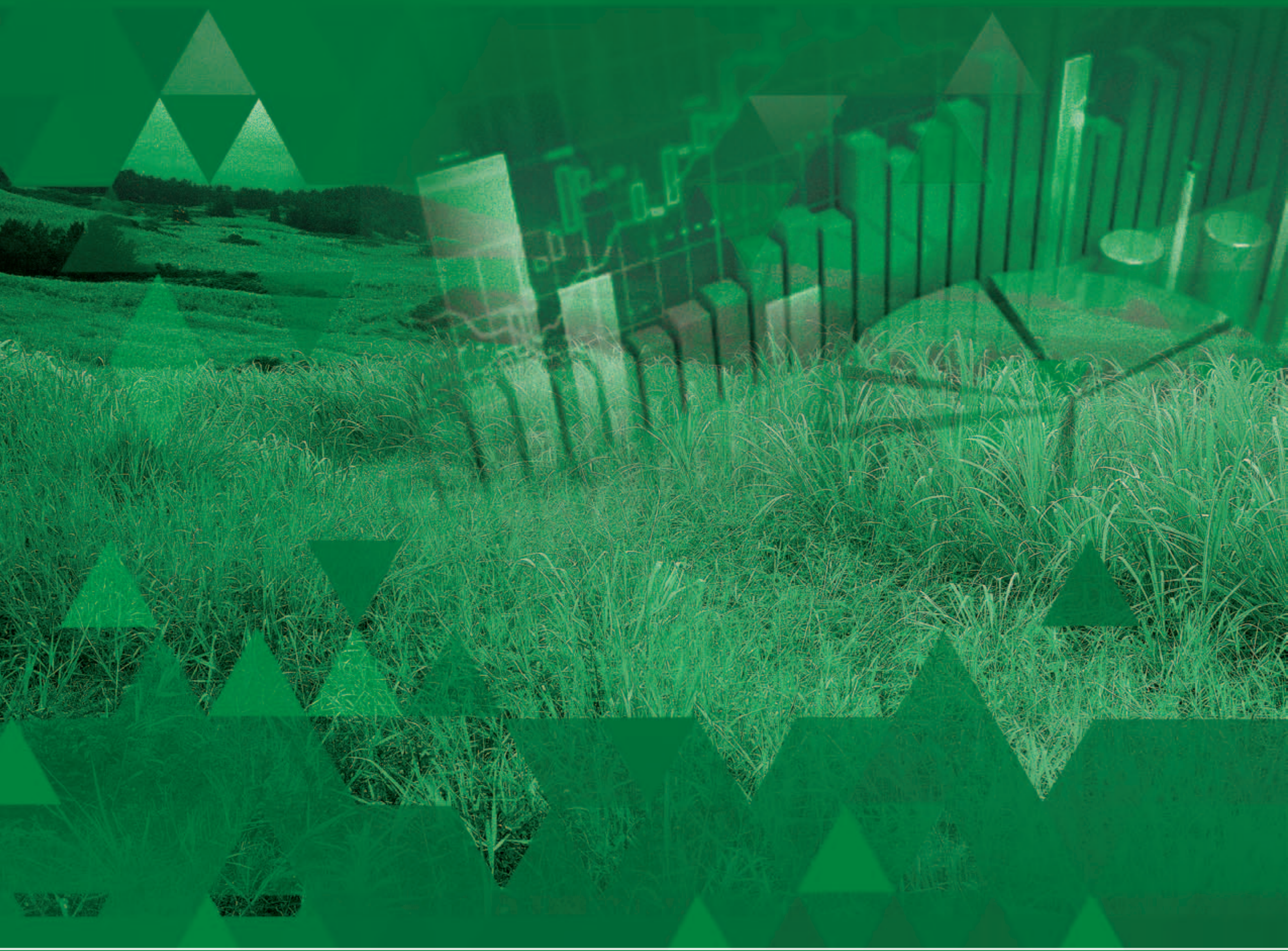
01 | Introduction



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1.1 Background

With the goal of informing national bioenergy and bioproducts research, development, and deployment strategies, the 2016 *U.S. Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (*BT16*), is the third in a series of national biomass resource assessments commissioned by the U.S. Department of Energy (DOE). The *BT16* report is composed of two volumes. Volume 1 focuses on biomass resource analysis (i.e., the potential economic availability of cellulosic and other feedstocks under specified market scenarios) as an update to the two previous Billion-Ton reports, i.e., the *2005 Billion-Ton Study* (Perlack et al. 2005) and the *2011 Billion-Ton Update* (*BT2*) (DOE 2011). In *BT16* volume 1, supplies are quantified under specified constraints. *BT16* volume 2, this report, investigates potential environmental effects of producing biomass supplies for a small set of scenarios simulated in volume 1.

