Sustainably Sourcing Biomass Feedstocks For Bioenergy With Carbon Capture And Storage In The United States

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Executive Summary

Bioenergy with carbon capture and storage (BECCS) can provide energy and carbon management services. Realizing these benefits at climate-relevant scales depends on sourcing large volumes of low-cost and environmentally sustainable biomass feedstocks. Economical and environmentally sustainable production at large scales requires feedstock sources with low input costs, minimal interference to existing agricultural production, and synergies with agro-ecosystem carbon storage.

This analysis finds a substantial renewable biomass resource in the United States to support BECCS as a negative-emissions strategy. Mobilization of these biomass resources for BECCS and other sectors can reduce risks associated with increasing atmospheric CO_2 concentrations and provide positive socioeconomic and sustainability benefits. We estimate that the current scale of the US bioenergy sector—approximately 360 million dry metric tonnes (MMT) of plant-derived feedstocks produced per year—can be doubled with existing resources (wastes, residues, and forest management) in the near term, and can be more than tripled with investments to increase production and develop efficient supply chains. This analysis finds that this level of additional biomass production and use can be realized while simultaneously meeting projected demands for food, feed, fiber, and exports, and while providing net benefits in terms of environmental services.

This report explores the potential for expanded BECCS feedstock production in the United States through the following components:

1. A review of detailed ***economic potentials*** of agricultural and forestry residues, dedicated energy crop production on cropland and pasture, and various waste streams under rigorous sustainability criteria[a]

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[a] See DOE (2016) glossary and text for feedstock definitions and criteria.

2. Consideration of geospatial relationships among potential biomass resources and suitable CO_2 sequestration basins, which influence the economic feasibility for using those feedstocks for BECCS
3. A literature review of the estimated ***technical potential*** for additional sources of ligno-cellulosic biomass—selected for their sustainability attributes—to support BECCS and the broader bioeconomy
4. Discussion of challenges associated with biomass feedstock production scale-up, and sustainability best practices

The 2016 Billion-Ton Report (BT16), supported by the US Department of Energy, provides a detailed assessment of current biomass use in the bioeconomy, and the potential for future scale-up of select categories of sustainable ligno-cellulosic biomass production.[1] Potential biomass supplies based on documented technical and economic assessments are estimated by resource type and sum to approximately 750 MMT/year by 2040 in a base case, and more than 1,000 MMT/year under market incentives to develop efficient supply chains and improve yields (Figure ES-1). The BT16 estimates supply potentials that are geospatially explicit, account for other (e.g., food, fiber, exports) market demands, and are supported by detailed descriptions of sustainability constraints and underlying assumptions. The full report and all underlying data are available online.[b]

The biomass resource described in the BT16 can support the growth of a future US BECCS industry. Based on known analyses to date, approximately one-third of the BT16 biomass resource is co-located in geological basins suitable for CO_2 storage, and another third could be accessed for BECCS via existing transport infrastructure or piping the resulting CO_2 to the appropriate location. Initial estimates of BECCS deployment utilizing this biomass resource suggest that up to **737 MMT of CO_2 could potentially be sequestered** annually at scenario-average costs ranging from \$42 to \$92/Mg CO_2.

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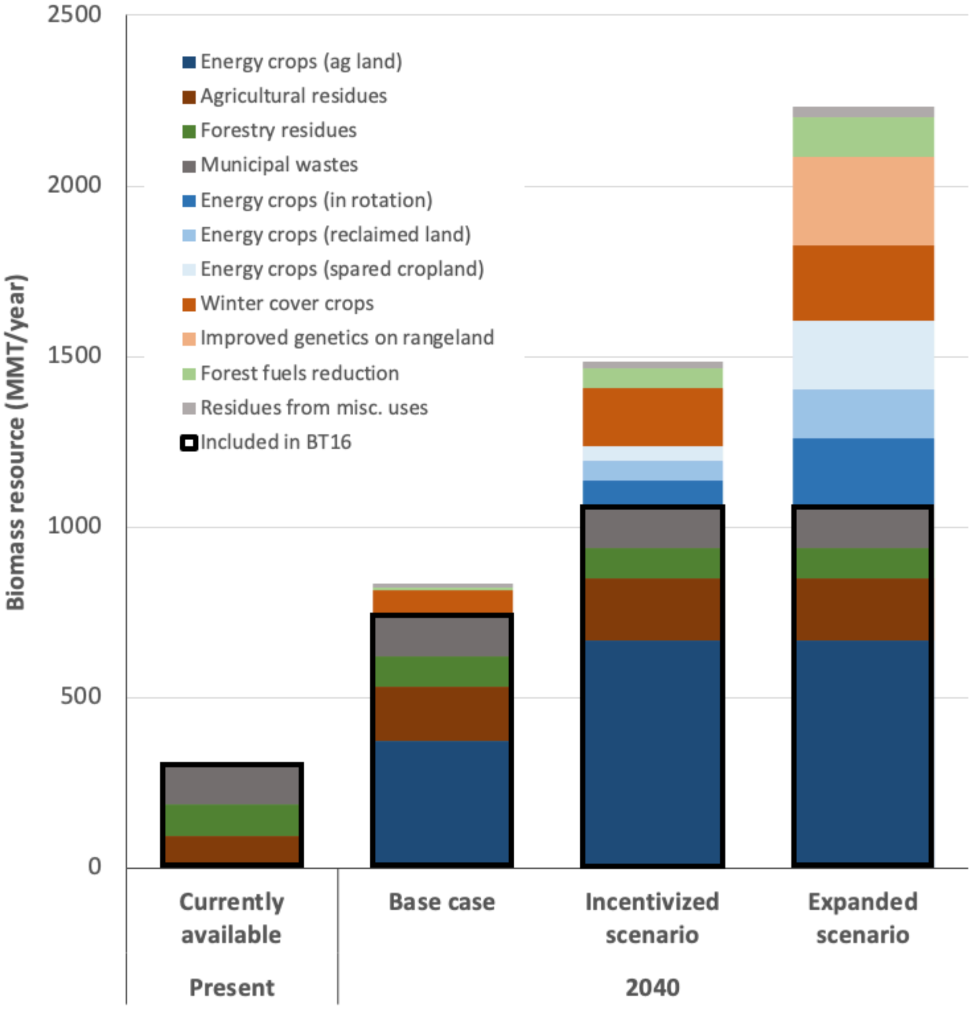
[b] https://www.energy.gov/eere/bioenergy/2016-billion-ton-report

Figure ES-1. Biomass supply potentials in the contiguous United States from specified sources, present and in 2040.



The black outline illustrates biomass economic potential quantified in the BT16; bars above the black outline represent the technical potential of other biomass sources assessed in this study. The base case represents a conservative estimate of well-documented resources that could be mobilized in near term; the incentivized scenario reflects more intensive production via investments in advanced production and logistic systems; the expanded scenario includes additional supplies that merit more study, such as genetic improvements to enable economic biomass production on a small share of US rangeland and other marginal lands. All potentials represent biomass supplies that could be developed in compliance with sustainability criteria and while contributing to multiple sustainable development goals.

Other potential biomass sources merit study beyond those considered in the BT16, including from cover cropping, energy crop cultivation on reclaimed mining land, and wildfire fuel reduction efforts. Several of these other emergent feedstocks are reviewed here, selected based on their potential to sustainably supply biomass with minimal impacts to current agricultural production or agro-ecosystem carbon storage. The estimated **technical potential of these resources (Figure ES-1) increase the BT16 volumes by**

- **85 MMT/year annually in a conservative base case,**
- **420 MMT/year in a scenario of greater production incentives,** and
- **Up to 1,170 MMT/year in an expanded scenario** with more optimistic assumptions of technology and land management improvements.

These values represent estimates of harvestable biomass that are distinct from the more detailed economic potentials developed in the BT16. The state of knowledge around the sustainability of each feedstock source is also reviewed.

The final section of this report considers sustainable scale-up of the US biomass supply for BECCS. It reviews a variety of market and sustainability challenges that have hindered expansion of US biomass production. It then presents four sets of principles and enabling conditions that could contribute to successfully overcoming those market and sustainability barriers, in particular highlighting ongoing challenges in defining science-based indicators of broad relevance to local stakeholders.

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1. 2016 Billion-Ton Report Assessment of Residues, Energy Crops, and Wastes

A robust and economic supply of biomass feedstocks is essential for successful development of bioenergy with carbon capture and storage (BECCS) at large scales. The 2016 Billion-Ton Report (BT16) is the latest in a series of detailed studies that identify biomass supply potentials in the contiguous United States.[2] The BT16 is broken into two volumes. Volume 1 quantifies biomass resources at the county level as a function of price, time, and scenario; Volume 2 quantifies biomass sustainability effects of select scenarios from Volume 1. Biomass resources are quantified within specified environmental constraints at county-level resolution and based on currently managed private lands. Potential agricultural and forestry biomass is quantified with economic models that account for conventional demands (food, feed, fiber, exports, and forest products) and simulate producer response to new biomass markets. Waste resources are quantified separately based on US Department of Agriculture (USDA) data and per-capita waste generation assumptions from the US Environmental Protection Agency (EPA). Methods and assumptions are documented in detail in DOE, Volume 1, for supply quantification.[3] The executive summary of DOE, Volume 2, provides an assessment of sustainability constraints applied and potential environmental effects.[4]

From 2015 to 2020, bioenergy comprised ~5% of annual US energy production, produced largely from wood, waste, and grains for power, heat, and fuels.[5,6] This bioenergy is derived from ~360 million dry metric tonnes (MMT) of biomass per year, largely forest mill residues for power and corn grain for ethanol.[c,7] The BT16 reports that the amount of biomass used for energy in the United States could be doubled within economic and environmental

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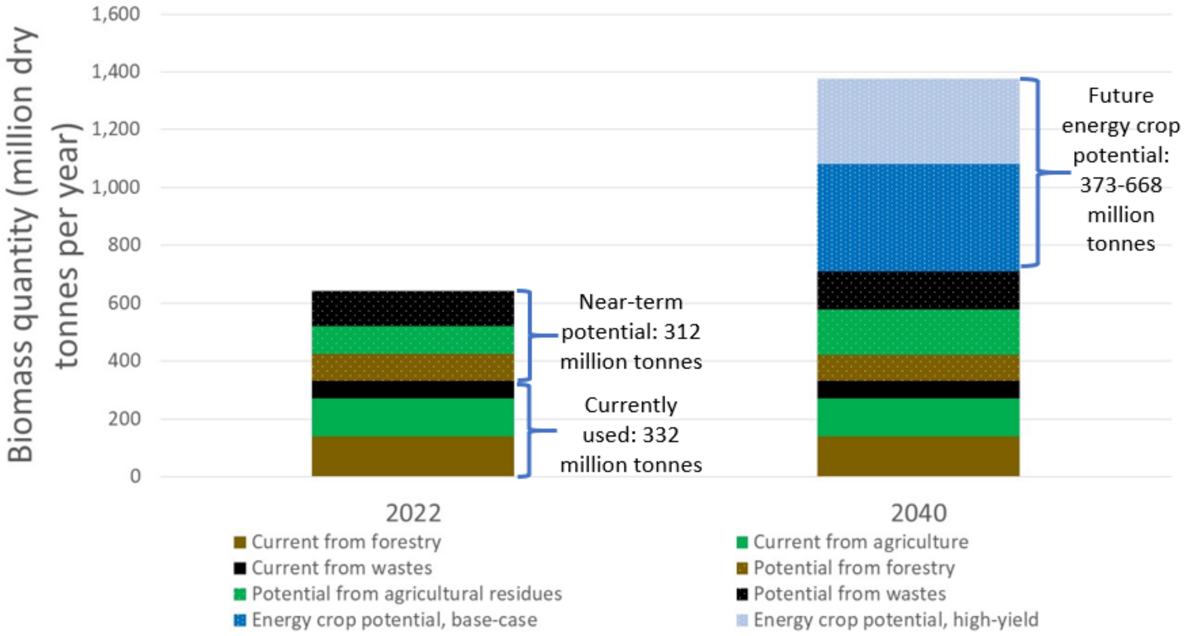
[c] The BT16 reported biomass volumes in US short tons, which represent 91% of a metric tonne. The tables and figures reproduced from BT16 report will reflect the original units. Tables and figures prepared for this report convert data to metric tonnes, or megagrams (Mg). Unless otherwise noted, all weights are reported as dry-weight equivalent. The typical feedstock moisture contents range from ~10% to 50% on a green weight basis.

sustainability constraints, and more than tripled when potential future energy crops are included (Figure 1), agnostic of end use.

Figure 1. Biomass resources that are currently used, currently available but unused, and potential energy crops that could be produced in the future.[8]



This chart assumes roadside prices of $66/Mg, base case agricultural scenario in the near-term, base case and high-yield scenarios in 2040, and a medium housing low energy demand forestry scenario. Currently used resources are based on 2017 values held constant. Adapted from Li et al. (in preparation).

