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LETTER

Deep decarbonization and U.S. biofuels production: a coordinated analysis with a detailed structural model and an integrated multisectoral model

Laura Vimmerstedt[1,*], Swaroop Atnoorkar[1], Candelaria Bergero[2], Marshall Wise[2], Steve Peterson[3], Emily Newes[1] and Daniel Inman[1]

[1] National Renewable Energy Laboratory, Golden, CO, United States of America
[2] Pacific Northwest National Laboratory, Joint Global Change Research Institute, College Park, MD, United States of America
[3] Independent Contractor, West Lebanon, NH, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: Laura.Vimmerstedt@nrel.gov

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Abstract

Scenarios for deep decarbonization involve biomass for biofuels, biopower, and bioproducts, and they often include negative emissions via carbon capture and storage or utilization. However, critical questions remain about the feasibility of rapid growth to high levels of biomass utilization, given biomass and land availability as well as historical growth rates of the biofuel industry. We address these questions through a unique coordinated analysis and comparison of carbon pricing effects on biomass utilization growth in the United States using a multisectoral integrated assessment model, the Global Change Analysis Model (GCAM), and a biomass-to-biofuels system dynamics model, the Bioenergy Scenario Model (BSM). We harmonized and varied key factors—such as carbon prices, vehicle electrification, and arable land availability—in the two models. We varied the rate of biorefinery construction, the fungibility of feedstock types across conversion processes, and policy incentives in BSM. The rate of growth in biomass deployment under a carbon price in both models is within the range of current literature. However, the reallocation of land to biomass feedstocks would need to overcome bottlenecks to achieve growth consistent with deep decarbonization scenarios. Investments as a result of near-term policy incentives can develop technology and expand capacity—reducing costs, enabling flexibility in feedstock use, and improving stability—but if biomass demand is high, these investments might not overcome land reallocation bottlenecks. Biomass utilization for deep decarbonization relies on extraordinary growth in biomass availability and industrial capacity. In this paper, we quantify and describe the potential challenges of this rapid change.

Glossary

AEO	Annual Energy Outlook
AgMIP	Agricultural Model Intercomparison and Improvement Project
BCAP	Biomass Crop Assistance Program
BECCS	Bioenergy with carbon capture and storage
BSM	Biomass Scenario Model
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CE	Cellulosic to ethanol
CHC	Cellulosic to hydrocarbon
CP	catalytic pyrolysis
CRP	Conversation Reserve Program
DMT	Demonstration and Market Transformation
DOE	U.S. Department of Energy
EMF	Energy Modeling Forum
EV	Electric vehicle
FAO	Food and Agriculture Organization
FOG	Fats, oils, and greases
FT	Fisher-Tropsch
GCAM	Global Change Analysis Model

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GHG	Greenhouse gas
GTAP	Global Trade Assessment Project
HEFA	Hydroprocessed esters and fatty acids
IAM	Integrated assessment model
IDL	Indirect liquefaction
IPCC	Intergovernmental Panel on Climate Change
LDV	Light-duty vehicle
OHC	Oil crop to hydrocarbon
RCP	Representative Concentration Pathway
ReEDS	Regional Energy Deployment System
RIN	Renewable identification number
SD	System dynamics
SE	Starch ethanol
SI	Supplemental information
SOT	State of technology
SSP	Shared socioeconomic pathway
tC	Metric ton carbon
USDA	U.S. Department of Agriculture

1. Introduction to a coordinated analysis of modeling bioenergy

Scenarios for deep decarbonization rely on biomass for biofuels, biopower, and bioproducts, and negative emissions via carbon capture and storage or utilization. However, critical questions remain about the feasibility of these scenarios. Due to complex interconnectedness of bioeconomic systems and their drivers, these questions are best addressed using systems frameworks. In this study, we explore whether the use of biomass in deep decarbonization scenarios appears feasible considering the magnitude and rates of change in biomass demand, biomass availability and constraints, and biofuels industry growth.

Rapid transitions to renewable energy technologies, including bioenergy and bioenergy with carbon capture and storage (BECCS), play a key role in deep decarbonization pathways. The Intergovernmental Panel on Climate Change (IPCC) found a low probability of reaching climate change mitigation goals without some form of carbon dioxide removal (CDR), with BECCS being a leading option (IPCC 2022). These analyses use integrated assessment models (IAMs) such as the Global Change Analysis Model (GCAM), which have been used to explore bioenergy demands, potential, costs, and risks.

Integrated assessment models (IAM)s are often high-dimensional, long-term global economic models that represent interactions between multiple economic sectors. Using a systems framework, the IAMs project future global energy demand and its interactions with land use, agriculture, energy economics and food prices in transformation pathways consistent with climate change mitigation goals (Muratori *et al* 2020). IAMs include dynamic changes in socioeconomic conditions, demand for food and land, technology innovation, carbon policies, and productivity in agriculture. Muratori *et al* (2020), like the IPCC, found that none of the IAMs assessed was able to limit warming to 1.5 °C without BECCS, the only CDR technology modeled. Several modeling studies have shown that the availability and costs of bioenergy and BECCS influence the costs of decarbonization pathways (Muratori *et al* 2020, Rose *et al* 2014, Rogelj *et al* 2018, Fuss *et al* 2018).

Many drivers for biomass deployment have been identified through IAM simulations. For example, the Energy Modeling Forum project on bioenergy (EMF-33) reported that the availability and cost of bioenergy conversion technologies, the ability to produce liquid transportation fuels from biomass, and carbon prices were all significant factors that influence biomass deployment (Bauer *et al* 2020). They also found that the availability and cost of mitigation alternatives across different end-use sectors, the speed of technological innovations in conversion facilities, and the availability of CDR technologies are impactful (Daioglou *et al* 2020). Another initiative, the Agricultural Model Intercomparison and Improvement Project (AgMIP), showed that food and feed demand, international trade, and land supply are also influential (Lotze-Campen *et al* 2014). Such comparative initiatives address the substantial uncertainty in modeling complex systems, and inclusion of models that use various simulation and optimization techniques enables model evaluation and structural uncertainty characterization (Wilson *et al* 2017).