Increasing biomass use can create economic opportunities, enhance energy security, and provide environmental benefits (Rogers et al. 2016). Federal policies aim to foster increased biomass utilization, focusing on growth of second-generation cellulosic biofuels. A report by EPA (2011) concluded that environmental effects of biomass use in the future will be determined by the choice of feedstock, land use change, cultivation, and conservation practices. *BT16* volume 2 investigates a range of these factors to improve understanding of potential environmental outcomes associated with increased biomass production.

Most analyses in volume 2 simulate environmental effects of potential agricultural and forestry biomass production at the county level.[1] The land-use (i.e., land management) change assumptions associated with the scenario transitions are described and discussed, including the assumption and modeling constraint that the agricultural and forestry land bases remain constant during the simulation period. This volume also presents a qualitative analysis of environmental effects of algae production under carbon dioxide (CO_2) co-location scenarios, as well as an analysis of climate sensitivity of agricultural feedstock productivity under a set of potential future scenarios. Finally, strategies to enhance environmental outcomes are described.

Several constraints designed to maintain aspects of environmental quality are employed in volume 1, carried over from the 2011 *BT2*. These constraints include assumptions about tillage classes, residue availability, irrigation, and land-exclusion areas. Supply constraints are summarized in chapter 2 and are described in more detail in BT16 volume 1. Some of these constraints reduce the national potential biomass supply estimates in volume 1 when compared to biomass potential without these constraints. Despite these supply reductions, volume 1 illustrates a situation where large volumes can be produced while not using environmentally sensitive lands or exacerbating soil erosion. However, more thorough analyses are required to estimate possible environmental effects of producing the potential biomass supplies simulated in *BT16* volume 1, and to determine how different types of environmental effects could vary across locations, years, biomass type, biomass yield increase rates, and management practices.

[1] The potential benefits of utilizing biomass wastes for energy (after reduce, reuse, and recycling options have been exhausted) are described in chapter 14 but are not evaluated quantitatively in this volume. Environmental effects of algae biomass are described qualitatively in chapter 12.

1.2 Objectives

BT16 volume 2 seeks to (1) advance the discussion and understanding of environmental effects that could result from significant increases in U.S. biomass production and (2) accelerate progress toward a sustainable bioeconomy by identifying actions and research that could enhance the environmental benefits while minimizing negative impacts of biomass production.

In previous DOE-funded research, indicators were identified that support evaluation of environmental sustainability for a variety of bioenergy systems (McBride et al. 2011; Efroymson and Dale 2015). For this study, environmental indicators were selected in the categories of soil carbon, greenhouse gas (GHG) emissions, water quality, water quantity, biodiversity, and air emissions (see section 1.3). *BT16* volume 2 also includes a discussion of land-use (i.e., land management) change assumptions associated with the scenario transitions (but not including analysis of indirect land-use change [LUC]), analyses of climate sensitivity of feedstock productivity under a set of potential scenarios, and a qualitative assessment of environmental effects of algae production under CO_2 co-location scenarios.

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 environmental benefits, opportunities, and limitations related to increasing biomass production at the local, regional, and national levels. For example, the analyses in this volume can help identify where care should be taken when producing certain feedstocks or where further safeguards are needed to prevent or mitigate potential negative impacts of commercial scale production. Results can also help stakeholders identify locations that are more or less appropriate for certain feedstocks given local conditions, or possible issues that will require further research, monitoring, and adaptive management.

Terrestrial biomass supply projections were simulated in volume 1 using the Policy Analysis System model for agriculture and the Forest Sustainable and Economic Analysis Model for forestry. *BT16* assumptions hold total forestland and total agriculture lands constant throughout the simulation period. Chapter 2 provides a summary of the methodology used to generate the data in volume 1 that are analyzed in volume 2.

It is important to note that the biomass supply potentials presented in volumes 1 and 2 are policy-independent and based on specified price and yield scenarios as well as guiding principles that reflect certain environmental and socioeconomic considerations. For example, some principles aim to maintain environmental quality, such as improved tillage and residue-removal practices, exclusion of irrigation, and reserved land areas to protect biodiversity and soil quality. In this sense, this report may differ from other efforts seeking to depict potential biomass demand and related market, environmental, and land-use interactions under business-as-usual (BAU) scenarios or other specific policy conditions. Further, the scenarios represent total potential biomass production at a market price of $60 per dry ton regardless of end use. Because future end uses may be some unknown mix of biofuels, biopower, and bioproducts, this report presents the biomass supplies as being potentially available for these end uses, but the analysis of environmental effects is limited to production, preprocessing, and delivery of the supplies.

