benefits of phytoremediation, mineland reclamation, and wastewater biomass production strategies should be considered within the context of environmental economics.

14.3.5 Monetary Strategies

Environmental economics evaluates the value of environmental effects, both positive and negative, and potential solutions to reduce market failure[1] (e.g., Iftekhar et al. 2016; Hanley and JF White 2002). One example of the application of environmental economics is emissions-trading amendments to the Clean Air Act of 1990 (Clean Air Act Amendments of 1990), which reduced SO_2 emissions and acid rain. As suggested in this volume and from other researchers (e.g., Werling et al. 2014), the production of perennial native grasses can enhance benefits of a range of ecosystem services. A biofuels industry that creates a market for these feedstocks may increase the provision of positive externalities[2]. Environmental economics can use markets to reduce environmental costs or improve environmental benefits associated with increased biomass production and use. Such an approach could foster environmental efficiency of an expanded bioeconomy.

Ecosystem services offer a useful framework from which to consider associated trade-offs among effects of biofuel production and use (Gasparatos et al. 2013). Developing agreement on values and indicators among stakeholders is a prerequisite to building community and policy support for programs that enhance ecosystem services. Ongoing modeling and field projects are evaluating how biomass production can provide and improve ecosystem services such as soil quality, water quality, and wildlife habitat (Ssegane et al. 2016; Dale et al. n.d.).

14.4 Looking Forward and Future Research Needs

Research, science-based monitoring, and adaptive management can be used to further enhance environmental benefits of biomass production while mitigating potential negative effects. *BT16* volume 2 has identified potential environmental considerations that are relevant and important as biomass production industries develop in the United States. Analyses of environmental effects for the scenarios considered in this volume can help the research community, industry, and other decision makers prioritize research efforts and data collection, as well as move toward identification of priority locations for biomass production and location-specific BMPs.

14.4.1 Summary of Key Research Needs Identified in *BT16* Volume 2

Research gaps and needs are identified in the chapters of *BT16* volume 2, ranging from local monitoring of environmental indicators to national modeling studies and global indirect LUC (ILUC). Some of the research recommendations relate to how biofuels (or biomass in this case) can be "done right" (Kline et al. 2009) to improve environmental effects; other research relates to how the modeling of biomass can be improved with respect to accuracy and precision (e.g., through improved data collection and broader validation of models). Implications of environmental effects measured in *BT16* volume 2 (e.g., effects of

[1] Market failure is a situation where markets are not efficient, i.e., a different market situation could improve benefits to society as a whole without negative impacts to market participants.

[2] Externalities are unintended impacts, positive or negative, of a commercial activity that affect stakeholders not involved in the economic transaction.

changes in stream flows on fish, effects of air pollutant emissions on local air quality) are also recommended. Additional research that could follow this study is described below.

The establishment of consistent definitions for land cover and land management are required to support a consistent analysis of change over time. Consistent and transparent use of terms and definitions for land cover classes, crop types and rotations, and characterization of land management are essential elements for improved LUC analysis. Some of the research needs related to GHG emissions include exploring the sensitivity of SOC changes to model assumptions, including the treatment of tillage and effects of rotation, crop yield, land-use history, and land transition matrices. Techniques could be explored to mitigate factors that lead to hotspots of SOC change. The relative contribution of aboveground carbon changes is an additional research gap. Temporal emissions accounting could be added to the treatment of forest-derived feedstocks in GHG modeling.

Research is needed to model biomass removal at finer spatial scales, such as within a watershed rather than a county, which is too coarse for the assessment of some water yield effects of forest biomass production. Future studies should examine the cumulative effects of forest biomass removal in specific watersheds where harvesting activities are expected to occur, and should focus on ecologically relevant indicators of streamflow. In addition, future studies should link water quantity and quality to allow for a comprehensive assessment of water resources at watershed-to-county levels.

The context of environmental effects may require regionally specific monitoring. For example, while current forestry BMPs are likely adequate to maintain stream water quality for intensive pine silviculture in the Southeastern Coastal Plain, dominant groundwater flow paths suggest that groundwater quality and transit times should be monitored and evaluated (pers. comm. Natalie Griffiths to Matthew Langholtz, December 2016).

Further research is needed on fugitive dust emissions from forestry management activities and biogenic emissions from agricultural and whole-tree biomass feedstocks. The emission estimates provided in this study could be coupled with air-quality screening tools to evaluate potential changes in emissions concentrations, to assess potential human health impacts, and to develop sustainability constraints (i.e., excluded lands) for future scenarios related to biomass production.

