WORLD RESOURCES INSTITUTE

WORKING PAPER

Biomass and land use in a decarbonizing U.S. economy

Haley Leslie-Bole, Audrey Denvir, Dan Lashof, Angela Scafidi, and Caroline Melo Ribeiro

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues.

Suggested Citation: Leslie-Bole, H., A. Denvir, D. Lashof, A. Scafidi, and C.M. Ribeiro. 2025. "Biomass and land use in a decarbonizing U.S. economy." Working Paper. Washington, DC: World Resources Institute. Available online at doi.org/10.46830/wriwp.24.00033.

Executive Summary

Highlights

- As the world pursues efforts to mitigate and adapt to the impacts of climate change, lands will be put under increasing pressure to meet demand for food, fiber, energy, carbon removal, and other ecosystem services. The efficiency of different land uses must be considered as the United States works toward its climate goals.
- Limited biomass use has the potential to support emissions reductions, but overuse risks increasing land use pressure, displacing food production, and causing cropland expansion that increases greenhouse gas emissions.
- Biomass sources that have lower risk of inducing land use change include wastes and residues from agriculture and forestry. Food crops grown for biofuel pose the highest risk of driving land use change.
- To most effectively support decarbonization, limited biomass resources may be used for carbon removal and replacing fossil fuels in the production of chemicals.
- Crop-based biofuels, such as corn ethanol or soybean oil aviation fuel, are not effective uses of biomass for decarbonization. When the land use cost is considered, it is clear that biofuels do not provide reduced greenhouse gas emissions over fossil fuels; thus, the decarbonization pathways modeled in this study do not rely on food crops in the energy system in 2050.

Context

As the global population grows, the increased demand for food, fuel, fiber, and expanded urban areas competes with the need to preserve and restore natural ecosystems and biodiversity. This competition creates a "global land squeeze" that will continue to intensify with increasing population and income. In the United States and globally, this presents an imperative to effectively manage lands to allow them to meet multiple demands.

The use of land to produce feedstocks for first-generation biofuels, such as corn ethanol and soy biodiesel, has changed crop cultivation patterns and triggered land use change in the United States and globally, exacerbating stress on land and ecosystems. Without appropriate policy guardrails, land devoted to crop-based fuels will likely expand as governments and industries look to decrease reliance on fossil fuels, especially for hard-to-abate sectors like aviation.

While reducing the use of fossil fuels is imperative, the use of biomass comes with its own set of environmental and climate dangers. There is a danger of overusing biomass resources for nonfood and fiber uses that could trigger land use change and ecological degradation and worsen, rather than mitigate, climate change. Using crops to produce energy is also less efficient than using the same land to site other low-carbon energy technologies.

If the United States is going to meet its goals of net zero emissions by 2050, new US policy must consider energy production and land use holistically and only incentivize feedstocks and clean energy sources that efficiently use land to support meaningful action toward these climate targets.

About this paper

This working paper seeks to answer three key questions to inform the responsible and climate-informed use of biomass:

- To what degree might future efforts to decarbonize the US economy drive biomass use, and how might biomass use change if guardrails reducing land carbon leakage and negative ecological impact are added?
- How effective are crop-based biofuels for supporting decarbonization in light of the opportunity costs of diverting this land from other uses, particularly the continued production of agricultural products?
- What are the most valuable uses of biomass to support decarbonization under various scenarios that assume increased biomass availability?

To answer these questions, the paper starts with projections of future biomass supply from the US Department of Energy and Lawrence Livermore National Laboratory, making additional adjustments to biomass potential by excluding or discouraging uses that would have high risks of increasing overall carbon emissions and other negative ecological impacts. With the remaining still-optimistic estimates for biomass potential, the analysis uses energy systems modeling, including an economy-wide carbon price, to understand the most effective uses of biomass to contribute to overall US decarbonization.

This paper is intended to advance discussions about the role of biomass and biofuels in US decarbonization and the need to fully account for land use emissions to ensure real climate benefits. This paper does not, however, intend to recommend certain levels of biomass use or certify that certain feedstocks can be used without consequence. Instead, it is intended to underscore the need to optimize land use to decarbonize the economy while providing food and fiber and supporting clean energy production.

Key findings

This analysis finds the following:

- **Adequate guardrails and accurate carbon accounting are necessary to prevent biomass use from negatively impacting climate, ecosystems, and food systems.** Without guardrails and accurate carbon accounting, the demand for biomass in a decarbonizing economy could cause increased greenhouse gas emissions and other unacceptable environmental harms.
- **If the United States pursues economy-wide action to meet 2050 climate targets, biomass is best utilized for carbon removal and replacing petrochemicals.** It plays a less valuable role as an energy source. Because biomass is a limited resource, it should be used strategically to provide the greatest climate benefit.
- **Crop-based biofuels are not an effective tool for achieving economy-wide decarbonization.** Modeled decarbonization pathways that account for land use change emissions do not use first-generation fuels made from food crops in the energy system in 2050.
- **Dependence on biomass—and, accordingly, land use pressure—can be reduced by accelerating electrification across economic sectors and increasing energy efficiency.**

INTRODUCTION

There is a finite quantity of land on Earth, and this land will increasingly be stressed by a changing climate, growing population, and an increasing demand for land-intensive products (Searchinger et al. 2023). In 2050, global lands will need to provide food for an estimated 9.7 billion people (United Nations 2024), provide resources like wood and fiber for buildings and clothing, and support biodiversity and carbon sequestration in plants and soils. This competition creates a "global land squeeze" that could trigger the continued loss of natural ecosystems (Searchinger et al. 2023). In the United States and globally, the land squeeze presents an imperative to effectively manage lands to meet the multiple demands placed upon them.

As countries look to decarbonize, biomass is increasingly viewed as a lower-carbon alternative to fossil fuels. However, the use of biomass comes with its own set of potential environmental and climate dangers (see Box 1 for definition of key terms). Many modeled US net zero trajectories rely on a large quantity of biomass (Wilson et al. 2023). These scenarios, however, likely overestimate the emissions reductions possible from biomass use because they fail to account for the full land carbon costs of using that biomass. As such, they may not represent true net zero trajectories.

When trees or crops are purpose-grown as biomass feedstocks for energy, they may displace necessary food or fiber production. To meet increasing global demand for food and fiber, land elsewhere may then need to be cleared to compensate for production loss, and cleared land emits carbon stored in soils and vegetation (Fargione et al. 2008; Wang and Khanna 2023). There is a critical danger in overusing biomass resources for nonfood and fiber uses: expansion of land devoted to biomass feedstocks can trigger land use change and ecological degradation and increase, rather than decrease, global greenhouse gas emissions. Using biomass crops to produce energy is also far less efficient than using the same land to site other energy technologies. In optimal transmission and storage scenarios, solar photovoltaic (PV) systems could provide approximately 100 times more energy per hectare than bioenergy (Searchinger and Heimlich 2015).

Despite the risks posed by certain biomass uses, there may also be an opportunity to utilize select biomass feedstocks to play a role in decarbonization. Other elements of decarbonization, such as the construction of large-scale renewable energy capacity, will also require land, so it is important to understand land use demands holistically.

This analysis identifies some of the risks associated with biomass use and some of the carbon accounting practices and guardrails needed to minimize the emissions and ecological impacts associated with biomass use. It then identifies how biomass may be best utilized across industries to support decarbonization. Because these biomass uses are based on assumptions that may be optimistic, additional evaluation would be needed to assess the environmental and emissions impacts of each feedstock.

Box 1 | **Key terms**

biofuel: A liquid fuel derived from biomass. This includes both first-generation fuels such as corn ethanol and bio-based diesel and second-generation or "advanced" biofuels such as cellulosic fuels and Fischer-Tropsch fuels.

biomass: Any material of a biogenic origin, including woody crops, perennial herbaceous crops, food crops, forestry residues, certain municipal wastes, and agricultural residues. Here, the term biomass is used as shorthand for all biomass for nonfood, -feed, -construction or -textile uses.

carbon opportunity cost (COC): The land carbon "cost" of using land to grow crops for energy instead of food. The COC represents the average carbon stock losses from the conversion of native ecosystems to agricultural land to replace the displaced food production and meet growing global food demand.

This analysis offers new insight into multisectoral biomass use in a decarbonizing US economy, acknowledging the inevitable competition between sectors for finite biomass and land resources. Moreover, this analysis examines emissions leakage and ecosystem impacts from biomass, illustrating the trade-offs associated with its use.

Biomass use today is driven by policy

Today, biomass supplies about 5 percent of US primary energy production, primarily as biofuel for transportation and wood burned for electricity and heat (EIA 2024). Biofuels use 30–40 percent of the annual US corn supply and 40–50 percent of the annual US soybean oil supply each year (USDA ERS 2025). Biomass use is driven by state, federal, and international policies that were originally intended to lower greenhouse gas emissions by displacing fossil fuels, support agricultural livelihoods, and supplement domestic energy supply. However, biofuels have not lived up to their claims. They have triggered myriad negative impacts, such as degrading ecosystems and displacing food production (Chen et al. 2021; Lark et al. 2022).

Policies driving biomass use include the US Renewable Fuel Standard (RFS), California's Low Carbon Fuel Standard (LCFS),[1] and tax credits for biofuels and electricity produced from biomass.

The RFS sets yearly gallon requirements for renewable fuels like ethanol and biodiesel. It was intended to increase production of cellulosic, or "advanced biofuels," which can be made from biomass wastes and residues rather than purpose-grown food crops.

However, production of advanced biofuels have not significantly increased due to high costs and technical challenges (Schnoor 2011; Zhao and Wang 2022); instead, production of "first-generation" biofuels that use food crops like corn and soy have skyrocketed. In 2004, the United States produced 3.4 billion gallons of ethanol and 0.07 billion gallons of bio-based diesel (biodiesel and renewable diesel, both derived from biogenic feedstocks). In 2023, the United States produced 15.62 billion gallons of ethanol and 4.29 billion gallons of bio-based diesel, an almost 500 percent increase (EIA 2024).