The BT16 reports that an additional 700–1,100 MMT of biomass per year can become available beyond the current supply at roadside prices of up to $66/tonne in a mature market scenario. Approximately one-third of this supply is currently available in the form of wastes and residues at lower prices. The remaining BT16 potentials are based on modeled producer response to biomass markets, reallocating ~8% agricultural lands (pastureland and cropland) to be managed as perennial crops for biomass. To put this in perspective, the 27 million acres of cropland that would be reallocated for perennial crops in this BT16 scenario represent about half of the approximately 52 million acres of cropland idled each year.[9] The biomass supplies reported in the BT16 provide the foundation for three published assessments of BECCS potential in the United States (as of writing)—Baik et al., Langholtz et al., and Larson et al.—which are discussed here.[10,11,12]

1.1 Technical potential and cost of biomass resources

The BT16 includes geospatial and economic assessments of currently available but underutilized biomass resources, as well as future potential from biomass crops. More than 640 MMT/year are currently available (about half of which is used) from agricultural residues, timberland resources, and wastes.[d] The future supply potential from energy crops (370–670 MMT/year) are estimated based on productivity data for switchgrass, miscanthus, poplar, and willow. The spatial distribution of wastes, agricultural residues, timberland resources, and energy crops are illustrated in Figure 2; key attributes of these categories are listed in Table 1. Biomass quantities shown are available at $66/Mg before transportation and processing costs, but biomass availability generally increases with price.[e] An array of feedstock supplies at various prices and scenario assumptions are available elsewhere.[f] Supplemental materials illustrate the relationship of the biomass resources characterized by DOE for the contiguous United States with other potential biomass resources discussed subsequently. More information is provided in the executive summary of the BT16.[13]

The BT16 breaks down its results in four feedstock categories: wastes, timberland resources, agricultural residues, and biomass crops, as summarized here.

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[d] The USDA Forest Service defines timberland as forestland that can produce more than 20 ft^3 per acre per year of industrial wood and is not withdrawn from timber utilization by statute or administrative regulation.

[e] $66/Mg is based on the price point of $60/short ton in the reference scenario, which is approximately the price where diminishing marginal supplies are available at higher costs; costs from $30–$100/short ton are reported at https://bioenergykdf.net/2016-billion-ton-report.

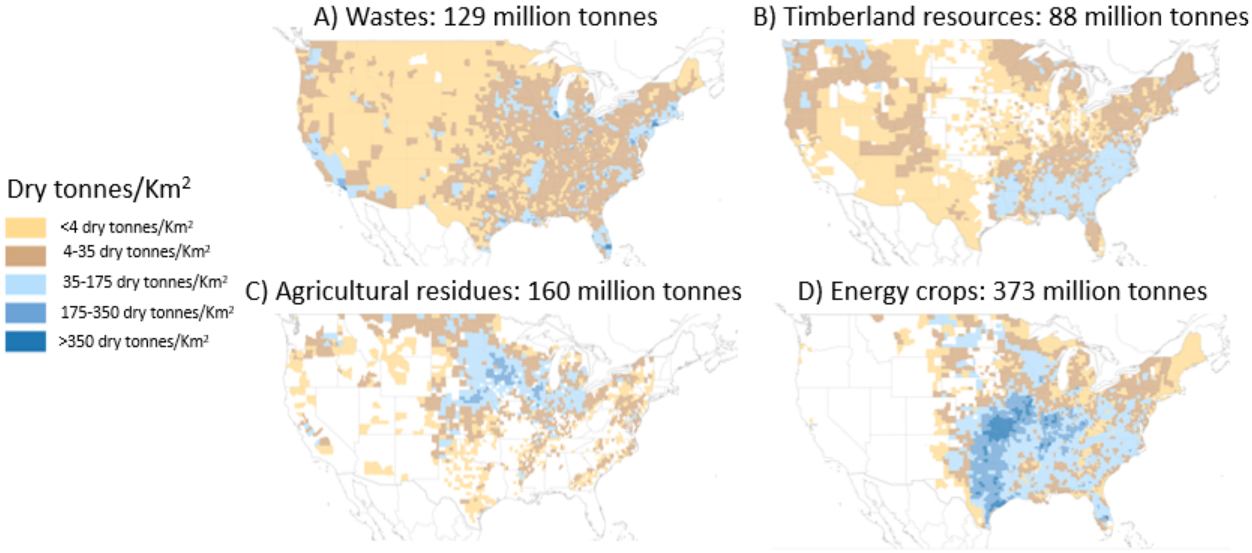
[f] https://bioenergykdf.net/2016-billion-ton-report

Table 1. Estimated quantity (potential above current uses), regional concentration, and other considerations for major biomass resource categories[14]

Resource	Estimated quantity* (MMT/year)	Region	Considerations
Wastes	130 (60–190)	Concentrated near populations	>20 waste types, primary and secondary. Favorable public perception but can be difficult to sort and process. Increasing competition for use
Timberland resources	90 (90–230)	Southeast, Northwest, and Northeast	~35% logging residues, ~65% small-diameter (<28 cm) trees. Larger cull trees are not included.[15] Conservative estimate of supplies within sustainability and operational constraints. Public perception challenges. Markets can contribute to sustainable forest management and healthier forests. ~20% of this supply is from federal lands
Agricultural residues	160 (130–290)	Corn Belt	Seasonally available as a coproduct. Advancements in variable-rate harvesting can increase environmental benefits and are important to capture full resource potential
Biomass energy crops	370–670	Southern Plains and Southeast	Supply consistent with first meeting projected demands for food, feed, corn ethanol, fiber, and exports to minimize risk of indirect effects. Public perception challenges, but perennials offer many environmental benefits and increase rural incomes. This potential is modeled to be produced on ~8% of cropland and pastureland. Transition of light-duty vehicles to electric vehicles can reduce corn ethanol demand and make more agricultural land available for perennial biomass crops

**Base case: $66/Mg (2014 USD) at roadside (i.e., before transportation and processing), contiguous United States*

Figure 2. Spatial distribution of potential wastes, timberland resources, agricultural residues, and energy crops estimated for 2040, as shown in Figure 1[16]



Wastes

Organic fractions of municipal solid wastes; fats, oils, and greases; secondary mill processing wastes; and manures from confined animal feeding operations represent ~127 MMT/year of unused wastes that may be available for new uses (Figure 2A), according to EPA and the USDA.[17]

Timberland resources

The forest products industry in the United States was the largest source of bioenergy in 2021.[18] Economic modeling that considers future forest product demand, timber stand age-class distribution, and logistical and sustainability constraints found that 88–99 MMT of additional biomass can be available annually (Figure 2B).[19]

Agricultural residues

Agricultural residues (e.g., corn stover, cereal straw) are currently available as a by-product of crop production. Applying constraints for soil conservation, maintenance of soil organic carbon (SOC), and logistical operations, DOE estimates 94–160 MMT/year (Figure 2C) available with no additional land demands.[20] Realizing this full potential may require variable-rate harvesting technology, which could simultaneously maximize production and soil conservation.

Biomass energy crops

The BT16 considers switchgrass, miscanthus, and short-rotation woody crops (e.g., poplar) as examples of potential biomass crops. These crops are grown only at limited scales today, but that can be expanded in response to market demand. Under constraints that prioritize demands for food, feed, fiber, and exports, the BT16 estimates that by 2040, energy crop production can produce 376 MMT/year in the base case scenario and 668 MMT/year in the high-yield scenario (Figure 2D). Perennial biomass crops offer benefits of soil conservation and water quality associated with no-till low-input agriculture and could be allocated to erosion-prone areas or as vegetative filters to reduce nutrient loading in waters.[21,22,23,24,25,26,27]

In summary, the current use of biomass for energy can be doubled by taking advantage of wastes and residues from forestry and agriculture, tripled with base case energy crop estimates, and quadrupled with high-yielding energy crops by 2040. This expanded supply has implications for decarbonization pathways. Assessments of the economically optimal use of biomass for carbon avoidance cost are in progress, with BECCS and aviation fuels among the priority contenders. Feedstock allocation will be determined by future markets and policies.

1.2 BT16 analysis of sustainability and land competition

Approximately half of the biomass resources explored in the BT16 are available with no land use change. These include the wastes, timberland resources, and agricultural residues shown in Figure 1, Figure 2, and Table 1, totaling ~380 MMT/year. The additional ~370 MMT/year of biomass resources in Figure 2 are from dedicated biomass crops, which would require land for production. If these biomass crops are produced on pastureland or cropland, changes in land management would be required.

As described in the BT16, historic rates of agricultural yield improvements are extrapolated into the future in 1%, 2%, 3%, and 4% yield improvement scenarios, which mitigates competition for agricultural lands. Still, producing ~370 MMT of biomass crops annually in the future involves a shift in land management. In the BT16 base case scenario, these biomass crops are modeled to be produced on up to 8% of current pastureland and cropland. Analyses of land use implications of the biomass resources reported in the BT16 and issues related to indirect or market-induced effects on land management are documented in Volume 2 of the BT16.[28] In summary, those analyses identify beneficial net effects associated with increased extent of perennial land cover under BT16 scenarios.

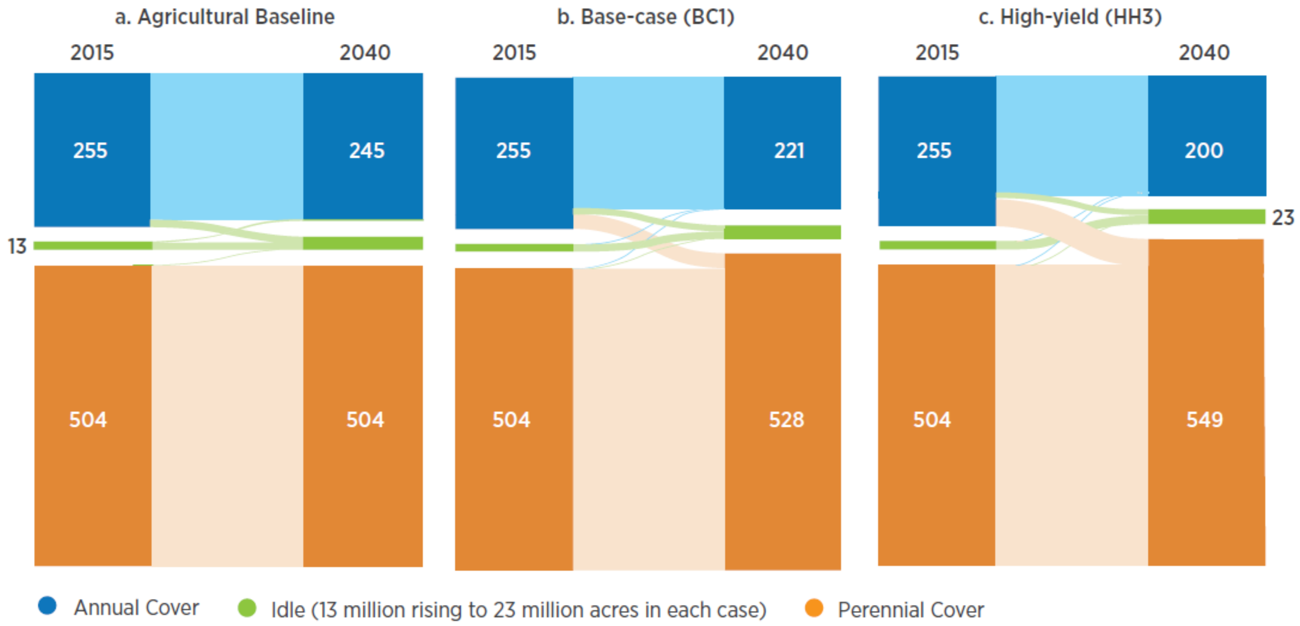
BT16 Volume 2 examines environmental sustainability indicators for biomass crops and other resources.[29] These sustainability indicators include SOC, water regimes and quality (e.g., nitrate, total phosphorus, and sediment concentrations), greenhouse gas emissions, biodiversity, and air quality (e.g., carbon monoxide, particulate matter, volatile organic carbons, particulate matter, and sulfur and nitrogen oxides).[30] Volume 2 reports that deployment of BT16 potential supplies can have neutral or beneficial environmental and socioeconomic effects if implemented with best management practices (e.g., employing integrated landscape management for optimal energy crop allocation, precision agriculture for variable-rate residue removal, and streamside management zones as vegetative filters).[31] These practices can reduce erosion, improve water quality, and provide improved habitat for species of concern relative to alternative land use options.[32,33] When best practices are employed, biomass resources used in this analysis have the potential to contribute to United Nations' Sustainable Development Goals, such as life on land, life below water, affordable and clean energy, decent work and economic growth, sustainable cities and communities, no poverty, and climate action, without compromising other Sustainable Development Goals.[34,35]

Simulated increases in national average commodity crop prices associated with producing the ~370 MMT/year of biomass crops are listed in Table 2, ranging from 4% to 32% by the end of the simulation in 2040 (DOE Table C-9).[36] Commodity crop price impacts in the high-yield scenario are similar to or lower than in the base case scenario because of greater per-acre yield assumptions (DOE Table C-10).[37] Impacts on retail food prices are expected to be less than 10% of the impacts on commodity crop prices. USDA-projected demands for food, feed, fiber, fuel, and exports are met before simulated markets for biomass additionally produce the biomass crops reported in the BT16. Direct land management acreage changes associated with this production are also shown in Figure 3. Indirect land use changes attributable to price changes reported in Table 2 are possible; these effects can be mitigated by using the identified waste and residue resources, using alternative emerging biomass resources described in subsequent sections of this report, and through agricultural intensification.