Other types of frameworks beyond IAMs highlight systems at scales that are important to understanding the effects of the bioeconomy. Biomass production impacts agricultural economies, land use and land albedo, carbon and nitrogen cycles, water, ecosystems, and local climates. Biomass production can compete with other land uses (Jia *et al* 2019), increase food prices (Rogelj *et al* 2018), lead to surface cooling (Georgescu *et al* 2011), and reduce soil moisture (Wang *et al* 2017) depending on the type and location of production. These complexities of the bioeconomy and its potential effects can be addressed through analyses that use systems frameworks of various types. For example, Uludere Aragon *et al* (2022) included integration of land use, hydrological, ecosystem, and economic systems. Robertson *et al* (2017) noted key life cycle, biogeochemical, ecosystem service, and bioeconomic systems findings for sustainability. In contrast, our analysis does not address biogeochemical, biogeophysical, or highly resolved land use and logistical systems but instead coordinates analysis of bioenergy within the global energy-economic system represented in an IAM, with a system dynamics assessment of the development of a biomass-to-biofuel supply chain in the United States.

We use the Global Change Assessment Model (GCAM), a global, multisectoral IAM that reaches equilibrium at 5 year time steps, which produces economy-wide results to determine conditions that are consistent with a target climate scenario considering inter-sectoral dynamics and global trade, the CDR, and linked systems: water, land, energy, climate, and socioeconomics. GCAM models bioenergy deployment under global climate mitigation scenarios using a multisector and economy-wide approach, accounting for biomass demand and resources under global climate mitigation scenarios to quantify bioenergy deployment over multiple decades.

In this analysis, we coordinate GCAM with a system dynamics (SD) model. SD models use stocks and flows to represent complex real-world systems in industry, organizations, and policy in simulations that move toward, but do not reach, equilibria between supplies and demands. By implementing feedback loops in the system, SD models can identify critical levers that control system performance. SD models have been used to analyze biofuel supply chains and their behaviors under various market conditions, constraints, and incentives at a national level. We use the Biomass Scenario Model (BSM), an SD model of the U.S. biomass-to-biofuels system that includes feedback and interactions in feedstock production and logistics, feedstock conversion, inventory, dispensing, distribution, fuel use, and vehicles. Its results depict U.S. sector-specific, nonequilibrium biomass production, biofuel production, and biofuel utilization development informed by empirical rates of change and lags in processes such as the adoption of new crops and biorefinery construction. With this approach, the BSM can identify logistical, industry and market constrains to rapid bioenergy expansion in the United States (Vimmerstedt *et al* 2015b).

1.1. Leveraging synergies between an IAM and SD to model bioenergy

Studies that use IAMs report a wide range of bioenergy usage needed for meeting global decarbonization goals. Bauer *et al* (2020) found an annual bioenergy requirement of 100–300 EJ globally to limit 2011–2100 emissions to 1000 $GtCO_2$. SD models can implement detailed representations of a sector to provide more granularity into the biomass deployment range feasibility. Thus, they can complement the long-term, equilibrium solution approach of multisector, economy-wide IAMs (Peterson *et al* 2019). A coordinated analysis of an IAM and a SD model can reveal challenges and uncertainties (e.g. the scale and speed of biofuels deployment and its impacts on land use) beyond those that might emerge from comparisons among IAMs.

In this study, using GCAM and BSM, we assess the feasibility of biomass utilization for deep decarbonization scenarios, considering technical and supply chain barriers. Specifically, we identify system constraints that impede biomass utilization in the context of carbon prices and vehicle electrification. We also explore whether these interdependent constraints might present challenges to reaching the U.S. biofuel production amounts indicated in deep decarbonization scenarios modeled with GCAM, and how policies might alleviate such constraints and bottlenecks, spur development in the biofuels industry, and increase demand for biomass.

Existing literature documents efforts to compare biomass and bioenergy results from various IAMs, but few studies compare IAMs and SD models. However, a recent study compared GCAM with another sectoral model—the Regional Energy Deployment System™ (ReEDS™)—that represents the U.S. electric power system in greater detail than GCAM (Iyer *et al* 2019). No previous study, to our knowledge, has applied a biomass-to-biofuels supply chain SD model to analyze the implications of the level of biomass deployment in the United States in scenarios consistent with an IAM decarbonization pathway. Our work contributes to model comparison efforts, which are deemed vital to understanding uncertainties in literature, to assess the feasibility of biomass deployment under deep decarbonization scenarios given current and historical rates of growth in biomass and land availability, land reallocation, and growth of the biofuels industry.

2. Methods

We coordinated scenarios and compared results from GCAM and BSM. We present the methods in the sections below: We describe the scenarios (2.1), present the approach used to harmonize GCAM and BSM (2.2), describe the simulations and key model features that affect the results (2.3), and discuss the metrics used for comparison (2.4). We used GCAM 5.3 (GCAMv5.3 2020) and BSM-public (National Renewable Energy Laboratory 2019) (both with modifications; see SI).

2.1. Scenario design

Using these two models enabled scenario exploration of the wide-ranging factors that influence biomass and bioenergy outcomes. In GCAM, we varied inputs for carbon price, transportation electrification, ethanol blending constraints, and arable land availability. In BSM, we varied inputs including the annual biorefinery construction limits, feedstock flexibility for use in various biomass-to-biofuels conversion pathways, and policy assumptions regarding tax incentives and the per-gallon production incentive based on renewable identification numbers (RINs). The scenario components, descriptions, variations, and names from the GCAM and BSM runs are listed in table 1. For scenario details, see SI tables S6 and S7.

Table 1. GCAM and BSM scenario components.

