U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Chapter 06 | Sustainability and Good Practices

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6 Sustainability and Good Practices

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This report and supporting documentation, data, and analysis tools are available online:

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Summary

Sustainability constraints applied to the biomass modeled in this report illustrate how the United States can increase biomass supplies in ways that support net carbon sequestration, water conservation, and other ecosystem services through land management practices, or what some modelers might describe as beneficial land use change (LUC). Whereas the report identifies specific sustainable supply opportunities, one cannot be certain that land management for biomass production will evolve following the assumed constraints. Thus, consistent monitoring, assessment, and good management practices are necessary for avoiding or minimizing detrimental effects on soil, water, and ecosystem services. This chapter:

- Describes the impact of relaxing select sustainability constraints on estimates of potential biomass.
- Estimates carbon intensity.
- Reviews LUC concepts, potential effects of BT23 biomass supply scenarios on the environment, and potential good management practices that can improve environmental sustainability of biomass.

The supply estimates and analyses are independent of a specific policy or end use. In contrast, the EPA publishes a triennial report to Congress on biofuels that estimates specific environmental effects of a policy, the Renewable Fuel Standard (Clark et al. 2022). Other

environmental analyses of biofuel are tied to specific current or future policies (e.g., Chen et al. 2021; Austin et al. 2022), whereas potential biomass and related analyses in this report are not.

Key points:

- Broad agreement exists on the essential role for biomass to achieve climate and circular economy goals. Agricultural and forest scenarios in other chapters of this report estimate sustainable U.S. biomass supplies under assumptions (sustainability constraints) that reflect good practices to protect the environment and mitigate impacts on food and forest product markets. This chapter considers the range of potential impacts that might result if specific constraints are relaxed or removed.
- Removing the sustainability constraints from model assumptions (e.g., residue removal limits, timberland clearcut restrictions, tree diameter limits, distance from roads, harvest intensities for timberlands) increases potential biomass production from agriculture and timberlands[1] but adds risk of adverse environmental effects.
    - Relaxing sustainability constraints for corn stover suggests that removals to maximize profit could approximately double the stover removal rates, going from about one-third of national supply to about two-thirds of national supply.
    - Relaxing sustainability constraints for logging residues increases overall collection rates from about 45% of total logging residues to about 60%, but about 40% remains unharvested after relaxing the constraints.
    - Removal of larger-diameter (i.e., >11-inch-DBH) trees is constrained by the biomass price of $70 per dry ton. If prices increase to $75 per dry ton, approximately 30 million tons per year of trees greater than 11-inch DBH could be added to the harvested quantity. For reference, about 30 million tons represents less than 1% of timberland growing stock.
- Some sustainability constraints applied in the report (e.g., residue removal limits in many forests) are aligned with prevailing management practices, historic trends, and economic and biophysical feasibility, and thus are likely to be implemented. However, due to limited market experience and social science research, data are not available to determine whether agricultural residue retention recommendations will be followed.
- Effects of biomass production on crop prices and food security may be beneficial for some groups (rural producers), detrimental for others (urban consumers), or, most likely, negligible relative to other factors. Harvesting forest biomass does not affect food security.

[1] Timberlands are defined as forestlands with potential to produce more than 20 cubic feet of industrial wood per acre per year. Timberlands exclude reserved forests (e.g., National Park Service forests and other protected forests).

- Under BT23 mature-market scenarios, many environmental benefits, such as improved water quality in streams (nutrients and pesticides) and carbon sequestration, could increase because of increased perennial and cover crop acreage. Benefits could be enhanced with more efficient and precision management practices at the field or subfield scale.
- Uncertainties in future land management scenarios are unavoidable and would affect any environmental projection. Differences in LUC projections are large and have potentially significant impacts on estimates of biomass greenhouse gas (GHG) emissions intensity and sustainability. Monitoring and responsive decision-making are important to mitigate potential negative effects associated with land cover and management practices.
- Common sustainability concerns about producing and harvesting biomass could be mitigated by using good management and siting practices and mechanisms for increasing their adoption.
- Biomass resource estimates could be lower or higher depending on criteria applied to support sustainability.

GHG emissions, primarily from the combustion of fossil fuels, are causing temperature increases, increased frequencies and magnitudes of extreme events, and associated health and environmental impacts. Applying good practices for the production and use of biomass is essential to advancing sustainability goals, such as reducing fossil emissions associated with power, transportation, fuel, chemicals, and materials (IEA 2021, 2022). The important role of biomass in achieving national climate goals is driving global efforts to identify and develop sustainable biomass supply chains (IEA 2023). *The U.S. National Blueprint for Transportation Decarbonization* (DOE, USDOT, EPA, and HUD 2023) and a National Academies report on accelerating decarbonization (National Academies of Sciences, Engineering, and Medicine 2023) target GHG emissions reductions from aviation and other hard-to-electrify sectors with biofuels.

As with any energy technology, and particularly any production system based on land management, trade-offs among social, economic, and environmental objectives are necessary (Robertson et al. 2017; Dale et al. 2018). An evaluation of the environmental sustainability effects and potential trade-offs associated with the U.S. biomass potential estimated in BT16 was the subject of a companion report (DOE 2017), herein called BT16 Volume 2, that includes supporting analyses, glossaries, and datasets. BT16 Volume 2 evaluated changes in land cover and management, soil carbon, water quality, water availability, air emissions, and biodiversity for many biomass feedstocks as a function of production and harvest scenarios and prices. It also considered potential changes in biomass production based on a set of climate change projections. The BT16 Volume 2 analyses remain relevant and applicable to BT23. Rather than repeat those analyses, here we focus on questions raised by stakeholders:

1. Which aspects of sustainability were incorporated in estimates of national biomass potential and potentially serve as constraints or guardrails?

2. How might the sustainability attributes of biomass supply vary if producers do not follow these assumed sustainability constraints or guardrails?
3. How would biomass supply potential change if sustainability constraints were relaxed?
4. Which aspects of sustainability have not yet been explicitly considered in these estimates of biomass potential but are important for siting or managing biomass?
5. Which management practices can promote more sustainable biomass production?

The first question is addressed in the report's introduction and in individual biomass supply chapters. The remaining questions are addressed in this chapter and focus on agriculture and forestry. Expected benefits associated with the biomass supply scenarios are discussed, followed by analyses of expected effects of relaxing specific sustainability constraints associated with BT23 supplies. Environmental and other effects of potential production and harvesting of biomass are also discussed, including LUC, potential impacts on food security, forest conservation, biodiversity, water, and air quality.

6.1 Key Benefits of Producing and Harvesting Biomass

6.1.1 Climate Change Services, Carbon Management, and Carbon Intensities

Broad agreement exists on the essential role for biomass to achieve climate and circular economy goals. Production of biofuel, biopower, and bioproducts can mitigate climate change by avoiding combustion of fossil fuels, accumulating soil carbon, and displacing more carbon-intensive products and materials (IEA 2022). Net benefits depend on proper resource management, including minimization of GHG emissions during the biomass production stage (Robertson et al. 2017; Dale et al. 2014). As described in Chapter 5, purpose-grown energy crops (hereafter "energy crops") in the mature-market medium scenario reference price can achieve a net flux reduction of about 18 million metric tons of CO_2.

Carbon emissions intensity (i.e., carbon intensity) is CO_2-equivalent (CO_2e) emissions per unit of energy or product. Carbon intensities are typically measured for products rather than feedstocks, but some general principles pertain to biomass. Modeled carbon intensity estimates for crops used for bioenergy and bioproducts vary widely depending on baseline land allocation and assumed emission profiles (Wise et al. 2015). Other factors being equal, the biomass carbon intensity declines as annual yields increase because of better seed varietals and growing conditions such as soil and climate (Wise et al. 2015). However, if yield improvements are achieved by using more emissions-intense production practices, such as greater applications of fertilizer or pesticides, carbon intensity may not improve with higher yields.

Carbon intensities were calculated for major biomass feedstocks in this study (Table 6.1) using Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model (Wang, Elgowainy, et al. 2022). The model captures upstream impacts, including fuels and chemicals manufacturing for biomass that requires fertilizer or pesticide. In Table 6.1, carbon uptake is the CO_2 absorbed by the plant during growth, treated as biogenic. It does not include LUC-related emissions, which can release soil organic carbon

(SOC). The supply chain emissions include biomass production, harvest or collection, and handling prior to transportation to the biorefinery. Transportation emissions and end use emissions are not included. Also not included are estimates of indirect emissions such as indirect LUC emissions, as have been assessed by the EPA for the RFS program or the California Air Resources Board for the Low Carbon Fuel Standard program. Differences between these estimates can be large and can have significant impacts on the overall carbon intensity estimates. A general discussion of LUC concepts is in Section 6.3.2. The carbon intensity values for petroleum include only crude oil recovery. Upstream emissions from exploration and related activities, as well as indirect effects, can be significant (Parish et al. 2013; National Research Council 2003).

Table 6.1. Example Carbon Intensity Values of Key Biomass and Fossil Resources, Based on GREET 2022 Revision 1

Category	Examples	Carbon Uptake [a]	Supply Chain Emissions [b]	Feedstock Total [c]	Unit (Short Tons)
Agricultural residues, primary	Corn stover	1,600,000	28,000	−1,572,000	g CO_2e/dry ton
	Wheat straw	1,300,000	240,000	−1,060,000	g CO_2e/dry ton
Primary forest residues	Logging residues	1,700,000	13,000	−1,687,000	g CO_2e/dry ton
	Hardwood	1,700,000	21,000	−1,679,000	g CO_2e/ton
	Softwood	1,700,000	21,000	−1,679,000	g CO_2e/ton
Herbaceous energy crops [d]	Miscanthus	1,600,000	67,000	−1,533,000	g CO_2e/dry ton
	Switchgrass	1,600,000	73,000	−1,527,000	g CO_2e/dry ton
Woody energy crops	Willow	1,600,000	36,000 [e]	−1,564,000	g CO_2e/dry ton
	Poplar	1,700,000	55,000	−1,645,000	g CO_2e/dry ton
	Pine	1,700,000	51,000	−1,649,000	g CO_2e/dry ton
Animal manures [f]	Hog manure	1,500,000	−1,100,000 [g]	−2,600,000	g CO_2e/ton solids
	Cow manure	1,600,000	5,500	−1,594,000	g CO_2e/ton solids
Municipal solid waste [f]	Food waste	460,000	−250,000	−710,000	g CO_2e/wet ton
	Paper and paperboard	540,000	250,000	−290,000	g CO_2e/wet ton
	Yard waste	270,000	−53,000	−323,000	g CO_2e/wet ton
Range for crude oils [h]	Conventional crude oil, sand recovery values, shale oil, U.S. average crude		200,000–1,300,000		g CO_2e/ton

[a] Based on biogenic carbon content of each feedstock, per dry ton.
[b] Includes everything up to the "edge of field"/forest road.
[c] Credits feedstock with carbon uptake.
[d] Energy cane and eucalyptus are not parameterized in GREET.
[e] GHG emissions are lower for willow than for poplar and pine because trucks with higher fuel efficiency are assumed to be used for transport of the former.
[f] Avoided "BAU" emissions are incorporated in supply chain results. However, the practice of allocating credits based on reductions relative to counterfactual BAU emissions is currently under review by the California Air Resources Board.

[g] Scientific and policy consensus on allocating credits for reductions in BAU emissions from historical manure management has not been reached; therefore, this credit may be eliminated by carbon intensity scoring systems or by the California Air Resources Board.
[h] The supply chain emissions range (g CO_2e/ton) for crude oils includes conventional crude oil (230,000), oil sand recovery values (surface mining, 520,000; *in situ* production, 830,000; surface mining + bitumen, 1,100,000; or synthetic crude oil, 1,300,000), shale oil (Bakken, 370,000; or Eagle Ford, 310,000), and U.S. average crude, 310,000. Notably, much more processing is needed for biomass than for crude oils.
Note: These values do not include estimates of indirect land use changes.

Carbon uptake values are large for all crops and residues in Table 6.1. The supply chain carbon intensity for hog manure is shown as large and negative in the table because in this case, unlike other biogenic feedstocks, the value reflects an assumed avoidance of methane emissions relative to a counterfactual fate of the manure. Carbon intensity values for the biomass production and supply chains are consistently lower than for fossil fuel supply chains, though, as noted, the estimates presented in Table 6.1 exclude certain categories of potentially substantial emissions.

6.1.2 Other Agricultural Ecosystem Services

Energy crops can generate ecosystem services beyond the carbon uptake benefits described above and carbon sequestration benefits in Chapter 5. People who consume water or use waterways for recreation can benefit from water purification and soil conservation services offered by lands managed for energy crops (Cacho et al. 2017; Jager et al. 2022). Additional ecosystem services provided by energy crops include wildlife habitat and pollination (Robertson et al. 2017). Growing these energy crops, as well as harvesting residues, also provides pest protection for adjacent crops (Robertson et al. 2017; Helms et al. 2020; Sindelar et al. 2013). Furthermore, energy crops can be used to restore abandoned mine land (Quinkenstein et al. 2012).