Estimates of US cropland expansion attributable to the RFS range from 0.01 to 7 million acres (Austin et al. 2022). That estimate, however, does not consider global land use change resulting from US policy, so impacts are likely much higher than the range presented in the study.

A second policy driving biomass use is California's LCFS. This policy is intended to lower the carbon intensity of transportation fuels by awarding credits for fuels that provide a lower carbon intensity than fossil fuels. California's LCFS has had positive impacts, such as increasing funding for transportation electrification, but it has also overincentivized biofuels that provide no climate benefit. Because of the LCFS, California now consumes more than half of the nation's bio-based diesel despite consuming only 7 percent of overall diesel (Martin 2024).

Until recently, most biomass-based diesel used in California was made from waste fats, oils, and grease (FOG), but diesel made from virgin vegetable oils has increased rapidly. Because global vegetable oil markets are interconnected (Santeramo and Searle 2019), increased demand for soy bio-based diesel in the United States will cause deforestation in other countries as forests are cleared to plant soy and palm oil crops to replace the soybean oil diverted from food markets (Soterroni et al. 2019).

The United States also uses woody biomass as an energy source. In the Southeast, wood is processed to create dry pellets that are combusted to generate electricity. Much of the market for these pellets is generated by the European Union's Renewable Energy Directive, which classifies wood as a low-carbon energy source despite many concerns from environmental advocates. As with crop-based biofuels, emissions from wood-based bioenergy are significantly undercounted in greenhouse gas inventories. Carbon intensity calculations often do not account for the lost (forgone) carbon sequestration potential from wood harvests and/or attribute carbon removals from unharvested forest growth to the wood-based bioenergy (Malcolm et al. 2020; Peng et al. 2023; Sterman et al. 2018; Tran et al. 2023; Walloe et al. 2024).

Justice and health impacts of current biomass use

Beyond climate impacts, the cultivation and processing of biomass has contributed to deterioration of air and water resources, leading to public health concerns. For example, tree harvests and wood pellet production has led to soil erosion, air quality deterioration, and water contamination in the US Southeast, which has particularly impacted marginalized communities in the region (Pollard et al. 2024; Shumway 2023). In the Midwest, increased cultivation of fertilizer-intensive corn for ethanol has led to nitrate leaching into drinking water, which can cause severe health problems (Temkin et al. 2019) and may increase water stress for communities in drought-prone areas (Wilson et al. 2023).

While the analysis presented here is limited to the United States, US biomass use has significant implications for people and ecosystems globally. Research has shown that increased biofuels production has likely raised food prices, caused ecosystem conversion, and displaced smallholder farmers globally (Bos 2024; Glauber and Hebebrand 2023; Gonzalez 2018).

RESEARCH METHODS

This analysis assesses how an economy-wide carbon price or similar decarbonization policy could drive changes in biomass use across industries in the United States in the lead up to 2050, and how this use could change when emissions leakage is fully counted. It employs energy systems modeling to allocate biomass use across industries and spatial analysis to determine land use requirements for domestic energy and biomass feedstocks. The analysis was repeated across multiple biomass supply scenarios that vary in how much they account for land emissions and ecological impacts associated with biomass feedstocks. These scenarios reflect theoretical policy scenarios with varying stringency levels for feedstock guardrails and biomass life cycle carbon accounting.

EnergyPATHWAYS and Regional Investment and Operations models

The energy systems modeling component of this research was completed in partnership with Evolved Energy Research (EER) using the EnergyPATHWAYS and Regional Investment and Operations (RIO) models. EnergyPATHWAYS uses data on current energy consumption trends to estimate future energy demand and demand-side equipment costs across the US energy sector. Energy demand and cost outputs are fed into the RIO model,[2] which produces least-cost US energy supply portfolios while respecting constraints, such as biomass feedstock supply, and reaching modeled net zero emissions. Modeled net zero emissions in some scenarios may not reflect true net zero when emissions leakage is not modeled (see Appendix F).

In each scenario, the model selects the most cost-effective pathways for reaching net zero, assuming that there is society-wide investment at the scale that is required to reach such targets. A key component in all net zero scenarios is an economy-wide price on carbon. The model endogenously calculates a marginal price per ton of carbon dioxide abatement that is needed at each five-year interval to reach modeled net zero emissions by 2050. The total costs and marginal abatement costs vary across scenarios.

Downscaling analysis

A spatial downscaling analysis was used to understand the land use requirements for biomass resources and renewable energy siting. The downscaling used methods derived from The Nature Conservancy's *Power of Place: National* report (TNC 2023) to place guardrails on both renewable energy siting and biomass sourcing to protect ecosystems and food systems. The report's "70% reduced impact" scenario was used as a default land protection level in most scenarios. These protections affect the optimal mix of energy resources and determine siting of onshore wind and solar PV energy infrastructure while avoiding sensitive ecological areas and prime farmland.

Biomass supply scenarios

The price and quantity of biomass assumed to be available in the United States is a critical variable that determines how biomass is used. This study uses biomass supply curves from the US Department of Energy (DOE) and the Lawrence Livermore National Laboratory (LLNL) that project biomass supply to 2050 and adjust supply assumptions to reflect additional environmental guardrails. All scenarios use the US Energy Information Administration's State Energy Data System dataset for 2021 levels of biomass use (EIA 2022). Guardrails in the study's two primary biomass supply scenarios differ in the degree to which they account for land emissions, prevent ecological impacts, and protect cropland. The *Billion-Ton* scenario draws primarily from the DOE's *2016 Billion-Ton Report (BT16)* and uses feedstock quantities available in a market that maximizes biomass harvests with limited restrictions on land use change. The adjusted *Roads to Removal (R2R)* scenario uses adjusted supply curves from LLNL's *Roads to Removal (R2R)* report (Pett-Ridge et al. 2023) to represent feedstock quantities with land emissions and ecological impacts more fully accounted for. Corn and soybean supply curves are added to both scenarios, with the carbon opportunity cost (COC) included in the adjusted *R2R* scenario and excluded from the *Billion-Ton* scenario (see Table 1).

Table 1 | **Data sources and feedstocks for *Billon-Ton*, adjusted *R2R*, and current policy scenarios for 2050**

SCENARIO	DATA SOURCE	DESCRIPTION	BIOMASS FEEDSTOCKS AVAILABLE TO THE MODEL
Billion-Ton	US Department of Energy's *2016 Billion-Ton Report*[a, b]	Represents a large increase in biomass use from market- and policy-driven sourcing intended to maximize biomass supply	Crop residues, mill and forestry residues, food waste, substantial wood harvests, municipal solid waste, biomass from expanded wildfire thinnings, perennial woody and herbaceous biomass crops, corn and soy without carbon opportunity cost emissions
Adjusted *R2R*	Lawrence Livermore National Laboratory's 2023 *Roads to Removal* report, adjusted by World Resources Institute[c]	Represents a large increase in biomass use but with more comprehensive guardrails on biomass sourcing that are intended to exclude sources that have large impacts on food systems and ecosystems	Crop residues, mill and forestry residues, food waste, municipal solid waste, biomass from existing levels of wildfire thinnings, switchgrass and native grasses on Conservation Reserve Program lands, corn and soy with carbon opportunity cost emissions
Current policy	Department of Energy's *2016 Billion-Ton* Report	Baseline scenario reflecting current policies as of 2021, including the Inflation Reduction Act; serves as a point of comparison for the two primary scenarios	Same as the *Billion-Ton* scenario above

Notes and Sources:

a. In 2024, after this analysis was conducted, the Department of Energy released the updated 2023 *Billion-Ton Report* (DOE 2024) on biomass availability and enabling conditions for biomass use. Like the 2016 report, the 2024 update finds that 1.1–1.5 billion tons of biomass could be available for use in a mature biomass market.

b. DOE 2016

c. Pett-Ridge et al. 2023

The *Billion-Ton* scenario for 2050 reflects DOE high-end estimates of potential biomass supply. It includes energy crops such as switchgrass from 'marginal land,' small-diameter trees from existing forests, and woody biomass from the ambitious wildfire treatment targets of the US Forest Service (USFS) as well as other wastes and residues. This scenario also includes the use of food crops to create biofuels but excludes a COC.

This scenario assumes that biomass feedstocks are carbon neutral, and it does not specifically assess the emissions footprint or counterfactual uses of individual feedstocks. While this scenario assumes carbon neutrality of biomass feedstocks, feedstocks that cause land use change, diminish forest or soil carbon, or distort food or fiber markets are not, in fact, carbon neutral because their emissions exceed carbon sequestered by plants as they grow. Guardrails on the adjusted *R2R* scenario remove many of the biomass sources that are most likely to result in net emissions, but even this analysis does not capture all potential emissions sources associated with biomass use. This study's purpose is not to endorse any biomass use scenario but instead to explore hypothetically how large quantities of biomass could be best used if it were available and carbon neutral.

The adjusted *R2R* scenario for 2050 uses the "zero cropland change" scenario from LLNL's *R2R* report as a starting point, which has a lower overall biomass supply projection than the *Billion-Ton* scenario. A COC is applied to crop-based biofuels to determine whether the average carbon losses of replacing foods exceed the benefits from the use of these crops for biofuels. Next, some other sources are excluded that risk increasing emissions when factoring in the costs of replacing food or the direct effects of harvest. The result is a potential biomass supply equal to about half that in the *Billion-Ton* scenario and about double current biomass use.

Also included is a baseline "current policy" scenario, designed to reflect US policies as of 2021. This model scenario does not have any imposed emissions constraint. This baseline scenario has an electrification rate that reflects Inflation Reduction Act (IRA) policies, and it does not apply any restrictions to biomass feedstock supply. This scenario primarily serves as a point of comparison for the two primary scenarios.

In addition to these core scenarios, a sensitivity analysis with a variety of other parameters, such as speed of electrification and various technology sensitivities, was used for further dynamic analysis. Sensitivities were run on a baseline scenario that included the COC and partially restricted feedstocks (see Appendix B).