1.2.1 Scenarios

Most chapters in volume 2 analyze three biomass scenarios from volume 1 or a subset of these, such as focusing only on agricultural or only on forestry scenarios. These scenarios assume a price of up to $60 per dry ton at the roadside (i.e., prior to transport, storage, and processing at a biorefinery). This price point is potentially viable and could provide more than 1 billion tons[2] of biomass by 2040. The scenarios include

- **BC1&ML 2017**: 2017 base-case agricultural combined with baseline forestry scenarios: 326 million dry tons[3]
- **BC1&ML 2040**: 2040 base-case agricultural combined with baseline forestry scenarios: 807 million dry tons
- **HH3&HH 2040**: 2040 3% high-yield agricultural combined with HH forestry scenarios: 1.1 billion dry tons.

In these scenarios, BC1 and HH3 are agricultural scenarios and ML and HH are forestry scenarios.

Chapter 2 provides a description of these scenarios. The scenarios were selected to assess and compare potential environmental effects during two time periods with two potential agricultural yield-increase assumptions for the latter year (2040). Potential near-term biomass production is represented in the 2017 scenarios, and significantly expanded biomass production that could occur is represented in the 2040 scenarios. Differences in environmental effects between relatively low and potentially high levels of annual biomass production can be considered by comparing the 2017 and 2040 scenarios. Yield-based environmental effects can be shown by comparing the two 2040 scenarios, given that future biomass availability would greatly depend on yield growth and other technological improvements. For more information on the base-case and high-yield scenarios, see chapter 2 or volume 1. Alternative future scenarios are possible.

In the scenarios identified above, resources evaluated in volume 2 are a subset of the potential resources identified in volume 1. The resources evaluated in volume 2 exclude waste resources and include only corn ethanol and soybean biodiesel portions of currently used resources. Total potential supplies identified in volume 1 and the subset of those supplies analyzed in volume 2 are identified in table 1.1.

Table 1.1 | Biomass Supplies Identified in *BT16* volume 1 and Evaluated in volume 2 for Select Scenarios and Years (in Million Dry Tons)

	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.		

[2] Here and elsewhere in the report, tons are reported as dry short tons, unless specified otherwise.

[3] The terms base case and baseline have specific meanings in *BT16* that may differ from definitions in other studies.

This study does not include a simulated 2040 BAU scenario because of data limitations and uncertainties about multiple sectors in the future that are outside the scope of this study. The 2017 scenario may represent some characteristics of a future BAU scenario because the former scenario includes only currently available resources (i.e., agricultural residues and forestland resources) with production of conventional crops maintained at current levels. However, the scenario does not include several important characteristics of a BAU case, such as future changes in overall demand, market impacts, and crop yields.

The distribution of potential biomass across the nation in the scenarios reflects the assumption that the total agricultural-land base and the total forestland base do not change between the present and 2040. Modifying scenarios to allow transitions between these major land classes could result in different estimates of environmental effects.

Certain indicators evaluated in this report, including air emissions and GHG emissions, could be affected not only by biomass production, but also by biomass harvest and transportation. To enable analyses of these indicators, logistics inputs (e.g., diesel) were estimated using the Supply Characterization Model (SCM). For the three scenarios, SCM was used to simulate distribution of potential biomass resources to a national grid of hypothetical biorefinery locations and to simulate associated fossil fuel consumption based on current road networks. The application of SCM is described in chapter 6 of *BT16* volume 1 and costs estimated in the model are described in section 2.4.4 of this volume.

1.2.2 Research Questions

BT16 volume 2 investigates and reports on the following questions related to potential biomass production in select scenarios:

- What are the 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?

Comparisons and insights are based on quantification of environmental indicators for the select scenarios.

1.3 Environmental Indicators of Bioenergy Sustainability

Sustainability is an aspirational concept that denotes the capacity to meet current needs while maintaining options for future generations to meet their needs. Enhancing sustainability of bioenergy systems is part of the mission of the DOE Bioenergy Technologies Office. Specifically, the Office's strategic goal for bioenergy sustainability is to understand and promote the positive environmental, economic, and social effects and reduce the potential negative impacts of bioenergy production activities (DOE 2016). To make the concept of sustainability operational, consistent approaches are required that facilitate comparable, science-based assessments using measurable indicators of environmental, economic, and social processes (Hecht et al. 2009; McBride et al. 2011; Dale et al. 2013). Progress toward defined sustainability objectives can be estimated using these indicators, which can guide behavior toward those intended outcomes.

