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Following is select front matter from the report and the selected chapter.

2016 BILLION-TON REPORT

Advancing Domestic Resources for a Thriving Bioeconomy

A Study Sponsored by U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Bioenergy Technologies Office

Volume 2:

Environmental Sustainability Effects of Select Scenarios from Volume 1

January 2017

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Additional Information

The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office and Oak Ridge National Laboratory provide access to information and publications on biomass availability and other topics. The following websites are available:

energy.gov

eere.energy.gov

bioenergy.energy.gov

web.ornl.gov/sci/transportation/research/bioenergy/

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DISCLAIMER

The authors have made every attempt to use the best information and data available, to provide transparency in the analysis, and to have experts provide input and review. However, the *2016 Billion-Ton Report* is a strategic assessment of potential biomass (volume 1) and a modeled assessment of potential environmental effects (volume 2). It alone is not sufficiently designed, developed, and validated to be a tactical planning and decision tool, and it should not be the sole source of information for supporting business decisions. *BT16* volume 2 is not a prediction of environmental effects of growing the bioeconomy, but rather, it evaluates specifically defined biomass-production scenarios to help researchers, industry, and other decision makers identify possible benefits, challenges, and research needs related to increasing biomass production. Users should refer to the chapters and associated information on the Bioenergy Knowledge Discovery Framework (bioenergykdf.net/billionton) to understand the assumptions and uncertainties of the analyses presented. The use of tradenames and brands are for reader convenience and are not an endorsement by the U.S. Department of Energy, Oak Ridge National Laboratory, or other contributors.

The foundation of the agricultural sector analysis is the USDA Agricultural Projections to 2024. From the report--“Projections cover agricultural commodities, agricultural trade, and aggregate indicators of the sector, such as farm income. The projections are based on specific assumptions about macroeconomic conditions, policy, weather, and international developments, with no domestic or external shocks to global agricultural markets.” The *2016 Billion-Ton Report* agricultural simulations of energy crops and primary crop residues are introduced in alternative scenarios to the 2015 USDA Long Term Forecast. Only 2015-2024 Billion-Ton national level baseline scenario results of crop supply, price, and planted and harvested acres for eight major crops are considered to be consistent with the 2015 USDA Long Term Forecast. Projections for 2025–2040 in the *2016 Billion-Ton Report* baseline scenario and the resulting regional and county level data were generated through application of separate data, analysis, and technical assumptions led by Oak Ridge National Laboratory and do not represent nor imply U.S. Department of Agriculture or U.S. Department of Energy quantitative forecasts or policy. The forest scenarios were adapted from U.S. Forest Service models and developed explicitly for this report and do not reflect, imply, or represent U.S. Forest Service policy or findings. The Federal Government prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and, where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program.

Executive Summary



Synopsis

With the goal of understanding environmental effects of a growing bioeconomy, the U.S. Department of Energy (DOE), national laboratories, and U.S. Forest Service research laboratories, together with academic and industry collaborators, undertook a study to estimate environmental effects of potential biomass production scenarios in the United States, with an emphasis on agricultural and forest biomass. Potential effects investigated include changes in soil organic carbon (SOC), greenhouse gas (GHG) emissions, water quality and quantity, air emissions, and biodiversity. Effects of altered land-management regimes were analyzed based on select county-level biomass-production scenarios for 2017 and 2040 taken from the *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy (BT16)*, volume 1, which assumes that the land bases for agricultural and forestry would not change over time. The scenarios reflect constraints on biomass supply (e.g., excluded areas; implementation of management practices; and consideration of food, feed, forage, and fiber demands and exports) that intend to address sustainability concerns. Nonetheless, both beneficial and adverse environmental effects might be expected. To characterize these potential effects, this research sought to estimate where and under what modeled scenarios or conditions positive and negative environmental effects could occur nationwide. The report also includes a discussion of land-use change (LUC) (i.e., land management change) assumptions associated with the scenario transitions (but not including analysis of indirect LUC [ILUC]), analyses of climate sensitivity of feedstock productivity under a set of potential scenarios, and a qualitative environmental effects analysis of algae production under carbon dioxide (CO₂) co-location scenarios. Because *BT16* biomass supplies are simulated independent of a defined end use, most analyses do not include benefits from displacing fossil fuels or other products, with the exception of including a few illustrative cases on potential reductions in GHG emissions and fossil energy consumption associated with using biomass supplies for fuel, power, heat, and chemicals.

Most analyses in volume 2 show potential for a substantial increase in biomass production with minimal or negligible environmental effects under the biomass supply constraints assumed in *BT16*. Although corn ethanol has been shown to achieve GHG emissions improvements over fossil fuels, cellulosic biomass shows further improvements in certain environmental indicators covered in this report. The harvest of agricultural and forestry residues generally shows the smallest contributions to changes in certain environmental indicators investigated. The scenarios show national-level net SOC gains. When expanding the system boundary in illustrative cases that consider biomass end use, reductions in GHG emissions are estimated for scenarios in which biomass—rather than oil, coal, and natural gas—is used to produce fuel, power, heat, and chemicals. Analyses of water quality reveal that there could be tradeoffs between biomass productivity and some water quality indicators, but better outcomes for both biomass productivity and water quality can be achieved with selected conservation practices. Biodiversity analyses show possible habitat benefits to some species, with other species showing potential adverse effects that may require additional safeguards. Increasing productivity of algae can reduce GHG emissions and water consumption associated with producing algal biomass, though the effects of water consumption are likely of greater concern in some regions than in others. Moreover, the effects of climate change on potential biomass production show gains and losses in yield among feedstocks across the continental United States. Key research gaps and priorities include actions that can enhance benefits and reduce potential for negative effects of increased biomass production. The results from this report will help DOE, the bioenergy industry, and other institutions continue important discussions on environmental effects and will help chart a path toward a more environmentally sustainable bioeconomy.