Table 2. Modeled commodity crop price effects associated with producing 373 MMT of biomass crops annually on agricultural lands from the BT16 base case scenario (DOE Table C-9)

	Extended USDA baseline				BT16 base case			
Crop	2017	2022	2030	2040	2017	2022	2030	2040
Corn ($/bu)	3.50	3.65	3.70	3.70	3.49	3.74	3.83	4.03
Grain sorghum ($/bu)	3.40	3.55	3.68	3.73	3.41	3.87	4.22	4.94
Oats ($/bu)	2.28	2.40	2.40	2.34	2.27	2.59	2.55	2.75
Barley ($/bu)	4.08	4.06	4.02	3.94	4.10	4.29	4.22	4.32
Wheat ($/bu)	4.75	4.85	5.01	5.28	4.72	5.35	5.68	6.48
Soybeans ($/bu)	8.80	9.40	9.36	9.17	8.83	9.86	10.08	10.97
Cotton ($/lb)	0.62	0.69	0.72	0.75	0.62	0.75	0.78	0.83
Rice ($/cwt)	14.90	15.80	16.69	18.29	14.90	15.82	16.86	18.94

Figure 3. Agricultural land (millions of acres) managed as annual crops, perennial cover, or idle cropland in 2015 and 2040 as estimated under the (a) agricultural baseline; (b) base case scenario (BC1); and (c) high-yield scenario (HH3) (Kline et al. 2017a).



Land allocation for energy crop biomass production in the BT16 can be illustrated in terms of current land cover and management (agricultural baseline) and 2040 scenarios for base case and high-yield scenarios, as shown in Figure 3. The net effect of energy crop production is an increase in perennial cover of 45 million acres, or about 8% of current agricultural land, in the high-yield scenario, or 24 million acres in the base case scenario. The latter area coincides with an area of cropland idled in the agricultural baseline, which is maintained in each scenario but could be used for perennial crops.

Broader trends in consumer behavior could affect these quantities. Approximately 14% of cropland is currently used for first-generation ethanol, and 17% for livestock feed. If the light-duty fleet is converted from liquid fuels to electric vehicles, or if US demand for beef continues to decline with shifts in dietary preferences, decreased demand for corn would provide increased opportunities for alternative crops. The BT16 provides details of each shift in cultivation simulated to generate the report’s biomass crop supply estimates.

Deep-rooted perennial grasses in the base case scenario are estimated to be produced on approximately 8% of cropland and 8% of pastureland, given projected land use intensification. One of the most significant factors in modeled energy crop availability is management intensive grazing, which has become easier and less expensive since the BT16 analysis (Sakas 2021).[38] Compared with annual crops that they might replace, deep-rooted perennial grasses reduce soil erosion, increase SOC, and provide greater wildlife habitat value.[39,40,41] As discussed in the previous section, integrated landscape management is proposed as a strategy to locate biomass energy crops where they provide benefits of reduced erosion, increased SOC, improved water quality, and economic advantages.

In summary, BT16 Volume 2 reports detailed analyses of potential land competition and corresponding induced changes.[42] Minimal potential was found for negative indirect effects for the scenarios documented in the BT16. Additionally, several potential positive indirect effects on land conditions were identified; based on observations, these could be significant and amplified with targeted incentives to continue to expand improved land management by incorporating perennial cover on agricultural landscapes.

Table 3. Biomass feedstock supplies, sustainability attributes, and models[43]

	Logging residues	Trees <28 cm DBH[2]	Biomass energy crops	Agricultural residues
Potential supply[1] (MMT/year in 2022; 2040)	17; 19	88; 86	0; 670	94; 160
Examples	Tops and limbs from conventional forest operations	Small-diameter (<28 cm) trees from timberlands. Larger cull trees not included[44]	Switchgrass, miscanthus, willow, poplar	Corn stover, wheat straw
Sustainability constraints	Sensitive lands excluded, no road building, costs assume best management practices, harvests are less than growth, >30% of logging residues left for soil conservation. Naturally regenerated stands not replaced with plantations		Demands for food, feed, fiber, and exports met before biomass resources are available	Constrained for soil conservation and SOC[3]
Assessment model and source	ForSEAM[45]		POLYSYS[46]	
Sustainability considerations[47]	Should be tailored to site-specific silvicultural conditions	Can be from forest thinnings to favor larger trees and fire risk reduction, or short-rotation plantations	Can be established on agricultural lands as an alternative to row crops to conserve soil, improve water quality, and improve farm incomes	Can enhance soil conservation when practiced with no- or reduced-till agriculture, cover crops, and precision/variable rate harvesting.

1 Cumulative supply at roadside at prices up to $110/Mg (including production and harvest but excluding transport or processing). Excludes ~15 MMT/year potentially available from federally owned timberlands[48]

2 Diameter at breast height

3 Constrained to not exceed the soil loss limit of the USDA Natural Resources Conservation Service based on the Revised Universal Soil Loss Equation 2 and the Wind Erosion Prediction System[49,50]

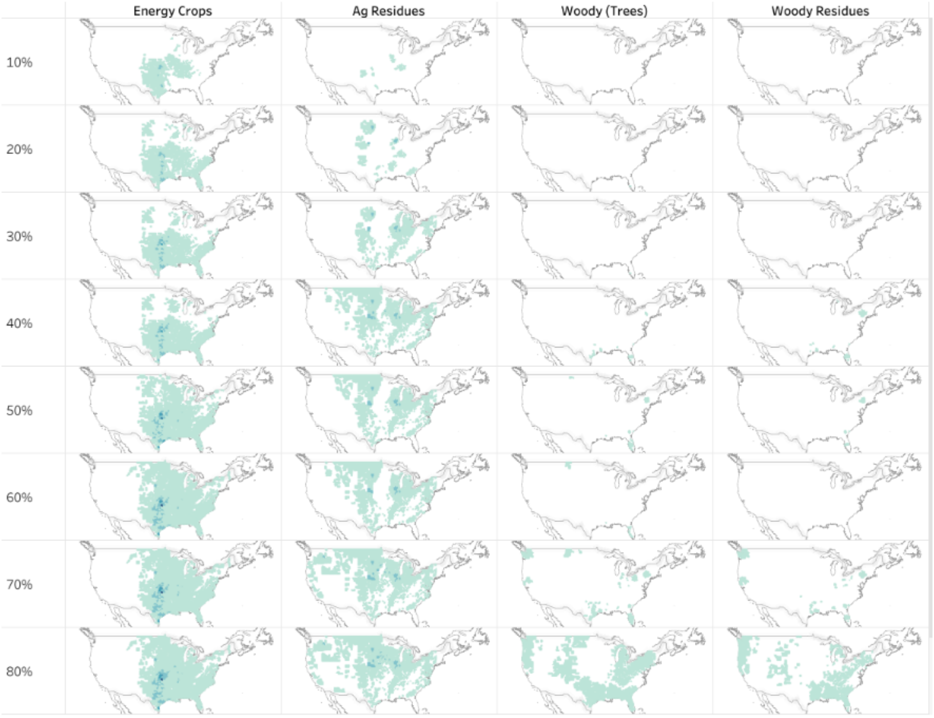
1.3 Forest cover and management

The ~750 million tonnes of biomass resources per year identified in the BT16 are modeled without conversion of forest land, and no expansion of forest plantations for biomass production is allowed. Forest managers can use two broad types of regeneration: naturally regenerated stands, and planted trees (plantations). The forest resource analysis in the BT16 does not permit naturally regenerated stands to convert to biomass plantations, nor clear-cutting of naturally regenerated stands for biomass. Of the 750 MMT of biomass potentially available per year in the base case scenario, 86 MMT/year comprise small-diameter trees from timberlands, primarily in the Southeast (Figure 2).[51] This supply is equivalent to ~0.3% of growing stock on timberlands, ~26% of annual removals, and ~28% of mortality reported by the USDA Forest Service.[52] This biomass can be harvested from forest thinnings, forest plantations, or a combination of both. Reviews of potential impacts on biodiversity report that the projected harvest intensity in each ecological region (Figure A-1) is so small (generally <2% for most regions) that it is unlikely to cause detrimental biodiversity responses.[53,54] Impacts can arise in specific sites, and beneficial effects can be derived from the removals of excess undergrowth and invasive species that improve habitat conditions for species of special concern.[55]

1.4 Potential BECCS Sites and Deployment relative to BT16 Feedstock Supplies

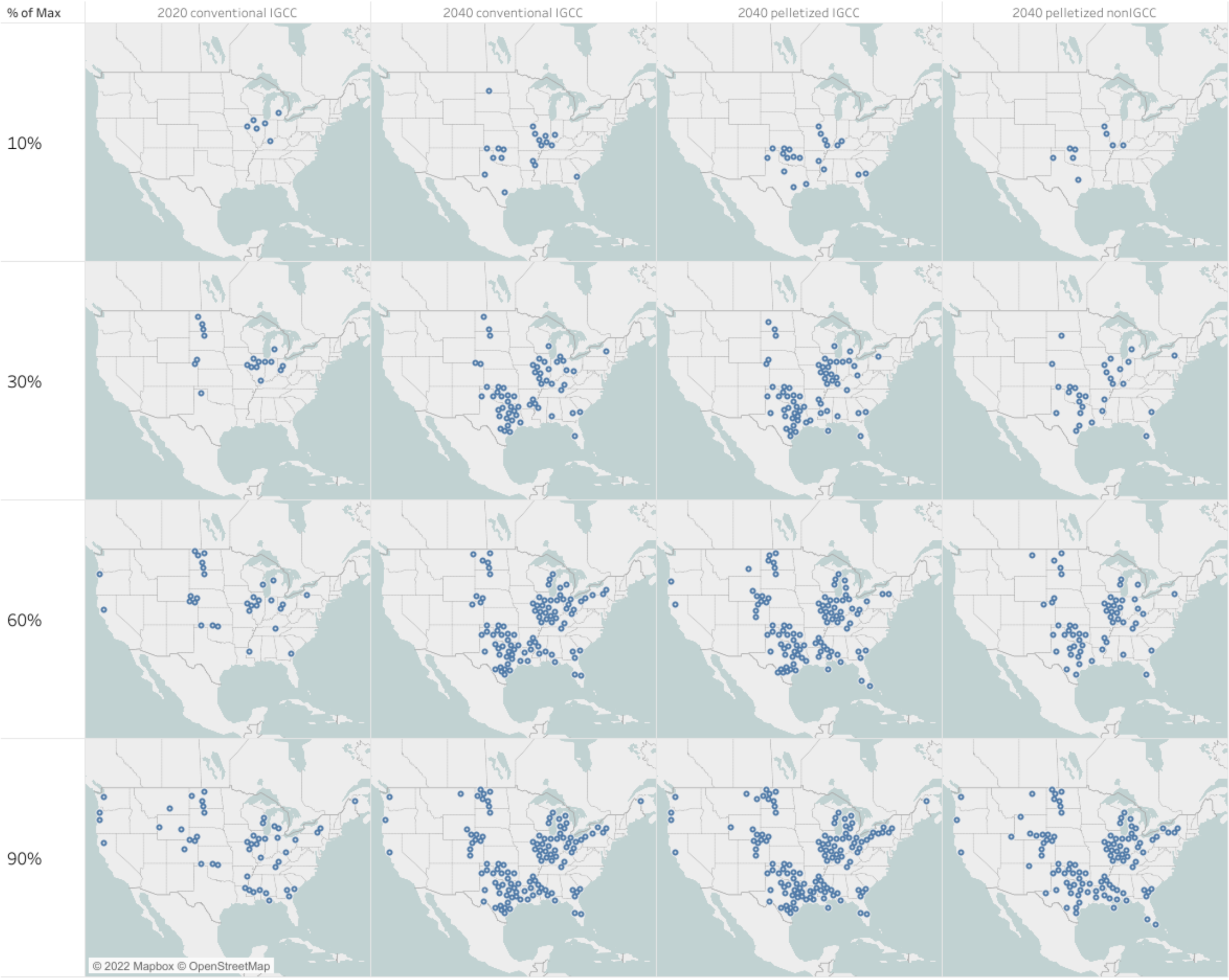
Previous analyses have considered the spatial distribution and economic accessibility of biomass resources from the BT16 in relation to potential geological storage basins in the potential deployment of BECCS. Assuming biomass resource data from the BT16, Baik et al. report that 30%–38% of potential biomass supplies are collocated with storage basins.[56,57] This corresponds to negative-emissions potential from BECCS of up to 400 MMT CO_2 for BT16 supplies in 2020 and 1,780 MMT CO_2 for BT16 supplies in 2040. Accounting for storage colocation, volume, and injectivity reduces these potentials to 110 MMT CO_2 in 2020 and 630 MMT CO_2 in 2040. Larson et al. use the near-term (wastes, residues, and forestland resources) and long-term (added biomass crops) biomass resources from the BT16 to explore a range of scenarios for the United States to achieve net carbon neutrality by 2050.[58] In four of five decarbonization scenarios, BECCS is included as a conversion technology, and H_2 production from biomass with carbon capture and storage provides an additional key technology to achieve net carbon neutrality. Their scenarios suggest that 8–19 exajoules of H_2 from biomass could be provided with carbon capture and storage. Langholtz et al. build on the Baik analysis, adding costs and CO_2 budgets across the supply chain to quantify the potential spatial distribution of biomass resources used (Figure 4), potential BECCS facility locations (Figure 5), and associated carbon avoidance cost curves (Figure 6).[59] Under a long-term scenario using up to 740 MMT of biomass per year, up to 128 BECCS facilities are potentially sited, depending on supply chain configurations. This results in up to 737 MMT CO_2 potentially sequestered annually at scenario-average costs ranging from \$42 to \$92/Mg CO_2. These optimistic cost results reflect the benefit of the combination of negative emissions through carbon capture and storage and avoided emissions through displaced fossil generation from BECCS facilities.