	Scenario component	Description	Variation	Variation name
GCAM	Carbon price (Note 2)	Carbon price = 0 in 2015 U.S. dollars ($)	Without	**No Carbon Price**
		Price trajectory that limits global warming potential to 2.6 W m^{-2} by 2100 under shared socioeconomic pathway (SSP) 2 conditions in default GCAM model. ($96/metric ton carbon (tC) in 2020—$1,516/tC in 2060 (in 2015$)	Energy system only	Carbon Price
		Energy system carbon price trajectory as above Land system price = 0.1 × energy system carbon price (applied to the carbon in land) ($9/tC in 2020–$151/tC in 2060 (in 2015$)	Land and energy system	Land Carbon Price
	Transportation electrification	Lower efficiency and higher costs for battery EVs	Low	**Low EV**
		Higher efficiency and lower costs for battery EVs	High	High EV
	Ethanol blending	A limit to the amount of ethanol that light-duty vehicle transportation can take (10% or 25%)	10% maximum 25% maximum	**E10** E25
	Other arable land availability for agriculture (Note 3)	Original available arable land in GCAM (426 000 sq.km) - arable land in BSM (196 000 sq.km) = other arable land (392 000 sq.km)	Original GCAM estimate 90% protection of other arable land	**More Land Availability** Less Land Availability (written as 'Avail.' in some figures)
BSM-Specific Components (See Note 3 about inputs from GCAM.)	Construction limit	Determines the maximum number of new biorefineries that can start construction each year. Set at the approximate historical maximum (25 plants/yr) or allowed to grow comparably to a rapid GCAM growth scenario	25 plants/yr Growing limit (begins at 25 plants/yr, reaches 105 plants/yr in 2043)	**25 plants/yr** Growing Limit
	Feedstock flexibility	Determines which feedstocks can be used in conversion pathways: Flexible conditions allow herbaceous feedstocks in thermochemical pathways; targeted conditions require that thermochemical pathways use only woody feedstocks.	Flexible Targeted	**Flexible Feedstock** Targeted Feedstock
	Policy	A combination of tax credits, loan guarantees, and RINs	No tax credits or loan guarantees and $0.70/RIN (expiring in 2031)	**Low Policy**
			Tax credit (varies by pathway; see SI table S13), 80% of the loan principal is guaranteed and $2.00/RIN (expiring in 2031)	High Policy

Note 1: Reference scenario variations for this study for each model appear in the cells with bold.
Note 2: Table S4 shows the default carbon intensity values for fuel pathways used in the BSM.
Note 3: The BSM inputs align land availability with the GCAM scenarios and include a set of GCAM outputs from each GCAM scenario: carbon price, oil price, domestic ethanol fuel demand, demand and export of agricultural commodity crops, and the yield growth rate for agricultural crops and hay.

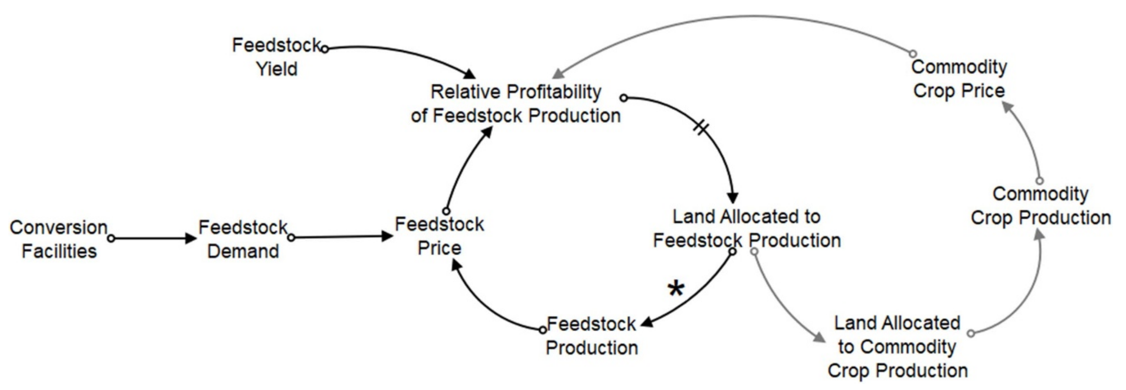

Figure 1. Model logic connecting biomass-to-biofuels conversion, feedstock demand, price, production, and land allocation in the Bioenergy Scenario Model. The length of maturation delay (shown by the parallel lines (||)) between the land allocation and the feedstock production determines the degree of instability in the land system. Longer delays, such as those associated with woody feedstocks, result in higher degrees of instability.

2.2. Model harmonization

To increase the comparability of the results, we directly input certain GCAM results into BSM—carbon and oil price trajectories, domestic ethanol fuel demand (no international market was assumed to exist), ethanol blending, and agricultural attributes—and harmonized arable land availability by adding options for each to use the other model's land amount (see figures S1, S4, and S5).

2.3. Key model features affecting results

The approaches to carbon pricing, land reallocation, and technology development modeling help explain the results. In both models, carbon pricing is an incentive to decrease greenhouse gas (GHG) emissions. Carbon prices increase biomass production because biofuels and biopower are assumed to be less carbon-intensive than fossil fuel. Responsiveness to carbon price depends on the net modeled carbon emissions difference. Equation (1) shows the difference in accounting for carbon credits to biofuel producers that increases the value of carbon pricing to biofuel producers more in GCAM than in BSM.

Equation 1. Value to biofuel producer ($/gal) of carbon price

In BSM: Carbon price ($/tC) * Emissions displaced compared to petroleum fuels (tC/gal)
In GCAM: Carbon price ($/tC) * Emissions displaced compared to petroleum fuels (tC/gal))
+ Carbon price ($/tC) × Carbon stored (tC)
Where carbon price is given per metric ton of carbon ($/tC).