Ecosystem services provided by energy crops may have substantial economic value that could decrease net costs if realized through incentives. Riparian buffers planted with perennial energy crops can provide targeted water quality benefits, many of which could be monetized (Jager et al. 2023). Nitrate and sediment removal services of energy crops have been valued or monetized in previous studies (Mishra et al. 2019; Jager et al. 2022; Ssegane et al. 2016). Services include water-based recreation, as well as wildlife viewing and pheasant hunting. Supporting pollinators could be of economic value to farmers (Donnison et al. 2021), even if these services are not monetized. Research projects funded through USDA conservation programs with Inflation Reduction Act funds may produce more data on the value of good management practices in the future (USDA 2023).

However, estimating the magnitude of ecosystem services generated under specific planting and harvesting scenarios is challenging because of a lack of empirical data and models adapted to local conditions and energy crop opportunities (Ventura et al. 2012). An exception and example of this future research direction is a recent study in Iowa that was able to use subfield data to show landscape- and watershed-scale differences in soil carbon sequestration and water quality indicators under different combinations of agricultural management practices related to corn stover harvesting and switchgrass plantings (Parish et al. 2023).

Cover crops and "intermediate" crop rotations, as described in Chapter 5, also provide ecosystem services (Daryanto et al. 2018). Cover crops are grasses, legumes, or small grains grown between the harvest and planting season of traditional commodity crops like corn, soybeans, and cotton. Cover crops provide soil conservation and conditioning services by providing cover to reduce erosion and through incorporation into soils when a field is ready for the next crop. By USDA definition, "cover crops" are unharvested. If a cover crop is harvested it becomes an "intermediate crop," which may also be described as double cropping or adding another crop into the rotation. Planting intermediate crops may improve conditions for the primary crop. Herbaceous cover crops such as rye, winter wheat, and hairy vetch offer ecosystem services including reductions in soil erosion and increased soil organic matter, improved water quality, weed suppression, and increased wildlife and pollinator habitat, along with increased yields of the main crop (Blanco-Canqui et al. 2015; Darysanto et al. 2018). Cover and intermediate crops can mitigate adverse environmental impacts of crop residue removal for biofuel production (Blanco-Canqui et al. 2015). However, lignocellulosic cover crops are more costly and difficult to refine into useful fuels than oilseeds. Oilseed intermediate crops such as pennycress, camelina, and carinata (Chapter 5) produce oil that can be converted to SAF, for example, without expanding the land base used for production of other products. However, cover and intermediate crops are not widely grown in the United States, comprising less than 6% of total cropland in 2017 (Wallander et al. 2021). Thus, the ecosystem services of these cover crops (Cubins et al. 2019) and effects of harvesting on ecosystem services (Blanco-Canqui et al. 2020) are less well studied. Recent studies (Taheripour, Sajedinia, and Karami 2022; Field et al. 2022) offer insight into opportunities to generate biomass from integrated production systems that incorporate cover and intermediate crops for multiple markets and services, generating climate benefits and biomass without reducing traditional commodity production.

6.1.3 Benefits of Woody Biomass Harvest in Forests

Mechanically thinning trees is a common wildfire fuel reduction treatment (i.e., "fuel treatment"). Mechanical thinning is intended to open the forest structure and reduce fire intensity, severity, and frequency by removing surface fuels and increasing the vertical distance to the canopy (Kalies and Kent 2016; Graham 2003; Reinhardt et al. 2008). As a fuel treatment, mechanical thinning is an alternative to prescribed burns, mastication, or manual pile and burn. Skog and Barbour (2006) identified timberland areas in Western states where thinning treatments would be needed to reduce fire hazard and could make forest products economically feasible. Kline (2004) summarizes many benefits or services promoted by reducing wildfire risk, including carbon sequestration, timber products, and recreation. Additional benefits of reduced wildfire risk would be improved water quality and reduced risk to homes, wildlife habitat, historic places, and sacred sites.

Benefits in addition to reduced wildfire risk can result. Collecting forest biomass for biofuel or bioproducts can reduce GHG emissions and air pollutant emissions from open pile burning of woody residues from logging operations. Furthermore, bioenergy market demand can help retain or increase forest area and productivity (Duden et al. 2023; Jonker et al. 2018).

6.1.4 Benefits of Waste Collection and Utilization

Collecting waste products and transforming them to a resource for energy and other uses has benefits and value (Tuck et al. 2012) that depend on the waste resource, including reducing demand on disposal facilities (e.g., landfills, waste treatment facilities), protecting water quality, improving air quality (e.g., reduction in field burning of residues, reduced emissions from raw manure), and controlling odor (from manure).

Managing MSW can reduce GHG emissions, with several potential options: capturing biogas from landfills, composting organic waste, anaerobically digesting organic waste, and reducing MSW generation (Hoy et al. 2023; Cuéllar and Webber 2008; Powell, Pons, and Chertow 2016). Reducing solid waste upstream (e.g., less consumption) and downstream through recycling and other means may be environmentally preferable and would reduce waste-based feedstock for bioenergy and bioproducts. The use of MSW for bioenergy may alleviate some concerns related to conventional disposal pathways such as limited landfill space for disposal and significant methane emissions from landfills (Powell, Pons, and Chertow 2016).

The collection of manures for biogas or other uses has 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. Reducing storage of livestock waste in lagoons can also reduce odors and emissions of methane and nitrous oxide (N_2O) from those lagoons.

6.2 Relaxing Sustainability Constraints

"With the proper safeguards, the likelihood of environmental payoff [of producing biomass] appears high" (Robertson et al. 2017). As discussed in Chapter 1, constraints on potential biomass supply (Figure 6.1) were implemented in the models to move toward the sourcing of more sustainable biomass (See Table 1.3, agriculture, and Table 1.4, forestry). Thus, the model scenarios reflected areas where new biomass could not be grown, harvested, or collected, as well as assumptions on sustainable management practices or restrictions on unsustainable management practices.

Transitions to or from forest or agricultural land cover were not options in the simulations, nor were transitions to or from other land cover types, including many grasslands. These constraints could not be relaxed because they are endogenous to the POLYSYS and ForSEAM models.

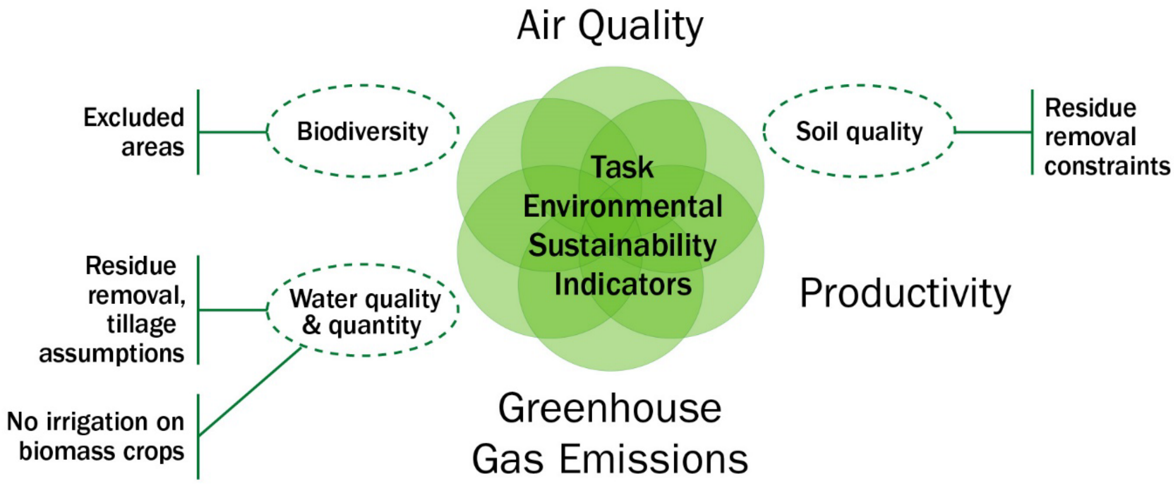

Figure 6.1. Sustainability constraints and sustainability indicator categories (green dashed circles) implemented in this report

This report illustrates how much and where different types of biomass *could* be supplied while attempting to minimize significant adverse environmental or food crop impacts. However, model simulations do not attempt to predict what *will* happen. For example, model results provide no guarantee that competition for biomass will not occur among different potential market demands (food, feed, fiber, bioenergy, and other bioproducts). Model simulations of what could be supplied sustainably do not preclude potential for adverse environmental effects if safeguards are not in place. If good management practices are not followed and excessive residue is removed, leaving soils unprotected, for example, accelerated soil erosion and nutrient loss could result (Hawks et al. 2023).

To address concerns about the effects of sustainability constraints assumed in this study, we tested scenarios in which certain constraints were relaxed. Results of the sensitivity analyses differ slightly from final results presented in Chapters 1, 4, and 5, but are presented to indicate directionality and magnitude. Thus, POLYSYS (used for agricultural lands) relaxed the residues collection constraint, and ForSEAM (used for timberlands) "freed up" timberland resources to supply biomass in addition to the quantity that could be supplied with these specific sustainability constraints in place. The new simulations illustrate how potential biomass supplies, prices, and locations change when residue retention limits and forestry demands are modified. We also consulted literature on farmer behavior and economic and physical harvesting constraints to begin to examine the likelihood that the sustainability constraints would be employed.

6.2.1 Relaxing Sustainability Constraints: Agriculture

To explore the effects of relaxing sustainability constraints on agricultural production of biomass, we altered the POLYSYS modeling runs to allow residues to be removed from conventionally tilled acres without regard to wind and water erosion or soil carbon loss. This meant relaxing the following constraints from Table 1.3:

- Crop residue removal prohibited in conventionally tilled acres.
- Crop residue removal limited based on wind and water erosion estimates and soil carbon loss.
- Acceptable residue removal different for reduced and no-till acres.

At current residue harvest machinery efficiency, a maximum of 50% of residues can be collected, but as machinery efficiency improves, up to 90% of residues could theoretically be removed if unconstrained by erosion and carbon limits. Relaxing the sustainability constraints (and applying only economic constraints and an operational efficiency constraint of up to 90%) led to a 140% increase in biomass from agricultural residues—from 174 million to 419 million dry tons at a reference price of $70 per dry ton. Thus, implementing the residue removal constraints in POLYSYS leads to a conservative estimate of the supply potential, which meets a specified environmental target (that may itself be conservative; see Khanna and Paulson 2016). However, if the machinery were available to cost-effectively remove higher volumes, and if contracts or regulations did not prevent it, operators could remove higher volumes of residues, and incentives to exceed assumed removal constraints increase with higher biomass prices. In one study, southern Illinois producers were willing to supply over 40% of their corn stover and wheat straw for bioenergy or bioproducts (Altman and Sanders 2012). The authors found a difference between maximum willingness to supply residues for bioenergy and willingness to supply at a given price.

A salient question is: Are farmers likely to harvest residues within the constraints assumed in this report, or are they likely to harvest more biomass than would meet sustainability targets? The risk of harvesting beyond sustainable targets is influenced by economic, technical, and social factors. Farmers could overharvest corn stover and other residues for short-term economic gain. Some who lease rather than own land may be less motivated to retain the nutrients from residues for long-term soil productivity. However, a 90% removal rate may not be technically, socially, or economically feasible in many contexts because it would require collection of smaller, less dense, and soil-contaminated residues that are costly to collect and transport, and that require additional advanced processing. A U.S. effort to commercialize cellulosic ethanol using corn stover shows the importance of technical constraints. Harvest guidelines were supported by machinery designed to collect and remove only the top 30% of the dried corn plant along with the cobs and husks from the sheller, thereby reducing dirt and ash content and ensuring high levels of residue remained on soils (BETO 2023; Slupska and Bushong 2019).

Constraints related to residue retention are included in POLYSYS at county-level resolution. However, many good practices for farmers harvesting residues are best determined at the subfield scale, based on grain yield data, slope, and soil characteristics (Muth et al. 2012; Parish et al. 2023). Precision agriculture applied to biomass production holds promise to reduce soil erosion, increase SOC, and improve profitability for the grower. In addition, smart combines can ensure that residue removal is limited to subfield-level sustainability constraints (see textbox).

However, data are not available for many locations to populate POLYSYS with good residue removal practices at the subfield scale. As noted above, actual residue retention for agriculture or forestry could be lower or higher than sustainable targets.