Introduction

For more than a decade, DOE has been quantifying the potential of U.S. biomass resources for production of renewable energy and bioproducts. *BT16* volume 1 (released in July 2016) estimates potential biomass that could be available for use in the future at specified prices, assuming a future market for the biomass. Volume 2 (this volume) is a first effort to analyze a range of potential environmental effects associated with illustrative near-term and long-term biomass-production scenarios from volume 1. Environmental effects of biomass production, including effects on SOC, GHG emissions, water quality, water quantity, air emissions, and biodiversity, are modeled. Land management changes associated with the scenario transitions are described and discussed, but modeling ILUC is outside the scope of this report.

As estimated in *BT16* volume 1, 0.8 billion dry tons or 1.2 billion dry tons of biomass are potentially available annually by 2040 at \$60 per dry ton or less,¹ under base-case and high-yield production scenarios² respectively. In addition, an estimated 365 million dry tons of currently used resources were used in 2015 (e.g., corn for ethanol, wood waste) and are assumed to remain constant through the simulation period to 2040 (see table ES.1 in *BT16* volume 1). These potential and current supplies include forestry, agricultural, and waste resources. *BT16* volume 2 focuses primarily on the largest categories of these total potential supplies, i.e., agricultural and forest biomass (see descriptions of feedstock types below). Although energy crops are scarce in the near term, they represent the greatest source of potential biomass in future scenarios.

BT16 assumptions hold total forestland and total agriculture lands constant throughout the 2017–2040 simulation period. The primary type of LUC implied in *BT16* supply scenarios involves land management

within agricultural land. When total land allocation in 2015 (agricultural baseline) is compared to land allocation in 2040 under biomass scenarios, 24 or 45 million acres (net) transition from annual crops to perennial crops under the *BT16* base case or high-yield scenarios, respectively. An additional 37 to 39 million acres of agricultural land transitions from pasture to perennial energy crops (about 8% of total pasture area in the 2015 agricultural baseline).

The potential biomass supplies in *BT16* volume 1 reflect guiding principles for environmental and socioeconomic considerations. These principles are consistent with DOE’s mission to develop biomass as a sustainable resource and with other research that applies environmental constraints to resource analysis (Schubert et al. 2009; Beringer, Lucht, and Schaphoff 2011). For example, simulations in *BT16* volume 1 aim to promote food security and incorporate projected future demands for food, feed, forage, and fiber in the simulations from 2017 through 2040. Constraints are embedded in the scenario assumptions to minimize land-use transitions of highest concern (e.g., the loss of forestlands or productive cropland). Land management constraints that promote environmental quality, such as reduced tillage and residue-retention practices, minimal irrigation (see chapter 2), and reserved land areas to protect biodiversity and soil quality, are assumed in the biomass supply scenarios (see chapter 1). The use of these constraints effectively reduces potential adverse environmental effects and the potential biomass supply itself, compared to biomass that could be available otherwise.

The guiding principles and supply constraints embedded in volume 1 illustrate biomass production opportunities that could minimize or avoid key environmental concerns. However, it is important to further investigate the potential environmental implications of land management changes portrayed in volume 1. This knowledge gap is the motivation behind *BT16* volume 2.

¹ This price is at farmgate or roadside, marginal cost. In GHG emissions analyses and air emissions analyses, supplies delivered to the biorefinery (up to a price of \$100 per dry ton at the reactor throat) are included.

² Scenarios are specific to *BT16* as described under “Scenarios and Data Inputs” and further elaborated in chapter 2.

Goals of Volume 2

In addition to investigating potential environmental effects associated with select biomass production scenarios in volume 1, *BT16* volume 2 also 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 the environmental benefits while minimizing negative impacts of biomass production.

Scenarios from 2017 and 2040 were selected to examine effects of a large increase in biomass production with an emphasis on cellulosic biomass in the future, as well as effects of increasing biomass yield. Key environmental indicators were modeled in the categories of SOC, GHG emissions, water quality, water quantity, air emissions, and biodiversity (see section 1.3). Most results are presented at the county level. Results primarily focus on cellulosic biomass, although some analyses include corn grain to estimate how future cellulosic biomass might compare to conventional biomass production. This volume also presents a qualitative analysis of environmental effects of algae production under a set of scenarios from volume 1 in which algae production is co-located with sources of waste CO₂. An analysis of climate sensitivity of agricultural feedstock productivity under a set of potential future scenarios is also included.