Land reallocation occurs in both models in response to biomass demand but at different rates. GCAM rapidly reallocates the necessary land, but BSM limits the rate of reallocation through a balancing feedback loop (figure 1). As the demand for feedstock increases, so does feedstock price. This reduces the attractiveness of biofuels production and production capacity expansion, which then decreases the demand for feedstock. BSM also assumes a multiyear lag between planting and harvesting certain feedstocks (e.g. woody energy crops), which delays the response to price signals (figure 1, '*') and augments the price increases from the land reallocation. This type of feedback loop and lag is known in SD and control theory to result in potential volatility in systems (Graham 1977).

Technology development in GCAM is an input. In BSM, technology development is based on learning-by-doing implemented within a feedback loop among industrial capacity investment, biofuel production, and advancements in technological maturity (learning) (Peterson et al 2019).

3. Results and discussion

Our results address the feasibility of the rates of change and the biomass levels attained in deep decarbonization scenarios by considering demand for biomass, biomass availability and constraints, and biofuels industry growth. Here, we consider the increase in the amount of biomass and the bottlenecks that can

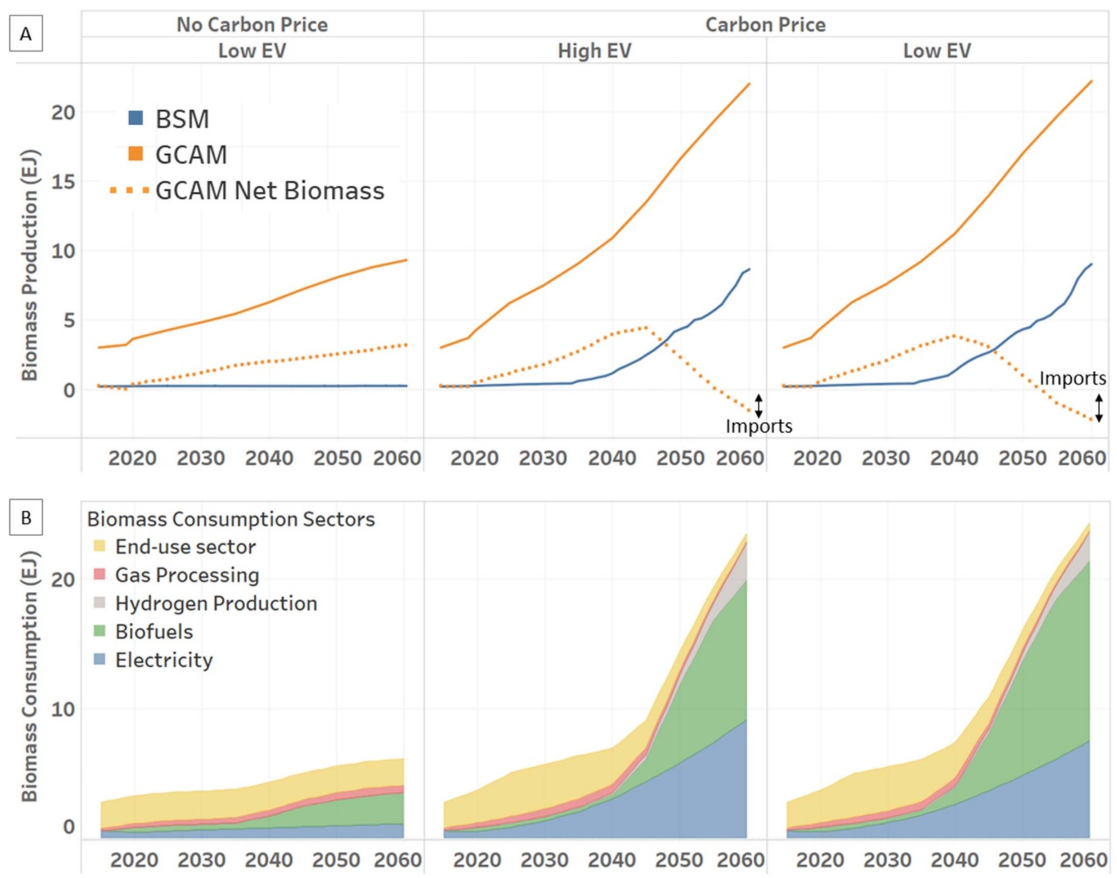

Figure 2. Comparison of total biomass production and consumption in the United States in the Global Change Analysis Model (GCAM) and the Bioenergy Scenario Model (BSM), shown by scenario component. Biomass production shown here includes cellulosic feedstock from agriculture, forests, and urban systems; fats, oils, and grease; and soy oil and camelina oil production in the BSM. In GCAM, residue and purpose-grown biomass production, along with municipal solid waste, is included; fats, oils, and grease production is not present in GCAM. (A) Effects of carbon price and transportation electrification in BSM. Each cell shows the biomass production in BSM and GCAM as well as the net production of biomass (production minus consumption) in the United States in GCAM. All other scenario variations correspond to the reference scenario (E10 ethanol blending, flexible feedstock, 25 plants/yr construction limit, and low policy). For net biomass, values greater than 0 indicate biomass exports, whereas values less than 0 indicate biomass imports. (B) Each cell shows biomass consumption by sector in the United States in GCAM. The end-use sector includes biomass use in buildings, industry, and passenger vehicles. In (A), GCAM biomass production includes the amount that is exported. BSM assumes no import or export of feedstocks for biofuels.

impede this growth such as the rates of land reallocation and biofuels industry growth.

3.1. Magnitude of biomass utilization in the two models

Results from both GCAM and BSM suggest that a carbon price increases annual biomass production and consumption. In BSM, annual biomass production is negligible when no carbon price is assumed, but it increases to approximately 9 EJ in 2060 with a carbon price trajectory of $96/tC in 2020 to $1516/tC in 2060 (figure 2(A)). In GCAM, annual biomass production increases from about 3 EJ in 2015 to around 9 EJ in 2060 without a carbon price. With a carbon price, the annual production in 2060 increases to approximately 22 EJ.