Site-specific sustainability targets that prevent erosion and protect health, such as residue removal limits, could be built into operations of cellulosic biofuels producers (i.e., energy crop users) (Kemp 2015). Economic incentives or regulations could increase the likelihood that sustainable quantities of residues are harvested (Searle and Bitnere 2017). Biorefineries have an interest in documenting that resources are sustainably managed, and contractual conditions to limit residue collection rates can be established with stover suppliers.

Energy crops are another important biomass resource, but sustainability constraints for these feedstocks, such as the prohibition of production in regions where irrigation would be required, were not relaxed in this chapter. In this report, potential biomass from energy crops is constrained economically, as discussed in Chapter 5.

Smart Technology Enables More Sustainable Farming

Software and state-of-the-art technology are making it easier for farmers to produce crops in an energy-efficient, cost-effective, and sustainable manner. Maintaining or improving soil conditions, harvesting only what's needed, and making use of biomass that otherwise would be wasted are some of the areas where new technology can enable efficiencies.

For example, a new kind of harvester header, the Straeter Cornrower Header, named for its inventor, Jim Straeter, can enable sustainable corn stover removal. Such a machine provides variable-rate harvest controls that respond to changing topography and soil conditions. This allows sustainable stover removal of about 1.5–2 tons of corn stover per acre in fields producing an average of 200 bushels of corn.

The process relies on a unique header that takes material off the field while leaving enough corn stover to maintain or improve soil carbon and keep the soil condition in shape for the next crop or cover crop. Using software developed at Iowa State University, algorithms determine when the door under the combine should be opened to let the farmer leave more or less stover on the field. A conveyor under the combine takes the biomass and puts it straight into a baler so it never hits the ground. Thus, the header eliminates the need for the farmer to make an additional pass over the field, as the machine combines two steps in one. Eliminating that extra pass saves labor, time, fuel, and overall costs.

The resulting stover bales contain 20% more biomass, which translates to less storage space required for the user. The farmer doesn't need shredders or rakes and gets more volume in a bale and a variable harvest rate. This is one example of smart technologies that promote more energy-efficient, cost-efficient, and sustainable ways to do agriculture.

Photo from William Belden, ANTARES Group Inc.

6.2.2 Relaxing Sustainability Constraints: Forestry

To explore the effects of relaxing sustainability constraints in ForSEAM on production of biomass from timberlands, we altered the following assumptions from the analysis in Chapter 4 to the description in parentheses:

- Exclude Class 1 trees—i.e., >11-inch DBH (relaxed to include Class 1 trees).
- Retain 30% of logging residues on slopes less than 40% (21.8°) (relaxed to 10% retention rate).
- Limit to land access within half-mile of roads, including USFS roads, where applicable (relaxed to within 3 miles of roads).
- Constrain maximum harvest intensity to 5% (relaxed to 10%).
- Constrain region-specific historic clearcut (relaxed to 100%).

Relaxing the above modeling constraints explores the risk of harvesting large trees for biomass, harvesting a greater percentage of logging residues than is recommended in many regions of the country (Titus et al. 2021), harvesting timberland biomass at a greater distance from roads, harvesting a larger area within each region within a year, or harvesting all biomass with clearcuts.

In addition, forest and cropland area are held constant in scenarios with sustainability constraints and in those where constraints are relaxed. What would happen to the areas of those land cover types without the constraints is uncertain, and the literature provides mixed assessments of what is possible (Rose et al. 2020). Historic evidence and modeling indicate that strong forest product markets can contribute to retention of or expansion of forest area (Galik and Abt 2016; Wear et al. 2013). For example, even though biomass demand for energy or bioproducts represents a relatively small part of total forest sector production, the impact of this demand on forest area is expected to be positive (i.e., contributing to an expanding forest area) if scenarios with and without bioenergy demand are compared in the Southeastern United States (Duden et al. 2023). Nonetheless, commodity prices and land rents can influence whether intensification or extensification occurs to meet market demand (Tian et al. 2018). The evidence from USFS FIA data and research to date suggest that the impact of bioenergy demand on total forest area is likely to be marginal relative to other drivers that determine forest area (Dale et al. 2017). If there is a notable effect, increasing woody biomass demand for energy is expected to facilitate small increases in forest area in the long term. Thus, whereas there is uncertainty, the assumption to keep forest area constant is probably somewhat conservative.

ForSEAM solves for national price and regional harvest distribution under a specified biomass demand pathway (e.g., a linear increase from 0 to 65 million tons per year from 2021 to 2050). A concern is that increased demand for biomass could drive prices up to the point that harvests could exceed the sustainability constraints specified in Table 1.4. For this report, the highest level of demand for which prices for woody biomass do not exceed $70 per dry ton (in 2022 dollars) was selected to be consistent with the national mature-market reference price for energy crops (comparable to the reference price of $60 per dry ton in 2014 dollars used in BT16). The resulting ForSEAM demand pathway is to harvest up to 54 million tons from timberlands in mature-market conditions (simulated as 2045). Relaxing this constraint to simulate biomass prices up to $75 per dry ton suggest about an additional 30 million tons per year of Class 1 trees could be harvested, as shown in Figure 6.2. Risk associated with increased demand or deviating from the sustainability constraints modeled in ForSEAM is explored below.

Relaxing the assumption of exclusion of Class 1 trees (largest diameter) and increasing the demand pathway were simulated simultaneously. ForSEAM models tree sizes as Class 1, 2, or 3. A Class 1 forest stand has an average DBH >11 inches, Class 2 has a DBH of 5–11 inches, and Class 3 has a DBH <5 inches. Results from the mature-market reference scenario suggest that increasing the mature-market demand target above 54 million tons per year (including 19 million and 35 million from logging residues and small-diameter trees, respectively) could drive market-equilibrium roadside prices above $70 per dry ton, which could incentivize harvest of Class 1 forest stands for biomass. Figure 6.2 illustrates a scenario targeting 75 million tons per year of biomass from timberlands by 2050. This scenario drives prices high enough to incentivize the harvest of Class 1 trees for biomass after demand surpasses 60 million tons per year in 2044. Class 1 trees generally have two to three times the market value of Class 2 trees due to their suitability for higher-value dimension lumber products and longer growth period to maturity. Thus, using Class 1 trees is likely to be cost prohibitive for biofuel uses.[2] For context, 35 million tons per year of small-diameter trees is about 11% of approximately 314 million tons per year of U.S. roundwood harvests for conventional forest products in 2019 (estimated from USFS 2023a).

While not incorporated in current ForSEAM scenarios, management of naturally regenerating forests using selective harvesting to maintain an uneven stand age with canopy structural complexity has been shown to be advantageous for carbon uptake rates, carbon storage, and the maintenance of ecological functions (Gough et al. 2021; Hardiman et al. 2011; Toda et al. 2023; Scheuermann et al. 2018; Murphy et al. 2022; Crockett et al. 2023). The research suggests that good management for some temperate forests can support increased harvests for both conventional timber markets and residual biomass, while maintaining net carbon uptake relative to unmanaged sites. The profitability of uneven-aged management of forests and plantations depends on tree species, residual basal area, and length of cutting cycle (Suseata et al. 2023), among other variables.

[2] For illustration, assuming $70 per ton and a biofuel yield of 60 gallons per ton indicates a feedstock cost of over $1 per gallon of biofuel, before logistics and conversion costs. Historical sawtimber stumpage prices in the range of $50–$60 per dry ton (timbermart-south.com, assuming 50% moisture content), plus an estimated $20 per dry ton harvest cost, exceed $70 per dry ton.

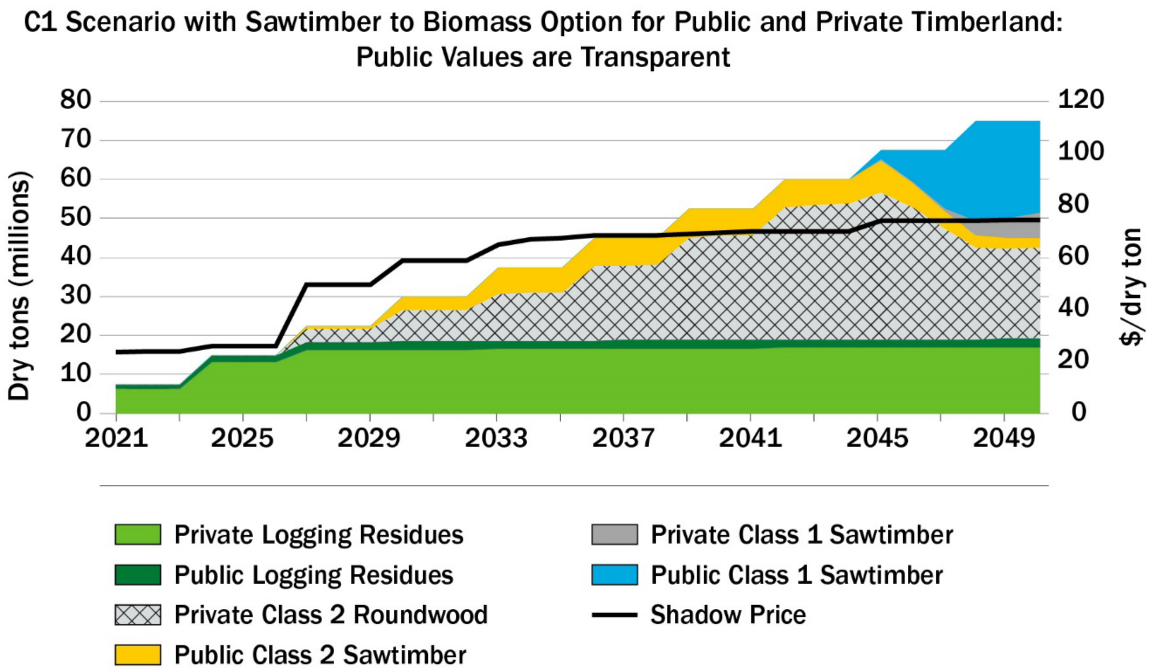

Figure 6.2. Example forest modeling results illustrating risk of exceeding $70 per dry ton roadside. Producing more than 60 million tons of biomass from timberlands risks driving market prices higher than $70 per dry ton at roadside and incentivizing production of Class 1 (C1) trees (i.e., >11-inch DBH) for bioenergy.

Relaxing the other forestry sustainability constraints under the base case also provided insights. For example, relaxing the logging residue constraint increased residue harvesting from 19 million to 25 million tons in 2050. For context, this is about 45% and 58% of the estimated 42 million tons per year of logging residues currently left in forests, respectively (USFS 2023b). Relaxing distance to roads or harvest intensity had little impact on production but decreased price in some outyears by up to $4 per ton. Relaxing the constraint on clearcutting also had little impact on production or price but resulted in up to 3.4 million additional tons of biomass from Class 1 plantations. In sum, these results suggest that if biomass prices exceed $70 per ton (dry basis, before delivery), biomass supplies from timberland could exceed about 55 million tons per year, and pressure could increase to deviate from sustainability constraints assumed in this analysis. For context, 55 million tons per year is less than 1% of about 22 billion tons of U.S. timberland growing stock (estimated from USFS 2023a). Given recent growth of woody biomass production in other nations, global competition is a key factor that is likely to moderate prices for woody biomass over the long term (e.g., Johnston and Kooten 2016; Aguilar et al. 2022).

As with agriculture, an important question is: Are forest managers likely to harvest residues within the constraints assumed in this report, or might they harvest beyond sustainable targets? Here we show that (1) sustainable residue retention and related good practices vary depending on environment and jurisdiction, (2) regionally limited field studies suggest that residues are not overharvested, and (3) mechanical and economic constraints generally prevent foresters from harvesting biomass beyond sustainable limits. Still, more studies are needed.

Several states are developing or have developed good management practices for residual biomass retention (Dirkswager et al. 2011; Titus et al. 2021). Residue retention targets range from at least 10% retained (Wisconsin) to 100% (part of Massachusetts), with most targets ranging from at least 20% to 33% (Titus et al. 2021, supplemental information). Notably, state retention targets are reported for the Pacific Northwest but not for other Western states or regions where rainfall is sparse (Titus et al. 2021). In fire-prone Western forests, rather than targets for residue retention, targets for biomass removals are set to bring total forest biomass down to recommended forest biomass density or stocking rates to improve productivity and fire resilience (North et al. 2022; USFS 2022).

Spatially explicit residue removal constraints could be imposed in forest models of biomass production, such as ForSEAM. The Forest Stewards Guild (2023) publishes regional forest biomass retention and harvesting guidelines. Some states caution harvesters against removal of biomass from specific soil types, such as poorly drained or low-nutrient soils (Benjamin 2010; Bronson et al. 2014), and this guidance could be reflected in model assumptions. The residue retention limit in this report is conservative for most environments.