BT16 volume 2 provides a spatially explicit illustration of potential biomass production opportunities and associated environmental implications, rather than a prediction of biomass production and environmental

effects that will inevitably occur. It is important to note that the biomass supply estimates presented in *BT16* are policy independent and based on specified price and yield scenarios that assume a market demand. This report differs from efforts that seek to depict potential biomass demand and related market, environmental, and land-use interactions under specifically defined business-as-usual or policy conditions. Assumptions used in *BT16* regarding land transitions and supply constraints have implications for the environmental effects analyses, and modifying these assumptions would likely result in different environmental effects.

Scenarios and Data Inputs

A small subset of the agricultural and forestry assessment scenarios and scenario years from *BT16* volume 1 was selected for analysis in *BT16* volume 2. The scenarios in volume 2 include a low- and a high-yield scenario and near-term and long-term estimates from volume 1. “Yield” refers to annual improvements in crop yield for commodity crops and energy crops. The \$60 per-dry-ton price model runs of the base-case³ (i.e., 1% annual yield increase, referred to as “BC1” in *BT16* volume 1) and high-yield (i.e., 3% annual yield increase, referred to as “HH3”) scenarios were chosen from the agricultural assessment in volume 1. From the forestry assessment, the baseline (moderate housing, low wood energy demand, referred to as “ML”) and high housing–high wood energy (“HH”) scenarios were selected.⁴

Most chapters in volume 2 analyze county-level outputs from the following volume 1 biomass scenar-

³ The terms base case and baseline have specific meanings in *BT16* that may differ from the use of these terms in other studies.

⁴ In the forestry assessment, biomass availability decreases from 2017 to 2040. Furthermore, biomass is lower in the HH 2040 scenario than the ML 2040 scenario because of the high demand assumed for housing.

ios, all assuming a roadside price of up to \$60 per dry ton⁵ (table ES.1; fig. ES.1; and table ES.2):

1. **BC1&ML 2017:** 2017 base-case agricultural combined with baseline forestry scenarios: 326 million dry tons
2. **BC1&ML 2040:** 2040 base-case agricultural combined with baseline forestry scenarios: 807 million dry tons

3. **HH3&HH 2040:** 2040 3% high-yield agricultural combined with HH forestry scenarios: 1.1 billion dry tons.

Many chapters analyze agricultural biomass only or forestry biomass only. Although the use of wastes for energy has potential environmental benefits, quantifying these effects is beyond the scope of this analysis. These effects are considered qualitatively in the final chapter of this report.

Table ES.1 | Biomass Supplies Identified in *BT16* Volume 1 and Evaluated in Volume 2 for Select Scenarios and Years (in Million Dry Tons)

Scenario	Identified in volume 1			Evaluated in volume 2		
	BC1&ML 2017	BC1&ML 2040	HH3&HH 2040	BC1&ML 2017	BC1&ML 2040	HH3&HH 2040
New potential	343	826	1,154	192	669	997
Currently used	365	365	365	134	138	139
Total	709	1,192	1,520	326	807	1,136
Notes	New potential and currently used resources include agricultural and forest biomass and waste resources.			New potential includes agricultural and forest biomass only. Currently used resources include only corn ethanol and soybean biodiesel portions. Waste resources are excluded.		

⁵ GHG and air emission analyses are limited to supplies at \$100 or less delivered to the biorefinery.

Figure ES.1 | Biomass resources of the three primary scenarios evaluated in this volume (in million dry tons)⁶