These results equate to average annual growth rates between 2020 and 2060 of 0.44 EJ yr^{-1} and 0.22 EJ yr^{-1} in GCAM and BSM, respectively, which are 4.5× and 1.6× the historical GCAM annual biomass deployment growth rate of approximately 0.08 EJ yr^{-1} from 1990 to 2020. The increase in biomass production with and without a carbon price is compared in figure 2(A). Carbon prices cause an increase in modeled biomass production because biomass utilization is assumed to reduce fossil fuel use and, in GCAM, to offer opportunities for carbon capture and storage.

Although only selected results are directly comparable due to the models' disparate scopes (see section 2), the differences in the biomass results between the two models highlight additional detail on the determinants of the magnitude of biomass use. In figure 2(B), because of GCAM's economy-wide coverage in contrast to BSM's focus on biofuels, only the portion of biomass consumption for biofuels (green) of the GCAM biomass consumption is directly comparable to BSM's results. The results show the effects of carbon price, CCS, and transportation electrification in both BSM and GCAM on biofuel

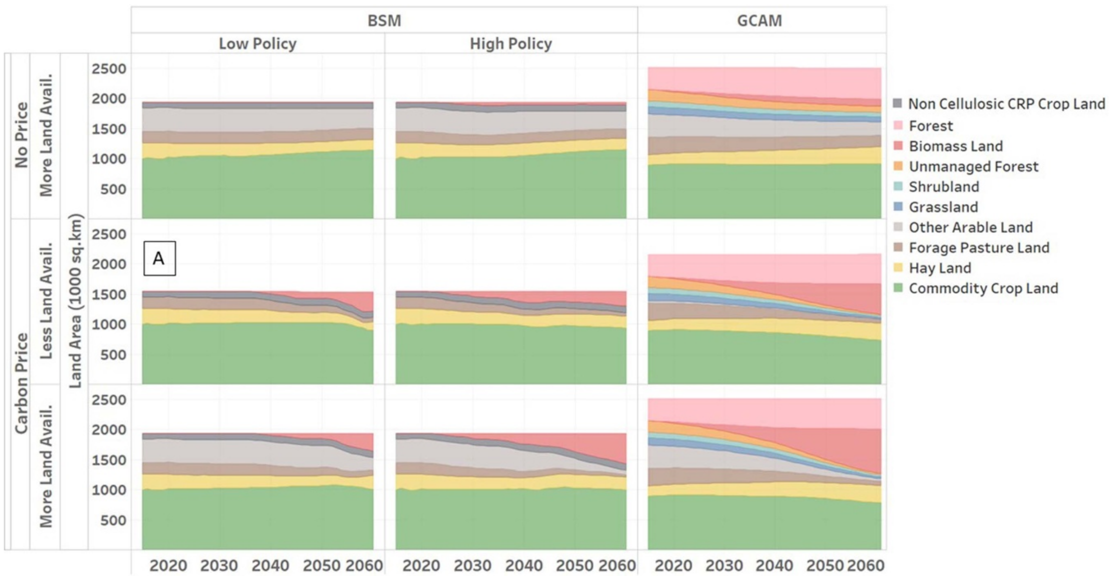

Figure 3. Agricultural land allocation by land category in the Unites States in the Global Change Analysis Model (GCAM) and the Bioenergy Scenario Model (BSM), shown by scenario component. The BSM results include the effects of policy incentives, other land availability, and carbon price. The GCAM results include the effects of carbon price and other arable land availability. Each cell shows land allocation. The shrubland, forest, unmanaged forest, and grassland categories in GCAM are not part of the BSM land base, but they are included because these categories change over time in GCAM. The rows show harmonized GCAM-BSM scenario variations for carbon price and land availability. The columns show BSM scenario variations for the low policy and high policy as well as the GCAM results. All other scenario variations correspond to the reference scenario (E10 ethanol blending, low electrification, flexible feedstock, and 25 plants/yr construction limit). Note: 'More land avail.' = More land availability; 'Less land avail.' = Less land availability; CRP = Conservation Reserve Program.

production. With a carbon price and low transportation electrification, approximately 13 EJ, or 57% (green) of biomass, is used in biofuels production in GCAM in 2060 (figure 2(B)). With higher transportation electrification (High EV), biomass use for biofuels decreases by approximately 3 EJ in 2060, with a slightly smaller increase in biomass used for biopower (blue). Overall biomass use slightly decreases, as transportation electrification enables greater GHG reduction than biofuels at the same carbon price. The higher total biomass consumption in the 'Low EV' scenario results in higher imports toward the end of the simulation (figure 2(A)).

With a carbon price, biofuels pathways with CCS receive higher incentive payments than those without CCS. Biomass consumption for biofuels in GCAM is 2–4 EJ higher than BSM under a carbon price in 2060, in part because GCAM includes biofuels pathways with CCS. Comparing biofuels production in the two models, BSM has lower ultimate biofuels production than GCAM under most scenarios (SI figure S11). Other potential reasons beyond CCS that could explain this difference between the models are provided later in this section. The maximum annual biofuel production in GCAM is 9 EJ in 2060 (SI figure S11, Row A) and 7 EJ in BSM (SI figure S11, Cell B).

3.2. Impacts of land availability and feedstock flexibility on biomass utilization

Like transportation biofuels, the magnitude of biomass utilization can vary based on carbon price and its amplification through CCS, the effects of competing technologies, and other policy incentives beyond carbon pricing. However, any scenario of rapid and extensive biomass utilization raises questions of feasibility of biomass production and land reallocation. We find that less land availability constrains the biomass production in both models, and a slow rate of land allocation in response to biomass demand can cause fluctuations in biomass pricing dynamics in BSM. Daioglou *et al* (2020) also highlighted the importance of feedstock availability and prices on the cost of deploying biomass technologies, and they also found that land constraints could impact the economic availability of feedstock.