Residues are not typically overharvested. Studies of effects of biomass versus conventional harvest sites in Virginia found greater residue removal at biomass sites than conventional sites but still sufficient downed woody debris and heavy slash to ensure best management practice (BMP) implementation related to erosion (Garren et al. 2022; Hawks et al. 2023; Barrett et al. 2016a). Similar results were documented in Michigan when historical records across 40 years were compared for whole-tree (including residue removal) and stem-only harvests (Premer, Froese, and Vance 2019). More importantly, whole-tree biomass removals did not impact stand productivity relative to stem-only removals. Following biomass collection, quantities of remaining downed woody debris averaged 10.98 tons/acre in the mountains (Garren et al. 2022) and 10.22 tons/acre in the Coastal Plain (Hawks et al. 2023). Residues and slash piles remaining in the Piedmont covered about 12% of the area (Barrett et al. 2016a).

Concerns about overharvesting forest residues often overlook the fact that harvesting technology and low prices, along with market requirements for clean, high-quality biomass, limit economic and technical feasibility of excessive residue removal (Premer, Froese, and Vance 2019). For example, large quantities of woody debris (about 18 tons/acre in Missouri) remain even where there are no removal restrictions (Kabrick, Goyne, and Stelzer 2019). Furthermore, methods to ensure that woody debris is retained are not specified in guidance documents, and the quantification of debris remaining is challenging (Fritts et al. 2014). Many studies show that retention recommendations are exceeded (i.e., far more debris is left following biomass collection) without deliberate effort (see references listed in Premer, Froese, and Vance 2019). In the Southeast, debris collection is limited by current operational and economic efficiencies rather than by less restrictive limits in the biomass harvest guidelines (Fritts et al. 2014). The minimum volume of residues retained in a North Carolina field study was three times the volume recommendation for the Piedmont and Coastal Plain physiographic regions (Forest Guild Southeast Biomass Working Group 2012).

Surveys find that both social and economic factors influence whether forest landowners are willing to harvest biomass (Butler et al. 2010; Gruchy et al. 2012; Hodges et al. 2019). For example, Hodges et al. (2019) find landowners consider the offered price along with other land management and conservation goals. However, information about the quantities of logging residue that forest owners and managers are willing to harvest or retain is limited, and survey results are complicated by variable interpretation of terminology. Some landowners may not be willing to harvest logging residues at all (Swinton, Dulys, and Klammer 2021). Others might be willing to collect a large quantity of residues, given an adequate price (Wolde et al. 2016). A financial analysis of forest biomass in Montana showed that harvesting can expand farther from bioenergy facilities, including along unpaved roads, if prices are high (Jones et al. 2013). Yet nonindustrial landowners may not be aware of technical constraints on residue removal, and some landowners may not be aware of applicable BMPs (Hodges et al. 2019). Forest management goals are affected by ownership tenure, history, role of hunting and other uses, whether land was purchased or inherited, size of forestland, forestland ownership objectives, and demographic features like household size and education (Hodges et al. 2019; Wolde et al. 2016).

6.3 Review of Potential Environmental Outcomes

Environmental implications of the further production and use of biomass in the economy go beyond the factors included among the sustainability constraints above. Here we present several categories of potential environmental outcomes associated with producing and harvesting agricultural and forest biomass, including plausible outcomes that may result depending on the degree to which producers choose to follow good management practices. This section addresses several specific environmental outcomes that may be affected by the adoption, or lack thereof, of sustainability practices: LUC, food availability, water consumption, air quality, and biodiversity. If products of biomass are needed for GHG reduction strategies, “what is the most effective and least harmful way of doing so?” (Pierrehumbert 2022).

6.3.1 Good Management Practices

Good management practices are recommended approaches that contribute to progress toward environmental sustainability of biomass production and harvesting. Management practices included in the modeling of potential biomass and termed “sustainability constraints” (Section 1.3) are a first step. Good management practices balance multiple societal goals such as improving environmental conditions or food security with the economic and productivity goals of producers.

Good management practices are sometimes documented as “BMPs” and may be officially designated by cognizant organizations. BMPs aim to be cost-effective, practical, and generally accepted. Some guidelines and certification processes are voluntary, context-specific, and just one way to do things (Lattimore, Smith, and Richardson 2010). Numerous good practices are available for agriculture and forestry, as well as for microalgae (Efroymson et al. 2021). Most BMPs are designed to protect water quality, but good management practices go beyond water quality. General good practices to ensure sustainable biomass production and use were recently developed under the Clean Energy Ministerial (Biofuture CEM 2023), emphasizing the importance of local context and engagement of local stakeholders. We use the general term "good management practice," except where BMPs are published and clearly recognized in the context of a specific activity and jurisdiction.

Good management practices can be used to refine model assumptions and outputs. Some practices may increase the price or reduce the quantity of potential biomass. On the other hand, some management practices, like the use of irrigation where sufficient water is available, could increase the quantity of potential biomass compared to quantities in this report. Some good management practices could serve as future sustainability constraints for modeling biomass or lead to biomass that is even more sustainable than the biomass in this study. Some practices are implemented at spatial scales much smaller than county-level simulations. The management practices highlighted below are examples, not a comprehensive review.

6.3.2 LUC

Land can provide simultaneous services (e.g., food, energy, species habitat), but land is a limited resource, and concerns about competition for land are growing (Searchinger et al. 2023). Therefore, research including biomass and bioenergy studies attempts to identify and apportion causes of LUC (Oladosu et al. 2012; Efroymson et al. 2016) and to quantify its environmental and human impacts (Robertson et al. 2017; Dunn et al. 2017). Land use, which typically includes land cover and land management, is defined by the IPCC (2022) as "the total of arrangements, activities and inputs applied to a parcel of land," and any change in these arrangements, including governance and zoning, is considered LUC.[3] Sustainability constraints applied to biomass models in this report are intended to support changes in land cover and management that are beneficial for societal goals and environmental outcomes. In other words, the biomass production is based on beneficial LUC.

The primary type of land change associated with the potential biomass supply estimates in this report consists of changes in agricultural land management practices, with modeling results indicating increases in land area under perennial crop cover and in productivity. The results show that energy crops are economically competitive only where conventional agricultural crops offer marginal returns (Figure 6.3). Change is minimal in areas where conventional crops have a comparative advantage, such as in the Corn Belt. It would be unreasonable to assume that most corn fields will transition to perennial grasses if it is not profitable to do so (Clark et al. 2013).

To model compensation for displaced forage production on pastureland, the agricultural modeling with POLYSYS includes assumptions of management-intensive grazing (described in

[3] LUC includes any change in land cover, management, or function associated with human activities. In this report, indirect or induced LUC is considered a part of total LUC.

the appendix to Chapter 5).[4] To estimate sustainable supply potential, change in primary land use was not permitted, and thus interactions between land in agricultural use and forestland were not modeled. Agricultural land available for biomass may depend on crop yields, livestock yields, and trends in dietary patterns and consumption of animal products (Donnison et al. 2021).

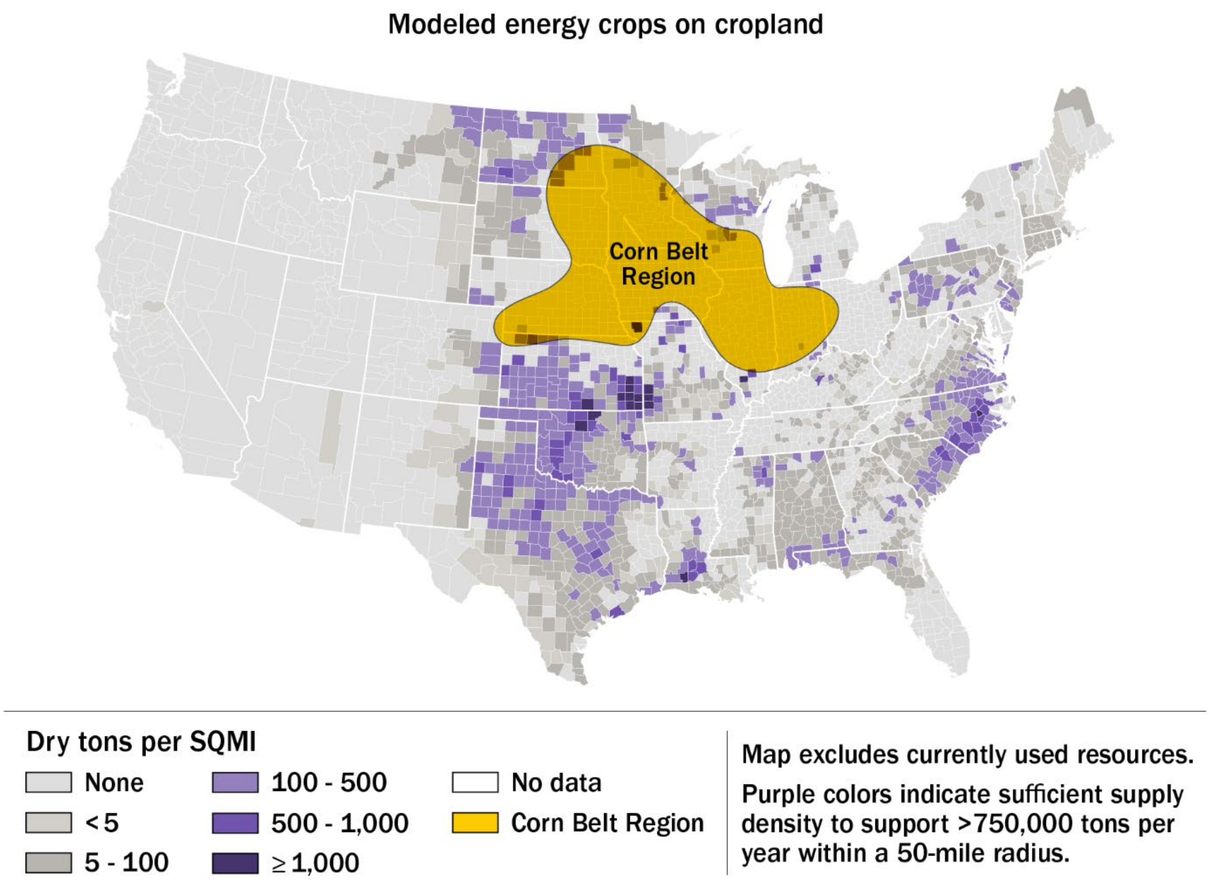

Figure 6.3. Spatial distribution of purpose-grown energy crops under the mature-market medium reference scenario on cropland, illustrating the comparative economic advantage of commodity crops in the Corn Belt

6.3.2.1 LUC-Related Concerns and Analytic Approaches

A specific concern about LUC is that expanded biomass production for bioenergy will directly or indirectly lead to the loss of grasslands, forests, and other carbon-rich ecosystems. Changes in land cover and management associated with biomass production can occur directly on the lands where biomass is grown and harvested or indirectly on distant lands through market-mediated effects such as higher commodity prices and shifts in trade flows. Bioenergy-induced LUC and the extent of its effects are typically estimated through modeling (Searchinger et al. 2023; Lark et al. 2022; Clark et al. 2022) and represent a great source of uncertainty regarding the carbon intensity and sustainability of biomass production. Land management and land cover influence

[4] Access BT23 appendices at www.energy.gov/eere/2023-billion-ton-report.html.

GHG emissions, food security, biodiversity, water quality, and water quantity, which are discussed later in this chapter.

Inferring and testing causal relationships between biomass and LUC may help analysts better estimate the effects of biomass production and use. However, to date, few papers have attempted to quantify causal connections between biomass production and LUC (e.g., Li, Miao, and Khanna 2019; Oladosu, Kline, and Langeveld 2021; Lee et al. 2021; Chen and Khanna 2018). The challenges of attribution analyses are discussed in *Biofuels and the Environment: Third Triennial Report to Congress* (Clark et al. 2022).

Results of LUC simulations depend on comparing a range of bioenergy scenarios with different reference or counterfactual scenarios (Koponen et al. 2018). A transparent land reference is especially important for determining results of bioenergy assessments (Koponen et al. 2018).

6.3.2.2 LUC-Related Models, Assumptions, and Data

Outputs of models of bioenergy and LUC are sensitive to assumptions (e.g., Khanna, Rajagopal, and Zilberman 2021; Oladosu et al. 2012). Some types of assumptions are unverifiable, but others can be tested empirically (Field 2021). Assumptions about the role of crop prices in LUC, for example, are in dispute (Persson 2016). Modeling is also founded on different assumptions about land ownership and management (Daioglou et al. 2020; Daioglou 2022; Efroymson et al. 2016; Kline et al. 2011). Agricultural land needs of the future are uncertain, and biomass crop yield improvements related to technology improvement and climate change are also the subject of debate (Field et al. 2020; Aggarwal et al. 2019; Zilberman 2017). Assumptions about coproducts are critical for estimating LUC attributable to biofuels and other end uses of biomass (Szabó 2023). Agricultural subsidies and programs such as the USDA Conservation Reserve Program (CRP) vary over time and are difficult to incorporate in models but are widely recognized to influence cropland area and prices in the United States (Taheripour and Tyner 2014; Frisvold 2004).