Figure 4. Potential biomass deployment scenario for BECCS in the long-term pulverized combustion scenario, including CO2 abatement scenarios ranging from 10% to 80% of maximum potential, from Langholtz et al.[60]



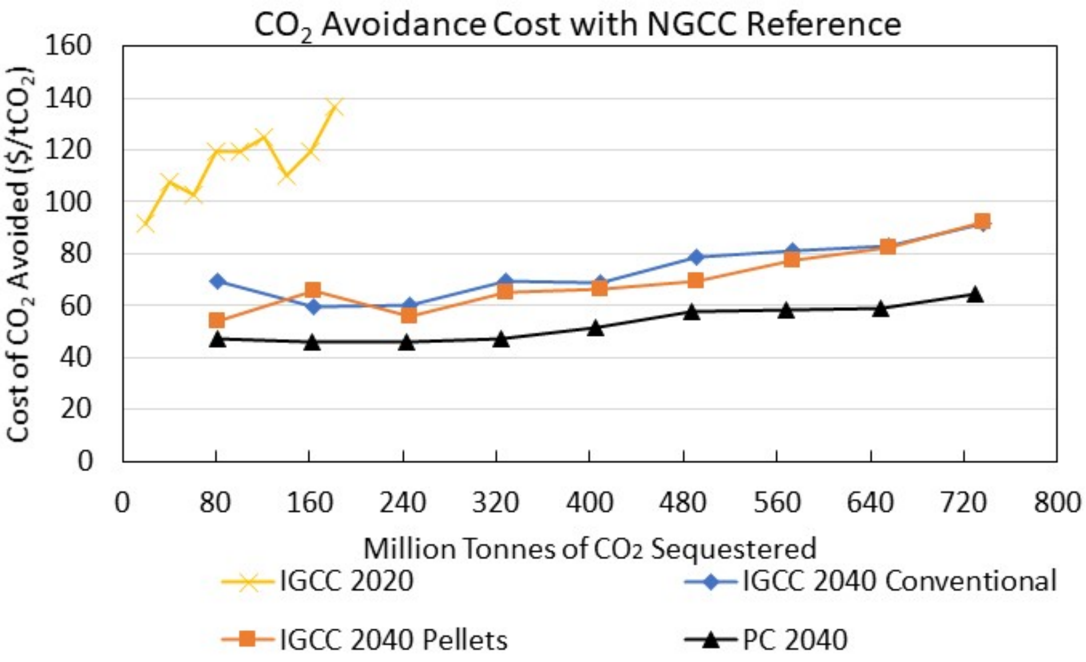
Interactive visualization available at https://doi.org/10.11578/1647453 Langholtz et al.[61]

Figure 5. Potential facility locations for BECCS deployment scenarios from Langholtz et al.[62]



Interactive visualization available at https://doi.org/10.11578/1647453 Langholtz et al.[63]

Figure 6. BECCS scenario-average CO_2 avoidance costs (\$/Mg CO_2) by CO_2 sequestered (MMT/year) under the natural gas combined cycle (NGCC) reference scenario, net after supply chain emissions for the four BECCS scenarios: 2020 integrated gasification combined cycle (IGCC) conventional, 2040 (IGCC) conventional, 2040 pulverized combustion pellets, and 2040 IGCC pellets.



"Conventional" refers to biomass handled as chips or bales; "pellets" refers to biomass converted to pellets in process depots.

2. Building on the BT16: Assessing Other Emergent Feedstocks for BECCS

Although the BT16 presents an authoritative view of future biomass supply potential, it was not meant to be comprehensive across all potential sources of ligno-cellulosic biomass feedstocks. Other potential sustainable feedstock sources have been articulated that merit additional consideration or further research. These include biomass crops grown on reclaimed or improved land, on “spared” agricultural land or Conservation Reserve Program (CRP) land, or in rotation with annuals; rotation intensification with winter cover or cash crops; genetic improvement of energy crops; and others. Table 4**Error! Reference source not found.** lists estimates of potential feedstock supply from these different categories. These categories all represent potential sources of ligno-cellulosic biomass suitable for various BECCS applications, proposed with sustainability in mind and designed to minimize competition with existing agricultural commodity production and/or to improve SOC and soil health. These categories are complementary to the BT16 and represent additional potential feedstock resources. However, the estimates in Table 4 generally consider a qualified ***technical potential*** for feedstock production, rather than the more carefully calculated ***economic potentials*** at specific price points explored in the BT16 using a consistent set of land and cost assumptions. Thus, care should be taken when comparing these estimates to the BT16 estimates in Table 1.

Here, feedstock estimates are differentiated based on three different scenarios:

- **Base case—**This consists of potential feedstock supplies that could likely be realized with minimal changes in policy, agricultural technology, or land cover and management (e.g., avoiding detrimental land use change). For example, winter cover crops are a potential feedstock source that could be integrated into existing annual crop rotations in the near term, with existing cropping technology, within existing agricultural landscapes, and avoiding indirect effects on land elsewhere. Expanding acreage of winter cover crops is an example of improved land cover and management.

- **Incentivized scenario—**This consists of potential feedstock supplies that may involve barriers requiring significant incentives, investments, or policy changes to overcome before the supply could be realized. For example, it may be possible to source large volumes of biomass from dedicated energy crops grown on reclaimed mine land, though this would likely require further improvement and regional adaptation of such crops, development of best management practices on highly degraded mine land sites, or policy incentives to monetize the value of ecosystem services.
- **Expanded scenario—**This consists of more speculative feedstock supplies that have not been well explored in the existing literature but merit further study and quantification. For example, exploratory work has examined the potential for genetic improvement and expanded cultivation of Crassulacean acid metabolism (CAM) photosynthesis crops in dryland systems, though the evidence base for such approaches is still limited. In these cases, initial back-of-the-envelope calculations were assembled to put the potential scale of feedstock supply in perspective.

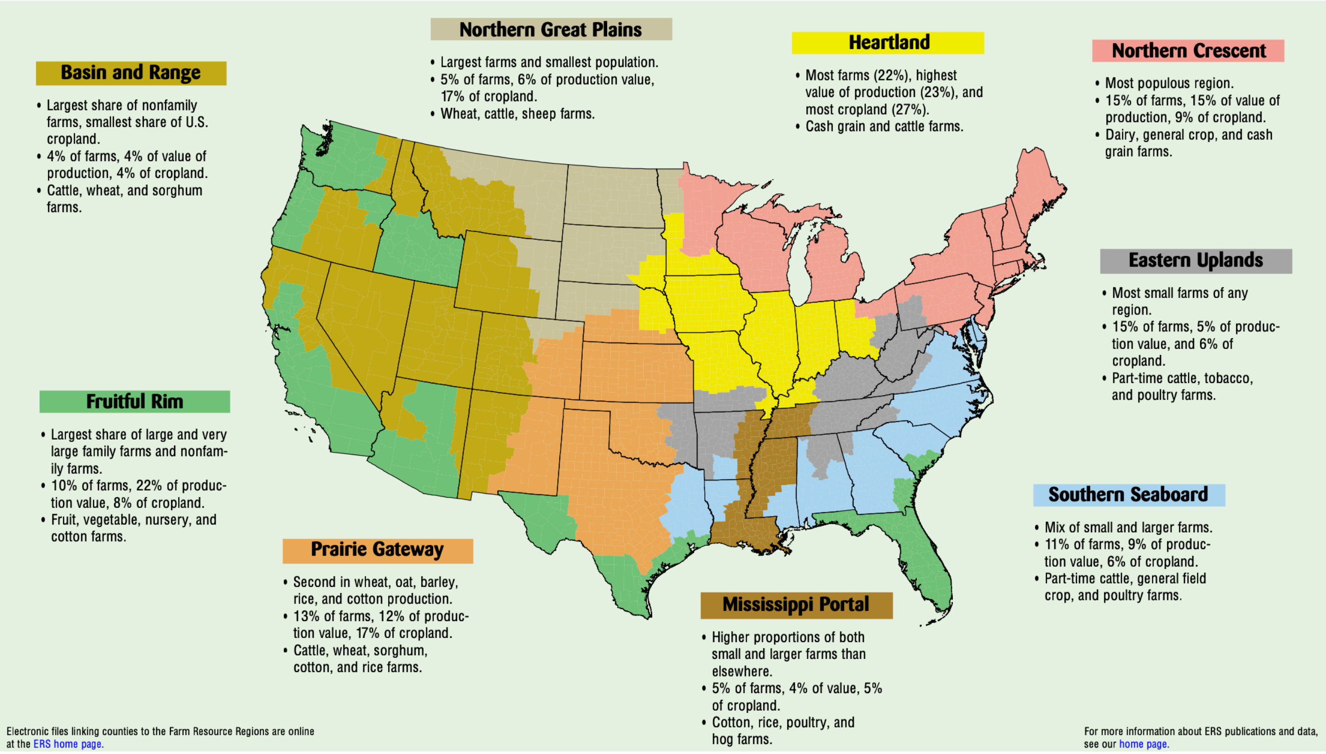
Table 4 breaks down feedstock supply estimates in terms of the relevant land area, the average yield of biomass per unit land, the total estimated biomass resource, and their approximate geographic distribution using the USDA Farm Resource Region system illustrated in Figure 7, which can provide a rough comparison to the BECCS deployment scenarios illustrated in Figure 4 and Figure 5.[64] In several places where literature estimates include highly optimistic yield assumptions, an alternative adjusted estimate is presented based on a standard yield estimate of 10 metric tonnes per hectare (Mg ha^{-1}) per year for dedicated energy grasses (shown in red italics). Where independent estimates of land area are not present, land area data from the USDA Major Uses of Land in the United States 2017 report Bigelow and Borchers are used, as per Merrill and Leatherby.[65,66]

Table 4. Other potential novel feedstock sources

	Land base (Mha)	Avg. yield (Mg ha^{-1} y^{-1})	Resource size (MMT y^{-1})	USDA Farm Resource Region(s)	Source	Direct crop displace-ment risk	SOC gain
Biomass crops on reclaimed or improved land	5.8	25 *10*	145 *58*	N. Crescent, Basin/Range	Milbrandt et al.[67] *(assuming 10 Mg ha^{-1} y^{-1})*	🟩	🟩
Biomass crops on "spared" agricultural land or CRP land	*20* *4.5*	*10* *10*	*200* *45*	Heartland, Prairie Gateway	Rizvi et al.[68] —	🟩	🟩
Biomass crops in rotation with annuals	10–26 (in any given year)	6.8–7.9	69–193	Heartland, Prairie Gateway	Englund et al. 2021)[69]	🟥	🟩
Rotation intensification with winter cover or cash crops	*27* 58	*6.2–8.1* 1.7–2.4 (oilseed residue) and 4.2 (fescue)	*170–220* 65	Heartland, Prairie Gateway	Kemp and Lyutse[70] Adapted from Taheripour et al.[71]	🟨	🟩
Genetically improved crops in semi-arid and arid areas	*26*	*10*	*260*	N. Plains, Prairie Gateway	—	🟩	🟩
Forest fuels reduction	—	—	7–*118*	Basin/Range, various others	Adapted from Cabiyo et al.[72]	🟩	🟨
Residues from misc. sources	*2.5–6*	*5*	*12–31*	Various	—	🟩	🟩

Red italics denote back-of-the-envelope estimates assuming a fixed universal biomass crop yield or other simplifications; other estimates are model-based and spatially resolved. For the two right-most columns, green shading denotes feedstocks with minimal risk for indirect land use change that are expected to increase local SOC storage. Red shading denotes greater environmental sustainability risks. Yellow shading indicates intermediate risks (assessed qualitatively and explained in more detail in the main text).