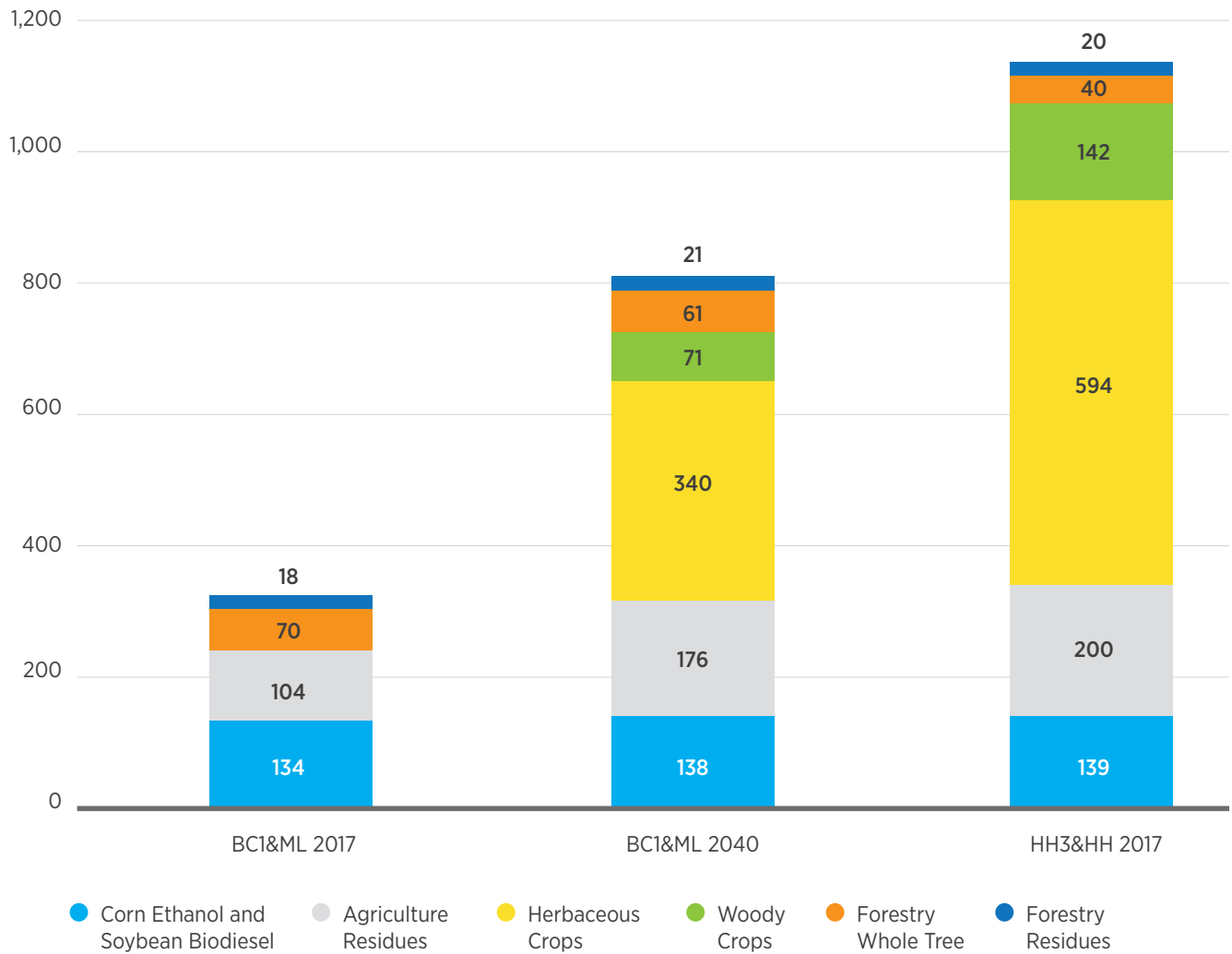


Table ES.2 describes the agricultural and forestry scenarios; chapter 2 provides more details on these scenarios and a brief summary of the methodology used to generate data in volume 1 that are analyzed in volume 2.

⁶ The supplies analyzed in volume 2 exclude about 230 million dry tons of currently used resources (current uses beyond corn ethanol and soybean biodiesel) and about 140 million dry tons of additional waste resource potential reported in volume 1. In the forestry assessment, biomass availability decreases from 2017 to 2040. Furthermore, biomass is lower in the HH 2040 scenario than the ML 2040 scenario because of the high demand assumed for housing.

Table ES.2 | Scenarios Considered in *BT16* Volume 2 Analyses

Combined agricultural and forestry scenarios		Agricultural scenarios			Forestry scenarios			
Combined identifier	Year	Identifier	Energy crop annual yield increase ^a	Corn annual yield increase	Identifier	Description	Housing starts	Wood energy demand
BC1&ML 2017	2017	BC1 (base-case yield)	1%	0.8%	ML (baseline)	Moderate housing–low wood energy	Returns to long-term average by 2025	Increases by 26% by 2040
BC1&ML 2040	2040	BC1 (base-case yield)	1%	0.8%	ML (baseline)	Moderate housing–low wood energy	Returns to long-term average by 2025	Increases by 26% by 2040
HH3&HH 2040	2040	HH3 (high yield)	3%	1.9%	HH (high demand)	High housing–high wood energy	Adds 10% to baseline in 2025 and beyond	Increases by 150% by 2040

^a Yield improvements are only applied at establishment and are not applied after year one for perennial crops until replanting

The following is a summary of results from chapters 3 through 13 in this report.

Land Allocation and Management

Chapter 3 of *BT16* volume 2 aims to clarify LUC implications of the select *BT16* scenarios. Unlike most LUC studies, volume 2 does not analyze the LUC effects of a policy. *BT16* assumptions hold the forestland and agricultural land base constant throughout the 2017–2040 simulation periods. Supply constraints limit the total land available for energy crops in *BT16*

based on rainfall, rates of transition, and caps on total area allowed to transition to new crops (see chapter 2).

The primary type of LUC associated with *BT16* supply scenarios involves changes in agricultural land management practices. For example, the area that would be managed as perennial cover in 2040 is 24 and 45 million acres greater under BC1 and HH3 (respectively) than the area of perennial cover in the U.S. Department of Agriculture (USDA) 2015 agricultural baseline. Additional changes in management occur on pasture: 37–39 million acres, or about 8% of total pasture area in the 2015 agricultural baseline, would undergo changes in management for ener-