In both models, land availability and the land reallocation rate in response to biomass demand limits biomass availability. When a carbon price is applied, annual biofuel production in GCAM reaches nearly twice that observed from the BSM by 2060, primarily due to model differences (see section 2). Both models reallocate agricultural land use to biomass cultivation when biomass demand increases to the extent that prices are favorable (figure 3, Row 1 vs. Row 2 and Row 3). Both models reallocate less commodity crop land than other land categories. When additional land is made available for biomass cultivation, it is used (figure 3, Row 2 vs Row 3). This increases biofuels production in both models (figure 6, Row 1 versus Row 2) because upward pressure on the feedstock price is reduced. Despite the changes we made to both models to align land availability (see section 2),

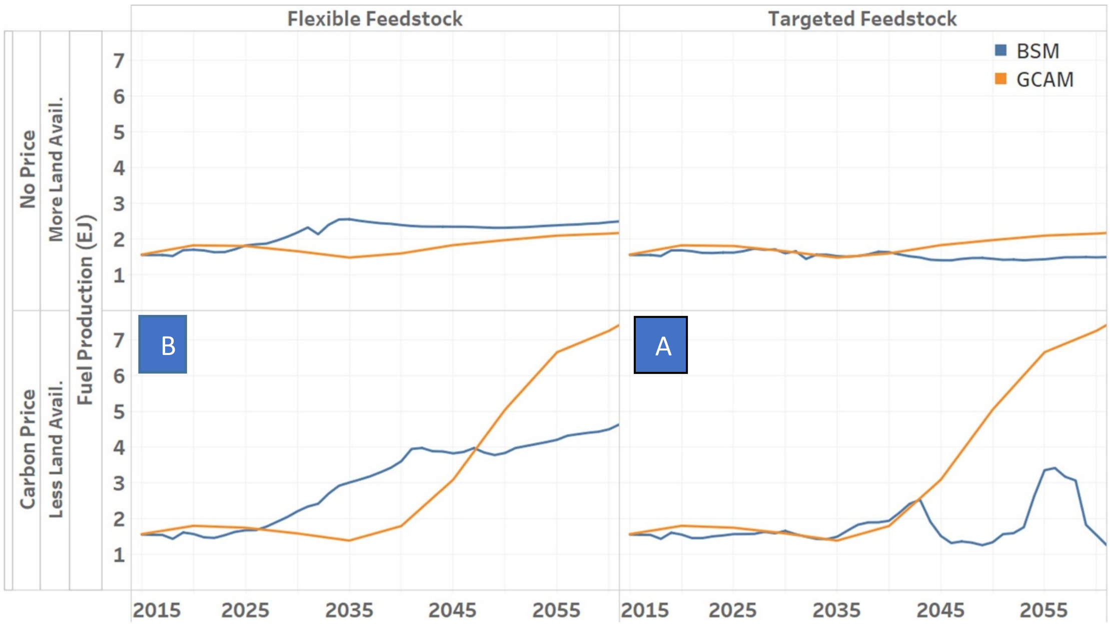

Figure 4. Comparison of total biofuel production in the United States in the Global Change Analysis Model (GCAM) and the Bioenergy Scenario Model (BSM), shown by scenario component. The effects of carbon price and feedstock type on biofuel production in BSM are shown, along with the effects of carbon price in GCAM. Each cell shows the total biofuel production in each model. The rows show harmonized GCAM-BSM scenario variations for carbon price and land availability. Only two distinct GCAM variations are shown: one in each row and repeated across the columns. The columns show BSM variations for feedstock flexibility. All other scenario variations correspond to the reference scenario (E10 ethanol blending, low electrification, and construction limit of 25 plants yr^{-1}).

the amount of land mobilized in the 'More Land Avail.' scenario is greater in GCAM than in the BSM (figure 3, Column 3 vs. Column 1 and Column 2), which could contribute to the lower cost of biomass production in GCAM than in BSM.

BSM limits the rate at which land reallocation can occur using a feedback loop that includes feedstock production, feedstock price, and relative profitability of investment (figure 1). This results in a slower biomass production response to increasing demand in BSM relative to GCAM as well as volatility in feedstock price and land allocation to biomass in some cases. For example, in figure 3, Cell A, the 'Biomass Land' (red) reaches highs in 2045 and 2057, followed by lows in 2050 and 2060. The 'High Policy' scenario is more stable because incentives increase relative profitability, moderating the low extreme of the oscillating cycle. The biomass demand increase in the 2040s in the 'Low Policy' scenario causes feedstock price/land allocation volatility that seeks—but overshoots—the more stable pattern in the 'High Policy' scenario. This common behavior of systems with feedback loops often indicates the presence of challenging constraints to change. In this case, the rate of increase in demand likely exceeds the assumed changes in land availability and feedstock production to meet demand. The effects of reducing this land availability constraint are shown in the comparison between figure 3, Cell A, 'Biomass Land' result and the result below it in the 'More Land Avail.' scenario.

The potential effects on biofuel production of the multiyear lag between the planting and harvesting of some biomass types are shown through a comparison of 'Targeted' and 'Flexible' feedstock scenarios (figure 4). Volatility from the 'land allocation–feedstock production–feedstock price' feedback loop leads to volatility in fuel production. In BSM 'Targeted' feedstock scenarios (e.g. only allowing use of woody feedstocks in thermochemical processes), this lag slows growth and triggers market instability through cyclical patterns of undersupply and oversupply (figure 4, Cell A). The BSM 'Flexible' feedstock (e.g. thermochemical processes can also use annual herbaceous feedstocks) scenarios mitigate this instability because there are more feedstocks without a multiyear lag between planting and harvesting (figure 4, Cell B).