Figure 7. USDA Farm Resource Regions denote broad areas supporting similar agricultural production patterns.



The patterns represent a simplified version of the USDA Soil Conservation Service Land Resource Regions, aligned with NASS Crop Reporting District boundaries.[73]

The final two columns in Table 4 are qualitative assessments of potential competition for land resources with other sectors [referred to as food vs. fuel or indirect land use change effects]; and effects on SOC levels.[74,75,76,77,78,79,80,81,82] These novel feedstocks were selected for their potential to minimize competition with existing production and thus be neutral or even beneficial in terms of indirect effects. For example, integrating winter oilseeds into existing crop rotations can improve the overall profitability and environmental sustainability of operation, leading to more widespread adoption of such rotations in addition to the increased supplies of high-protein biomass and oils. SOC represents a large reservoir of ecosystem carbon and a central element of soil health and fertility, though historic agricultural activity has caused a loss of >100 Gt of SOC to the atmosphere.[83] Feedstock production that contributes to increasing SOC stocks is aligned with the broader goal of sustainable intensification and contributes to healthier, more productive soils available for future agriculture.[84] Feedstock production by these means avoids creating new demand for arable cropland and provides a clear basis for establishing carbon additionality (i.e., expressing the carbon benefits of bioenergy/BECCS production in terms of increased ecosystem carbon fluxes resulting from feedstock production).[85,86] Finally, increasing SOC improves the perceived "naturalness" of different carbon management approaches and may contribute to improved public perceptions of BECCS and increased social license to operate.[87]

Market interactions and environmental effects can involve trade-offs and synergies that merit assessment, considering land suitability and integrated land planning designed to optimize benefits to society while advancing toward multiple social, environmental, and economic objectives. Such analyses require site- and context-specific study.[88] Once options are more clearly defined within a specific context, more specific assessments can consider the inherently complex interactions among markets, social wellbeing, and environmental conditions.

2.1 Biomass crops on reclaimed or improved land

One of the most promising routes to low-impact feedstock production is to target former mine land or brownfield sites. Such areas are often highly disturbed and currently do not support agricultural production. Poplar has long been studied as a means of reclaiming and remediating mined areas where the topsoil has largely been stripped away. Highly disturbed sites have difficulties supporting even perennial crops. However, many studies have explored using biochar for land remediation/reclamation, especially of highly disturbed mining areas (e.g. Ippolito et al.) or other industrial sites with heavy metal contamination.[89,90] In these situations, biochar can serve as an enabling technology, allowing feedstock production on land that would otherwise be biophysically or economically unlikely to support it. Biochar can also be used to manage soil acidification and aluminum toxicity, though it competes with other low-cost and widely available liming agents in those applications, so it is not considered as a separate novel feedstock production category in this assessment.[91,92]

Technical potential

Adapting a prior model-based estimate from Milbrandt et al., an annual technical potential of 58–145 MMT from dedicated energy crops grown on 5.8 million hectares (Mha) of reclaimed mine land and brownfield sites is estimated, as detailed in Appendix section A1.[93] These sites are widely distributed across the Northern Crescent and Basin and Range Farm Resource Regions (Figure 7). No supply is assumed in the base case scenario, 58 MMT/year under the incentivized scenario, and the more optimistic 145 MMT/year supply estimate from Milbrandt et al. under the expanded scenario.[94]

Sustainability outlook

Restored mine land and other industrial sites are typically highly disturbed, often lacking the upper organic matter–rich layers of the soil profile entirely. If perennial crops can be successfully produced in such areas, they would likely lead to a substantial SOC increase, reduced erosion and runoff pollution, and a variety of additional ecosystem services. A hybrid strategy of using carbon-negative biochar to reclaim land for carbon-negative BECCS feedstock production has been suggested.[95] This hybrid land restoration strategy would increase SOC levels through both biochar application and the ongoing cultivation of deep-rooted perennials and would offer economic development opportunities in rural areas impacted by the transition from fossil to renewable energy. Biochar also has an N_2O suppression effect, reducing the greenhouse gas emissions burden of fertilizer application in biomass crops.[96]

2.2 Biomass crops on “spared” agricultural land or CRP

In 2021, approximately 9 Mha (22 million acres) of US cropland were held out of annual crop production and managed for conservation purposes via CRP contracts. Various studies have examined the possibility of managing a share of these lands for periodic cellulosic biomass harvests that can be timed to facilitate wildlife management or other conservation objectives. For example, case studies are described in the Antares Landscape Design Project Final Report.[97] Such strategies can support multiple land management and conservation goals while providing income to landowners and feedstock for biobased industries.

Alternatively, the physical footprint of existing row-crop agriculture can potentially be reduced to free up more land for land-based mitigation measures, such as energy crops and other natural climate solutions. Such land sparing could be enabled through ongoing steady improvements in agricultural productivity or demand-side measures such as dietary shifts and reductions in food waste.[98,99] Historic improvements in per-area crop yields have led to increased overall production despite a trend of slightly declining total US cropland area since the 1970s.[100] However, the degree to which these improvements can be sustained in a changing climate is uncertain.[101] Biochar application can improve agricultural yields in tropical climates and/or poor (e.g., acid, coarse-textured) soils but is unlikely to significantly increase yields or spare land when applied to high-quality intensively managed US croplands.[102]

Technical potential

Current CRP policy prohibits biomass production, so this feedstock source is not considered in the base case scenario. For the incentivized scenario, a simple back-of-the-envelope estimate suggests that converting half of the current 9 Mha of CRP land to energy crops could produce 45 MMT/year, assuming a conservative energy crop yield rate of 10 Mg ha^{-1} y^{-1}. More ambitiously for the expanded scenario, Rizvi et al. suggest that following USDA guideline diets in the United States could spare approximately 20 Mha of current agricultural land, primarily cropland used to produce grain for livestock (Heartland and adjacent regions).[103] Under the same yield assumption, a total of 200 MMT of biomass could be produced annually on this spared cropland.

Sustainability outlook

Land sparing and abandoned cropland reoccupation do not conflict with existing agricultural production. Converting annual cropland to perennial energy crops is expected to increase SOC storage, though SOC may be transiently reduced when CRP is converted to energy crops depending on the establishment method. Cultivating perennial energy crops is one strategy for restoring degraded cropland, which would presumably improve the soil health and productivity of such lands if these needed to be pressed back into food production in the future.[104,105,106]

2.3 Biomass crops in rotation with annuals

Instead of the long-term conversion of annual cropland to perennials discussed in the previous section, perennials can be integrated for short periods within annual crop rotations. Perennial cover in a long-term rotation with annuals is one of the oldest and most common forms of swidden agriculture (i.e., shifting cultivation). Rotation of perennial crops such as mixed grasses and alfalfa for hay with annuals remains a common strategy on modern farms to rest and rejuvenate soils between periods of continuous annual commodity production (e.g., rotations of corn, soybean, wheat). Such approaches can be particularly valuable in arid regions where risk of annual crop failure is high, and perennial cover builds soil conditions that reduce such risks.

Technical potential

Englund et al. modeled the technical potential to provide sustainable biomass and SOC increases from implementing such rotations on degraded cropland across Europe that has suffered significant historic SOC losses.[107] They estimated that integrating mixtures of perennial energy grasses (miscanthus, switchgrass, and reed canary grass) and clover over 2 to 4 year intervals within annual crop rotations could produce 102–286 MMT biomass per year. This is scaled by 0.68 (the ratio of total 2020 crop production in the United States compared to Europe, as per Food and Agriculture Organization statistics, assuming the same average yields) to arrive at a back-of-the-envelope estimate of 69–193 MMT/year potential from perennial crop integration into US annual rotations (using the lower bound in the incentivized scenario, and the upper bound in the expanded scenario). Biomass potential from these rotation crops is excluded from the base case scenario.

Sustainability outlook

Soil improvement is a central rationale for this cropping system, and Englund et al. estimated an average SOC increase rate of up to 0.14 metric tonnes of carbon per hectare per year (Mg C ha^{-1} y^{-1}) over the three decades following the integration of perennials into annual crop rotations.[108] Such integration would take approximately one-third of all affected cropland out of production each year, which could generate substantial indirect effects. However, Englund et al. suggest that this impact could be reduced in part through the recovery of protein from the harvested biomass, and from the positive effects of increased SOC on yields during the annual crop years of the rotation.[109]

2.4 Rotation intensification with winter cover or cash crops

Cover crops (i.e., temporal intensification) provide an alternative feedstock source from existing agricultural lands and can contribute to beneficial changes in terms of erosion control, moisture retention, soil carbon, and nutrient cycling.[110,111] Common cover crops that are disced into the soils as “green manure” in the spring typically involve mixes of grasses (e.g., rye, oats), legumes (e.g., clover, vetch, peas), and brassicas (e.g., radishes, turnips). Cover crops can alternatively be harvested if conditions (e.g., yield, market, weather) are favorable. When planting cover crops for potential harvests, a single variety is preferable, adapted to the location. Crops with potential markets include rapid-maturation grasses (for cellulosic biomass) or oilseeds, such as carinata (i.e., Ethiopian mustard) in the Southeast or pennycress in the upper Midwest.[112,113] Although oilseeds are primarily valued as a source of lipids to produce sustainable aviation fuels and other high-value products, separating out their lipid and protein content leaves a fiber coproduct with potential value as a BECCS feedstock. Recent studies offer insight into potential opportunities to generate biomass from integrated production systems for multiple markets rather than assuming competition for land among exclusive land uses. In this case, with adequate incentives and assurance of market demand a cover crop can generate climate benefits and additional biomass.[114,115,116,117]

Technical potential

Taheripour, Sajedinia, and Karami identified potential to produce winter oilseeds every other year on up to 50% of US corn–soy rotation land (29 Mha; primarily in the Heartland region) during fallow periods, resulting in a double-crop of oil seeds (i.e., cover crop harvest in the spring, soy in the fall).[118] Combining their 1.7–2.4 Mg ha^{-1} oilseed yield estimate with an oilseed fiber content of 0.35% Carré et al. suggests a potential to coproduce 10 MMT of BECCS feedstock annually.[119] These and other estimates of winter oilseed production are reviewed in Appendix section A2. Additionally, a fast-growing annual grass such as fescue could be cultivated during the non-oilseed preceding corn, and annually on the other 50% (29 Mha) of corn–soy rotation land. Assuming an average yield of 4.2 Mg ha^{-1} and the ability to harvest that biomass on average 30% of time, this results in an additional 55 MMT biomass per year, for a total of 65 MMT/year.[120] Given that these measures can be readily adopted within existing annual crop rotations, this value is used in the base case scenario. This estimate of BECCS feedstocks from winter cash and cover crops is, however, conservative compared with back-of-the-envelope estimates of Kemp and Lyutse.[121] In their moderate estimate, cover crops are adopted on 30% of appropriate cropland (27 Mha), producing 170–220 MMT/year. The lower bound of that range is used in the incentivized scenario, and the upper bound in the expanded scenario.

Sustainability outlook

The soil carbon benefits of winter cover crops (where aboveground biomass is typically mulched or tilled back into soil prior to summer cash crop planting) are well established, with meta-analyses reporting SOC increases of 0.3–0.5 Mg C ha^{-1} y^{-1}, as detailed in the Appendix section A3. Winter crops harvested for biomass will likely have somewhat less soil carbon sequestration because the aboveground biomass is harvested. Using a carinata cover crop modeled with DayCent, for example, SOC sequestration is expected to increase at a rate of ~0.1 Mg C ha^{-1} y^{-1} when carinata is grown once every three winters in existing crop rotations.[122] Additionally, replacing winter fallow periods with cover or cash crops may affect summer crop yields, depending on many factors including prior soil conditions, nutrient cycling, and the prevailing weather conditions in the spring and fall.[123] A literature review by Abdalla et al. showed a central tendency of a 4% reduction in main summer crop yield associated with the adoption of cover crops, but a positive effect on yields from cover crop mixes that include legumes. Similarly, Deines et al. used remote sensing to study yield effects across 90,000 fields in the Corn Belt where cover cropping was adopted and found a 5.5% reduction in summer corn yields and a 3.5% reduction in soybean yields.[124]

2.5 Genetically improved crops in semi-arid and arid areas

Large research efforts are devoted to improving energy crop productivity on marginal lands.[125] Efforts to improve crop water use efficiency may be particularly important given the large areas of semi-arid and arid lands in the United States, many of which have been over-exploited by livestock grazing and affected by erosion and other forms of soil degradation. Even small improvements in crop productivity and management can lead to significant biomass production on this large land base, along with other benefits in terms of habitats, water cycling, soil carbon storage, and so on. Crops such as agave that use the CAM photosynthetic pathway are particularly promising because they achieve high water use efficiency by assimilating carbon at night and thus are well adapted to rain-fed production in semi-arid regions.[126] Breeding and improvement of such CAM crops may create new opportunities in biomass production, increasing the total land area where cultivation becomes viable. Because of the technology barriers involved, this potential feedstock is only considered in the expanded scenario.