Adjusted *R2R* biomass feedstock considerations

The biomass feedstock categories in the adjusted *R2R* scenario are restricted beyond the sustainability constraints in the *R2R* report to further reduce the risk of displacing agriculture or triggering carbon leakage. Adjustments and considerations for each biomass feedstock category are described below.

Perennial grasses on Conservation Reserve Program (CRP) lands. CRP lands are croplands that the United States pays farmers to take out of production to provide habitat, limit soil erosion, and produce water-quality benefits. The quantity of perennial grasses assumed in the adjusted *R2R* scenario (see Table 4) would likely require high yields on a high percentage of CRP general enrollments, so it should be viewed as optimistic. This assumes that CRP lands remain enrolled in the program through 2050 and current restrictions on mowing these lands are lifted. For the purposes of this analysis, it is assumed that there is no COC to growing native grasses for biomass on CRP land because these lands are purposefully retired from crop production for conservation purposes.

Agricultural residues. Agricultural residues in this analysis come from the by-products of grains such as corn, wheat, rice, and sorghum; cotton by-products; orchard waste; and animal by-products. A high percentage of agricultural operations would need to harvest and sell residues to produce the residue estimates in this analysis (see Table 2). Given diverse farming needs and local constraints, these harvest levels are ambitious.

The estimate of crop residues within the *R2R* report is constrained to avoid soil erosion and preserve soil carbon. However, some estimate that any residue removal reduces soil carbon (Liska et al. 2014; O'Brien et al. 2020). This study uses the more optimistic assumption and treats this biomass as carbon neutral.

Forestry residues from commercial wood harvests. The adjusted *R2R* scenario incorporates sustainability guardrails, including exclusion of wetlands and other sensitive areas, prohibition of roadbuilding, leaving at least 30 percent of residues on site, and a requirement that timber growth exceeds harvest at the state level. Still, there may be heterogeneous carbon costs that remain unaccounted for, depending on residue size and end use. There is evidence that harvest and use for bioenergy of anything but fine residues could increase emissions for 30–50 years even when factoring in reduced fossil fuel emissions (Booth 2018; Camia et al. 2021). There are also concerns with effects on biodiversity, as woody residues play valuable ecological roles.

Forestry residues from fire treatments. Studies have found that thinnings reduce high-severity burns by removing "ladder trees" that lead to crown fires (Davis et al. 2024; Prichard et al. 2021).

Others find that controlled burns are more effective at reducing fire risks and that thinning can cause an overall reduction in forest carbon stocks (Banerjee 2020; Bradley et al. 2016). Thinning is necessary in many forest areas, however, to make prescribed burns feasible without a high risk of the prescribed burn getting out of control. The thinnings estimates in the *R2R* report assume large fractions of wood removed per acre. The net carbon impact of thinning depends on the quantity of emissions saved by avoided fire, the quantity of carbon emitted by thinning, and the end use of thinned wood. This study's analysis does not assume that these thinnings reduce overall carbon emissions. Instead, the adjusted *R2R* scenario merely assumes that recent levels of thinnings will continue to occur.

Certain feedstocks are categorically excluded from the adjusted *R2R* scenario. First, the *R2R* report finds that significant quantities of energy crops could be grown on 'marginal land.' The *R2R* report defines 'marginal land' as land not in agricultural use, but this could include land otherwise suitable for grazing. The adjusted *R2R* scenario excludes uses of 'marginal land' to avoid the risk of displacing livestock production. The *R2R* study also includes biomass from small-diameter, precommercial thinning. There is evidence that although such thinning increases the quantity of plantations' merchantable timber, the effect on carbon is to reduce carbon storage, and data on the frequency of this practice are scarce (Brack et al. 2021; Zhou et al. 2013). For this reason, this feedstock is excluded from the adjusted *R2R* scenario.

Yet even with these limitations, the modeled amount of biomass used in the scenario is almost twice the amount of biomass used in 2020. Such an increase should be approached cautiously; even the biomass resources in the adjusted *R2R* scenario may have emissions or other significant environmental impacts associated with their use that are not captured in this model. Therefore, this scenario should not be thought of as a "sustainable biomass use" scenario but rather a scenario with significant growth in biomass use with some categorical nature and climate safeguards.[3]

COC

The COC is an additional emissions factor applied per unit of corn and soy selected in the RIO model. It represents the average carbon stock losses from the conversion of native ecosystems to agricultural land to replace displaced food production and meet growing global food demand. In this analysis, the COC specifically accounts for the emissions associated with using land to grow crops for energy instead of food.

Land use emissions from biofuels in other economic models are often added using estimates of indirect land use change due to a policy-driven "shock" in biofuels production. This approach generally undercounts emissions from global land use change due to unrealistic assumptions about land use and food production (Malins et al. 2020). The COC is an alternative approach that assigns an emissions cost to the land used for biofuels.[4]

This study's modeling applies a COC of 2.8 kilograms of carbon dioxide equivalent per kilogram (kg CO_2e/kg) for corn ethanol and 7.9 kg CO_2e/kg for soy bio-based diesel. This equates to a land use emissions intensity of 103.6 grams (g) CO_2e per megajoule (MJ) for corn ethanol and 180.4 g CO_2e/MJ for soy bio-based diesel (Searchinger et al. 2018). These numbers account for by-products of biofuel production that have some carbon-saving benefits (e.g., distiller's grain for animal feed).

The COC assigns higher land use emissions to biofuels than the emission factors used in current US policies. For example, the RFS uses 32 g CO_2e/MJ as the indirect land use change (ILUC) emissions factor for corn ethanol and around 36 g CO_2e/MJ for soybean oil (EPA 2010). California's LCFS uses even lower numbers: about 20 g CO_2e/MJ for corn ethanol and 29 g CO_2e/MJ for soy-based diesel (CARB 2020). These numbers, however, likely underestimate emissions from land use change and fall on the low end of values found in the literature (Daioglou et al. 2020). The RFS uses ILUC factors that come from a collection of models, including the Global Trade Analysis Project (GTAP) model, which makes inappropriate assumptions about the effects of biofuel demand on land use, including assumptions that higher food prices will decrease food consumption and will also induce farmers to boost yields (Berry et al. 2024; Malins et al. 2020).

Table 2 | **Comparison of ILUC factors and Carbon Opportunity Cost**

POLICY	CORN ETHANOL LAND USE EMISSIONS (g CO_2e/MJ)[a]	SOY BIO-BASED DIESEL LAND USE EMISSIONS (g CO_2e/MJ)
Carbon opportunity cost (COC)	103.6	180.4
Renewable Fuel Standard	32.0	36.0
California Low Carbon Fuel Standard	20.0	29.0

Note: a. The scenario analysis results show that corn ethanol-based jet fuel becomes uncompetitive with land use emissions around 20 grams of carbon dioxide equivalent per megajoule (g CO_2e/MJ) if there is a cost applied to emissions.

While these COC values are higher than those used in current US policies, a sensitivity analysis (discussed in the "Results and key takeaways" section) indicates that this paper's key findings hold true even if the land use emissions values used here are reduced by more than 50 percent (see "Key takeaway 2").

In this analysis, the COC gives important insight into the relative efficiency of land use for emissions mitigation and carbon sequestration. It allows emissions associated with the dedicated use of land to produce energy instead of food to be assigned to the product grown on that land.

RESULTS AND KEY TAKEAWAYS

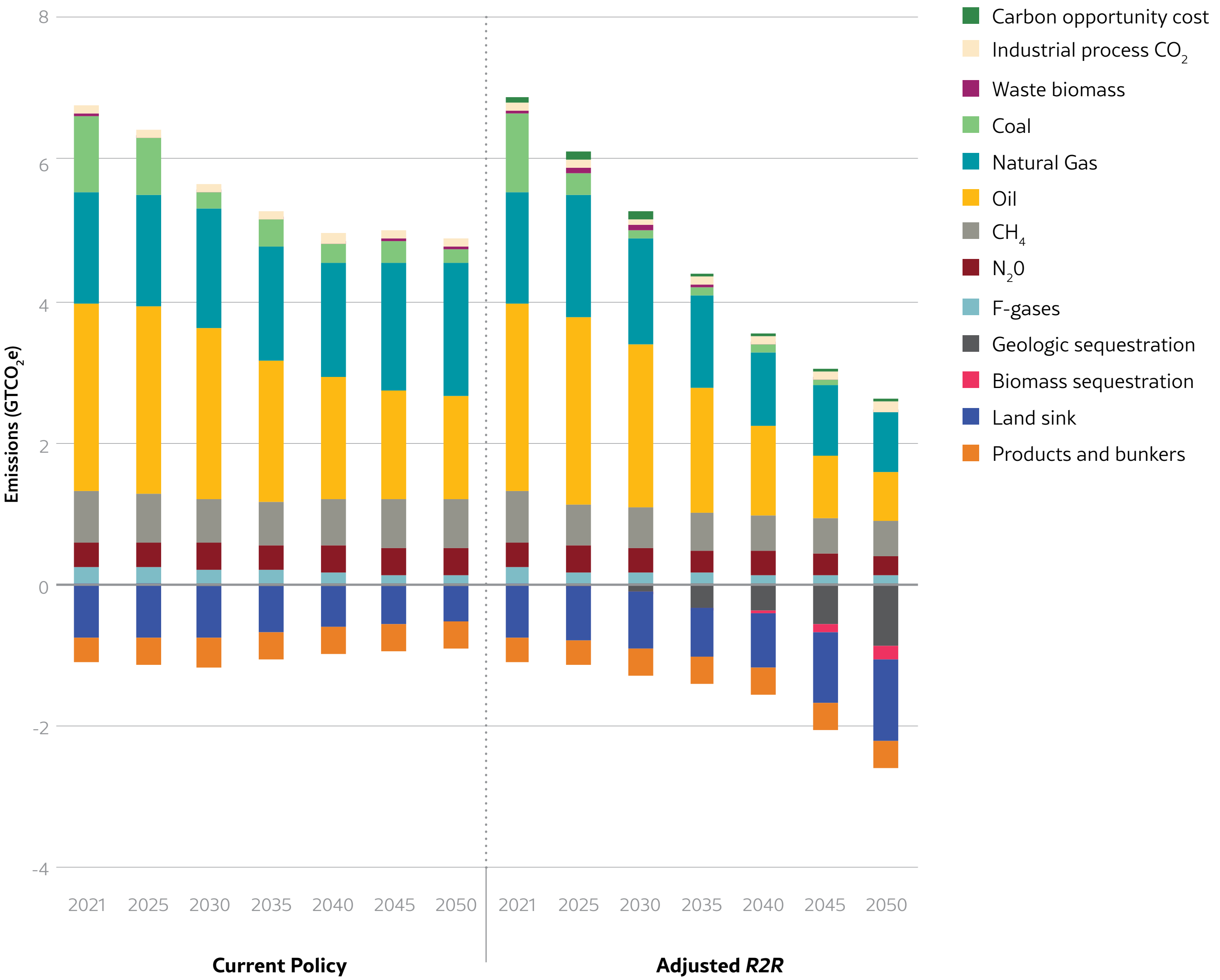
Based on the results of the analysis, these are the key takeaways:

- **Key takeaway 1: Adequate guardrails and accurate carbon accounting are necessary to prevent biomass use from negatively impacting climate, ecosystems, and food systems.** Without guardrails and accurate carbon accounting, the demand for biomass in a decarbonizing economy could cause expanded use of prime cropland and forestland to cultivate purpose-grown biomass crops and forest products.
- **Key takeaway 2: If the United States pursues economy-wide action to meet 2050 climate targets, biomass is best utilized for carbon removal and replacing petrochemicals.** It plays a less valuable role as an energy source. Because biomass is a limited resource, it should be used strategically to provide the greatest climate benefit.
- **Key takeaway 3: Crop-based biofuels are not an effective tool for achieving economy-wide decarbonization.** When land use change emissions are accounted for, modeled decarbonization pathways do not rely on first-generation fuels made from food crops in the energy system in 2050.
- **Key takeaway 4: Dependence on biomass—and, accordingly, land use pressure—can be reduced by accelerating electrification across economic sectors and increasing energy efficiency.**

For the United States to reach net zero emissions, all decarbonization scenarios show that deep reductions in fossil fuel use are necessary. Significantly increasing solar and wind capacity is also critical to replace fossil energy and power new pathways necessary for decarbonization, such as renewable hydrogen and direct air capture (DAC). Residual emissions will need to be counterbalanced by carbon removal from the land carbon sink, geologic carbon sequestration, and biomass carbon sequestration (see Figure 1). Results from this analysis suggest that, when used responsibly, biomass could play a limited but important role in reaching net zero emissions in the United States.

The analysis finds that, although biomass has a variety of potential uses in a net zero economy, demand could exceed sustainable supply, and appropriate guardrails will be needed to guide climate-friendly biomass use. Results also indicate that no one sector will be able to rely entirely on biomass for decarbonization because its use is distributed across industries. Biomass provides the highest decarbonization value when used to substitute materials that have limited nonfossil alternatives or to provide carbon removal (Figure 2). First-generation biofuels are not an effective use of biomass to address climate change. See Table 3 and Figure 2 for detail on biomass end uses.

Figure 1 | **US Economy-wide emissions reductions trajectories in 'Current Policies' and 'Adjusted *R2R*' scenarios**



Notes: f-gases = fluorinated greenhouse gases; $GTCO_2e$ = gigatons of carbon dioxide equivalent. Negative emissions from bunker fuels are a result of the model removing double-counted emissions that occur in international waters. Emissions from fuels used for international transport (i.e., shipping fuels) are initially counted by the model because they are produced by US craft, but per Intergovernmental Panel on Climate Change guidance, emissions from these fuels should not be counted in national inventories and reported separately instead. As such, the "bunkers" category does not represent carbon removal; rather, it represents emissions that have been counted and then zeroed out. Negative emissions from products represent embodied emissions in products, the majority of which is ethylene that is used in products like plastics.

Source: WRI authors.

Table 3 | **Biomass end uses in 2050 in primary scenarios in exajoules (EJ)**

	CURRENT POLICY 2050	ADJUSTED *R2R* 2050	*BILLION-TON* 2050
End use (EJ)			
Direct biomass sequestration	0	1.64	2.82
Bulk chemicals	0.51	1.03	2.84
Asphalt	0.04	0.89	1.32
Paper and allied products	1.1	0.84	0.84
Building heating	0.43	0.55	0.64
Road transport[a]	0.19	0.50	0.88
Cement and lime	0.39	0.42	0.44
Other industry	0.32	0.32	0.39
Other transport[b]	0.13	0.16	0.43
Other building use (pipeline gas)	0.11	0.08	0.14
Aviation	0.29	0.05	0.86
Electricity	0.06	0.04	0.05
TOTAL (EJ from biomass)	**3.57**	**6.52**	**11.65**

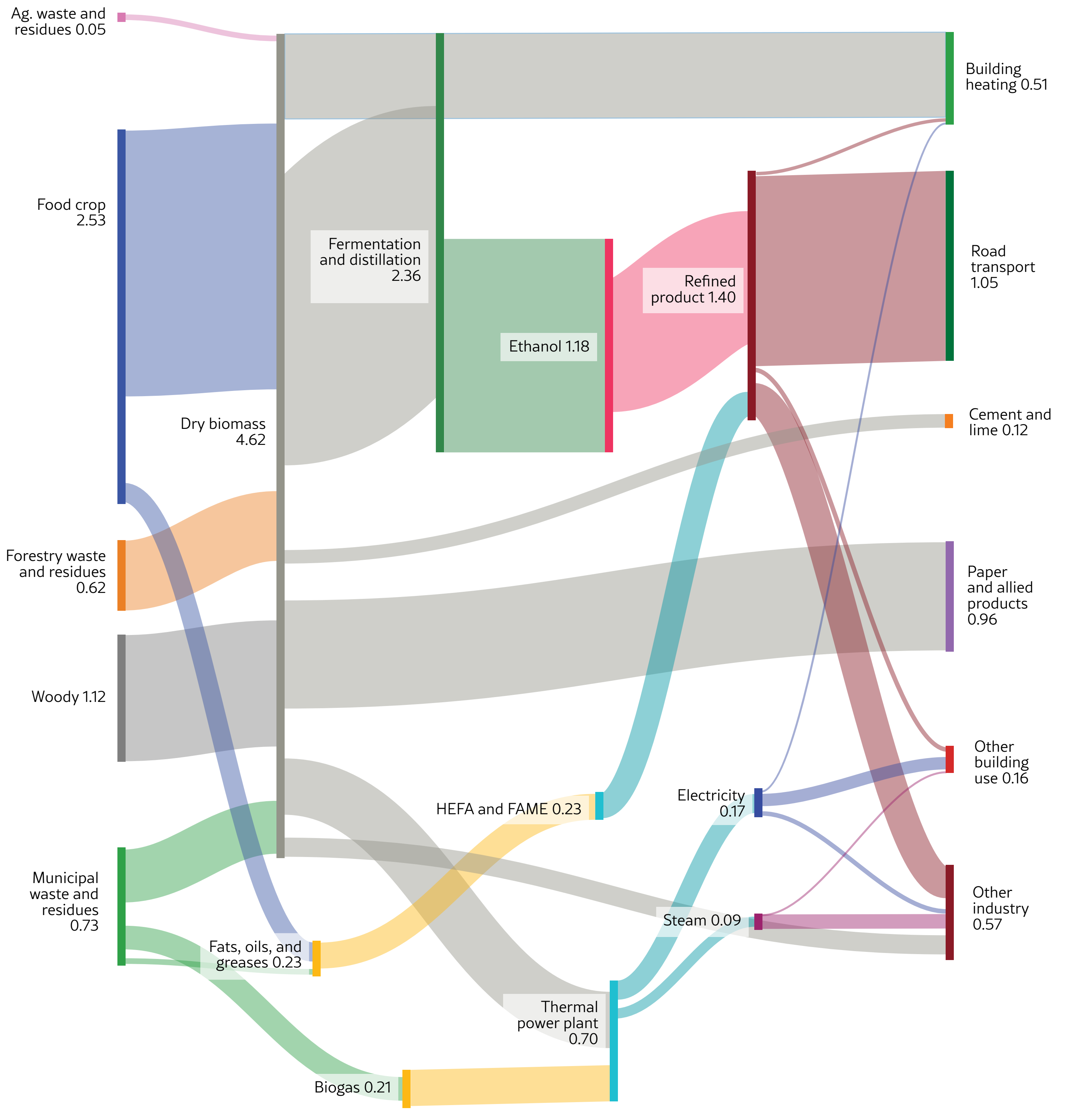
Notes: All model results, even end uses that are not energy uses, are reported in exajoules (EJ) for the sake of comparability.

a. While our model results show a phasing out of biofuels such as corn ethanol, it finds a continued but smaller role for biomass-based road fuels. These are produced using different feedstocks and processes than first-generation biofuels.

b. Other transportation consists of domestic shipping, freight rail, international shipping, military use, passenger rail, and recreational boats.

Source: WRI authors.