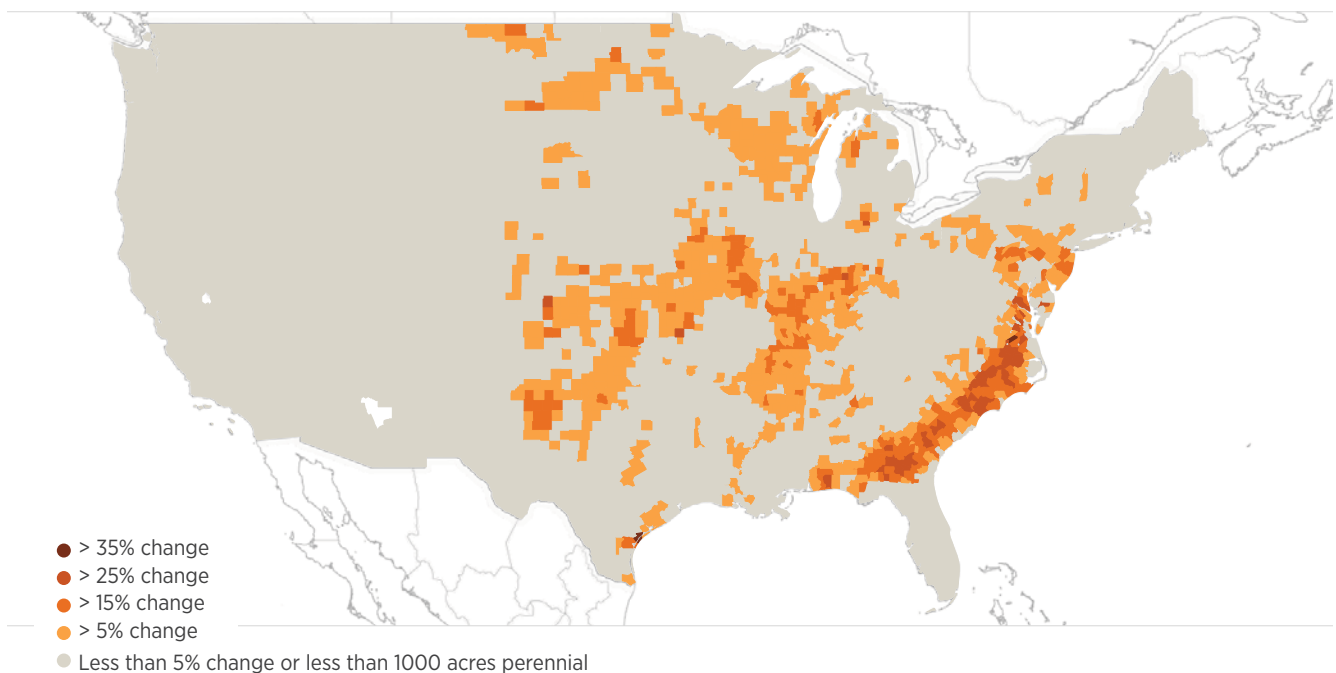
gy crops by 2040. Fencing and pasture rotation are management practices that are assumed to intensify production on another 60 million acres of pasture.

The geospatial distribution of the net change from annual to perennial cover in BC1 is illustrated in figure ES.2. By 2040, changes in land management affect about 3% of total cropland (e.g., transition from annual to perennial cover) and 19% of total pastureland, with 11% being intensified and 8% being managed for energy crops (percentages here are relative to the total areas of cropland and pastureland in the 2015 agricultural baseline). As with any model, input

parameters and assumptions regarding land classes, land area available for different uses, and productivity influence how land is allocated among traditional and energy crops over time.

Chapter 3 includes a review of LUC studies and concludes that clear definitions of land parameters and effects are essential to improve LUC analyses. The large variability in results from previous LUC analyses associated with increased biomass production underscores the need for more consistent and transparent approaches.

Figure ES.2 | Geospatial distribution of changes in perennial cover under the base-case (BC1) scenario



Change in perennial cover by county is the difference between the percentage of total agricultural acres (cropland +pasture +idle land) managed as perennial cover in the 2040 base case (BC1) and the percentage managed as perennial cover in the 2015 agricultural baseline. The maximum county-level increase in perennial cover in BC1 was 38%. The light grey shading over the majority of counties indicates that change was below 5% (either an increase or decrease in perennial cover). Larger increases in percentage of perennial cover occur on agriculture land in the Southeastern Plains and in areas where simulated returns from conventional crops are not as competitive with energy crops under the conditions defined in the base-case scenario.

Greenhouse Gas Emissions, Soil Carbon, and Fossil Energy Consumption

The GHG emissions and fossil energy consumption associated with producing potential biomass supply in the select *BT16* scenarios include emissions and energy consumption from biomass production, harvest/collection, transport, and pre-processing activities to the reactor throat. Emissions associated with energy, fertilizers, and agricultural chemicals that are consumed in biomass production are also included. Energy consumption and emissions for biomass logistics are considered only for biomass with delivered costs below \$100 per dry ton. The contribution of changes in SOC to GHG emissions as a result of producing agricultural biomass is also considered. Changes in forestry soil carbon are not analyzed because the land area in forestry stayed constant and no major forestry land management changes were considered. However, a review of potential impacts of using forest biomass as a bioenergy feedstock on soil carbon is discussed. This analysis indicates potential GHG-emissions hotspots from producing biomass and illuminates drivers for these emissions, which can inform efforts to reduce the GHG emissions and energy consumption of biomass-derived fuels, products, and power.

Generally, results show that conventional crops would have a higher share of GHG emissions per ton than energy crops, and the GHG intensity (emissions per mass) of biomass production would be lower in higher-yield scenarios (e.g., HH3 and HH 2040). Emissions from the production of forestry biomass would be, in general, lower than for other crops because not all forestry plots undergo site preparation, which consumes diesel fuel, and because fertilizers are used more sparingly than for agricultural crops. Overall, forest residues would be a minor contributor

to both biomass tonnage and GHG emissions in these scenarios. Other factors besides yield that influence GHG-emissions intensity include advanced logistics operations and SOC changes. The latter factor varies in importance by region, yield, and by final and initial land allocations. In general, growing energy crops on historical cropland typically leads to SOC gains. When pasture is used to produce biomass, however, only a few energy crops sequester soil carbon. This analysis found that under the two *BT16* 2040 scenarios, changes in SOC could result in a net soil carbon sink nationally, largely due to the land transition to energy crops (particularly miscanthus).