Many institutions and researchers have proposed indicators to evaluate sustainability of bioenergy pathways (e.g., Roundtable on Sustainable Biomaterials [RSB 2010]; Global Bioenergy Partnership [GBEP 2011]; and the Council on Sustainable Biomass Production [CSBP 2012]). Building from these efforts, researchers at Oak Ridge National Laboratory selected a generic and practical set of indicators to support environmental sustainability of biomass and bioenergy (McBride et al. 2011). Most of these indicators are modeled in this study (table 1.2). These include indicators of soil carbon, water quality and quantity, GHGs, biodiversity, and air emissions. For the purposes of *BT16* volume 2, these indicators are termed “environmental indicators.”

Appropriate indicators for a particular application depend on the context for their intended use (Efroymson et al. 2013); therefore, the set of indicators from McBride et al. (2011) in table 1.2 is appropriate for some but not all uses. The context of an assessment of environmental effects typically includes the purpose of the assessment, biomass production and distribution systems, end use, policy conditions, stakeholder values, location, temporal influences, spatial scale, baselines, and reference scenarios. This study adopts a slightly modified list of the indicators proposed in McBride et al. (2011) for the purpose of this initial effort to analyze environmental effects of select terrestrial biomass scenarios from volume 1 (table 1.2). Furthermore, a slightly different set of indicators has been proposed to evaluate the environmental effects of algal biofuels (Efroymson and Dale 2015) and is described in chapter 12.

Table 1.2 | General Environmental Indicators from McBride et al. (2011) (Numbered) and Indicators Modeled for This Analysis (Light Green)

Indicator category	Indicator
Soil quality	1. Total organic carbon (TOC)
	2. Total nitrogen (N)
	3. Extractable phosphorus (P)
	4. Bulk density
Water quality and quantity	5. Nitrate concentration in streams (and export)
	6. Total phosphorus (P) concentration in streams (and export)
	7. Suspended sediment concentration in streams (and export)
	8. Herbicide concentration in streams (and export)
	9. Storm flow
	10. Minimum base flow
	11. Consumptive water use
	Additional: Water yield
Greenhouse gases	12. CO_2 equivalent emissions (CO_2 and N_2O)
Biodiversity	13. Presence of taxa of special concern
	14. Habitat area of taxa of special concern
Air quality	15. Tropospheric ozone
	16. Carbon monoxide
	17. Total particulate matter less than 2.5µm diameter ($PM_{2.5}$)
	18. Total particulate matter less than 10µm diameter (PM_{10})
	Additional: VOCs, SO_x, NO_x
Productivity	19. Aboveground net primary productivity or Yield

1.4 Scope and Scale

The scope of the report is summarized in table 1.3. Agricultural feedstocks include conventional crops, energy crops, and crop residues (fig. 1.1) while forestry feedstocks include logging residues and whole-tree biomass (fig. 1.2). A subset of these feedstocks is considered in various chapters in this volume. In addition, microalgae are the subject of a qualitative analysis. Most analyses consider production and harvest, while analyses of air emissions and GHG emissions consider transport to the biorefinery as well.