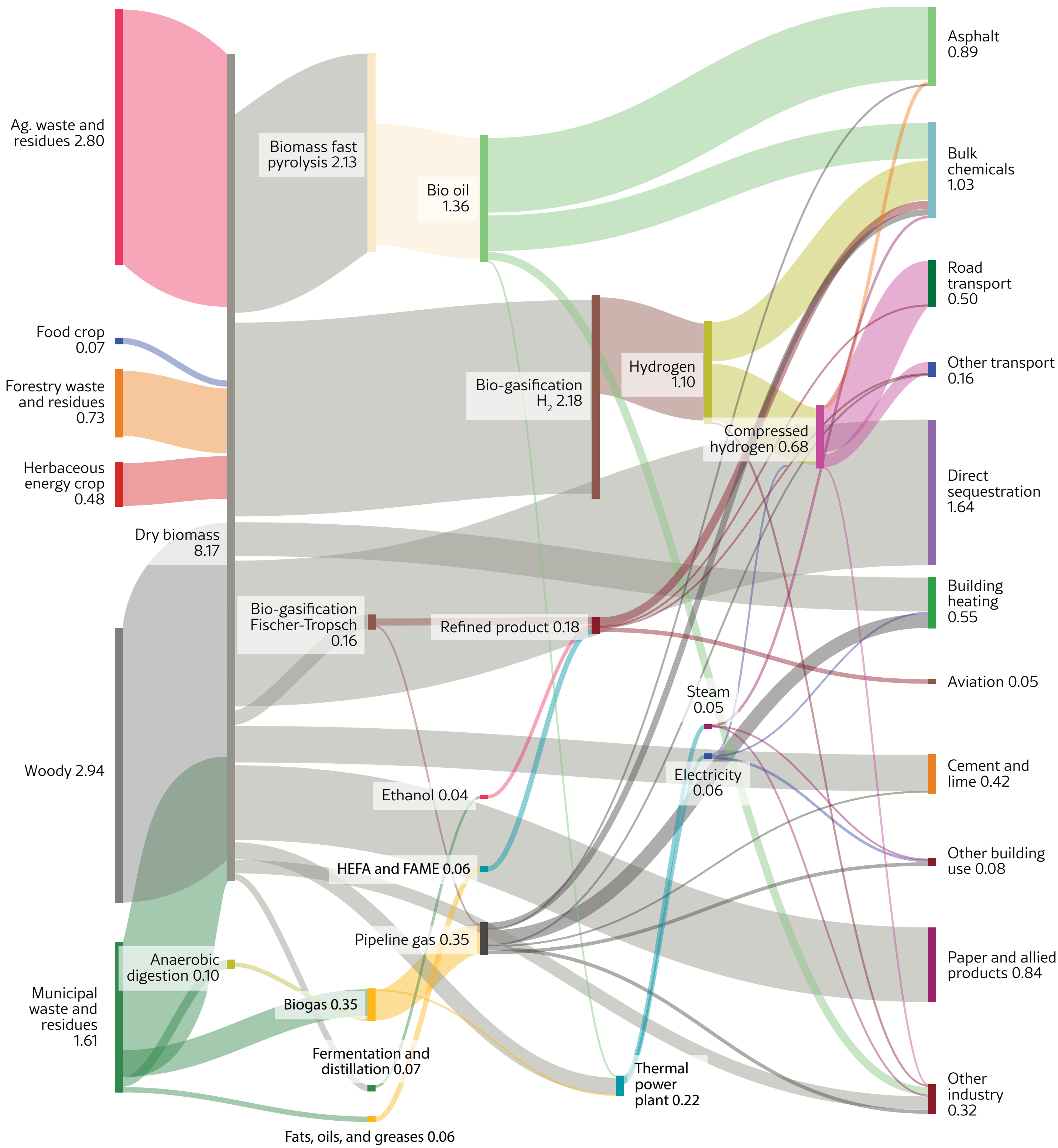
Figure 2a | **Sankey diagram of present day biomass use**



Note: All values are represented in exajoules (EJ).

Source: WRI authors.

Figure 2b | **Sankey diagram of biomass use in 2050 in 'Adjusted *R2R*' scenario**



Note: All values are represented in exajoules (EJ).

Source: WRI authors.

Key takeaway 1: Adequate guardrails and accurate carbon accounting are necessary to prevent biomass use from negatively impacting climate, ecosystems, and food systems

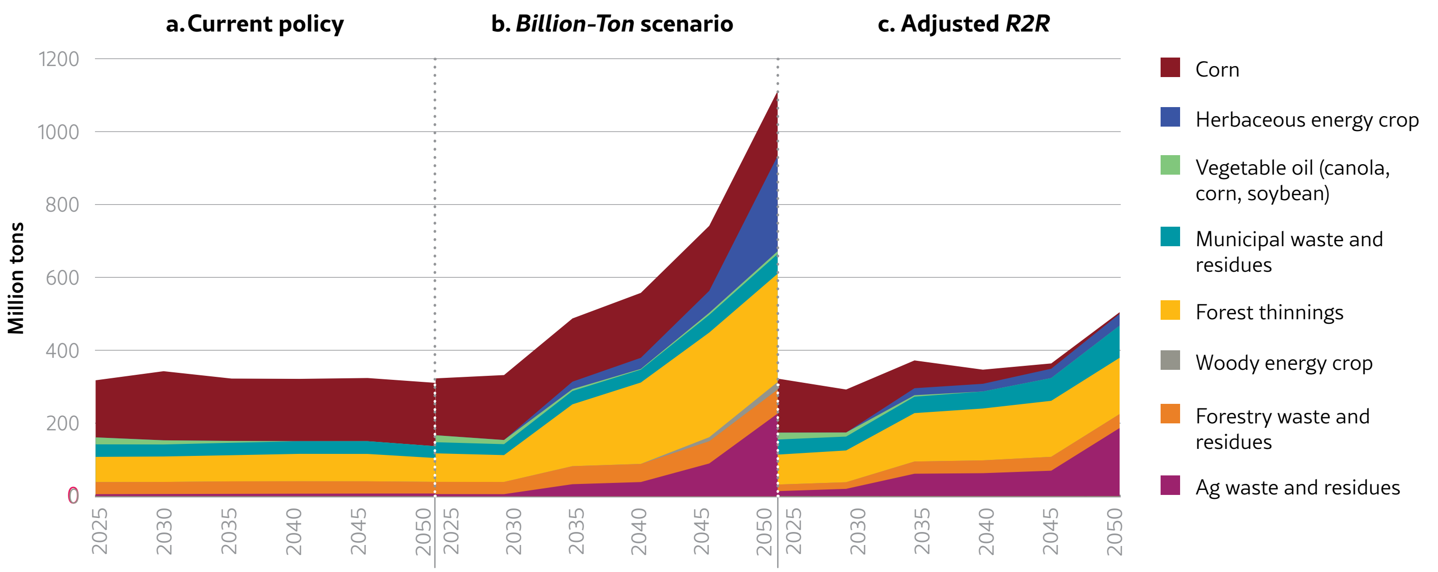
While many communities in the United States are grappling with important questions about wind and solar energy siting, less attention is paid to guardrails around biomass and land use. Purpose-grown biomass crops, however, currently consume far more land than wind and solar energy and will continue to do so if guardrails are not in place.

In all modeled scenarios, biomass land use would exceed land directly devoted to wind and solar (Appendix D). In the *Billion-Ton* scenario, over five times more direct land use is devoted to biomass crops than to wind and solar energy (Figure 2). Even when the total land area devoted to renewable energy is considered by including the space between wind turbines and nondeveloped land in a solar PV plant, biomass land use in the *Billion-Ton* scenario exceeds total land use devoted to wind and solar.

This paper finds that policy guardrails affect both how much and how biomass is utilized toward reaching modeled net zero emissions (Table 4). In the *Billion-Ton* scenario, 1,112 million tons of biomass were used in 2050 (Figure 3, panel b). With more stringent sustainability restrictions in the adjusted *R2R* scenario, biomass usage decreases to 504 million tons in 2050 (Table 3, panel c), although this is still twice the amount of biomass used in 2020. As will be discussed in Key takeaway 2, scenarios with more restricted biomass availability see higher shares of biomass used for sequestration and chemical feedstocks.

The difference in biomass use in these scenarios is largely explained by a difference in reliance on purpose-grown crops. With an adjusted *R2R* supply, switchgrass on CRP land accounts for 32 million tons of overall biomass use. In the *Billion-Ton* scenario, use of woody and herbaceous crops increases to 282 million tons, not including corn and soy crops.

Figure 3 | **Biomass use by feedstock category for primary scenarios from 2025 to 2050**



Source: WRI authors.

Table 4 | **Biomass use by feedstock category in 2050 in primary scenarios**

	CURRENT POLICY 2050	ADJUSTED *R2R* 2050	*BILLION-TON* 2050
Biomass use by feedstock (million tons)			
Agricultural wastes and residues	7	187	227
Forestry wastes and residues	32	38	66
Woody energy crop	0	0	21
Forest thinnings	65	155	297
Municipal wastes and residues	32	88	54
Vegetable oil (canola, corn, soybean)	0	0	8
Herbaceous energy crop	0	32	261
Corn	174	5	178
Totals	**311**	**504**	**1,112**