It is important to note that *BT16* is not a life-cycle analysis of fuels, products, or power produced from the biomass. However, a few illustrative case studies were 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.

Water Quality (Agriculture)

A water-quality analysis addressed the question: how can future biomass production be managed to protect water quality with minimal decreases to feedstock yield? Two tributary basins of the Mississippi River that have contrasting future biomass-feedstock profiles under the BC1 2040 scenario were selected for analysis. The Iowa River Basin (IRB) supports

corn-soy-dominated agriculture with corn stover as the dominant potential cellulosic feedstock. The Arkansas-White-Red (AWR) River Basin grows a broader diversity of cellulosic feedstocks including perennial grasses in the 2040 scenario; sorghum; and residues from wheat, corn, and grain sorghum. This analysis found that suitable combinations of conservation practices improved water quality with relatively small decreases in feedstock yield in both river basins. Results for the IRB suggest that four practices (i.e., riparian buffer, cover crop, slow-release nitrogen fertilizer, and tile-drain control), if additive, could reduce nitrogen loading by more than 65% for watersheds planted in corn. In the AWR River Basin, higher fertilizer levels produced higher yields of perennial grasses and short-rotation woody crops (SRWCs), higher nitrate loading, and lower levels of sediment and phosphorus draining into this basin. Thus, the challenge is to balance the other three indicators (i.e., productivity, sediment, and phosphorus) against nitrate. In addition, the results reflected a water-quality benefit of coppiced willow, which minimized trade-off between nutrient and sediment reduction and biomass yield. Filter strips also provided water-quality benefits from SRWCs. Results from this analysis can be used to identify location-specific management practices that can achieve simultaneous biomass production and water-quality goals.

Water Quality (Forestry)

Despite decades of research into forest harvest effects on water quality, longterm and consistently collected data to parameterize process-based models of water-quality related to biomass removal in forests are scarce. Therefore, this analysis developed a simple, empirical modeling approach to estimate sediment and nutrient response to the total acres harvested for biomass within a given county. Results were aggregated to three regions of the United States: the South, West, and North (see chapter 6, fig. 6.1, for

regional divisions). Modeled estimates show there could be regional variation in how biomass harvest would influence water quality. Sediment loads often increase after intensive site preparation in plantations. Because these practices are most common in the South, results indicate that absolute sediment loads and percent increases over reference conditions could be greatest in the South, with smaller increases in the West and North. Alternatively, results indicate that absolute nitrate loads could increase most in the North; however, when considered as an increase over regional reference, the highest increase occurs in the South, followed by the North and then the West in ML 2017. In the ML 2040 and HH 2040 scenarios, the largest percent increase is still in the South, but the North is surpassed by the West. For the scenarios investigated, sediment flux is the most dynamic water-quality parameter, as it could increase nearly 40% or more after biomass harvests, particularly in areas where mechanical site preparation is common prior to planting. Responses for nitrate and total phosphorus tend to be less dynamic, with high-yield scenarios typically resulting in <10% increase over baseline loadings. Continued adherence to and increased adoption of best management practices on lands on which silviculture is practiced should minimize biomass-harvest impacts.

Water Quantity (Forestry)

The amount and distribution of live forest biomass is closely related to water yield (outflow from a drainage basin) and water supply. Biomass harvesting has the potential to alter water quantity indicators by altering the ecohydrological processes (evapotranspiration in the ecosystem in particular). This analysis investigated how prescribed forest-harvesting scenarios affect mean seasonal and annual water yield at the county level. The three scenarios modeled all have minor impacts on water quantity at the county level, with water-yield responses increasing 0.3% or

less, largely because of the small areas of harvesting (<5%) in most counties. The small magnitude of hydrological response to biomass removal may not have much significance, positive or negative, in terms of water supply at the county level; however, concentrated biomass-removal activities may cause substantial local impacts on watershed hydrology, such as increasing stormflow volume and potentially causing water-quality concerns. County-level estimates of biomass harvesting do not provide the spatial information sufficient for watershed-scale assessment. However, this assessment identifies regions that are most likely to experience hydrological impacts under the scenarios investigated. Future watershed-scale studies should focus on these regions. Also, other ecologically relevant hydrologic parameters, such as base flow and peak flow rates, should be examined in addition to annual water yield.