Table 1.3 | Scope of Terrestrial Biomass Chapters in *BT16* volume 2

Chap	Indicator category	Indicator	Spatial Extent	Biomass	Scenario	Model	Output
4	Soil quality	Soil organic carbon	Contermi-nous United States	Corn and soybeans for biofuels, wheat, switchgrass, mis-canthus, willow, poplar (surrogates for barley, cotton, oats, sorghum, biomass sorghum)[a]	BC1 2017 BC1 2040 HH3 2040	Surrogate CENTURY Soil Organic Carbon model	Soil organic carbon emissions factor (Mg C/ha/yr)
4	GHGs	CO_2 equivalent emissions (CO_2 and nitrous oxide [N_2O])	Contermi-nous United States	Corn and soybeans for biofuels, biomass sorghum, energy cane, eucalyptus, loblolly pine, miscanthus, poplar, switchgrass, willow, barley straw, corn stover, oats straw, sorghum stubble, wheat straw, hard-wood lowlands (tree), hardwood uplands (tree), mixed wood, softwood natural, softwood planted	BC1&ML 2017 BC1&ML 2040 HH3&HH 2040	Greenhouse gases, Regulated Emissions, and Energy use in Transpor-tation Model (GREET)	GHG intensity (g CO_2e/dt), GHG emissions (g CO_2e, tons CO_2e)
5	Water quality	Total nitrogen load-ing, nitrate loading, total phosphorus loading, sediment loading	Arkansas -White-Red River Basin (AWR) and Iowa River Basin (IRB)	Corn stover (IRB), miscanthus, willow, switchgrass, energy sorghum, sorghum stubble, poplar, willow, (AWR)	BC1 2040 with con-servation practices added	Soil and Water Assessment Tool (SWAT)	Total nitrogen loadings (kg/ha), nitrate loadings (kg/ha), total P loadings (kg/ha), total suspended sediment loading (t/ha), water yield (mm), productivi-ty (t/ha)
6	Water quality	Nitrate loading, total phosphorus loading, sediment loading	Contermi-nous United States	Whole trees (thinnings and clearcuts)	ML 2017 ML 2040 HH 2040	Empirical model	Regional nitrate, phosphorus, and sediment load response curves (kg/ha), increase over pre-harvest reference
7	Water quantity	Water yield	Contermi-nous United States	Whole trees (thinnings and clearcuts)	ML 2017 ML 2040 HH 2040	Water Supply Stress Index (WaSSI) Ecosystem Services Model	Annual water yield (gal/yr), seasonal water yield (gal/month), water yield as an incremental percentage, compared to reference