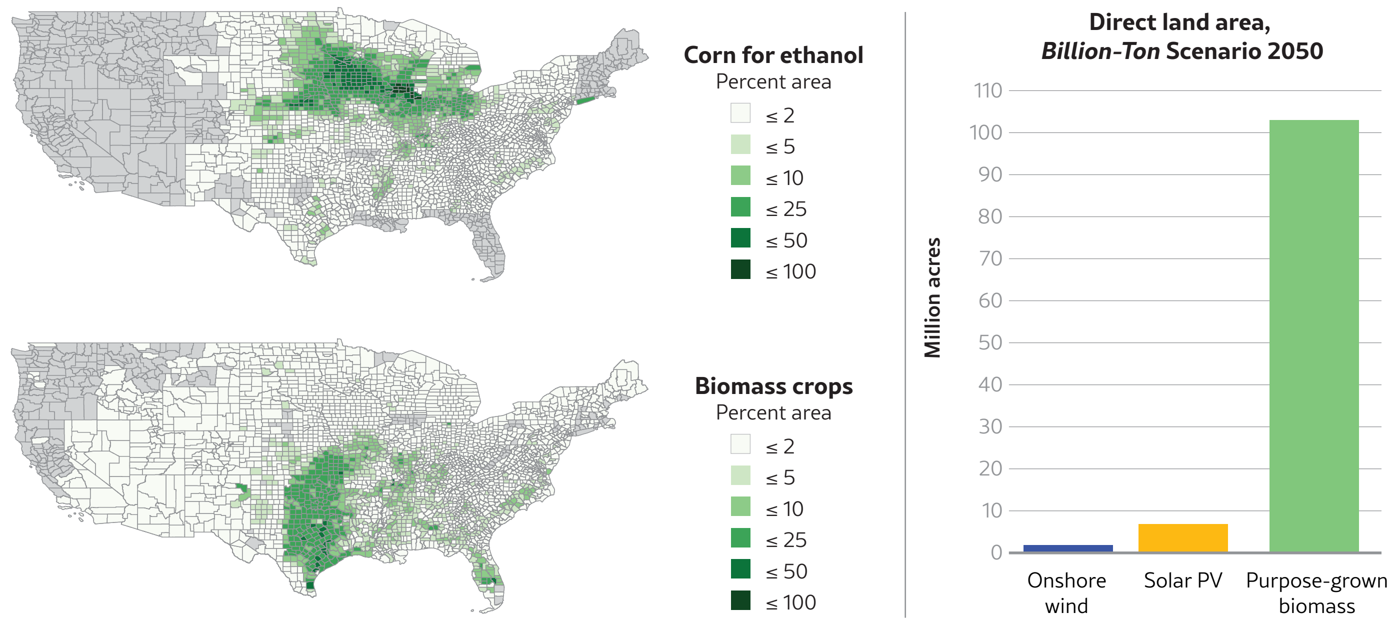
Note: Model results are reported in exajoules; conversion to tons is done using conversion factors. As such, estimates of tons used in 2050 are not precise modeled findings.
Source: WRI authors.

Policy and implementation

Because of its outsized land footprint, biomass use poses a greater threat to land use, food production, and ecosystem health than wind and solar energy (Figure 4). Policy guardrails to constrain the impact of biomass use could include explicit restrictions on the types and quantities of certain feedstocks, such as banning or capping the use of crops to make biofuels.

Guardrails could also include rigorous requirements for projects to conduct life cycle assessments (LCAs); assessment of alternative uses of biomass for greater climate benefit; and monitoring, reporting, and verification (MRV) of climate impact. No one approach alone is sufficient to avoid unintended negative consequences that would undermine decarbonization and other environmental goals.

Figure 4 | **Land devoted to biomass production in 2050 in *Billion-Ton* scenario**



Note: Without biomass guardrails, the land impact of biomass use is many times larger than that of wind and solar energy.
Source: WRI authors.

Biomass-related LCA and MRV methods are not standardized, and the best methods to use for some key calculations, such as indirect land use change, are not widely agreed upon. Lack of oversight and standard protocols could allow a project or technology to claim climate benefits based on faulty or selective accounting (Lebling et al. 2024).

In addition to land use, guardrails can also improve the public health impacts of biomass use. Biomass uses that divert wastes and residues that were previously burned in open piles could prevent particulate emissions from smoke. A reorientation toward more environmentally sound and sustainable biomass feedstocks could prevent further deterioration of air and water resources that negatively impact community health.

Key takeaway 2: If the United States pursues economy-wide action to meet 2050 climate targets, biomass is best utilized for carbon removal and replacing petrochemicals

While this analysis finds that biomass can be used in a variety of products and processes, there are several synthesis technologies and end uses that are particularly valuable. When the land emissions and ecological impacts of biomass feedstocks are more fully accounted for in the adjusted *R2R* scenario, the use of biomass in most end uses scales down according to the reduced availability relative to the *Billion-Ton* scenario. Certain end-use technologies, however, increase when biomass supply is limited. In particular, fast pyrolysis with carbon capture, which is used for bulk chemical production, increases as an end use as biomass is limited (see Figure 5). Similarly, direct biomass sequestration becomes a larger portion of total biomass use as total biomass is restricted. For simplicity, durable products that effectively store carbon over long time horizons are included in this end-use category.

Carbon contained in biomass is valuable because it can replace petrochemicals

Fast pyrolysis uses biomass to make synthetic substitutes for fossil fuel–based products, such as asphalt or plastics. These products are high-value uses of biomass because they have limited nonfossil replacements. In an economy with decreased reliance on fossil fuels, biomass is an important source of carbon molecules needed to create nonfossil replacements for petrochemicals (Sparks 2024). Other products, like many liquid transportation fuels, can be replaced by electrification of transportation or hydrogen- or ammonia-based fuels.

Biomass is likely more valuable for direct carbon sequestration than for primary energy production in a decarbonized economy

Given policies that establish a value for both reducing carbon emissions and implementing carbon removal, using biomass for carbon sequestration is more valuable as a climate mitigation pathway than using biomass to produce primary energy. While some biomass is used to produce secondary energy products such as hydrogen or next-generation fuels, the results of this analysis show that direct carbon sequestration becomes an increasingly important part of the biomass portfolio when biomass supplies are limited by guardrails (see Figure 5).

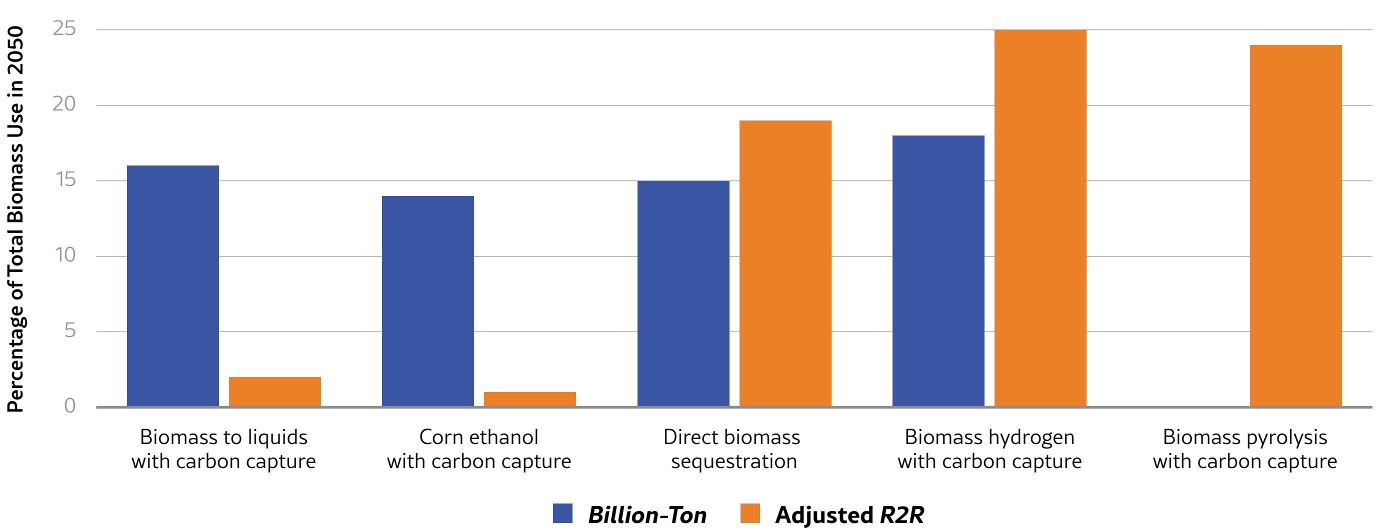
In the adjusted *R2R* scenario, biomass sequestration increases in prominence as an end use, indicating the relative decarbonization value of this biomass use: in the *Billion-Ton* scenario, biomass sequestration accounts for 15 percent of total biomass use, whereas in the adjusted *R2R* scenario, biomass sequestration accounts for 19 percent of biomass use (see Figure 5).

In this analysis, direct biomass sequestration includes technologies that prevent the carbon in biomass from being released into the atmosphere with minimal chemical or heat alteration of the biomass (Sandalow et al. 2021). This includes approaches like permanent biomass burial, or "wood vaulting" (see Appendix E). This could also include the use of biomass in long-lived wood products or other innovative products, but these end uses are not explicitly modeled. Only woody biomass feedstocks were allowed for biomass sequestration to reduce the risk of food crops being used for carbon removal.

The results of the analysis indicate that, in some cases, the most cost-effective way to use biomass for climate mitigation is carbon sequestration rather than energy production with carbon removal as a coproduct. Building and operating new gasification facilities or scaling other carbon removal pathways is, in many cases, far more costly and slower to scale than vaulting biomass or using it in a durable product. Biomass also can often be buried near its source, reducing transportation costs. See Figure 6 for a comparison of the modeled cost between biomass sequestration and biomass hydrogen with carbon capture.

Biomass burial may prevent some of the loss of forest carbon stock from harvests and wildfires. However, care must be taken to ensure such actions do not do more ecological harm than good (risks are outlined more below in "Policy and implementation").

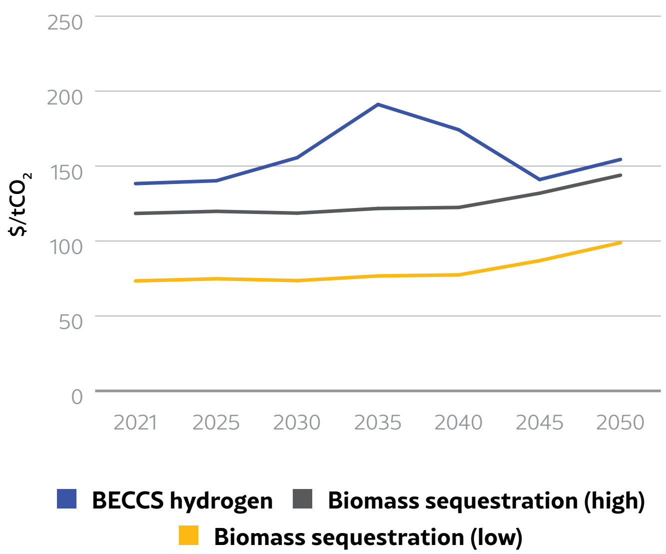
Figure 5 | **Comparing the use of certain biomass technologies in the *Billion-Ton* and adjusted *R2R* scenarios**



Note: From the less restricted *Billion-Ton* supply to the more restricted adjusted *R2R* supply, the proportion of biomass used for liquid fuel and corn ethanol use decreases and the proportion of biomass used for direct sequestration, hydrogen with carbon capture, and pyrolysis with carbon capture increases.