Water Consumption Footprint (Agriculture and Forestry)

BT16 volume 1 showed the potential for increasing biomass production without reliance on irrigation. This water footprint analysis investigated water-resource demand for the three select *BT16* scenarios (agricultural combined with forestry scenarios) by estimating the water footprint and conducting geospatial analyses to examine the interplay between feedstock mix and water consumption at three scales: county, state, and national. Biomass requires water from irrigation or rainfall, and some deep-rooted energy crops, such as perennial grasses and SRWCs, as well as forest biomass, can grow without irrigation, which was the assumption in *BT16* volume 1. The water footprint analysis illustrated greater rainfall use on a volume basis for both agricultural and forest biomass in 2040 scenarios, compared to 2017, with

more biomass produced and harvested in the 2040 scenarios. Lower consumption of irrigation water is associated with the water footprint of 2040 scenarios compared to 2017. Irrigation for corn was attributed to the grain rather than the residues. Overall, water consumption to produce a ton of biomass remains unchanged in the scenarios. Although both rain water and irrigation water are consumed, rain water is generally preferred because of its low cost, especially in the water-rich regions. Additional research is needed to place water consumption findings in the context of regional water needs.

Air Pollutant Emissions (Agriculture and Forestry)

This analysis developed county-level emission inventories for seven non-GHG, regulated air pollutants⁷ for the three biomass supply scenarios (agriculture combined with forestry). These inventories consider emissions from field preparation through harvest, including chemical application and on-farm (or on-forest) transportation, along with transportation and preprocessing for a selected portion of feedstock to the biorefinery. Upstream air emissions (e.g., emissions associated with fertilizer production) and air emissions avoided by displacing other products or fuels with biomass-derived products or fuels were beyond the scope of this study. However, emissions reductions from displacement or upstream emissions may be substantial and should be the focus of future study.

The results indicate that although the air pollutant emissions per dry ton of feedstock produced would vary by county and pollutant, they are generally lower for cellulosic feedstocks than for corn grain. However, this study also shows that the emissions resulting from increased biomass feedstock produc-

⁷ The seven pollutants include ammonia, nitrogen oxides, volatile organic compounds, particulate matter (PM_{2.5}, PM₁₀), carbon monoxide, and sulfur oxides.

tion could pose challenges for local compliance with air-quality regulations. The variability in county-level emission estimates suggests that certain practices and production locations result in much lower emissions than others. Higher yields, lower tillage requirements, and lower fertilizer and chemical inputs are important factors that contribute to lower air emissions. In addition, using biomass more locally or using more fuel-efficient long-distance transportation methods (e.g., rail or densified biomass) could potentially decrease emissions from truck transport.

For the *BT16* scenarios analyzed, about a quarter of the counties are estimated to emit direct and precursor criteria pollutant mass emissions around 1% to 10% of the current National Emissions Inventory (NEI) (see chapter 9). Emissions in areas currently in attainment could pose challenges in the future or for surrounding areas. In areas currently in non-attainment for the Clean Air Act's National Ambient Air Quality Standards (NAAQS), the absolute increase in mass emissions under *BT16* scenarios is estimated to be small (a few percentage points of the current NEI baseline emissions; see chapter 9) relative to current attainment counties. Emissions in non-attainment counties are more likely to pose challenges to meeting the Clean Air Act's NAAQS in the context of population and economic growth.

The emission estimates provided in this study could be coupled with air-quality screening tools to evaluate changes in emission concentrations, to assess human health impacts, and to help inform future air-quality planning.

Biodiversity (Agriculture)

Bird species habitat and species richness in agricultural landscapes were modeled as a way to investigate questions about potential effects to biodiversity resulting from increased energy crop production. The approach used species-distribution modeling to mod-

el bird probabilities of occurrence in different geographic locations as a function of climate and land use/land cover. For the majority of counties, grassland, forest, and generalist birds showed no change in occupancy under the base-case scenario (BC1) in 2040. For the other counties, nearly equal percentages of species were estimated to occupy fewer and more counties. However, decreases in richness were larger than increases for forest and generalist species. The analysis showed that grassland birds would respond positively to switchgrass in comparison to row crops, but the responses to miscanthus in the United States are less well understood. Because many species are affected by the type and timing of management activities, as well as by land cover, guidelines for managing bioenergy crops may be needed to maintain biodiversity of grassland birds and other species as biomass production increases. This analysis is useful in showing where energy crops could be grown with potential benefits to bird species and where more research is needed to understand the wildlife consequences of adopting particular energy crops and management practices.

Biodiversity (Forestry)

Using harvest acres generated in volume 1 of *BT16*, this analysis assesses and compares implications for biodiversity of potential forest biomass produced in the near term (2017) and long term (2040). A coarse-filter approach was taken to assess effects of woody-biomass harvesting on biodiversity. Woody-biomass harvest in the examined scenarios would primarily affect biodiversity through changes in forest structure, both at the stand (e.g., loss of canopy cover and residues) and landscape scales (e.g., distribution of stand ages from clearcutting smaller-diameter trees). Species could be negatively or positively affected at the ecoregion scale based on the primary forest-habitat type sourcing the feedstock, and at the local scale based on species distributions, specific habitat requirements, and the proportion of

forest types affected by biomass harvest. Case studies of taxonomic groups or single species with life-history traits that rely functionally on dead and downed wood or changing canopy cover are discussed. This information may be used in conjunction with other finer-scale biodiversity assessments (e.g., state wildlife action plans, county project planning, etc.) to identify species that may be vulnerable to changes. Conservation of species amidst an increasing national demand for woody biomass will require taking a multi-scale planning approach and continued monitoring of species that are functionally dependent on the material to fulfill their life-history requirements.