Regarding vertebrate biodiversity in agricultural systems, research is required to (1) measure and model responses of additional combinations of wildlife taxa and nonnative feedstocks such as miscanthus; (2) increase the feasibility of production systems that employ more diverse communities of plants as feedstocks; (3) understand logistic, social, and economic barriers that could prevent farmers from adopting practices that benefit wildlife; (4) quantify relative effects of pesticide use for bioenergy feedstocks and for other managed lands; and (5) identify geographic hotspots where attention to wildlife-friendly practices is needed.

To further study the effects of forest biomass harvests on biodiversity, more manipulative studies need to be conducted (1) that vary amounts of coarse and fine woody debris retained across gradients in forest cover and forest types and (2) that measure the response of multiple species across trophic levels. Manipulative studies can also help determine whether responses are due to the forest-harvest treatment itself or the additive effect of removing dead and downed wood. Also, established studies should continue over longer time periods so that the effects of removing coarse woody debris and fine woody debris during second- and third-harvest rotations can be better understood. General relationships observed in this volume should be viewed as the basis for establishing testable hypotheses regarding biodiversity response to biomass harvest.

Research needs for algae production include quantifying the environmental effects that are only described in qualitative terms in this report. Quantitative estimates of the GHG emissions of biomass production alone are not possible for an algal biomass system that is highly integrated, so a life-cycle analysis would need to evaluate the whole supply chain for co-location of production facilities with various sources of CO_2. Water consumption must be understood in the context of regional competitive use. In addition, research is needed to evaluate potential biodiversity, air quality, water quality, and primary productivity effects of growing diverse species of algae at the commercial scale. As algae-produced food (protein) and feed become commercially viable, understanding the interactions between the profitability, food security, energy security, and water quantity will become paramount.

To advance climate change adaptation, research is needed on the development and genetic improvement of energy crops for climate-related stress; management practices to reflect climate change implications for plant establishment, maturation, and harvesting; and the implications of shifting energy crop yields and economic competitiveness for the biomass supply chain, including transportation and refining. The development of a more process-based understanding of biomass feedstock responses to changing climatic conditions that includes factors such as climate variability and extremes, the effects of CO_2 fertilization, and different management practices and economic constraints would assist in reducing uncertainties associated with purely empirical methods.

An additional research need is to model watersheds with multiple land uses so that silviculture, agriculture, urban, and other land uses can all be integrated in models of cumulative effects while assessing their individual effects as well. For example, long-term watershed-scale research should continue to measure the effects of traditional and emerging silvicultural practices on water quality. Moreover, tradeoffs could be studied between the environmental effects associated with increased residential development and those associated with the biomass harvesting that could generate income to slow development.

Determining the drivers and effects of land-cover and land-management changes attributable to biomass production—or to any specific intervention—requires monitoring both the effects over time and the human behaviors driving those effects. Models are not useful without monitoring to provide parameters or a measure of their validity. Most models used in *BT16* volume 2 are validated or verified under many conditions, and models that were created for this study (biodiversity and forest water quality models) are developed from empirical data. Yet, none of the model results have been validated with commercial-scale data for biomass across all of the regions where the models are employed. As data from operational systems become available, this validation will be critical for reducing uncertainties and increasing accuracy of modeled results.

14.4.2 Integrated Consideration of Environmental Indicators

BT16 volume 2 is a collection of analyses that consider categories of indicators independently. To help decision makers consider a suite of environmental effects in a region, tradeoffs among indicators, as well as aggregation functions, could be investigated. The joint consideration of environmental indicators could reveal locations of potential concern among indicators. The GHG, water quality, and biodiversity analyses, for example, show locations where biomass production could lead to environmental indicators that are less favorable than particular reference conditions. Further analyses with uniform assumptions would be needed to examine the analyses together.

Similarly, the integrated consideration of indicators could reveal tradeoffs. The water quality analysis for agriculture (chapter 5) was an initial step toward investigating tradeoffs among indicators, i.e., water quality and productivity indicators. This analysis found complementarities between increasing biomass yield and reducing total suspended sediment and total phosphorus, and tradeoffs between biomass yield and nitrate for perennial grasses and SRWCs. In addition, the analysis revealed water-quality benefits of coppiced willow, which minimized trade-offs between nutrient and sediment reduction and biomass yield in the scenario. Biodiversity studies (chapters 10 and 11) revealed potential tradeoffs among species, i.e., benefits of land transitions and biomass harvesting for some species (e.g., forest species that prefer young forests and grassland birds such as ring-necked pheasant) and decreases in range for some grassland species and potential reductions in species that require moist forest floors. Additional integration of indicator analyses with evaluation of a broad range of tradeoffs is needed.