Source: WRI authors.

Figure 6 | **Comparison of carbon removal costs from biomass hydrogen energy with carbon capture and storage versus biomass sequestration in the *Billion-Ton* scenario**



Notes: BECCS hydrogen = biomass hydrogen energy with carbon capture and storage. "High" cost and "low" cost reflect a range of possible costs, from US$99 to $144 per ton of carbon dioxide in 2050, for biomass sequestration. Increasing the marginal cost for biomass is responsible for the gradual upward trend at the end of the time period. The marginal value of hydrogen, which is increased by the 45V tax credit until 2035, is responsible for the inverted V shape for BECCS.

Source: WRI authors.

Policy and implementation

Results from the scenario analysis indicate that although biomass sequestration is a prominent end use in all scenarios, certain policy variables lessen the need for direct biomass sequestration or provide alternatives. For example, when the price of DAC is lowered by 50 percent, as in our "DAC breakthrough" sensitivity scenario, the use of biomass for sequestration is reduced, indicating greater substitutability between types of carbon removal if DAC prices are competitive. In our "no biomass sequestration" sensitivity scenario, which does not allow biomass burial, results show increased investment to maximize the land carbon sink and increased geologic storage of carbon dioxide, which also suggests that carbon removal needs can be met by other means, but at a higher cost.

Although direct biomass sequestration may be an efficient use of biomass for climate mitigation, it entails its own set of risks. Biomass burial could offer relatively low-cost carbon removal, and if demand for carbon removal were high and environmental guardrails were insufficient, this could result in the overharvesting of biomass and the risk of negative ecological impact. This could threaten the net negativity of biomass sequestration if it were to cause land use change, increase forest harvests to meet growing demand for timber, or disrupt food systems.

It is important to note that, given the projected increase in global demand for timber and the risk of conversion of ecosystems to meet this demand (Searchinger et al. 2023), one climate-friendly use of woody biomass wastes and residues may be in long-lived products that reduce the need for production of virgin wood. Given this, durable products that effectively store the carbon contained in biomass are also included in the end-use category of "direct biomass sequestration."

These risks highlight the imperative to scale a portfolio of different technologies to support climate-friendly biomass use. For biomass to be used efficiently in a net zero economy, novel technologies that convert the sustainable feedstocks into fuel or products—such as Fischer-Tropsch biogasification, biogasification to hydrogen, fast pyrolysis, and direct biomass sequestration—must all receive investment to scale many times beyond their current levels to allow biomass to be used for its most valuable product uses. Investment in carbon capture technology is also critical to allow the carbon in biomass to be sequestered as biomass is processed.

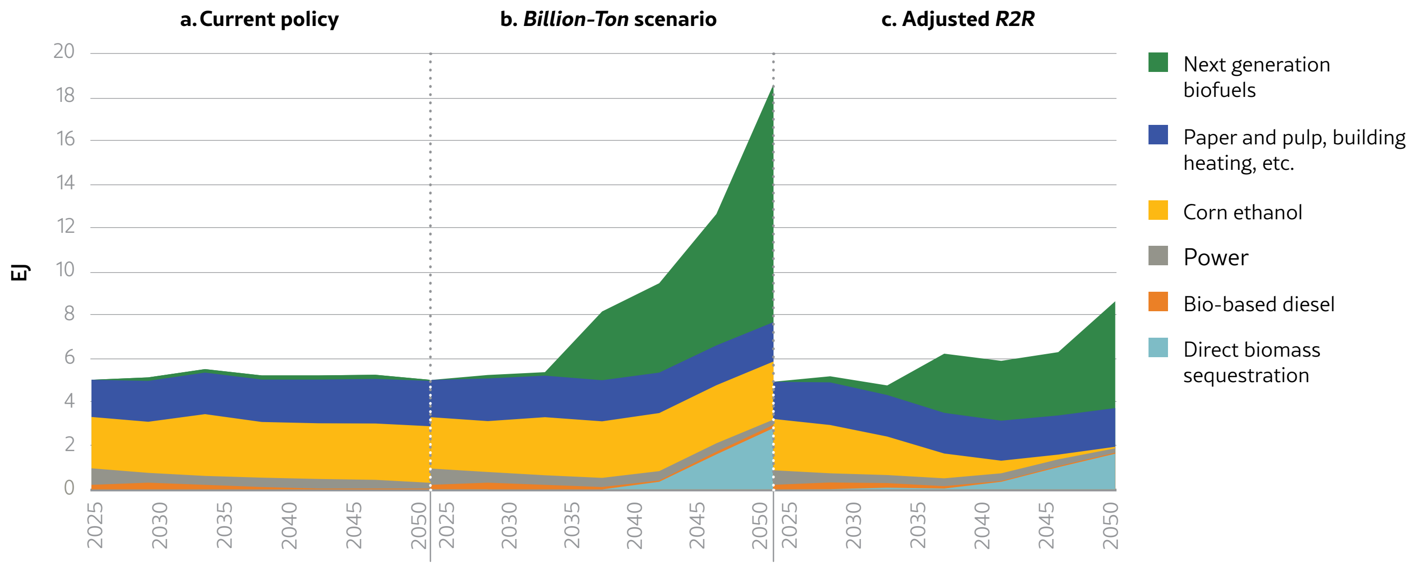
Key takeaway 3: Crop-based biofuels are not an effective tool for achieving economy-wide decarbonization

This analysis finds that the land carbon cost of first-generation biofuels outweighs any climate benefit of displacing fossil fuels. Model results show that the land carbon cost of using food crops to produce fuels is so high that these fuels decline and are phased out of use almost entirely by 2050 in a modeled net zero economy.

Corn ethanol

The current policy scenario anticipates that demand for ethanol blended in gasoline would significantly decline as electric vehicles are adopted widely. However, this decline in demand for ethanol may be matched by increasing demand for ethanol for aviation fuel (see Box 2). Therefore, under a baseline scenario without consideration of the COC, overall use of corn ethanol is projected to remain mostly steady between the present and 2050 (see Figures 7 and 8). Under this scenario, existing ethanol biorefineries are retrofitted to produce ethanol-to-jet fuel and some employ carbon capture and storage technology to reduce emissions associated with fuel production; however, facility

Figure 7 | **Biomass use by technology**



Note: In scenarios with biomass sustainability restrictions and carbon opportunity costs, the use of crop-based biofuels declines to near zero by 2050.
Source: WRI authors.

capacity is not projected to increase. Even in the *Billion-Ton* scenario, which allows potential corn production to triple and does not consider the COC emissions associated with land use, corn-based aviation fuel would only fulfill around one-third of the US goal to produce 35 billion gallons of sustainable aviation fuel (SAF) by 2050. Although tripled corn production is allowed in this *Billion-Ton* scenario, the model did not end up selecting increased cultivation for biofuels because capital costs and emissions associated with increased use of nitrogen fertilizer for corn production are prohibitively high.

In the adjusted *R2R* scenario, which accounts for the COC, the model eliminates ethanol production almost completely by 2050, including ethanol production for jet fuel (Figure 8). The analysis assessed the sensitivity of the results to different COC values; this finding holds true even if the COC were half the value used in this analysis (103 g CO_2/MJ for corn ethanol). If the COC were approximately one-sixth of the value used in the main scenarios, the use of ethanol would decline but not reach zero by 2050. This finding emphasizes the fact that the inclusion of even low levels of land use emissions in the carbon intensity of ethanol makes ethanol uncompetitive as a climate solution.

Although model results demonstrate that corn ethanol is an ineffective tool for decarbonization, US policies risk allowing the ongoing or even increased use of this technology. These policies, such as ethanol blending mandates, biofuel subsidies, or inadequate land use emissions accounting, are detrimental to US decarbonization goals.