Technical potential

It is difficult to quantify how genetically improved crops could increase the viability of biomass production in marginal semi-arid or arid landscapes. The rain-fed yields of current agave species range from 1 to 25 Mg ha^{-1} across the semi-arid and arid regions of North America.[127] For a preliminary back-of-the-envelope estimate, future crop improvement efforts are assumed to lead to consistent achievement of 10 Mg ha^{-1} of CAM crops on average across the 265 Mha of US pasture and rangeland. Cultivating such crops for biomass on 10% of US pasture and rangeland would thus produce 260 MTT of feedstock annually.

Sustainability outlook

More intensive management of livestock production could spare rangeland for biomass production from CAM crops. Achieving higher productivity on these lands not only implies more carbon storage but also higher resilience and less conflict with lands currently used for other purposes (e.g., feed and food production).

2.6 Forest fuels reduction

Many dry western low-elevation forests are overstocked because of post-settlement management practices such as fire suppression and livestock.[128] Thinning such forests can have important benefits for wildfire management and restoration of forest diversity, and expanded forest management has been a priority of the Biden administration through the Bipartisan Infrastructure Law and other policies. The use of fuel reduction and restoration treatment biomass as a feedstock source is covered in detail in a companion white paper within the same Energy Futures Initiative BECCS series.

Technical potential

Cabiyo et al. estimated that 7.3 MMT of biomass could be generated annually from California forests under scenarios of expanded forest thinning and fuels reduction treatments, a value adopted in the base case scenario.[129] The back-of-the-envelope estimate for the incentivized scenario scales that figure to cover the total US timberland area (×8.1), resulting in a total feedstock potential of 59 MMT/year. For the expanded scenario, the combined effects of futures subsidies, increases in forest disturbance, and expansion of treatment into woodlands and scrub lands are assumed to conceivably double the resource size to 118 MMT/year.

Sustainability outlook

Thinning and fuels reduction treatments can support management goals including reducing fuels loading, make landscapes more defensible, and increase stand value for timber production. The degree to which such measures affect forest carbon balance through increased productivity or reduced wildfire losses are debated.[130,131,132,133] Sustainability concerns are covered in greater detail in the companion Energy Futures Initiative white paper.

2.7 Residues from misc. uses

In many cases, natural vegetation must be managed to preserve land or infrastructure functioning. Examples of lands requiring active vegetation management include urban tree management; rural residential areas; farmsteads; rights-of-way along roads, electricity transmission lines, cell towers, and renewable energy generation infrastructure; and federally owned (e.g., US Department of Defense, DOE) lands. This feedstock is included in the base case scenario since the biomass in question already exists and is often already managed as a nuisance. With the growth of BECCS markets and incentives, such waste biomass could be valorized as a feedstock.

Technical potential

A rough back-of-the-envelope estimate is derived considering the amount of land classified as urban (28 Mha), special use (68 Mha), or miscellaneous (28 Mha) as per Merrill and Leatherby.[134] Biomass is assumed to be recovered from 2% of this land base in the base case scenario, 3% in the incentivized scenario, and 5% in the expanded scenario. Native vegetation in those areas is assumed to yield 5 Mg of dry biomass per hectare per year based on the lower end of the range of prior modeling in the eastern United States (Field et al. 2020), which is equivalent to half of the standard yield assumption of 10 Mg ha^{-1} for managed energy crops. This results in an estimate of 12, 19, and 31 MMT y^{-1} feedstock in those scenarios, respectively.[135]

Sustainability outlook

As a waste material that is often already managed and disposed of via composting, landfilling, or burning, levering this biomass as a BECCS feedstock should incur minimal environmental impacts.

2.8 Comparison to biomass crop estimates on abandoned or marginal land

Many studies have considered the potential of dedicated energy crop production on abandoned or marginal agricultural land.[136,137,138] These definitions are typically based on land use history or land quality and may manifest as a variety of current land covers (e.g., idle land, pasture). Therefore, these estimates cannot be compared directly with the BT16 resource assessment (which did not model land use change as a function of land quality or previous land use history) or with most of the emergent feedstock categories explored here.

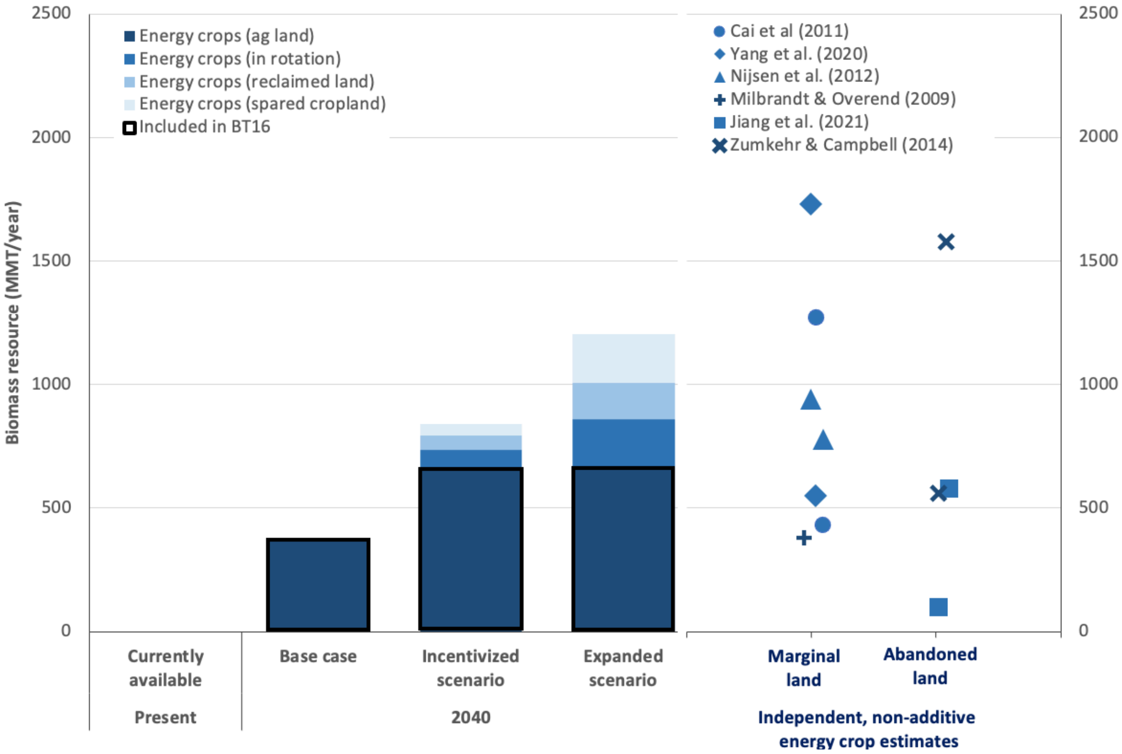
However, these estimates can be used as a "reality-check" against which to compare the total estimates of the BT16 and non-BT16 energy crop feedstocks tabulated previously. A variety of such estimates is listed in Table 5, and in Figure 8, is compared with the total estimate of energy crop potential. The estimates of total feedstock potential from energy crops (including those quantified previously in the BT16 and those explored for the first time in Table 4) range from 370 to 1,200 MMT/year, depending on the scenario. These estimates fall largely within the range of energy crop production potential assessed previously on marginal (400–1,750 MMT/year) and abandoned (100–1,600 MMT/year) croplands. Thus, **energy crop modeling based on current land cover definitions, land use history, or land quality all indicate a broadly similar range of feedstock production potential.**

Table 5. Energy crop production on abandoned and marginal lands (a non-independent feedstock estimate, to be used strictly as a reality-check)

	Land base (Mha)	**Avg. yield (Mg ha^{-1} y^{-1})**	**Resource size (MMT y^{-1})**	**USDA Farm Resource Region(s)**	**Source**
Crops on historically abandoned or transitional agricultural land	10–58	*10*	*100–580*	N. Plains, Fruitful Rim	Jiang et al. [139]
	45	14–39	560–1580	S. seaboard, N. Crescent	Zumkehr and Campbell[140]
Crops on marginal (degraded or low-yielding) agricultural land	43–127	*10*	*430–1270*	N. Crescent, Miss. Portal	Yang, Zhao, and Cai [141]
	55–173	*10*	*550–1730*	N. Plains, Prairie Gateway	Cai, Zhang, and Wang [142]
	80	10–12	780–940	Heartland, Prairie Gateway	Nijsen et al.[143]
	121	3.1	380	N. Plains, Prairie Gateway	Milbrandt and Overend [144]

Red italics denote back-of-the-envelope estimates assuming a fixed universal biomass crop yield or other simplifying assumptions; estimates in black are model-based and spatially resolved.

Figure 8. Estimates of biomass crop production potential on spared cropland and reclaimed land from this study (blue bars) in comparison to published estimates of energy crop production potential on abandoned or marginal agricultural land (blue symbols).



Because these estimates of energy crop potential on marginal/abandoned lands are derived from various non-commensurate land definitions, they potentially overlap with the BT16 and non-BT16 supply potentials illustrated in the bar chart, and thus they should not be considered additive with those estimates or with one another.

Energy crops on historically abandoned or transitional agricultural land

The Northeast and Southeast United States have historically experienced large amounts of cropland abandonment and reforestation as commodity crop production shifted toward the Corn Belt and other regions.[145] Any abandoned cropland that has not reforested or been developed offers an attractive target for bioenergy feedstock production because it does not currently support food production. In many cases, abandoned cropland is subject to unmanaged secondary succession (i.e., spontaneous revegetation).[146] Because the secondary succession of native vegetation may in many cases proceed slowly, such areas may not yet have recovered their original native carbon storage or ecosystem service value (Isbell et al. and thus may offer an opportunity for relatively low-impact feedstock production (Khanna et al.; Field et al..[147,148,149] Cultivating dedicated perennial crops on former cropland is usually associated with increases in SOC.[150,151] In the case of cropland that has been abandoned for some time, SOC outcomes will depend on what has occurred on that land in the time since abandonment.

Historically abandoned cropland is concentrated in the Northeast, Southeast, Midwest, and Great Plains.[152,153] Based on analysis of historic county cropping records, Zumkehr and Campbell estimated that as many as 45 Mha of abandoned cropland may exist across the United States suitable for bioenergy crop production (i.e., that has not been reforested or developed).[154] Using a process-based model, they estimated that land could support the production of 620–1,760 MMT of biomass per year at a very optimistic average per-area crop yield range of 14 Mg ha^{-1} for switchgrass and 39 Mg ha^{-1} for miscanthus (Table 5). Jiang et al. (2021) used the remotely sensed Cropland Data Layer product to estimate a potential range of 10–58 Mha of transitional agricultural land concentrated in the Western Great Plains, Palouse, California Central Valley, and Southwest. Assuming a generic biomass crop yield rate of 10 Mg ha^{-1}, this corresponds to a resource potential of 100–580 MMT of biomass annually.[155]

Energy crops on marginal agricultural land

In addition to this historically abandoned cropland, so-called “marginal” cropland at the edge of profitability is observed to transition from a cultivated to an idle state depending on agricultural commodity prices and other conditions over time.[156] These areas have a similar sustainability rationale for bioenergy use as historically abandoned cropland; they do not consistently support food production at present, and their history of disturbance suggests they have limited carbon storage and ecosystem service value compared with undisturbed native ecosystems.[157] Functional definitions of marginal land are highly varied, ranging from indicators such as land capability classification rating, to more detailed biophysical productivity indicators, or directly observed via remote sensing (Englund et al. 2023; Schulte et al. 2021).[158,159,160,161,162,163] Yields of energy crops are lower on marginal lands than on prime agricultural land.[164] However, energy crops are less sensitive to land quality than annual crops, so they can represent the most profitable use of intermediate-quality land between prime cropland and land that cannot support cropping.[165,166]

Biophysically marginal land is often concentrated in the Great Plains (i.e., not productive enough for annuals, but not so unproductive that the land should be left under native plant cover) and Mississippi River Valley.[167,168,169] Managing marginal cropland for bioenergy production represents an opportunity cost to the degree that it displaces current production of annual crops or constrains that option in the future. However, marginal land targeting can intensify the management of agricultural landscapes and improve soil quality compared with current management.

2.9 Opportunities from high-power computing and big data

Most of the described feedstock resource estimates are derived from process-based agro-ecosystem models such as DayCent, process-based Earth system models, statistical models, or hybrid approaches that combine modeling with expert.[170,171,172,173,174,175,176] Parameterization of such models typically relies on relatively modest amounts of data, such as harvested yields and flux tower measurements of gas exchange from small-scale energy crop field trials.[177,178,179,180] In a variety of areas, more computationally intensive big data approaches can provide new avenues to inform the underlying climate conditions, land biophysical properties, and socioeconomic conditions that could support the deployment of novel bioenergy crops and associated soil carbon banking and ecosystem service co-benefits.