The concept and measurement of LUC are dependent on the model and user-selected parameters (e.g., land categories, definitions, time periods). Change estimates vary widely depending on the points in time being compared and specific geographic areas included in an analysis, in part because land cover and management associated with agriculture and forestry are extremely dynamic, as illustrated in Figure 6.4.

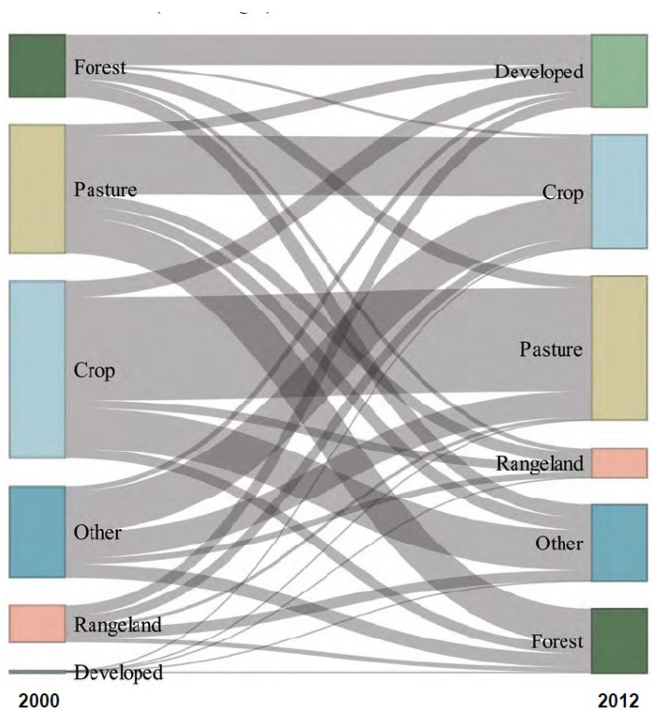

Figure 6.4. Gross LUC in the CONUS from 2000 to 2012. For land moving out of a specific land use in 2000 (bars on left), the width of the gray flows indicate the relative area moving into each new use in 2012 (bars on right).

Source: Riitters et al. 2023

Variable land cover classifications affect LUC estimates (Singh et al. 2017). Variability from year to year in reported acreage in different categories used by the USDA Census of Agriculture (USDA 2019)—including idle, summer fallow, non-cultivated, and harvested cropland—and discrepancies in classification due to field boundaries, changing remote sensing technologies, and other factors can result in a range of ±20 million acres in reported cropland in a given year (Wang, Wander, et al. 2022), further complicating LUC analyses. Independent of classification errors, the Census of Agriculture finds that harvested cropland varied by ±20 million acres around a 305-million-acre midpoint, and total cropland area decreased slightly (−10 million acres) from 2007 to 2017 (Clark et al. 2022, Figure 5.3), while harvested cropland increased slightly (+10 million acres). The increase in harvested acres reflects the expiration of contracts paid to farmers to take cropland out of production under federally funded set-asides such as the CRP. Thus, LUC estimates depend on the time periods and data sources selected for analysis, how CRP lands are classified, and how uncertainty is considered (Copenhaver et al. 2021). For example, some studies focus on the recent expansion of cultivated crops and calculate LUC for any return of CRP grassland to its prior use (cultivated crops) (Lark et al. 2020). Others focus on the persistent loss of farms and prime cropland to urban and other developments (Francis et al. 2012; Hunter et al. 2022). Further, as discussed above, literature establishing causal historical connections between cropland change and biomass or bioenergy production is preliminary and inconclusive.

The gaps and uncertainties associated with land cover and management data, aggregation, and definitions required to assign land "use" classes, as well as choices of model assumptions, illustrate why model results associated with LUC have large margins of uncertainty. For example, an analysis sponsored by the EPA estimated that between zero acres and a maximum of 2 million acres of new cropland (or 0%–0.5% of total cropland) are attributable to the RFS (Clark et al. 2022).

Because LUC modeling is dependent on multiple assumed relationships and general land use classifications, minor differences in approach lead to widely disparate estimates of LUC impacts of biomass and bioenergy production (e.g., Scully et al. 2021; Broch, Hoekman, and Unnasch 2013) with contrasting conclusions—i.e., that highly detrimental (Searchinger et al. 2008) or beneficial (Donnison et al. 2021; Oladosu et al. 2012) effects associated with land and GHG emissions are likely. Modeled estimates of indirect LUC attributable to bioenergy production are unverifiable (Babcock 2009; Smith et al. 2014; Scarlat and Dallemand 2019). A recent EPA literature review of biofuel carbon intensity modeling found widely varying LUC, as well as overall GHG emissions results, varying with study, modeling framework, and scenario assumptions for both corn starch ethanol and soybean oil biodiesel (EPA 2023b).

6.3.2.3 Cropland, Forest, and Grassland Areas and Interactions with Commodity Prices

Crop price and acreage responses in models are influenced by elements that impact extensive and intensive responses. The extensive response is the addition of new land, and the intensive response is the intensification of existing agricultural land by improvement in technology, the introduction of double cropping, or other practices to improve yields. Reviews by Babcock (2015) and Khanna, Rajagopal, and Zilberman (2021) present theoretical and empirical evidence of the importance of intensification in the response of prices to changes in biofuels demand and on the response of cropland.

Modeling results related to price and LUC can be sensitive to assumptions in the dynamics of the response to the extensive and intensive margin. Whereas elasticity factors have been applied to perform LUC modeling since the early 2000s (Hertel et al. 2010), the price elasticities that determine LUC responses in the models are based on sparse data (Lambin and Meyfroidt 2011).

One limitation of this billion-ton report is the assumption that agricultural prices have zero impact on the intensification of land use, and therefore on increasing yields. Consequently, model results could overestimate the increase in crop prices. However, the crop yield improvement assumptions in the low, medium, and high mature-market scenarios in POLYSYS could represent future crop intensification (DOE 2009), and the management-intensive grazing described above represents a type of intensification on pastureland.

An example of the importance of the intensification can be obtained by looking at the commodity crop price increase in the $70/dry-ton, mature-market high scenario, in which the price of corn compared to the mature-market medium reference case drops from $4.20/bu to

$3.82/bu. As a result of this crop intensification, the quantity of the biomass produced increases from 575 million tons per year to 838 million tons per year.

Regarding causation, some studies find that U.S. biofuel policies or corn ethanol production are drivers of higher crop prices and cropland acreage expansion (Li, Miao, and Khanna 2019; Lark et al. 2022), and others find no significant influence of U.S. corn ethanol production as a driver of LUC via the causal mechanisms of higher prices or displacement of exports (Oladosu, Kline, and Langeveld 2021). The expansion of total agricultural land may be more influenced by non-price elements than by commodity prices or bioenergy markets (Zilberman 2017; Kline et al. 2011). Land tenure regimes, government development policies, agricultural subsidies, infrastructure development, existence of production contracts, policy incentives to convert nonagricultural land (i.e., primary forest and natural pasture), and other localized sociopolitical and economic factors are important drivers of LUC (Kline et al. 2009, 2015; Kline and Dale 2020).

Under the mature-market medium scenario at a biomass price of $70 per dry ton in Chapter 5, 398 million tons per year of energy crops are produced. This production is on 76 million acres of agricultural land, including 26 million acres of cropland and 50 million acres of pastureland (Figure 5.9). Farmers are expected to produce crops that have local comparative economic advantage. Thus, modeling in Chapter 5 explores likely interactions with U.S. conventional crop markets. Under modeled price impacts of the mature-market medium scenario, wheat has the largest price increase (19%), followed by soybeans (9%) and corn (5%), compared to the extended USDA baseline. This results in a weighted average price increase of 6% (Figure 5.11). In all cases, these price increases are far below the price spikes experienced in 2007–2008 and 2011–2012. These price increases, and the low total U.S. agricultural land price elasticities reported by Barr et al. (2011)[5] and Roberts and Schlenker (2013), suggest land use responses to changes in price may be relatively inelastic. Li et al. (2023) analyzed data from USDA and reported that for the last 20 years or more, the U.S. aggregate cropland remained relatively constant between 2000 and 2021. Results also suggest there is an inelastic response to price, but there is a trend of increasing acreage for corn and soy production as a replacement for other crops in the 1980s (USDA NRCS 2023b). The historical data reported in the Food and Agricultural Policy Research Institute's 2023 agricultural outlook show that annual variations in U.S. land use for major crops, hay, and CRP for the last 20 years have been in the range of ±0.3% despite significant crop price variations (FAPRI 2023).

[5] Barr et al. (2011) found that the elasticity of total land used in agriculture with respect to agricultural prices is 0.03, and in Brazil the same elasticity stabilized at 0.05 after 2000, even in the presence of soaring prices. One additional finding is that the elasticity of total land use in Brazil is much lower when pastureland is included than when only crops are considered; this indicates a significant shift from pasture to cropland and could indicate a small impact on deforestation. A later econometric study by Roberts and Schlenker (2013) found similar results for the cropland elasticity in Brazil, but significantly higher (0.28) for the United States. However, when they introduce set-asides and land retirement programs, the supply response drops sharply, and it is inconclusive. This remains an area of uncertainty in the literature.

Economic theory suggests that the risks of induced LUCs are higher as prices for commodity crops increase. These risks are uncertain and unquantified in this study. Figure 5.11 shows that commodity crop price impacts under the $70/ton, mature-market medium scenario are in the range of approximately 5% to 19%, a wide range that varies both by crop and the level of biomass demanded. These simulated price responses reflect the effects of changes in the demand for agricultural land, while other factors are assumed to be held constant. Despite persistently increasing global demand, long-term trends for corn, wheat, and soybean prices show declines in real terms. The fall in real prices is driven mostly by the intensification of agricultural land; 95% of global food growth has come from the increase of output per hectare (Maletta 2016). Because the current modeling approach includes only changes in land use in the United States, the global intensification or extensification of agricultural lands (including both cropland and livestock pasture) into nonagricultural lands and associated environmental impacts resulting from these price increases cannot be quantified in this study. Impacts on non-U.S. commodity consumption, production, and demand are not quantified in this study and could range from small to very substantial, although that is an area of substantial uncertainty.

Local policies, technical assistance, and financing are among factors that influence whether production intensifies and allows for expansion of conserved areas (as occurred in most high-income nations over the past 50 years), or if agriculture expands and impacts forests and potentially biodiversity (as occurred in nations with less stable governance and land tenure regimes). Characterizing potential impacts of increased commodity prices on forests is complex, as effects vary greatly depending on local context (Zabel et al. 2019; Kline et al. 2015). Global commodity prices influence crop choice, but there are various factors that lead to deforestation including local drivers (Kline and Dale 2020). The fieldwork required to determine actual causes of deforestation and changes in biodiversity is difficult, costly, and often dangerous. Thus, most published research is based on remotely sensed land cover data, correlations, and models that do not always incorporate factors such as local land acquisition customs, governance, security, property rights, illegal logging, incremental forest degradation, wildfires, or land invasions (Efroymson et al. 2016; Kline et al. 2009). A recent analysis by Brazilian researchers illustrates the critical role of local governance in Brazil, independent of agricultural commodity prices (Rochedo et al. 2018). For these reasons, it is not possible to determine with certainty how a small increase in U.S. commodity prices could affect forests, but evidence suggests that any effects, whether beneficial via intensification or detrimental via extensification, and also have uncertainty similar to other factors impacting forests, such as those related to changing climate, including sea level rise, extreme weather events, and wildfires (Kline and Dale 2020; Kline et al. 2015). Wildfire-burned areas, for example, are trending upward in the United States (Salguero et al. 2020).

Corn ethanol and, to a lesser extent, soybean oil biodiesel have been the focus of simulations of future market-mediated impacts of potential biomass-induced agricultural price increases on forest extent. This literature suggests a very wide range of potential global impacts (EPA 2023b) whose uncertainty would increase if energy crops were planted. A recent large-scale attempt to understand such impacts, the Stanford Energy Modeling Forum's EMF 33 study, also suggests a very wide range of potential LUC impacts associated with cellulosic biomass. Further research is needed to better quantify the range of potential market-mediated impacts of energy crops compared to those of corn- and soy-based bioenergy.

In addition to modeling energy crop production on cropland, results in the mature-market medium reference scenario at a price of $70 per ton of biomass include energy crop production on 50 million acres of pastureland. This represents 12% of the 415 million acres of pastureland on farmland, or 8% of the 655 million total acres classified as grassland pasture and range by the USDA's National Agricultural Statistics Service (USDA 2014).