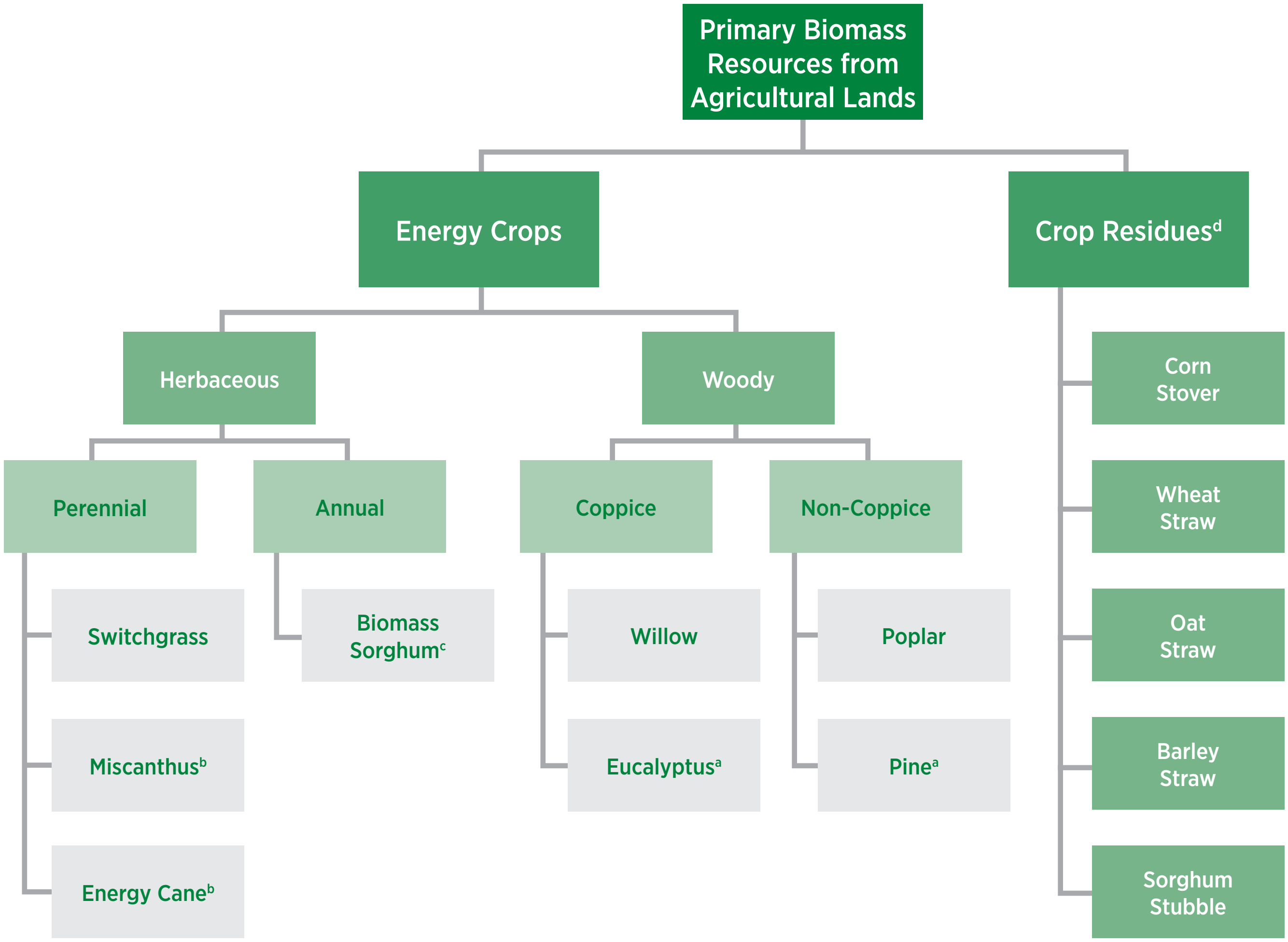
Chap	Indicator category	Indicator	Spatial Extent	Biomass	Scenario	Model	Output
8	Water quantity	Consumptive water use	Contermi-nous United States	Corn for biofuels, corn stover, soybean to biofuels, wheat straw, switchgrass, miscanthus, willow, poplar, southern pine, softwood and hard-wood resources	BC1&ML 2017 BC1&ML 2040 HH3&HH 2040	Water Analysis Tool for Energy Resources (WATER)	Rainwater requirements (gal), (gal/acre); irrigation requirements (gal), (gal/acre)
9	Air emissions	Total particulate matter less than 2.5μm diameter ($PM_{2.5}$), total particulate matter less than 10μm diameter (PM_{10}), ammonia (NH_3), oxides of sulfur (SO_x), volatile organic compounds (VOCs), carbon monoxide (CO)	Contermi-nous United States	Corn, corn stover, sorghum stubble, wheat straw, barley straw, oats straw, switchgrass, miscanthus, hardwood trees, softwood trees, mixed wood trees, hardwood residues, softwood residues, mixed wood residues	BC1&ML 2017 BC1&ML 2040 HH3&HH 2040	Feedstock Production Emissions to Air Model (FPEAM)	Emissions per ton, emissions compared (as ratios) to emissions in the National Emissions Inventory
10	Biodiver-sity	Presence of avian species (grassland, forest, or generalist species), species richness, habitat area (range) of avian species	Contermi-nous United States	Switchgrass, miscanthus, energy cane, pine, poplar, willow, eucalyptus, sorghum, corn, soybean, wheat	BC1 2040, reference 2014	Species distribution model, Bio-EST[b]	Percentage of counties occupied by grassland birds and forest birds, species richness
11	Biodiver-sity	Species among taxa of concern categories: rare native species, keystone species that have a disproportionately large impact relative to abundance, bioindicator taxa that monitor the condition of the environment, species of commercial value, species of cultural importance or species of recreational value	Contermi-nous United States	Logging residue, whole trees (clearcuts and thinnings)	ML 2017 ML 2040 HH 2040	Habitat suitability framework	Harvest acres, qualitative analysis of habitat suitability at ecoregion scales

[a] Chapter includes appendix that discusses soil organic carbon changes that could result from biomass harvest in forests.

[b] Bio-EST – Bioenergy-biodiversity Estimation modeling framework

Abbreviations: Mg C/ha/yr – megagrams of carbon per hectare per year; g CO_2e/dt – grams of carbon dioxide equivalent per dry ton; kg/ha – kilogram per hectare; t/ha – ton per hectare; mm – millimeter; gal/yr – gallons per year; gal/month – gallons per month; gal/acre – gallons per acre

Figure 1.1 | Agricultural feedstocks considered in volume 1 of *BT16*, subsets of which are considered in analyses in volume 2