Marginal land classification

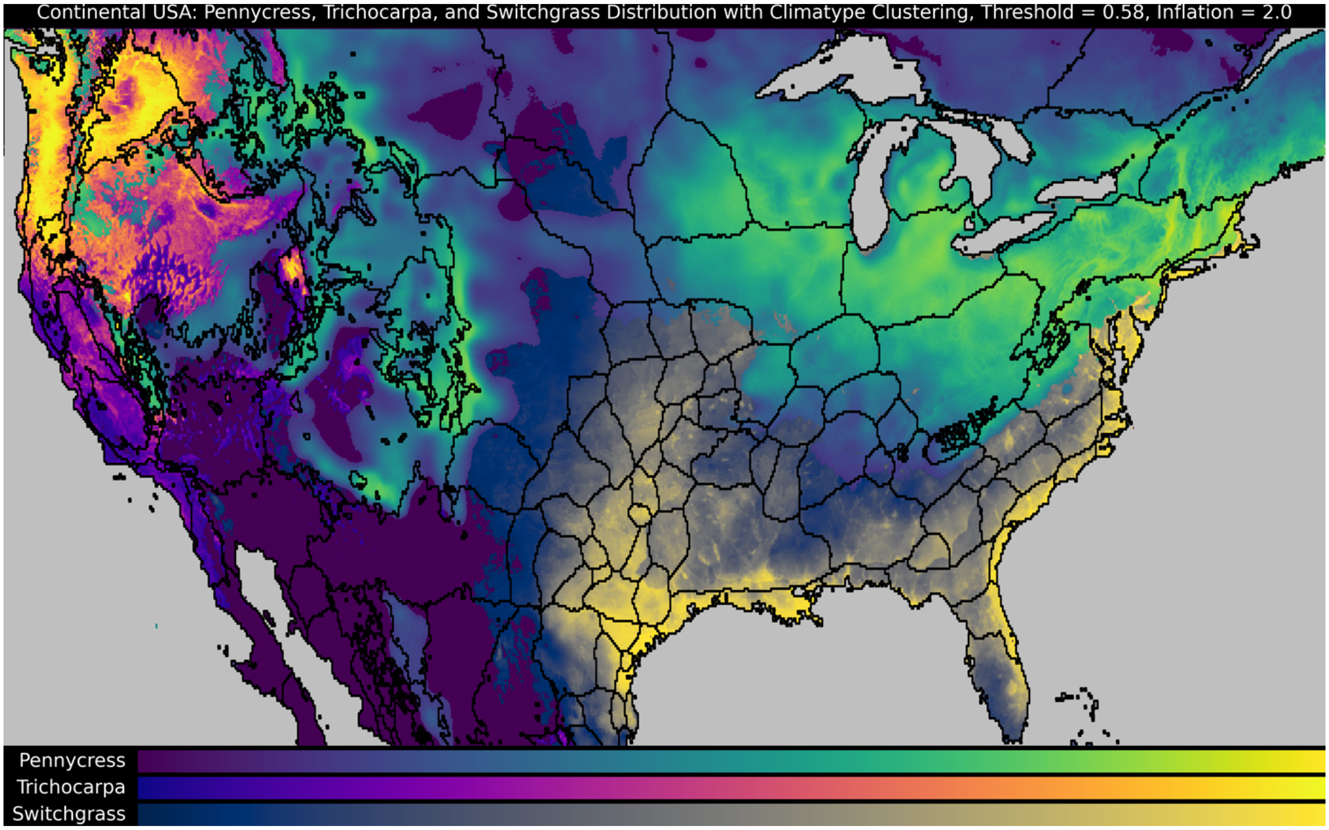
Bioenergy cropping is often targeted toward low-value marginal land that minimizes conflicts with existing agricultural production and areas of high restoration/conservation value.[181] Ongoing research efforts examine how to better characterize and quantify such land areas in the United States. Studies of observed marginal land use transitions have shown that marginal land is often associated with intermediate quality biophysical characteristics (i.e., lower biophysical suitability than stable cropland, but higher than non-cultivated land).[182] Machine learning approaches have also been applied to analyze the underlying biophysical drivers of observed remotely sensed variations in crop.[183] This can be used to identify areas of the existing cropland that could be more productive and profitable under alternative bioenergy crops, or to estimate the potential productivity of land that is not currently cultivated.

However, many of these prior efforts have been based on relatively modest amounts of climate data and have used black box methods that cannot necessarily communicate the underlying drivers of the patterns observed. In contrast, explainable artificial intelligence methods can be utilized to extract patterns from larger volumes of data more transparently.[184] Furthermore, integrating large volumes of geospatially explicit socioeconomic and demographic data with geophysical (land cover, slope, soils) and climatic data to improve understanding and forecasting of risks and opportunities is becoming more feasible. For example, landowners close to retirement age are correlated with the probability of agricultural land retirement and enrollment in CRP.[185] Current research aims to quantify the importance of specific social factors and corresponding biophysical land conditions in determining land management decisions, such as cropland retirement or changing forested lands to other non-forest uses.

Biomass crop climate range estimation

Climate clustering work such as that illustrated in Figure 9 can help identify potential niches for new and improved biomass crops.[186] Climate clustering is analogous to the designation of Land Resource Regions and Major Land Resource Areas by the Natural Resources Conservation Service but is more data-intensive and has higher spatiotemporal resolution.[187] For example, the climate clustering incorporates data including the maximum temperature, temperature range, vapor pressure, precipitation accumulation, downward surface shortwave radiation, wind speed, reference evapotranspiration, runoff, actual evapotranspiration, climate water deficit, soil moisture, snow water equivalent, Palmer Drought Severity Index, and vapor pressure deficit to project water availability for vegetative growth. Additionally, this climate clustering is not static like the Natural Resources Conservation Service designations, but rather can be combined with longitudinal analysis to identify areas where important climatic transitions and changes are taking place, as well as areas where conditions are relatively stable. The climate clustering approach can be combined with observations of candidate energy crop productivity at different sites to capture the underlying climatic envelopes in which such crops thrive. This information can be used to generate high-resolution range maps for novel energy crops.

Figure 9. Preliminary results of climate clustering to illustrate potential for selected bioenergy crops.[188]



Biogeochemical analysis

The previous sections focus on how big data and machine learning can inform ***where*** bioenergy crops might be produced in the future. In addition, such methods may also prove useful for estimating the ***environmental performance*** of such crops. Ensuring bioenergy system sustainability requires understanding of changes in SOC storage, soil N_2O emissions, evapotranspiration fluxes under bioenergy crop production, and myriad additional social and environmental considerations, many of which are site-specific. Modeling SOC and N_2O is particularly difficult because they show greater spatial and temporal heterogeneity than crop yields and are more laborious to measure.

Currently, process-based models such as DayCent, RothC, DNDC, and MEMS are used to estimate the relevant biogeochemical fluxes of carbon, nitrogen, and water through agroecosystems. These models synthesize a variety of hypothesis about the key climatic, soil edaphic, and management controls of those fluxes into quantitative estimates. Such models were typically developed and parameterized when observations were limited and have evolved incrementally as new datasets have become available over the years.[189,190] The details of that evolution and the underlying data sources used is rarely well documented. Although interest exists in more formal data–model integration and data assimilation, use of these data- and computationally intensive techniques remains limited in this application.[191]

Machine learning can be used to generate new empirical models of and N_2O emissions outside of existing process-based modeling paradigms.[192,193,194] Such efforts can now leverage new centralized databases of soil core and N_2O emissions data.[195,196] Furthermore, synthesizing process-based modeling results as inputs to machine learning can be used as a proxy for ecological theory and expert opinion, allowing that information to be captured within an otherwise empirical modeling approach. This synthesis can help to systematically characterize the shortcomings of existing process-based models—information that is invaluable to those model development communities. For example, Cengic et al. (2023)[197] report how machine learning of past changes in land cover can be used to provide downscaled projections of fine-grained patterns (300 m resolution) of future agricultural expansion.

3. Sustainable Scale-Up

Expanding US biomass supplies for BECCS to climate-relevant scales requires a shift in understanding, governance, and acceptance of the role of biomass to help societies achieve net-zero emissions and other sustainable development goals. Nature-based solutions that comprise better management of productive landscapes to provide environmental services along with biomass products for food, feed, fiber, and fuels via integrated systems are necessary to achieve climate goals.[198,199,200,201] However, opposition to bioenergy remains strong because of concerns over potential harm associated with environmental effects, social effects, and especially resource competition (i.e., alternative uses and products from the land, water, and biomass that might otherwise be dedicated to bioenergy and BECCS). Despite two decades of intense debate and analyses, no consensus exists regarding the scale of bioenergy use that is most beneficial to society, in part because little consensus exists on how to consistently and properly measure sustainability.

Key market and sustainability challenges that have hindered scale-up of the US bioeconomy are reviewed here, followed by a set of principles and enabling conditions that could help to navigate these challenges moving forward. Scaling up US biomass production for BECCS and other climate-relevant applications depends on markets; policy frameworks; the timing and scale of investments in high-yielding production and more efficient logistics, collection, and processing technologies; and overcoming broad sustainability concerns.

3.1 Challenges for sustainable scale-up

Biomass logistical and market challenges

Biomass is often bulky, wet, and variable in productivity (e.g., depending on seasonal weather and other conditions), which creates special challenges for managing the costs of feedstock production, collection, transport, and utilization. Even for cases where biomass is “free” (i.e., an existing by-product of other land management activities), recovery of the biomass resource can be difficult and prohibitively expensive. For example, efforts to manage forest wildfire fuel load or remove invasive plant species and enhance biodiversity generate significant quantities of biomass in specific times and places, yet most of this biomass is either piled to decay or simply burned on site for disposal. Similarly, increasing frequencies and intensities of extreme weather events (e.g., hurricane, flood, drought, derecho winds, ice), saltwater intrusion, diseases, and pests generate large quantities of biomass that are usually temporally and geospatially disparate. Such intermittently available resources are difficult or impossible to access, collect, and densify without incurring high economic costs or causing additional environmental harms.

Broad sustainability definitions

While the importance of sustainability is increasingly recognized, the term is rarely defined in a manner that permits practical applications.[202] The 1987 Brundtland definition of sustainable development—development that meets the environmental, social and economic needs of the present without compromising the ability of future generations to meet their own needs—is often cited but is difficult to interpret in practice because it relies on subjective values that must be assigned to current needs and the unknown future needs of our descendants.[203] International standards are also cited but have not been applied consistently because of subjective and aspirational recommendations.[204] In fact, no single, widely accepted, concise definition of sustainability exists that permits evidence-based comparison of options and verification of compliance with sustainability goals.[205] However, this is not surprising given that stakeholders need to define priorities to more toward more sustainable practices based on available options in a given place and time.[206]

For applications relevant to biomass and BECCS, definitions are complex, are politically determined, and involve multiple principles, goals, criteria, and indicators—all of which require their own respective sets of definitions. Further complicating matters, more than 400 sustainability standards and measurement schemes have been published and most undergo persistent revisions, thus creating moving targets. In addition, the effects of bioenergy will always depend on a set of assumed counterfactual conditions (i.e., what would occur in the absence of the production and use of biomass for energy). Counterfactual scenarios are by nature impossible to define with certainty, and discrepancies between different counterfactual assumptions result in wide divergence in the estimated effects of a given bioenergy system.[207,208,209]

Greenhouse gas emissions accounting challenges

The emergent feedstock categories assessed in the previous section were selected based on the criteria of growing or maintaining ecosystem carbon stocks (in particular, soil carbon) and minimizing competition with existing agricultural commodity production. However, comprehensive greenhouse gas emissions accounting in bioenergy systems is complex, and standardized best practices have yet to be developed for many methodological issues.[210] Such life cycle assessment methodological issues are covered in a companion white paper within the same Energy Futures Initiative BECCS series, and two specific concerns are highlighted here.

The ***carbon neutrality*** of bioenergy has been widely debated in the literature. Some studies have argued that bioenergy can increase CO_2 emissions from forest or agricultural lands and from biomass combustion.[211,212,213] Langholtz et al. included changes in carbon stores on the landscape in calculating CO_2 sequestration by BECCS, net of CO_2 emissions from biomass production, and supply chain operations.[214] Changes in aboveground vegetation may require consideration of a carbon breakeven period depending on local conditions.[215]

In addition, time accounting for forestry resources, net effects of wildfire fuel reduction, and other aspects of ***woody bioenergy*** have generated extensive debate and misunderstanding.[216] The BT16 estimates of forest feedstocks focused on residues and small-diameter trees—the harvest of which is not expected to change carbon stocks when averaged across the landscape and across time. Furthermore, associated indicators of environmental sustainability have been carefully documented.[217] However, forests may provide a sustainable source of other types of biomass, as well. Forest thinnings in the wildland–urban interface can reduce risks of serious disaster, and the use of hurricane and storm debris can reduce wastes.[218,219,220,221] Additionally, harvest of invasive exotic tree species could aid in ecological restoration, and sourcing biomass from agroforestry systems can provide multiple agronomic benefits.[222] Long-term monitoring and evaluation of environmental and socioeconomic effects is recommended to ensure that potential negative effects are avoided and potential positive effects are enhanced.[223,224]

Concerns about competition with food production

The concern that BECCS and bioenergy will cause land competition with food production reflects the need to implement incentives that would ensure that biomass production and use enhances food security and forest conservation goals.[225,226,227,228,229,230] From a food security perspective, inflation-adjusted commodity crop prices paid to US farmers remain near historic lows, US farm bankruptcies have been rising since 2015, and billions of dollars are spent annually on US farm subsidies.[231,232,233] The BT16 identified opportunities for perennial cellulosic biomass feedstocks as an alternative revenue stream for US farmers while meeting food production goals. Ongoing dietary shifts (e.g., reduced consumption of red meat) and increases in the electric vehicle fleet are among several factors that could continue these trends. Of the approximately 1 billion tonnes of potential biomass in the United States reported in the BT16, about half is estimated to come from nonagricultural sources.[234] The remaining portion, in the form of dedicated energy crops, can be produced on approximately 8% of US cropland, with modest projected impacts on retail food prices.[235]

3.2 Sustainable scale-up principles and enabling conditions

Four principles and enabling conditions are described here that could help this sector to navigate these market and sustainability challenges and expand biomass feedstock production to climatically relevant scales.