Qualitative Analysis of Environmental Effects of Algae Production

The environmental effects analysis for algae emphasizes scenarios from volume 1 of *BT16*, wherein open-pond biomass-production facilities are co-located with coal-fired power plants, natural gas power plants, or ethanol-production plants to reduce cost and to use waste CO₂ that would otherwise be emitted directly into the air. GHG emissions and water-quality indicators are emphasized, though other indicators are discussed. Variables include freshwater and saltwater strains, current and future high-productivity scenarios, and fully and minimally lined ponds. Few examples of commercial algae production exist, and few environmental indicators have been measured for systems resembling those that were modeled. However, some qualitative results are clear: (1) increasing productivity has benefits for water consumption on a per-mass basis; (2) GHG emissions are generated from plastic liner production and piping CO₂ in flue gas to production facilities, so minimizing that infrastructure can minimize GHG emissions; and (3) water consumption can be reduced through the use of sealed systems or recycling, but the broader significance of doing so depends on the regional context, including weather and climate, competing water uses,

type of water used, and requirements of regional biota. Enclosed photobioreactors would have different environmental effects, such as lower water consumption because of very low evaporation, but these were not examined in *BT16* volume 1.

Climate Sensitivity of Feedstock Productivity

The modeling of potential biomass feedstock responses to alternative climate change scenarios indicates that, much like conventional crops and other vegetation, biomass feedstocks are sensitive to climatic conditions. The U.S. climate is projected to change significantly in coming decades, particularly for regions such as the Midwest and Southeast, which are considered priority landscapes for the development of biomass resources. Projections of biomass-yield responses to climate change scenarios indicate that the expected warmer climate could alter yields and shift the geographic distribution of commercially important feedstocks (e.g., sugarcane could be grown in more northerly latitudes than is done currently). Projections show that both significant increases and decreases in feedstock yields could occur in future decades, given the current genetic composition of feedstocks, the levels of technology and management associated with feedstock production, and the biomass supply chain. These changes may have greater significance at the regional level than at the national level. Variability in feedstock response is a function not only of geographic variability in current climate and future climate change, but also variability in the inherent sensitivity of different feedstocks and cultivars to particular changes in climate. 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 CO₂ fertilization, and different management practices and economic constraints would assist in reducing uncertainties associated with purely empirical methods.

Synthesis and Conclusions

BT16 volume 1 demonstrates the technical and economic potential for increasing national biomass production to support a thriving U.S. bioeconomy. Volume 2 of *BT16* is a first effort to quantify potential environmental effects associated with illustrative near-term and long-term biomass-production scenarios from *BT16* volume 1. Taken together, this collection of analyses reveals benefits, opportunities, challenges, and tradeoffs that should be considered as biomass production increases.

The results must be interpreted in light of uncertainties. As with *BT16* volume 1, results presented in *BT16* volume 2 are neither predictions nor final answers, and they pertain only to the select scenarios. For example, the scenarios reflect the assumption 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 direction than the comparisons presented here.

Although environmental effects vary by location and biomass type, several general conclusions across indicators are apparent from the simulated results and analyses. Most counties analyzed in the scenarios show potential for a substantial increase in biomass production with minimal or negligible effects on water quality, water quantity, air pollutant emissions, and biodiversity (for avian species analyzed in agricultural scenarios) under the biomass supply constraints assumed in *BT16*. Cellulosic biomass generally shows, favorable performance relative to conventional feedstocks, with harvest of agricultural and forestry residues generally showing the smallest contributions to changes in environmental indicators.

As evaluated in volume 2, biomass produced and delivered to the reactor throat generates GHG emissions because fuel, fertilizer, and agricultural chemicals are consumed. In some counties SOC gains from producing deep-rooted cellulosic feedstocks offset these emissions. Furthermore, as shown in illustrative cases, displacing fossil fuel-derived fuels and products with biomass-derived fuels and products can reduce GHG emissions on a full life-cycle basis that takes into account all life-cycle stages: biomass production and transportation, biomass conversion, and biofuel combustion.

In some locations and under some biomass supply scenarios, challenges may arise for SOC, air quality, water availability, and water-quality management, all of which would benefit from further research and technological improvements. For example, conclusions regarding water consumption by algae in production ponds improve if the recycling of process water is considered. The significance of biomass-related water quality and air quality changes for human health and ecosystems would need to be studied. Biodiversity analyses show a range of outcomes depending on species and location, with possible benefits to richness and range for some species and with other species showing potential adverse impacts that may require additional safeguards and development of wildlife-friendly practices.

This collection of analyses illustrates that biomass production should be integrated into agricultural and forestry systems with consideration of local and regional environmental contexts. Estimates of environmental effects for the scenarios considered in this volume can help the research community, industry, and other decision makers in prioritizing research efforts and data collection, as well as moving toward recommendations of priority locations for biomass production and location-specific best management practices. Research, science-based monitoring, and adaptive management can be used to further enhance environmental benefits of biomass production while

mitigating potential negative effects. Strategies to enhance environmental outcomes from biomass production (e.g., landscape design, precision agriculture, the use of waste, and biomass production in conjunction with wastewater remediation) are discussed in chapter 14. Although this study focuses on environmental

effects, it is important that future studies investigate environmental, social, and economic effects in a more integrated manner to provide a broader view of sustainability with respect to expanded biomass production in the United States.

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