Large quantities of data about diverse aspects of environmental (as well as social and economic) sustainability are difficult to visualize without some sort of reduction in dimensionality (Pollesch and Dale 2015). Aggregation functions are used to simplify data and clarify communication. Aggregation theory is an area of mathematics that explores the form and properties of such aggregation functions. In their book, Aggregation Functions, Grabisch et al. (2009) present a comprehensive mathematical treatment of aggregation functions that Pollesch and Dale (2015, 2016) have adopted for bioenergy assessment. Pollesch and Dale (2016) use methods that allow for inclusion of context-specific baselines and target values.

Parish et al. (2016) developed one example of aggregation applied to switchgrass in east Tennessee. A suite of 35 environmental and socioeconomic indicators in 12 categories was considered in a holistic assessment of a 5-year switchgrass-to-ethanol production experiment centered on a demonstration-scale biorefinery in Vonore, Tennessee. Three alternative scenarios were compared within a qualitative sustainability evaluation framework built for the case study using freely available DEXi 4.0 software that was designed to solve complex decision problems that involve 15 or more attributes, inaccurate and/or missing data, group decision-making, and expert judgment (Bohanec et al. 2013). Within this east Tennessee context, switchgrass production can improve environmental and social trajectories without adverse economic impacts, which can lead to enhanced sustainability overall (Parish et al. 2016). Future research could apply aggregation theory to biomass production in other contexts.

14.4.3 Integration across Environmental, Social, and Economic Effects

BT16 volume 2 focuses on environmental effects, but it is important that future studies investigate environmental, social, and economic effects in a more integrated manner to provide a broader view of sustainability of expanding biomass production in the United States. Integrating environmental, social, and economic analyses should give a geographic picture of locations and regions that could benefit most from biomass production and those which might experience adverse effects or tradeoffs among effects.

Socioeconomic indicators have been proposed to measure and model sustainability of bioenergy systems (Dale et al. 2013; Efroymson et al. 2016). These indicators represent social well-being, energy security, external trade, profitability, resource conservation, and social acceptability. Social and economic effects of biomass production have been investigated elsewhere and suggest a range of potential benefits. For example, a substantial increase in rural jobs has been associated with biomass production over the past decade (Golden et al. 2015; Golden et al. 2016), and one would expect this to continue with an expanding biomass industry. Agricultural systems designed to integrate energy crops are more diversified and resilient, factors that improve market stability and food security (Kline et al. 2016), as well as economic stability in communities. An important aspect of enhancing sustainability is building markets that provide economic incentives for sustainable land-use practices. Markets that improve the economic viability of working forests can help keep forests as forests and mitigate conversion of forestland to residential and commercial development.

Despite these potential social and economic benefits, more research is needed (1) to quantify and validate these effects as biomass production expands and (2) to evaluate how growth in the bioeconomy sector causes beneficial or adverse effects to other sectors. Future research on the application of aggregation applied to bioenergy, as discussed in section 14.4.2, would assist in quantifying these complex relationships between environmental, social, and economic effects. Visualization tools would help researchers and decision makers understand the relationships between multi-dimensional effects.

Integrating social and economic research with the environmental analyses in *BT16* volume 2 could lead to modifications of economic assumptions in volume 1. Environmental effects of energy crops, such as improved water quality and wildlife habitat, have been shown to influence some farmers' motivations for adopting perennial energy crops (Hipple and Duffy 2002). Caldas et al. (2014) note many economic and cultural factors that may affect Kansas farmers' willingness to grow cellulosic energy crops or to harvest residues, and Song et al. (2011) have found that farmers need large incentives to compensate for risk and potential reversibility of transitioning to perennial energy crops.

14.4.4 Concluding Thoughts

Integrating resource analysis and sustainability concepts should continue to be a broad goal for future research on potential biomass supply in the United States. *BT16* volume 2 is a first effort to consider potential biomass supply and environmental effects in a more integrated manner. This study can assist stakeholders in identifying beneficial biomass production opportunities while considering their local conditions and specific environmental goals. For example, the DOE Bioenergy Knowledge Discovery Framework (www.bioenergykdf.net) provides data sets from both *BT16* volume 1 and volume 2 as well as interactive tools that can be used to investigate relationships between biomass production and environmental effects and explore how different assumptions can influence outcomes. Furthermore, *BT16* volume 2 provides an extensive resource for informing future research and development efforts to enhance environmental benefits and mitigate negative effects associated with a growing bioeconomy.

As identified in the *BT16* volume 1, a wide range of feedstocks and suitable lands are potentially available to realize a future bioeconomy vision. BT16 volume 2 begins to examine the factors that are needed to make that vision more environmentally sustainable. As with existing agricultural and forest production, environmental outcomes of biomass production are contingent on local decisions and practices. This report suggests that with continued diligence and innovation, biomass can be produced and harvested in ways that avoid or mitigate adverse environmental effects while providing tangible environmental benefits.

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