Markets: Consistent price signals, feedstock specifications, and a level playing field

Cost-effective biomass feedstock supply chains require efficient production, collection, processing, and transport of inherently bulky, wet, heterogenous biomaterials. The history of successes and failures in recent biomass supply chains suggests that stable, long-term biomass markets are key to promote required investments in the necessary equipment and technology.[236] This includes the need for consistent demand or long-term price assurances for investors, as well as clarity regarding biomass supply specifications (e.g., size, density, moisture, ash content). In addition, the fossil-fueled status quo that bioenergy aims to displace is often supported by a variety of subsidies, which makes transition much more challenging. Removal of fossil fuel subsidies combined with a consistent and appropriate tax reflecting the social and environmental costs of fossil fuel use are fundamental policy choices that can determine whether renewables will make significant progress in displacing reliance on fossil resources (IPCC WGIII 2022).[237]

Biomass as a coproduct enabling broader lang management goals

Intensified biomass production specifically for energy purposes (e.g., bioenergy plantations) is often proposed to mitigate the costs and challenges of working with more dispersed biomass resources. Many sustainability concerns derive from modeling that simplifies reality and assumes that the planting, management, and harvests of biomass are performed exclusively for bioenergy.[238] However, nearly all successful biomass supply chains around the world are based on integrated systems that serve multiple sectors, with energy being a relatively minor coproduct. For example, although there has been great debate about woody pellet fuels, wood used for pellets represents only about 3% of total removals from US forests and primarily comprises residues from the larger forest products industries.[239] An integrated natural resource management perspective considers that biomass can often be a useful coproduct of land management geared toward producing multiple services and achieving multiple goals simultaneously, including strategic integration with other clean energy and sustainable development initiatives.

In any agricultural or forestry system, biomass can be produced in ways that are environmentally or socially detrimental or beneficial, depending on practices in the field and system-specific contexts.[240,241,242,243,244,245,246,247] Biomass supplies that are integrated within more sustainable landscape designs can be produced in ways that improve many indicators of sustainability.[248,249,250,251,252] Improving the mixture and extent of ground cover on degraded or eroding lands, or replacing annual crops with perennial grasses in unprofitable areas, can be economically preferable while improving water and soil quality and providing habitat for pollinators and other wildlife.[253,254] Deep-rooted, drought-resistant, perennial biomass crops offer strategies to reduce economic risk in climate change and extreme weather conditions.[255,256] Forest management can benefit from price supports for harvesting small-diameter trees to reduce threats of forest fires, mitigate pine beetle infestations, and realize desired future stand conditions.

Equipment and technologies can be mobilized to sites that temporarily offer surplus biomass to efficiently process materials to generate standardized, densified feedstocks. Mobile biomass processing units could contribute to overall landscape management goals but require investments that are unlikely to occur without market assurances and other incentives.

Iterative, stakeholder-driven assessment

Sustainability for bioenergy cannot be easily generalized since needs and conditions change over time and space.[257] Sustainability cannot be proven beyond doubt based on a standard set of paperwork, and defining a single set of valid measures that can be systematically applied to assess the sustainability of biomass production and use is difficult.[258,259] The complexity of human–land interactions means that no static set of standards is appropriate and applicable across time, place, and scales (local to global). Addressing sustainability concerns and assessing sustainable biomass supply potentials therefore requires a context-specific, stakeholder-driven, iterative long-term process supporting continual improvement of practices for sustainable management in the corresponding sector (e.g., forestry, agriculture, processing industries).

Building more sustainable bio-economies is best designed and implemented from the bottom up, focusing on concerted actions to provide the right incentives for renewable resources to be properly managed.[260] Identifying appropriate sustainability indicators must involve the diversity of stakeholders affected by renewable energy transitions. Ideally, those local stakeholders should be involved throughout the lifetime of a project, including the initial analysis of options, identification of desired future conditions, and development of best management practices across each stage of the supply chains (biomass production, collection, transport, processing, densification or biorefining, pollution controls, utilization). Such a local stakeholder-driven process can also inform the highest value uses of biomass toward more sustainable land management because the highest-value options depend on context.[261,262] Iterative stakeholder engagement and sustainability assessment support continual learning, adaptation, and resilience in climate change and under different social and economic conditions.

Transparent sustainability monitoring and reporting

Continual learning also requires monitoring, analysis, communication, and capacity to implement decisions that will guide future activities to better achieve goals. Stakeholders should be engaged early and persistently to build ownership and capacities to continue transparent, evidence-based management and analyses of the effects in their communities." Policymakers can contribute to advancing trust by supporting monitoring systems with site-specific targets using science-based indicators to measure and document change over time (i.e., criteria for sustainability must be relevant to local context), in a manner that enables communications and reporting across national or international markets. Verifiable monitoring and reporting support transparency and accountability, particularly in support of performance-based policies and incentives that are agnostic in terms of feedstock or technology.

4. Conclusion

Understanding biomass resource availability is foundational to supporting bioenergy as an approach to abating CO_2 emissions and meeting climate goals. This analysis reports a substantial supply of renewable biomass resources in the United States to support BECCS as a negative-emissions strategy. Potential biomass supplies based on the latest DOE national biomass resource assessment sum to approximately 750 MMT/year by 2040 in a base case, and more than 1,000 MMT/year under market incentives to develop efficient supply chains and improve yields. These supply estimates are constrained for economic and sustainability criteria while meeting projected demands for food, feed, fiber, and exports.

Known analyses to date indicate that approximately one-third of the BT16 biomass resource is co-located in geological basins suitable for CO_2 storage, and another third could be accessed for BECCS via existing transport infrastructure or piping the resulting CO_2 to the appropriate location. Key challenges to scale-up include sustained market signals needed to reduce investment risks associated with establishment of efficient biomass supply chains, and lack of consensus on and social acceptance of practical, locally defined criteria for sustainable biomass production and use.

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5. Appendix

A1: Technical potential of biomass crops on reclaimed or improved land

Milbrandt et al. quantified a broad set of underutilized land that may be appropriate for bioenergy production.[263] Their estimate included 5.8 Mha of mine land and brownfield land availability, widely distributed across the Northern Crescent and Basin and Range Farm Resource Regions. Using county-specific estimates of miscanthus yields from the Energy Biosciences Institute's Biofuel Ecophysiological Traits and Yields Database, they estimate this land has a technical potential of 145 MMT of annual biomass production. This corresponds to a highly optimistic modeled biomass yield rate of 25.4 Mg ha^{-1} y^{-1} across the wide range of climates represented across this land base, which seems optimistic. For comparable estimates in Table 4, a constant average yield of 10 Mg ha^{-1} y^{-1} is assumed, more in line with the other studies in this review, which would result in an adjusted potential of 58 MMT/year across this 5.8 Mha of land.

A2: Winter cash and cover crop estimates

Beyond the Taheripour, Sajedinia, and Karami study cited in the main text, a variety of bottom-up studies report the yields of individual oilseed crops over more limited geographic regions.[264] These include 2 MMT/year for carinata in the Southeast, 23 MMT/year for camelina across the Wheat Belt, and 14 MMT/year for pennycress in the Corn Belt Together, these sum to 39 MMT/year, compared with an estimate of approximately 58 MMT/year for all oilseeds from Taheripour, Sajedinia, and Karami.[265]

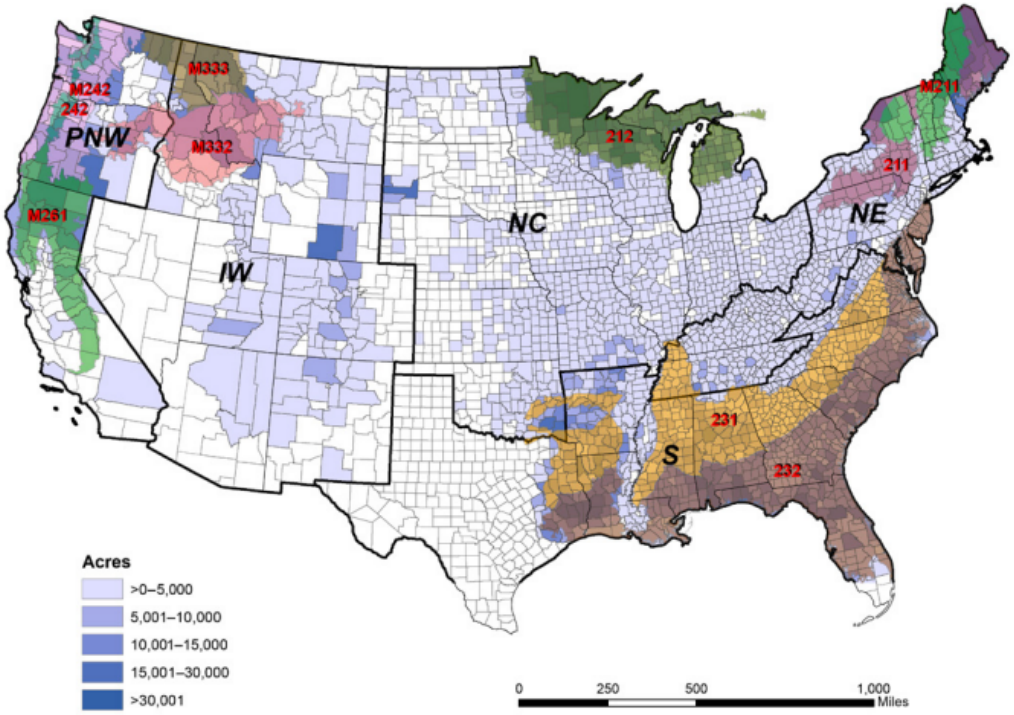
Carré et al. report that 29%–43% of oilseed yield tonnage is fiber. The amount of fiber potential depends on yields and seed type, with lower fiber concentrations in carinata and higher in pennycress.[266]

Kemp and Lyutse estimate US cover crop potential that is double the estimate of this white paper based on a model (RyeGro) that identified 39 Mha of land suitable for cover crops and assumed an average biomass yield for the 30 locations of 4.2 Mg ha^{-1} y^{-1}.[267] This is broadly similar to the method used by Fargione et al. to estimate the cropland area available for fallow period cover-cropping (i.e., conservation agriculture) in the United States by taking the total area under the five major field crops in the United States as per the National Agricultural Statistics Service, and subtracting out the total area under cover crops as per the USDA Census of Agriculture.[268] Other estimates of global-scale cover crop potential based on Siebert, Portmann, and Döll and Poeplau and Don are summarized by Griscom et al. (2017).[269,270,271]

A3: Effects of cover cropping on SOC

McDaniel, Tiemann, and Grandy report cover crop adoption associated with 8.5% higher soil carbon.[272] Poeplau and Don report cover crop adoption associated with soil carbon sequestration at rates of 0.3 Mg C ha^{-1} y^{-1}.[273] Abdalla et al. report cover crop adoption associated with soil carbon sequestration at rates of 0.5 Mg C ha^{-1} y^{-1} and reductions in main summer crop yield of ~4%.[274] Jian et al. report SOC increase of 0.6 Mg C ha^{-1} y^{-1}, with the greatest rates observed in fine-textured soils and temperate climates.[275] McClelland, Paustian, and Schipanski report cover crop adoption associated with 12% higher soil carbon, roughly equivalent to an SOC increase rate of 0.2 Mg C ha^{-1} y^{-1}.[276] For comparison, meta-analysis shows that removing the residue from summer crop harvest (conceptually opposite to cover cropping because it decreases net annual carbon input to the soil) is associated with 8% lower soil carbon, whereas residue retention is associated with SOC increase of 0.4 Mg C ha^{-1} y^{-1}.[277]

Figure A-1. Delineation of ecoregion provinces (numbered regions) overlaid on total potential acres harvested under the BT16 base case forestry scenario, which had the greatest quantity of total acres harvested of all scenarios.



Black letters indicate modeling regions outlined by bold black lines; red numbers indicate province ecoregions. Figure from Donner, Wigley, and Miller.[278]

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