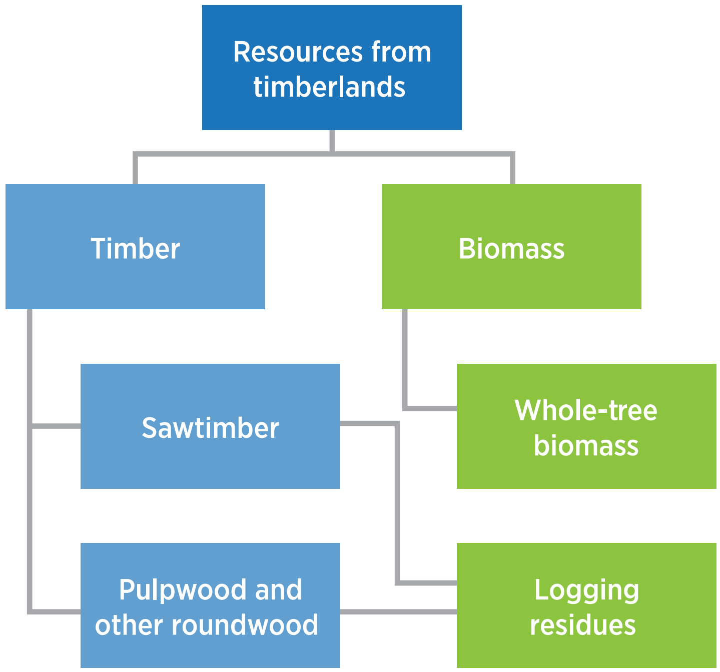
[a] Eucalyptus and pine are newly added feedstocks. They were generalized in the 2011 *BT2* as 8-year rotation, short-rotation woody crops under single-stem management.

[b] Energy cane and miscanthus are newly added feedstocks to the Billion-Ton reporting. They were generalized in the 2011 *BT2* as perennial grasses, along with switchgrass.

[c] The 2011 *BT2* discussed several types of sorghum. For the purposes of this report, "biomass sorghum" depicts any variety developed for high biomass yields, and neither for grain nor sugar content. Budgets for biomass sorghum can represent biomass sorghum, forage sorghum, or sweet sorghum. Modeled yields represent either biomass or forage sorghum; the variety with the highest productivity in a certain region was used.

[d] Agricultural resources already used for biofuels or bioenergy, such as sugar cane bagasse, are reported in volume 1, chapter 2.

Figure 1.2 | Forest feedstocks considered in volume 1 of *BT16*, subsets of which are considered in analyses in volume 2



The extent of analysis in volume 1 is the conterminous United States. Hawaii and Alaska were not included because of a lack of commodity crop data and scarce Forest Inventory Analysis data to support modeling. Most environmental analyses are performed at a national (conterminous United States) extent, with the exception of the water quality analysis for agriculture, which includes case studies focused on the Iowa River Basin and the Arkansas-White-Red Basin. As with volume 1, most analyses and reporting of results are at the county scale. Exceptions include watershed-level analyses for water quality and quantity.

1.5 Supply Constraints in *BT16* volume 1

Several supply constraints designed to reflect guiding principles that account for environmental and socioeconomic considerations were employed in *BT16* volume 1 as well as the 2011 *BT2*. 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). These constraints (summarized in fig. 1.3 and explained further in chapter 2) were carefully chosen to reflect practices that are commonly used in the industry or likely to be adopted in the future. Some of these practices are regulated while others are common industry practices with widespread compliance. Simulations are intended to fulfill projected needs for food, feed, forage, and fiber production, and some constraints are implemented to avoid production on lands with high ecological value.

When deciding which supply constraints to impose in *BT16* volume 1, it was deemed impractical and unrealistic to generate supply projections that are not technically feasible (e.g., removing all residue and debris) or cannot be sustained in the long term (e.g., harvesting residues at levels that exacerbate soil erosion). Using the potential biomass estimates from *BT16* volume 1 means that the same supply constraints are adopted in volume 2, but it is critical to recognize that the environmental effects results are contingent on these constraints. *BT16* volume 2 does not represent the full range of possible environmental effects of potential biomass in the United States; should biomass production practices not follow these modeled supply constraints (for example, using extensive irrigation in the western United States), there would likely be more adverse environmental effects. Analyzing the full range of worst- and best-case scenarios is outside the scope of volume 2. The potential biomass quantified in volume 1 represents a potential future that enables new insights into the environmental effects of biomass production. *BT16* volume 2 analyses will help determine whether the supply constraints applied in volume 1 are sufficient to protect many aspects of the environment or whether adverse effects remain and additional safeguards are needed.