In light of studies that attempt to quantify grassland-to-agriculture transitions in recent years (Mladenoff et al. 2016; Lark, Salmon, and Gibbs 2015; Lark et al. 2019, 2020; Comer et al. 2018; Gage, Olimb, and Nelson 2016), the question arises whether energy crop production might further threaten grasslands. Several studies document correlations between conventional biofuel production and recent transitions of grassland to cultivated cropland in the United States (e.g., Li, Miao, and Khanna 2019; Lark et al. 2020). Researchers have identified grasslands likeliest to transition to agriculture in the future (Gage, Olimb, and Nelson 2016; Olimb and Robinson 2019) based on soil, climate, and topographic variables. Others acknowledge that commodity prices and revenues are likely to influence land cover transitions as well (Rashford, Walker, and Bastian 2011). However, estimates of extents of transition have large uncertainties (Rashford, Albeke, and Lewis 2013; Singh et al. 2017). Little research, if any, projects potential effects of energy crop expansion on grasslands. Environmental consequences will depend on the types of crops, management practices, and conditions of the grasslands. Better understanding of causal relationships that influence cropland expansion could help direct future conservation and energy policy (Olimb and Robinson 2019).

6.3.2.4 Sustainability Constraints and LUC in BT23

BT23 scenarios are based on sustainability constraints applied to the agricultural (Table 1.3) and forest (Table 1.4) model parameters and land classes. The analyses attempt to minimize transformation of new lands, exclude biomass harvest in administratively reserved forestlands, and apply practices (e.g., conservation, no tillage) that support or improve important ecosystem functions and services. Agricultural and forestry lands remain fixed in the agricultural land model (POLYSYS, described in Chapter 5). The restriction that no forest or pastureland may transition to annual cropland is assumed so that estimates of potential biomass in this report do not rely on deforestation or other transition of natural land in the United States. However, this modeling restriction does not ensure that these transitions will not actually happen. The constraints could drive intensification, but that is not endogenously modeled.

Some concerns about induced LUC are addressed in BT23 scenarios by ensuring that primary demands (food feed, forage, and fiber, Table 1.3) are met in tandem with additional biomass production while demonstrating the potential to expand perennial cover in regions of lower-profit (economically marginal) pasture and croplands. The bioenergy scenarios result in higher land productivity overall. Food security is addressed in more detail in Section 6.3.3.1.

The constraint of avoiding planting energy crops, or crops in general, on nonagricultural land (Table 1.3) is consistent with observations that overall acreage in agricultural production is not sensitive to price changes in ranges considered here (Dunn et al. 2017). Cultivated agricultural area in the United States fell by 70 million acres between 1982 and 2007 and then rebounded by 10 million acres from 2007 to 2017 (USDA NRCS 2023b). Government subsidies and land set-aside programs exert large influence on crops and total area under cultivation in the United States (Frisvold 2004). Thus, while cultivated cropland area increased by 10 million acres from 2007 to 2017, more than 13 million acres were released back to farmers for potential cultivation because of expiring CRP contracts over the same period.

There is no way to ensure that biomass production will evolve following assumed constraints and land distribution illustrated in Figure 6.3. Monitoring land cover, land management, and associated environmental effects, combined with public access to transparent and consistent reporting, are important steps to help identify if problems arise that merit corrective action. Timely monitoring can support safeguards and management to minimize potential detrimental changes in land cover and management.

6.3.2.5 Moving Forward with LUC Studies and Good Practices

Additional research is needed to verify historical changes in land cover and land management, and to discern causal drivers. Quantifying LUC involves uncertainties but is nonetheless important. The uncertainties underlying LUC models are irreducible unless verifiable land cover categories are applied consistently to understand historical trends in conjunction with analyses to identify local drivers for land management decisions, focusing on areas where critical changes occur. Research is also needed to explore the potential magnitude and impacts of cropland extensification into nonagricultural lands in response to biomass production scenarios; this could involve linking POLYSYS and ForSEAM. Balboni et al. (2023) conclude that research is needed to go beyond traditional economic modeling approaches, to employ rapidly improving remotely sensed data on land cover and carbon stocks, and to collect field data on local variables that influence LUC such as local political cycles, accountability, subsidies, enforcement capabilities, and land insecurity.

In addition, constructive resolution of questions about LUC requires testing, especially place-based testing, of causal inferences related to biomass and LUC. A basic question relates to the direction of causation. Some statistical causal analysis studies based on empirical data (e.g., Katrakilidis et al. 2015; Natanelov et al. 2011; Roman, Górecka, and Domagała 2020) find that ethanol production quickly responds to, rather than causes, price changes. Monitoring land cover conditions in near real time is now technologically possible and can help distinguish effects of biomass production from effects of other agents. Understanding causation can help analysts identify effective solutions that promote beneficial changes in land management and associated ecosystem functions (Daioglou et al. 2020; Daioglou 2022; Efroymson et al. 2016; Kline et al. 2011).

Good practices can mitigate concerns associated with LUC. For example, growing perennial energy crops on degraded grassland or low-fertility lands can provide ecological benefits and reduce the likelihood that forest or grassland transition to annual cropland (Gelfland et al. 2013; Robertson et al. 2017; Daioglou et al. 2020). In a study in the Northeastern United States, landowners who owned marginal lands were more likely to plant energy crops and for a lower price than landowners who did not own these marginal lands (Jiang, Zipp, and Jacobson 2018). The use of agricultural and forest residues reduces competition for land (Calvin et al. 2020; Daioglou et al. 2020). Investments in integrated production systems, infrastructure, and technologies that improve land management and productivity can convert concerns about competition to synergies and co-benefits (Dale et al. 2014; Souza et al. 2017; Kline, Msangi, et al. 2017). Protecting lands with high carbon or biodiversity value is a good practice (Daioglou et al. 2020) that is a sustainability constraint in POLYSYS and ForSEAM. Other opportunities for beneficial LUC are not considered in BT23 but may merit additional study. Many of these add costs but could benefit from payments for ecosystem services, in addition to biomass supplied. For example, one recent study found that the technical potential of biomass from diverse sustainable sources—such as biomass grown and managed as part of land reclamation from contaminants, restoration of former mining lands, removal of invasive species to improve habitat for native or endangered species, improved regulation of runoff in catchment basins, and biomass removal (rather than mowing, herbicides, or fire) to manage vegetation in powerline and road rights-of-way—is estimated at half a billion tons per year or more (Field et al. 2023). The same study found that another 100 million metric tons of biomass could be generated by reducing wildfire risks in the West. These biomass resources do not compete for land for other productive uses. Information describing and quantifying adoption of good practices will lead to more realistic future scenarios of biomass production.

Good practices that safeguard sustainability need to be appropriate for local conditions; consider the practical, place-based opportunities and constraints; and be developed with stakeholders who are informed by reliable monitoring and evaluation data to support continual improvement. Biomass markets that provide performance-based incentives support safeguards by promoting investment in technologies for more sustainable agricultural practices that reduce supply chain emissions and other detrimental effects.

6.3.3 Good Management Practices in Agriculture

Many good management practices, including guidelines and official BMPs (usually termed conservation practices), have been developed for agriculture. The Natural Resources Conservation Service is the main source of agricultural BMPs for water and soil quality. U.S. states and researchers from the National Corn Growers Association, Water Research Foundation, and United Soybean Board have contributed to BMPs. However, the knowledge base to support the development and implementation of good practices may still be low for some energy crops.

A few studies of adoption of good management practices have been undertaken in agriculture. The USDA found that more than 80% of farm acreage has adopted tillage, nutrient management, and irrigation management practices. In the same study, cover crops were found to be adopted by only 40.5% of farmland and 61.3% of farmers (USDA NASS 2022). In contrast, Wade, Claasen, and Wallander (2015) found much lower adoption rates for good practices by farmers growing annual commodity crops (e.g., 40% of combined acreage of corn, soy, wheat, and cotton in no-till/strip-till in 2010–2011). Adoption rates differ by region and crop, with adoption rates high for some crops (e.g., soy) and some regions (e.g., Southern seaboard) (Wade, Claasen, and Wallander 2015). Factors that determine adoption by farmers include information, profits (farm income and off-farm income), land tenure, farm size, experience, and education (Liu, Bruins, and Heberling 2018). Access to good information, government subsidies, environmental consciousness, and profits associated with practices leads to greater adoption of BMPs (Liu, Bruins, and Heberling 2018), and additional social science research can increase understanding of how to increase adoption of good practices (Delaroche 2020). BMP compliance can be affected by regulatory push and community pull (Welch and Marc-Aurele 2001). The performance of certification programs has not been evaluated (Liu, Bruins, and Heberling 2018). Rates of adoption of good practices for farmers growing energy crops or harvesting crop residues (as mentioned above) are uncertain. Identifying decision makers who could increase the likelihood of compliance with good management practices and regulations for harvesting stover would be important. Decision makers could include farmers, harvesters, stover aggregators, biomass users (Kemp 2015), or policymakers.

6.3.3.1 Food Security

Food security questions in the context of biomass are not new, and guidelines have been published to build synergies between the development of biomass markets, food security, and other sustainable development goals (e.g., FAO 2014). BT23 estimates potential biomass while meeting food, feed, and fiber needs concurrently. Integrated modeling of the bioeconomy helps inform strategies to avoid unintended impacts of LUC on food crops (Daioglou et al. 2020).

As specified above and in Chapter 5, production of nearly 400 million tons of energy crops per year under the mature-market medium scenario could cause commodity crop prices to increase, raising farmer returns above the costs of production and raising corn prices 5%, wheat prices 19%, and soy prices 9%. These are modest increases compared with those observed in 2008, 2012, and 2022. Associated impacts on food prices would be low given that food commodities comprised an average of 16.6% of the price of finished food prices from 1993 to 2022 (USDA ERS 2023), with the remaining 83.4% attributed to off-farm costs. Thus, commodity price increases in the range of 5%–20% would correspond to finished food price increases of 0.8%–3.3%.

Key determinants of hunger are not commodity prices, but rather the political and governance conditions that influence access to social safety nets in times of need (e.g., crop failures, natural disasters) and, of course, poverty (Kline, Msangi, et al. 2017), with the rural poor consistently at highest risk (FAO 2017). As noted in *Enough: Why the World's Poorest Starve in an Age of Plenty*, people are at risk of food insecurity and hunger in modern times not because of a lack of global food production, but rather because of poor distribution of wealth and resources (Thurow and Kilman 2009). Changes in commodity prices have a more direct effect on income for agricultural producers than for consumers. This can be beneficial for food security because more than two-thirds of global poor live in rural areas, and their incomes strongly depend on agriculture (World Bank 2015). Economic growth in the agricultural sector has two to four times the impact of growth in any other sector in reducing poverty (World Bank 2007, 2015). Consequently, increases in commodity prices paid to farmers improve farm wages and food security, and in countries in which agriculture provides a significant proportion of rural employment, these increases are likely to reduce overall poverty rates (Headey and Hirvonen 2023).

Integrating food crop and biomass crop production improves resource management (Kline, Msangi, et al. 2017). For example, the use of cover and intermediate crops is a good management practice that integrates food cropland and energy crops without requiring more land. Food concerns are also mitigated, as scenarios target croplands that are economically marginal because of relatively low productivity and higher operational costs. Expanding marketing options and allowing flexible end use of crops can help ensure sufficient food surplus to help meet unforeseen supply disruptions, along with ecosystem services, biofuel, and bioproducts (Vural-Gursel et al. 2021).

As shown in Chapter 5, the contribution of biomass production to farmers' total net market returns is projected to be $27 billion/year, or 52% over baseline for the case of the mature-market medium scenario at $70 per dry ton. These increased returns are generated by higher crop prices (26%), residue collection (9%), and harvesting of purpose-grown energy crops (18%). This not only offers a significant increase in income for farmers and rural communities, but also implies a reduction of government support and subsidies to agricultural income. Such an increase in crop prices could be expected to reduce the level of subsidized U.S. agricultural exports and contribute to increased agricultural incomes of farmers and rural communities around the globe. Increased rural incomes contribute to improved food security for the more than 800 million poor whose incomes depend on agriculture.

6.3.3.2 GHG Emissions

The carbon benefits of growing and harvesting energy crops, including uptake of CO_2 by vegetation and carbon sequestration by soils, were described above and in Chapter 5. We revisit the GHG emissions topic here to describe good management practices and remaining concerns. We acknowledge that it is impossible to predict the extent to which producers will choose to follow all good management practices, and adoption rates are not within the scope of this study.