3.3. Exploring the interactions of land availability, technology development, capacity expansion, and incentives on biofuel expansion feasibility

Our key results show how these findings interact with technology development and production capacity expansion to affect the opportunities for biomass utilization as a decarbonization strategy. First, we describe the potential role that technology development could play in mitigating price volatility. Second, we consider the potential role of other incentives, beyond carbon pricing, in accelerating production capacity expansion. Third, we explore how land

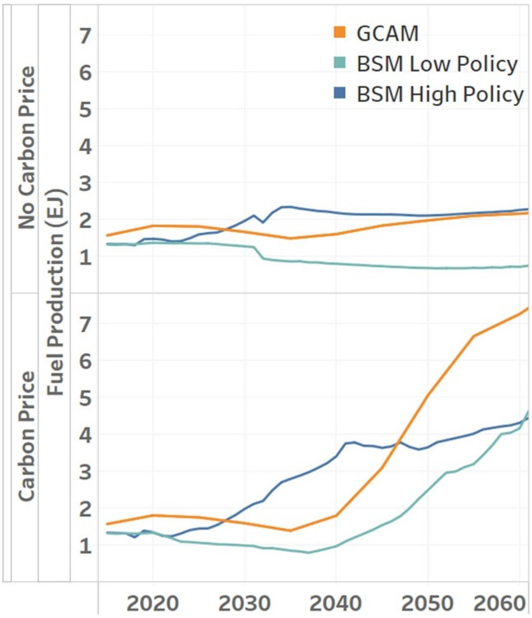

Figure 5. Comparison of total biofuel production in the United States in the Global Change Analysis Model (GCAM) and the Bioenergy Scenario Model (BSM) under the High Policy and Low Policy scenarios, shown by scenario component. The effect of carbon price on biofuel production in BSM and GCAM is shown, along with the effect of policy on BSM results. Each cell shows fuel production. The rows show harmonized GCAM-BSM scenario variations for carbon price. All other scenario variations correspond to the reference scenario (E10 ethanol blending, flexible feedstock, 25 plants/yr construction limit, and low EV).

availability and incentives interact with production capacity expansion rates.

Technology development in BSM is modeled with learning feedback that increases yield and reduces production cost (Vimmerstedt *et al* 2015a). The rapid development of technologies that align with the 'flexible feedstock' representation in BSM, either through biomass-to-biofuels conversion technology development or through feedstock technology development, could prevent fluctuations by increasing availability of feedstocks to biofuel technologies.

We also find that other policies beyond carbon pricing accelerate production capacity expansion. We modeled certain incentives only in the BSM, including RINs, tax credits, and loan guarantees, and these were found to accelerate bioeconomy growth and increase the ultimate amount of biomass used with or without a carbon price (figure 5). In fact, the simulations show that near-term policy increases industry growth even after policy expiration. Even in the absence of a carbon price, policy expiring in 2031 reduces costs and risks to investors of additional plants built after 2031. Incentives applied in BSM increase biofuels production over GCAM (which did not explicitly represent these incentives) levels, in contrast to the other scenario results in this study. In scenarios with carbon prices, early policy implementation helps technologies mature quickly, and the resulting investment acceleration has enduring effects.

Technology development and production capacity expansion interacts with land availability and policy. Figure 6 shows biofuel production in BSM for high and low policy levels and two limits on annual biorefinery construction: a 25 plants yr^{-1} construction limit and a limit that grows from 25 plants yr^{-1} in 2015 to 105 plants yr^{-1} in 2060. When policies are provided to increase biofuel production, the demand for biomass is high. Inertia in land reallocation slows biofuels production in BSM relative to GCAM, even when constraints on construction capacity are removed (Growing Limit). This is visible in figure 6, Cell A versus Cell B, where under high policy and more land available scenarios, using the increasing instead of the constrained limits on the annual construction capacity results in only a small difference in annual BSM biofuel production in 2060. Under the 'Low Policy' scenario variation, when biomass demand is not driving feedstock prices so high, the land reallocation/feedstock price dynamics no longer dominate, and the growing limit scenario variation substantially increases biofuel production (figure 6, Cell C versus Cell D).

In contrast to the limited BSM response to changes in annual construction capacity when demand is high, a change from less to more land availability increases biofuels production in both models by reducing the upward pressure on feedstock price (figure 6, Row 1 versus Row 2). This emphasizes the importance of land reallocation constraints that lead to feedstock price volatility under high-demand conditions, over increased capacity to construct biorefineries.

4. Conclusion

GHG mitigation efforts in deep decarbonization scenarios rely on extensive bioenergy deployment—including biofuels and biopower, often with CCS—across the global and U.S. economies. In this study, we coordinated and compared GCAM and BSM to assess the feasibility of biomass deployment consistent with a 2.6 W m^{-2}, middle-of-the-road shared social pathway (SSP2) mitigation scenario. Both models represent complex, interlinked biomass-to-bioenergy systems, and comparing the models reveals insights and topics for further investigation to inform deep decarbonization efforts.

Using the global, multisector, and economy-wide approach of GCAM with the detailed, sectoral, and country-specific representation of the biomass-to-biofuels supply chain in BSM, we addressed whether the indicated amount of biomass could be feasibly produced and deployed given the constraints on the availability of biomass and biofuel industry growth. Differences in results between the two models point