Figure 1.3 | Supply constraints employed in *BT16* volume 1 and adopted in BT*16* volume 2

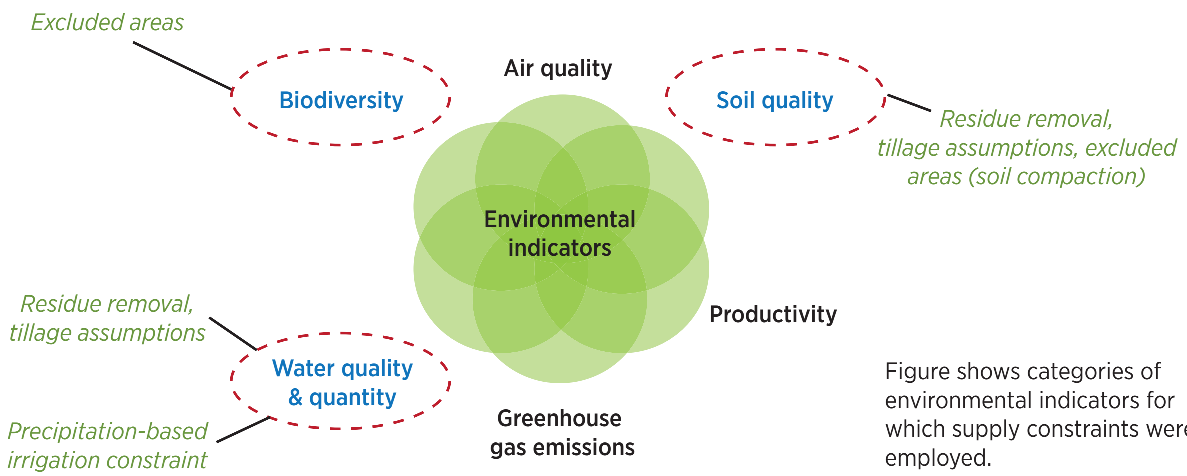


Figure shows categories of environmental indicators for which supply constraints were employed.

1.6 Limitations

Many types of environmental effects are not included in this initial environmental analysis of select *BT16* scenarios. For example, the scenario comparisons do not include an estimate of ecosystem-productivity changes or aquatic-biodiversity changes. In addition, many soil-quality effects (e.g., soil nitrogen, phosphorus, and bulk density) are not modeled. Peak-flow and base-flow indicators of water quantity are discussed but not estimated, and water yield for agriculture is not investigated in detail. The biodiversity analysis addresses select taxa in select regions or ecosystems. The potential for indirect LUC effects nationally and internationally from potential biomass expansion is not quantified in this volume, though issues and definitions are discussed. Environmental indicators for algae biomass for the scenarios in *BT16* volume 1 are not quantified, with the exception of water consumption estimates, but many types of environmental effects are addressed qualitatively. While some aspects of possible economic and social effects are mentioned, *BT16* volume 2 does not investigate these types of potential effects.

Efforts were made to coordinate the various analyses in *BT16* volume 2 to achieve consistency across scenarios and assumptions; however, this initial environmental effects analysis for a Billion-Ton report does not fully integrate results across categories, agriculture, or forestry. Further integration in future Billion-Ton reports will enable more robust understanding of the quantitative relationships—the synergies and trade-offs—between different types of potential environmental effects of biomass production.

1.7 *BT16* volume 2 Organization

The majority of chapters in this second volume of BT16 investigate environmental effects of potential agricultural and forest biomass produced in select 2017 and 2040 scenarios simulated in volume 1 (chapters 4–11). Chapter 2 describes the methodology used in volume 1 to estimate potential biomass supplies and summarizes the scenarios used in volume 2. Chapter 3 provides information to help readers interpret biomass supply results from *BT16* related to LUC (land management). Chapter 4 estimates fossil energy consumption and GHG emissions associated with producing biomass and considers the contribution of changes in soil carbon as a result of producing agricultural biomass on land that was previously in other states or under different management practices prior to production of biomass. Chapters 5 and 6 investigate effects on water quality, i.e., nutrient and sediment loadings associated with agricultural and forestry biomass production, respectively. Chapter 7 evaluates the potential effects of forest biomass harvesting on water yields, and chapter 8 examines the water footprint of agricultural and forest biomass as well as the interplay between feedstock mix and water use. Chapter 9 investigates air pollutant emissions associated with agricultural and forest biomass production and how the spatial distribution of air emissions could potentially impact local air quality. To investigate possible effects on biodiversity, chapters 10 and 11 consider habitat-related responses of select wildlife taxa to potential agricultural and forestry biomass production. Chapter 12 provides a qualitative assessment of environmental effects of microalgae in the context of scenarios in which algae production is co-located with CO_2 sources and that waste CO_2 is used for algae production. Chapter 13 evaluates the sensitivity of potential future biomass productivity to climate. Finally, chapter 14 summarizes and interprets results of previous chapters and explores strategies that could be used to enhance environmental outcomes of biomass production. These include strategies identified in this volume and strategies that are employed or under development elsewhere.

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