Many recommended practices for mitigating agricultural GHG emissions are related to fertilizer management (e.g., Langholtz et al. 2021) and soil carbon sequestration. Purpose-grown, perennial energy crops generally have lower fertilizer requirements than annual crops, as discussed below. Soil carbon can be enhanced through crop selection, harvesting practices, nutrient management, residue management, erosion control, and improved management on marginal or degraded lands. Growing perennial biomass on former cropland, for example, can improve sequestration of soil carbon (West and Post 2002). BT16 estimated SOC changes from simulated biomass, with benefits where potential deep-rooted feedstocks were simulated to grow (Canter et al. 2017). Life cycle and other analyses show that planting perennial crops provides greater GHG emissions reductions than corn (Farrell et al. 2006; Morales et al. 2015; Davis et al. 2012; Wang et al. 2012). Follett et al. (2012) describe management parameters for switchgrass that lead to increases in soil carbon in subsoil. Good management practices for residues led to many of the sustainability constraints in Table 1.3. Altering the plant microbiome for energy crops could lead to further carbon gains (Robertson et al. 2017).

More intensive crop management systems can reduce net GHG emissions, in part by allowing the succession of uncultivated lands to forests (Snyder, Bruulsema, and Jensen 2007; Barbier, Burgess, and Grainger 2010; Yeo and Huang 2013), as has occurred in the United States, especially in Eastern states (e.g., Thompson et al. 2013).

Existing literature suggests purpose-grown biomass may realize minimal to substantial net GHG benefits, depending on factors such as the initial site conditions, on-site management practices used, and the severity and direction of market-mediated impacts. Whereas market-mediated price changes for commodity crops were estimated in POLYSYS scenarios, potential impacts of price changes on net GHG emissions were not estimated. Further research will be needed to quantify these impacts. N_2O is the dominant GHG source from agriculture (on a warming potential basis) and the third-largest GHG source for the country as a whole (EPA 2023a). Thus, the question of whether biomass production scenarios will lead to higher or lower net N_2O emissions is important (Robertson et al. 2017).

N_2O emissions are highly variable and difficult to model. Fertilizer application rates and emissions factors for energy crops are among the largest uncertainties for projections of future N_2O emissions (Davidson and Kanter 2014). Therefore, additional field studies (e.g., poplar in Robertson, Paul, and Harwood [2000]) are needed to help researchers identify concerns and good management practices. However, there is strong evidence that perennial energy crops have lower N_2O emissions per area (Whitaker et al. 2018) and per unit of nitrogen applied (Field 2015) than annual cropping systems, likely due to their greater nitrogen use efficiency enabled by more developed root systems.

Few recommendations for biomass crop management are focused on N_2O. The source, application rate, timing, placement, and nutrient balance of fertilizer can affect N_2O emissions rates (Snyder, Bruulsema, and Jensen 2007), so optimizing fertilizer nitrogen use efficiency (Smeets et al. 2009; van Groenigen et al. 2011; Wang et al. 2015), increasing yield (Smeets et al. 2009), and possibly switching the form of nitrogen applied or using nitrification inhibitors (Smeets et al. 2009; Subbarao and Searchinger 2021) are good management practices. Practices that reduce N_2O currently emitted from wet soils in the Corn Belt would also be important (Lawrence et al. 2021).

Fertilizer production is a GHG emission-intensive process, and the associated CO_2e is an important component of biomass production and the bioproduct life cycle, given the fertilizer needs of energy crops (Wang et al. 2012). Energy required to produce fertilizer through the Haber-Bosch process using fossil energy sources and process emissions are sources of CO_2 emissions, while the nitric acid production process also releases N_2O, which has a substantially higher global warming potential (Camargo, Ryan, and Richard 2013). GHG emissions could be reduced by using renewable energy for the process or by planting legumes as cover crops or in rotations to meet part of the crop nitrogen requirement (Camargo, Ryan, and Richard 2013; Northrup et al. 2021).

6.3.3.3 Water Quantity

Competition for water can affect biomass production or alter the preferred feedstock and possibly the total potential biomass in this report. Groundwater storage volumes are declining rapidly in many parts of the Ogallala Aquifer (Bailey, Schipanski, and Kisekka 2020), and demand is increasing in the Apalachicola-Chattahoochee-Flint Basin in the Southeast, which includes Atlanta (Schlef, Steinschneider, and Brown 2018). Warming temperatures and declining precipitation, along with population growth, are reducing water availability, especially for new uses (Wu et al. 2020).

Could the potential energy crops in this report use more or less water than the vegetation they replace, altering groundwater and surface water flows? Crop type, climate, and management practices influence water use (Ferchaud et al. 2015; Moore et al. 2015). Some energy crops (e.g., eucalyptus) use more water than others (e.g., switchgrass); deep-rooted perennial grasses and short-rotation woody crops grow well without irrigation (Gerbens-Leenes, Hoekstra, and van der Meer 2009; Wu and Ha 2017). However, studies show similar water use by maize and perennial systems in the Midwest (Hamilton et al. 2015; Abraha et al. 2015). A review of water use efficiencies suggests that the evapotranspiration rate of energy crops would have little negative impact on water balances in temperate humid areas (Robertson et al. 2017).

Concerns about irrigation (Stenzel et al. 2021) are important but not pertinent to BT23 model outputs because energy crops are not irrigated, a sustainability constraint in POLYSYS. Groundwater consumption for irrigation in this study could decrease largely because energy crops, which would replace some irrigated crops, are assumed not to be irrigated, as in BT16 (Wu and Ha 2017). The irrigation constraint was not relaxed in model scenarios, so we do not know how potential biomass supply or prices might be affected by irrigation. Some regions, such as some watersheds in the Ogallala Aquifer (Irmak et al. 2010), restrict the amount of water available for irrigation, and cooperative, dynamic management of this common water resource can lead to low to no groundwater depletion (Steiner et al. 2021).

Water requirements for processing biomass, which are not considered in POLYSYS modeling, may influence local market demand for biomass in a region. Some regions may have high biomass potential but possibly insufficient water for a biorefinery (e.g., the Great Plains). New biorefineries could diminish limited surface water and groundwater resources, especially in the Arkansas-White-Red River basin in the Great Plains, and also in the Republican River basin in the High Plains, the California Central Valley, and the Columbia-Snake River basin in Washington (Yang, Piao, and Cai 2022). In contrast, watersheds in the Midwest, the Mississippi Delta, Appalachia, and the Northeast have abundant water and potential biomass feedstock for bioenergy and bioproducts. Existing water supply infrastructure might need to be expanded to meet processing needs (Yang, Piao, and Cai 2022).

In water-limited regions, good management practices for water conservation need to consider competing demands for water resources and associated restrictions (Berndes 2002). For example, farmers in nearby counties that lack access to Ogallala groundwater employ management practices that are less water intensive and more drought resistant (Hornbeck and Keskin 2014). Wastewater or processing water could be used in some water-competitive or arid locations (Zema et al. 2012). Good water use management practices can include irrigation scheduling (if irrigation is used), as well as crop residue management and conservation tillage (to conserve soil moisture) (Texas Water Development Board 2005), which are important for maintaining soil carbon and promoting water quality as well. Good practices on water-stressed sites can include selection for drought-tolerant genotypes (Zalesny et al. 2019).

In flood-prone agricultural areas, deep-rooted perennial energy crops, including grasses and trees, can be an adaptation strategy (Jager et al. 2020; Langholtz et al. 2014). In addition to droughts, floods will likely increase in frequency in the future climate, and perennial crops are superior to annuals for controlling erosion during flood events.

6.3.3.4 Water Quality

Water quality can represent a benefit or a risk of producing and harvesting biomass, depending on the crop, location, and previous land cover and land management. Fertilizer requirements and related nutrient runoff tend to be lower for perennials like switchgrass than for annuals like corn. Similarly, perennial energy crops do not require as much herbicide or insecticide as annual crops (e.g., *Salix* spp. in Nordberg, Cederberg, and Berndes [2014]), and pesticide runoff from perennials is lower than for annuals. In contrast, transitions of grassland to energy crops would likely increase fertilizer use and could increase the use of herbicides, which are applied during establishment, potentially decreasing water quality in streams or groundwater. Trade-offs among water quality variables (nitrate, total suspended solids, and total phosphorus) were simulated in BT16, with short-rotation woody crops, for example, offering water quality benefits (Jager, Wu, et al. 2017).

Modeling of agricultural biomass resources in this report does not include constraints for protecting water quality, other than the residue retention targets and use of cover crops. For example, in POLYSYS we do not exclude highly fertilized corn from riparian zones that exceed nutrient-related federal water quality criteria.

Good management practices would improve environmental effects by reducing the quantity of nutrients and sediments moving to streams. In biomass field and modeling studies, riparian buffers, cover crops, and switchgrass planting decreased nutrient and sediment loadings from annual cropland (Ha and Wu 2017; Brandes et al. 2018; Jager et al. 2023). These benefits, along with those of cover crops, slow-release nitrogen fertilizer, and tile-drain control, were also demonstrated in BT16 (Jager, Wu, et al. 2017). Minimizing the quantity of fertilizer is clearly a best practice. Harvest cutting height and timing can be optimized for water quality and to retain nutrients on-site (Ventura et al. 2012). For short-rotation woody crops, coppicing is typically done at the end of the growing season to retain nutrients (Ventura et al. 2012).

6.3.3.5 Air Quality

Air pollutant emissions from biomass occur at stages from field preparation through harvest, including chemical application and on-farm (or on-forest) transportation, along with transportation and preprocessing prior to the biorefinery or other end use. The full implications of the production and use of biomass will vary depending on many factors, including counterfactual assumptions and how the substitution effects are considered in terms of decreased fossil-related emissions. Inventories of seven non-GHG regulated air pollutants were estimated for BT16, not including upstream air emissions (e.g., from fertilizer production) (Warner et al. 2017). In BT16, about a quarter of U.S. counties growing the potential biomass were estimated to emit direct and precursor criteria pollutant mass emissions equivalent to 1% to 10% of the current National Emissions Inventory (Warner et al. 2017). The National Emissions Inventory is a triennial estimate of air emissions of criteria pollutants, their precursors, and hazardous air pollutants from emissions sources.

Emissions resulting from increased biomass feedstock production could pose challenges for local compliance with air quality regulations in some areas (Warner et al. 2017). Thus, Clean Air Act nonattainment areas—i.e., those with worse air quality than National Ambient Air Quality Standards—may affect if and how energy crops could be grown or harvested. In addition, an industrial facility converting biomass to fuel or other products may be collocated near biomass production and would create more air pollution (Lee et al. 2021). Current sustainability constraints in POLYSYS do not address air quality; if implemented, such model constraints could modify potential biomass quantities estimated in this report. However, locations of nonattainment areas can change as standards change and as industrial facilities are built and closed. So, whereas nonattainment areas could be excluded from the POLYSYS land base, they may be more dynamic than wilderness areas, wetlands, and other excluded areas.

Agricultural activities contribute to air quality issues in some regions of the United States, and air quality conservation measures, developed by the USDA Natural Resources Conservation Service and EPA, minimize wind erosion and machinery particulate matter generation (USDA NRCS 2012) and could be applied to biomass production. These include methods to maintain soil surface cover (e.g., residue and tillage management, mulching, cover crops); minimize in-field vehicle passes while tilling, planting, mowing, fertilizing, etc.; modify timing of operations; manage unpaved roadways; provide wind barriers; modify equipment; and manage fire and smoke. Additional good practices for farm machinery have been published, such as restrictions on idling time of farm machinery (Pennsylvania Department of Environmental Protection 2013).

Species and site selection may be important predictors of air quality in actual and potential biomass fields that represent good practices. In general, emissions for cellulosic feedstocks are lower than for corn grain (Warner et al. 2017). For example, isoprene, an ozone precursor, was not detected above a *Miscanthus* canopy (Copeland, Cape, and Heal 2012). Isoprene emissions at the scale of current poplar plantations in Europe do not significantly affect ground-level ozone concentration (Zenone et al. 2016). However, ozone was projected to increase under some conditions where the giant cane *Arundo donax* and short-rotation coppice willow, *Salix* spp., could be cultivated. (Porter et al. 2012).

Good management practices for reducing air emissions (per mass of biomass) include higher yields, lower tillage, and lower fertilizer and chemical inputs. Getting lightweight, bulky residues and grasses to a depot or biorefinery can take more truck trips than conventional crops. Using biomass more locally or using more fuel-efficient long-distance transportation methods (e.g., rail, densified biomass) could potentially decrease emissions from truck transport (Warner et al. 2017).

6.3.3.6 Biodiversity

How does biomass crop production affect the diversity of plant and animal species? The answer depends on whether and where land cover and management would be modified, as well as what land management practices are replaced. In this study, the structure of the POLYSYS model restricted the U.S. agricultural land base from changing. This study does not address the potential for impacts on biodiversity due to any biomass production-induced LUC in other nations.

Transitions to cropland from other land cover types such as grassland can reduce diversity of flora through fertilization (Werling et al. 2014) or diversity of fauna by altering landscape structure (Fletcher et al. 2011; Lark 2023). Changes from perennial cover (e.g., grasslands) to annual crops have negatively impacted biodiversity (LeDuc et al. 2022). Furthermore, the extent of fragmentation and the adjacency of cropland to valued animal species habitat are important factors determining biodiversity (Lark 2023). Crop management schedules may affect different species differently and can be designed to favor specific species of concern (Jager and Kreig 2018).