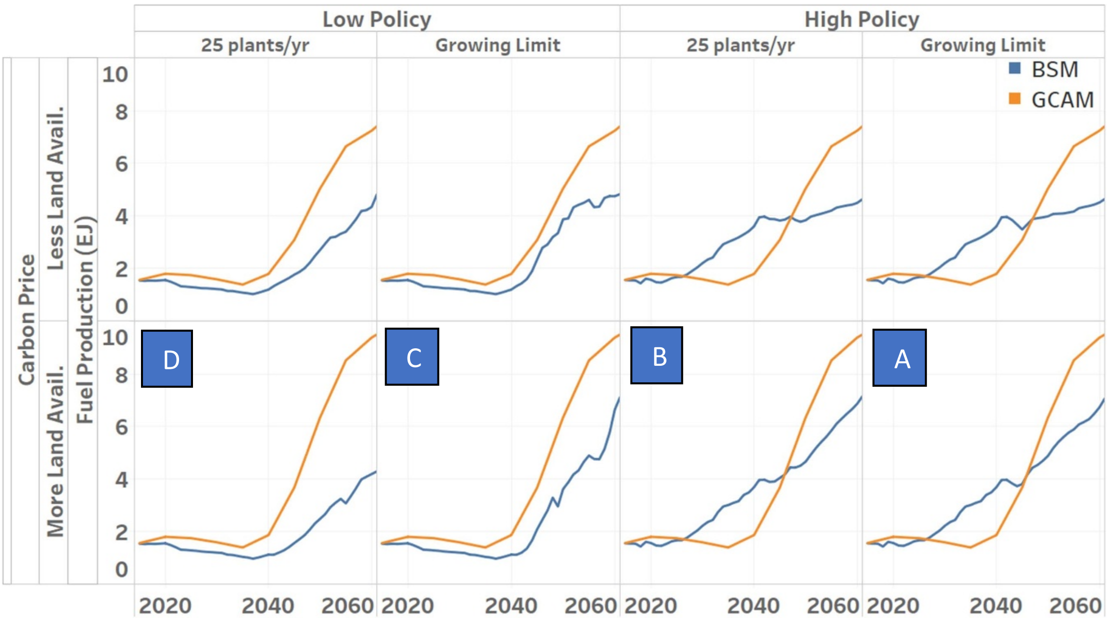

Figure 6. Comparison of total biofuels production in the United States in the Global Change Analysis Model (GCAM) and the Bioenergy Scenario Model (BSM) shown by scenario component. The figure shows the effects of other arable land availability, policy incentives, and plant construction limits in the BSM scenarios on biofuel production results from BSM and compares these to the effects of other arable land availability in GCAM. Each cell shows the total biofuel production in each model. The rows show harmonized GCAM-BSM scenario variations for land availability. Two distinct GCAM variations are shown: one in each row and repeated across the columns. The columns show BSM variations for policy and construction limit. All other scenario variations correspond to the reference scenario (E10 ethanol blending, low electrification, and flexible feedstock), except carbon price. Note: 'More land avail.' = More land availability; 'Less land avail.' = Less land availability.

to potential barriers to reaching these decarbonization goals using biofuels: land availability and land reallocation rate for biomass, coordinated development of the feedstock and biofuels systems (including accounting for lags in harvesting), and conversion technology development and cost reductions (including CCS). Our results show that these barriers could be mitigated through research, development, demonstration and deployment, policy incentives, and changes in investment decisions.

The rate of increase in annual biomass utilization varies in response to scenario inputs. In one example, the rate of annual biomass production growth between 2020 and 2060 is 0.22 EJ yr^{-1} in (BSM) and 0.44 EJ yr^{-1} in (GCAM) when a carbon price is applied, 4.5× and 1.6× the historical rate of 0.08 EJ yr^{-1}. These changes in growth rates for the United States are within the range found in literature for global effects of carbon pricing on the bioeconomy. For example, in EMF-33, annual growth rates after 2020 varied by up to 4.8× of that before 2020 (Bauer *et al* 2020). In our study, the increased production of biomass is comparable to the high end in literature for GCAM but is significantly lower for BSM. In addition to carbon price, CCS and transportation electrification influence biomass deployment, thus highlighting the opportunity to manage biomass demand by these strategies.

Land availability is a key constraint on biomass production. In scenarios with more land available, feedstock prices are moderated by the ability to produce more biomass, resulting in more biomass use. In periods of high demand, the rate of land reallocation plays an important role in determining the trajectory of biomass deployment. In BSM, a limit on this rate resulted in instability in biomass prices, which is further reflected in the slow growth of the biofuels industry and fluctuations in biomass demand. Such system instability points to challenges associated with biomass deployment levels exceeding historical growth rates, which is consistent with Daioglou *et al* (2020). In addition to increased availability of land and higher reallocation rates in response to biomass demand, technology development can mitigate the challenges of a rapidly growing system by enabling more flexible use of different feedstock types.

Literature suggests current investment levels are insufficient for development of the industry even in developed countries (Baker *et al* 2015). For biofuels industry growth, policy incentives other than carbon pricing are found to be important levers. Policy can help spur the necessary increase in investments and have persistent impacts on growth even after the incentives expire. Incentivizing biofuel production with tax credits, loan guarantees, and RINs in BSM accelerated bioeconomy growth. Incentives in the next decade will increase near-term biofuel deployment, thereby increasing technological progress, and allowing the system to change more rapidly in the future before showing signs of potentially infeasible increases. An investment rate in biofuels industrial capacity expansion that is limited to historical precedents constrains biomass deployment when the demand for biomass is low. When carbon pricing and policy drive biomass demand up, however, land reallocation becomes the dominant bottleneck, highlighting how a rapid increase in biomass deployment can stress current resource systems and impede growth. We suggest prioritizing an improved understanding of factors for further research: land availability for agricultural use and the value of carbon in land, the feasible land reallocation rate to energy crops, policy effects on technology adoption (e.g. RINS, tax credits, loan guarantees for biofuels, and transportation electrification incentives), the costs and flexibility of matching feedstocks to specific biomass-to-biofuels conversion processes, conditions that might prompt capital investments that exceed historical conditions, and changes in the carbon intensity value of biofuels with volume.

By coordinating and comparing the results from two types of models—GCAM (multisector and global) and BSM (regional and focused on supply chain dynamics—we highlight specific processes of biomass utilization and industry development that might impede growth at the levels of demand spurred by carbon pricing for decarbonization. Our results, along with the additional research we suggest, could improve the understanding of challenges to biomass growth, enhancing the analytic capabilities of models and helping to target efforts to facilitate biomass utilization in support of decarbonization objectives.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iDs

Laura Vimmerstedt https://orcid.org/0000-0002-0392-4431
Swaroop Atnoorkar https://orcid.org/0000-0002-3262-9845
Candelaria Bergero https://orcid.org/0000-0002-8937-6367
Marshall Wise https://orcid.org/0000-0002-2718-0051
Steve Peterson https://orcid.org/0000-0003-1202-8281
Emily Newes https://orcid.org/0000-0001-7303-2589
Daniel Inman https://orcid.org/0000-0002-8103-2076

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