Growing energy crops on arable cropland can increase the abundance and diversity of birds and arthropods and microbial biomass and plant species richness (Werling et al. 2014; Donnison et al. 2021; Helms et al. 2020). Greater benefits were observed when land transitioned from arable land to short-rotation woody crops (e.g., poplar and willow), compared to grasses (*Miscanthus*, switchgrass, and prairie grass) (Donnison et al. 2021). The benefits may be dependent on landscape heterogeneity. Grassland birds respond negatively to corn and soy planted in a North Dakota grassland region (van der Burg, Otto, and MacDonald 2023). Simulations of birds in BT16 showed varied changes in occupancy or richness depending on feedstock, climate, land use, and land management (Jager, Wang, et al. 2017). As in many simulations, high uncertainties were associated with the lack of empirical data for many species and regions. Effects of biomass production and harvesting on mammals is a research gap (Donnison et al. 2021).

Would conserving land to protect species limit the quantity of biomass potentially available? This study employed a model constraint in which many high-biodiversity lands (wetlands, wilderness areas, and legally protected areas) were excluded from production. Regulations keep biomass from being grown on protected lands, many of which are state- or federally managed.

The Conservation Reserve Enhancement Program and several state and local programs provide incentives to employ specific management practices in productive agricultural systems to “enhance critical threatened and endangered plant and animal species survival” and restore wildlife habitats (USDA FSA 2023). The Environmental Quality Incentives Program helps producers manage habitat for targeted bird species through selective use of crop planting and harvest timing (USDA NRCS 2023a). There are also state- and local-level programs to promote biodiversity conservation on agricultural lands where biomass is produced and harvested. Avoiding cultivation of nonnative or invasive energy crops on land with conservation value would be important (Robertson et al. 2017). Integrating prairie strips (i.e., native perennial vegetation) with row crops can improve abundance and diversity of birds, insect pollinators (Schulte et al. 2017), and some arthropods (Kemmerling et al. 2022).

6.3.4 Good Management Practices in Forestry

Good management practices are common in forestry, and their implementation would maintain or increase sustainability of potential forest biomass. Relevant forestry management activities relate to timber and biomass harvesting, site preparation, stream crossings, riparian management, road construction, and fire management (Shepard 2006; Southern Group of State Foresters 2018). BMPs can be mandatory in some states (Ice et al. 2004) and voluntary in others (Ice and Stuart 2001; Kilgore and Blinn 2004; Shepard 2006). Studies of compliance with BMPs are more common in forestry than in agriculture (Wang and Goff 2008; Ice, Schilling, and Vowell 2010), including for biomass harvesting (Barrett et al. 2016b). We describe good management practices for forest biomass harvesting below.

Several sustainability categories are not addressed below. It is important to note that harvesting biomass from forests has no impact on food security. Because Sun et al. (2017) estimated little change in water yields from thinning of forests for biomass in BT16, we do not review water availability. However, it is notable that when fuel treatments for wildfire risk reduction are undertaken in the West, water availability in streams or for vegetation may increase (Bart et al. 2020). Air quality effects and best practices are not addressed. Fuel use was the major source of ammonia and nitrogen oxides for logging residues and whole-tree biomass in BT16 (Warner et al. 2017). Sources of particulate emissions are fuel combustion and fugitive dust emissions.

Clearly, reducing fuel use would be a good practice for promoting air quality. GHG emissions from forestry are reviewed in BT16 (Canter et al. 2017). Life cycle emissions from production of forest biomass and especially residues are generally lower than for agricultural crops because of the lower quantities of diesel fuel used for site preparation and sparing use of fertilizer.

6.3.4.1 Water Quality

Water quality effects of harvesting forest biomass were roughly estimated in BT16 based on an empirical model. For example, sediment load for harvesting biomass from plantations was estimated to be less than 9 Mg/ha over 4.4 years (Rau et al. 2017), a rate much lower than that associated with agriculture, especially with BMPs (Hill 1991). Potential forest biomass estimates in this report do not reflect any constraints intended to protect water quality, though residue retention constraints, which minimize ground disturbance, are useful for that purpose.

The driver for development of most forestry BMPs is the Clean Water Act; thus, most federal BMPs were established to protect water quality by controlling nonpoint source pollution. State and nongovernment publications also recommend management practices to protect water quality. Most national forests and grasslands monitor implementation of BMPs.

Blinn and Kilgore (2001) reviewed state guidelines for managing and protecting riparian resources in forests. Most riparian guidelines include three components: width of riparian management zone, minimum quantity of trees remaining following timber harvest, and other management practices (e.g., management of forbs and grasses) (Blinn and Kilgore 2001), all of which can be implemented in biomass harvest zones (Shepard 2006). State guidelines vary, and some depend on the local or regional context (Blinn and Kilgore 2001).

BMP implementation in forests is generally high, including in a biomass harvesting context (Garren et al. 2022; Hawks et al. 2023). The overall national rate of BMP implementation in forestry was estimated in 2010 to be 89% (Ice, Schilling, and Vowell 2010). In one study, implementation of some BMPs at biomass harvest sites in Virginia was lower than for conventional harvests—these related to adequacy of streamside management zones and design and installation of stream crossings, roads, and skid trails (Barrett et al. 2016b).

6.3.4.2 Biodiversity

Woody biomass harvest, including residue treatment, can affect diversity of overstory and understory communities, potentially increasing them (Premer et al. 2016). Vertebrate biodiversity can be altered through changes in forest structure at the stand (e.g., canopy cover, residues) and landscape scales (e.g., distribution of stand ages following age-dependent harvesting) (Janowiak and Webster 2010; Donner, Wigley, and Miller 2017). Forest types, structural heterogeneity (including snags and down deadwood), and species life history traits would be some of the determinants of species diversity and related metrics. Forest harvest residues provide habitat for small mammals such as voles (Sullivan et al. 2011) and birds (Grodsky et al. 2016), and the abundance and richness of species may be dependent on the quantity of downed woody debris. However, leaving too much forest debris in place can increase the risk of wildfires, an ecosystem disservice.

Biomass can be harvested using management practices that promote forest biodiversity. For example, habitats of rare and valued species that are not already excluded from harvesting (and the biomass simulations in this report) can be avoided. However, many habitat areas suitable for specific species occur at spatial scales smaller than the county-level resolution of ForSEAM, and most do not occur in production timberlands where ForSEAM is applied. Also, the timing and spacing of harvests that maintain biodiversity metrics (e.g., suitable wildlife habitat, number of avian species present) could be applied across broader areas. The timing of harvest can be conducted so that diverse ecosystem structure is maintained across the landscape. In the specific context of salvage logging in disturbed areas, there is a concern that mechanical operations could impede recovery of native species and increase invasion by nonnative species. Stands with the highest bioenergy potential may also have the highest recruitment of new seedlings and saplings that could be damaged (Barrette, Thiffault, and Paré 2013). Species that germinate by fire could be vulnerable to post-fire salvage logging (Knapp and Ritchie 2016). Timing salvage logging to mitigate adverse impacts on biodiversity would be important (Barrette, Thiffault, and Paré 2013).

Five principles have been recommended to guide the development of BMPs for biodiversity in forests: maintaining connectivity, maintaining landscape heterogeneity, maintaining stand structural complexity, maintaining aquatic ecosystem integrity, and aligning human disturbance regimes with natural disturbance regimes (Lindenmayer, Franklin, and Fischer 2006). These principles are compatible with biomass harvesting in forests. Some BMPs designed to protect water quality may have synergistic benefits, such as streamside management zones that protect wildlife habitat (USFS 2012). Evaluating potential environmental costs of biomass harvest from forests requires site-specific analyses, as there can be a wide range of benefits for biodiversity, ecosystem function, and other services in many situations (Premer et al. 2016; Kline and Dale 2020).

Many of these BMPs could be integrated in ForSEAM. However, most BMPs are site-specific and applied only in certain contexts and at subcounty scales. Thus, the practices could be more easily applied if the model were run at finer resolution.

6.4 Concluding Thoughts

Some studies question whether sufficient land (Searchinger et al. 2023) and water (Damerau, Patt, and van Vliet 2016) are available for both food and energy crops. Other studies suggest that what is lacking is good management (Woods et al. 2015; Kline, Msangi, et al. 2017). Overall, there is significant uncertainty regarding the degree to which producers will adopt good management practices and what environmental outcomes may result from the large-scale production of biomass.

Effects of biomass supply on GHG emissions, other environmental metrics, and food depend on context (Efroymson et al. 2013) and are affected by feedstock, management practices, climatic regions, scale of deployment, reference land cover, land management, and energy systems, as well as by spatial and temporal scales (Calvin et al. 2020; DOE 2017). In this report, national biomass resource potential is quantified as a function of price, market maturity, and specified economic and environmental modeling assumptions, including constraints specifically designed to support more sustainable land management.

To test effects of deviating from sustainability constraints in the mature-market medium scenario under a reference price of $70 per ton, we relaxed sustainability constraints in models specified in Chapters 4 and 5. Results suggest:

- The simulated production of small-diameter trees from timberland is bound by economic assumptions, competing market demands, and the $70-per-ton reference price. A higher price could incentivize harvest of additional biomass from timberlands, some potentially from trees greater than 11-inch DBH. Expanding the permitted distance to road restriction also increases available forest residues.
- The simulated production of logging residues from timberland is estimated to increase from about 45% of total logging residues to 60% under the reference offered price of $70 per ton. While there is always a possibility that excessive volumes of residues are removed relative to local site requirements, this analysis suggests that about 40% of logging residues in the forest is stranded due to economic or operational accessibility. Experience suggests that for forest biomass harvesting in at least some regions, machinery designed to meet market quality requirements for low ash and contaminants also supports the sustainability constraints assumed here.
- The simulated production of agricultural residues is bound by the environmental sustainability constraints assumed in this report. Potential supply could more than double if the sustainability constraints in POLYSYS were relaxed. While deviation of future practices (e.g., harvest limits for agricultural residues) from those assumed in this report could lead to risk of overharvesting and unintended environmental consequences, market requirements for clean and sustainable biomass mitigate this risk.
- The simulated production potential of energy crop supply is determined by local profitability, competing market demands, and the $70-per-ton reference price. A higher price could drive more energy crop production. Simulation results showed energy crops established on 7% of cropland and 12% of pastureland. Modifying the model assumptions to expand energy crop production on nonagricultural land was not explored.

“Good” or “best” management practices, if employed, may contribute to sustainability and what has been termed a “social license for a growing bioeconomy” (Titus et al. 2021). Better management of productive landscapes to provide ecosystem services along with biomass products for food, feed, fiber, and fuels via integrated systems is necessary to achieve climate goals (Schulte et al. 2022; DeFries et al. 2022; Robertson et al. 2022; IEA 2021). Monitoring, outreach, incentives for ecosystem services, and regulation are options to reduce risk of undesirable sustainability outcomes. Sustainability constraints used here indicate future needs for certification or regulation to promote or enforce good practices.

Good practices that safeguard sustainability need to fit local conditions; consider practical, place-based opportunities and constraints; and incorporate knowledge of stakeholders who are informed by reliable monitoring and evaluation data to support continual improvement. This national-scale assessment does not capture opportunities that local stakeholders may identify for synergistic practices to increase both biomass potential and ecosystem services. Biomass markets that provide performance-based incentives support safeguards by promoting investment in technologies for more sustainable agricultural practices that reduce supply chain emissions and other detrimental effects.

Furthermore, biomass markets offer advantages related to sustainable development goals that were not discussed in this chapter. These include employment and reduction of wastes (Blair et al. 2021; Kline et al. 2021). The reduction of wildfire risk through fuel treatments (thinning of forests) was only touched on in this chapter and has the potential to increase biomass and benefit society.

Social acceptability is also required before the potential biomass in this report can be realized. Engaging with the public, farmers (Donnison et al. 2021), and foresters (Gruchy et al. 2012) will be important for understanding and achieving social acceptability of biomass production and harvesting. Transportation, processing, and end uses for bioenergy and bioproducts could raise additional concerns about water availability, air pollution, and distributional or environmental justice. In general, agricultural and forestry models and future resource assessments such as this could benefit from social science perspectives and applied research on human decision-making and behavior (Schrieks et al. 2021).

BT16 Volume 2 estimated the environmental impacts of harvesting about 1 billion tons of biomass. This chapter begins to evaluate the role of sustainability constraints used in U.S. national renewable carbon resource assessments in limiting potential biomass and minimizing adverse environmental effects. Monitoring and research are needed to determine whether these sustainability constraints and other good practices are being followed, and which interventions are most effective in supporting sustainable development goals.

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