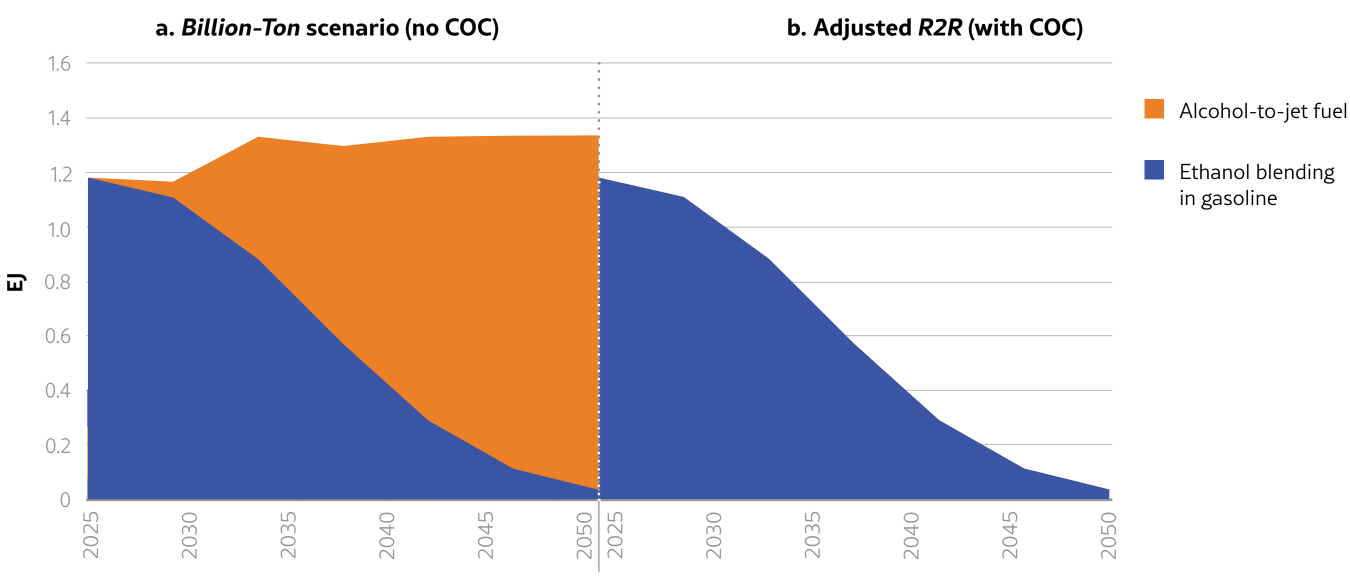
Box 2 | Aviation fuels

There is increasing interest in "sustainable" aviation fuels (SAF), which are nonfossil fuels that can either be made from biomass or from electro-fuels, a class of drop-in replacement fuels made from captured carbon and hydrogen produced using clean energy. Biomass-based aviation fuels can be sourced from wastes and residues or from corn, soy, or other purpose-grown crops. Concerningly, the *Billion-Ton* scenario, which does not account for land use emissions and has very few restrictions on biomass, shows an increase in production of aviation fuel derived from soybean hydroprocessed esters and fatty acids (HEFA) and corn ethanol by 2050. This reflects current policies that either significantly underestimate or completely fail to account for the land impact of these fuels.[a] Airlines are looking to these fuels to meet their climate targets because they are relatively inexpensive compared to electrofuels or fuels made from biomass wastes and residues. However, incomplete land carbon accounting may cause such approaches to actually increase, rather than decrease, emissions relative to using fossil fuels.[b] On the other hand, the model scenarios that account for the carbon opportunity cost of soy and corn do not show any growth in crop-based SAF production, demonstrating that this type of SAF does not help the aviation industry reach decarbonization goals.

While our scenarios show that more ethanol than HEFA would likely be diverted for use in aviation fuel, economic and political factors beyond the scope of this analysis could increase the competitiveness of the use of HEFA for aviation fuel. Using HEFA for aviation fuel would have an even greater negative land use and climate impact than ethanol: soy feedstocks have a higher carbon opportunity cost than corn feedstocks because they are much more land intensive. Furthermore, the expansion of cropland for oilseed production is a leading driver of recent deforestation in carbon-dense ecosystems. Although HEFA can be made from waste oils, most of the global supply of waste oils is already in use, and additional demand will likely be met with virgin oils.[c] Increased use of HEFA for aviation fuel poses a danger to both climate goals and global biodiversity.

Sources: a. Berry et al. 2024; b. Lark et al. 2022; Searchinger et al. 2018; c. Seber 2024.

Figure 8 | Corn ethanol use without and with COC



Notes: COC = Carbon Opportunity Cost. Without COC, ethanol is redirected to aviation fuel as ground transportation electrifies. With COC, corn ethanol decreases to virtually zero in 2050.

Source: WRI authors.

Soy bio-based diesel

Soy-based biofuels are much more land intensive than corn-based biofuels. For example, soy yields approximately 70 gallons of aviation fuel per acre, whereas corn yields approximately 330 gallons of aviation fuel per acre (Swanson and Smith 2024). Moreover, the global market for soybean oil is tightly coupled with markets for other vegetable oils, including palm oil, which has driven deforestation in tropical countries (Vijay et al. 2016). If soybean oil is diverted to fuel production in the United States, the demand for vegetable oil in food products would likely be substituted by products linked to deforestation, such as soybean oil in Brazil or palm oil in Indonesia (Santeramo and Searle 2019).

The current policy scenario projects an increase in bio-based diesel made from both hydroprocessed esters and fatty acids (HEFA) and fatty acid methyl esters (FAME) through 2035, followed by a reduction by 2050. HEFA fuel can be produced from waste fats and greases, but it is also largely produced using virgin vegetable oils, particularly soybean oil. HEFA fuel is an attractive alternative because it can replace or be directly blended with fossil diesel or jet fuel. While results show a long-term decrease in HEFA use by 2050, decarbonization scenarios see an increase in renewable diesel from HEFA in the near-term triggered by state low-carbon fuel standards that incentivize fuels made from HEFA. As with other biofuels, HEFA fuel is projected to increase most when the carbon cost of land use is not considered. Such an increase would likely trigger deforestation and land use change emissions globally.

When the COC is applied to soybean oil production, the short-term increase in HEFA is greatly reduced because the land carbon cost of biofuels made from virgin oil makes them uncompetitive.

While drop-in fuels (liquid fuels that can easily replace petroleum-based fuels) may appear to be a relatively attractive alternative to fossil fuels in the short term, this analysis finds that they are more expensive than investment in wind and solar energy in the long term. While these results suggest that HEFA fuel is uncompetitive as a decarbonization strategy in the long term, political factors outside the parameters of this analysis impact the demand for, and competitiveness of, HEFA. For example, incomplete carbon accounting or biofuel subsidies could accelerate the expansion of bio-based diesel fuels.

Policy and implementation

The federal RFS, California's LCFS, and the IRA Clean Fuel Production Tax Credit, among others, treat crop-based biofuels as beneficial to achieving US and state decarbonization targets despite previous research finding that biofuels offer no reduced emissions over fossil fuels and likely increase emissions when land use is considered (Lark et al. 2022; Searchinger et al. 2018). State low-carbon fuel standards that do not cap support for consumption of HEFA and federal aviation fuel tax credits could drive increased demand for both corn ethanol and soy bio-based diesel at the expense of food production and land carbon sequestration.

Key takeaway 4: Dependence on biomass—and, accordingly, land use pressure—can be reduced by accelerating electrification across economic sectors and increasing energy efficiency

Sensitivity scenarios show that the rate of electrification is one of the most powerful variables impacting biomass demand and land use pressure in the United States. The rate of electrification depends on a number of factors, including the rate of build-out of clean energy and adoption of electric technologies, such as heat pumps and electric vehicles. When comparing electrification rates across sensitivity scenarios, slower electrification leads to more demand for biomass to decarbonize. When slow electrification is paired with fewer guardrails, land devoted to biomass production and food crops for biofuels increases to its highest levels across all scenarios and sensitivities—over 139 million acres in 2050, approximately the size of California and New York combined (see Appendix D). This would be an area larger than the total amount of land in the United States currently dedicated to all corn and soy production for all uses.[5] This level of biomass utilization depends on purpose-grown feedstocks that use agricultural land to produce biomass for products and carbon removal. For full reporting of land use across scenarios, see Appendix D.

Land use trade-offs between biofuels, fossil fuels, and renewable energy

Generally, liquid fuel demand in a decarbonizing US economy can be met with three categories of fuels: fossil fuels counterbalanced by increased carbon removal, electrofuels generated using clean energy, or fuels derived from biomass. Heavy restriction of one of these fuel sources requires increased reliance on the others. In all but the "100 percent renewable" sensitivity scenario (see Appendix B), fossil fuels are still used at low levels in 2050, and emissions from these fuels are counterbalanced by carbon removal.

The 100 percent renewable sensitivity scenario, where fossil fuels are eliminated entirely in 2050, shows an increase in overall biomass usage in comparison to other scenarios. This scenario projects a resurgence of corn ethanol approaching 2050, despite its COC, to compensate for lost fossil fuel energy supply with drop-in fuels. While all scenarios entail a drastic reduction in fossil fuels, completely eliminating fossil fuels could increase demand for biofuels and renewables, both of which have a land use impact that could be detrimental in the absence of responsible guardrails and holistic land use policy. This trade-off underscores the importance of appropriate biomass restrictions, complete carbon accounting, and siting policies for wind and solar that protect ecosystem services (Jones et al. 2023).

Policy and implementation

The best case for meeting energy demand, reducing land use impact and reducing emissions is to invest in an ambitious build-out of renewable energy, electrification, and energy efficiency while placing guardrails to guide optimal land use for both renewable energy siting and biomass sourcing. Other innovative, land-saving strategies, such as colocating wind and solar or designing agrivoltaic systems (i.e., the dual use of land for solar and food production) could reduce the amount of land required to produce energy. At the same time, development of nascent technologies with lower land footprints, such as next-generation geothermal energy, could eventually relieve pressure on lands.

Incentivizing reduced energy demand could also support US decarbonization goals. The "low energy demand" sensitivity scenario reduces primary energy demand across all sectors. This includes, for example, a 40 percent reduction in passenger miles for aviation and a 20 percent reduction in material demand. The low energy demand sensitivity scenario results in significantly lower biomass demand (see Appendix C). This scenario, however, represents a radical break from energy consumption trends and projected future demand for aviation, yet even so, the modeled demand reduction alone does not bring the US economy to modeled net zero. While energy conservation and efficiency are important to bring decarbonization within arm's reach, these interventions alone are not sufficient. Instead, energy demand reduction must be paired with aggressive investment in net zero technologies and electrification.

General modeling considerations and limitations

Given the structure of the modeling, the amount of biomass that is utilized in each scenario is sensitive to assumptions on how much biomass will be available at any given price as well as assumptions about the future costs of currently nascent technologies. The scenarios in this study are designed to highlight how least-cost allocation changes with different assumptions, but they should not be interpreted as projections or forecasts.

This scenario analysis applies different assumptions regarding biomass availability. As noted above, the *Billion-Ton* scenario does not account for carbon leakage, and as such, even though the model is forced to reach "net zero" emissions within the United States under the scenario's carbon accounting structure, it does not represent a true net zero scenario. The adjusted *R2R* scenario incorporates assumptions intended to lower the risk of emissions leakage, such as including the COC of dedicating cropland to energy production and restricting the quantity of woody biomass to reduce the risk of overharvesting. Nonetheless, there may be carbon costs that remain unaccounted for, like the COC of residues or carbon loss from wildfire treatments, that prevent this scenario from reaching a true net zero as well. Importantly, the adjusted *R2R* scenario is not a recommendation for an optimal level of biomass use in 2050 because a full analysis of the environmental and social implications of this scenario are outside the scope of this paper.

Conclusion

Our analysis shows that biomass is a limited and valuable resource; as such, it is critical that it be used in a way that is most effective for emissions mitigation. It is vital that the value of biomass production be weighed against the many other demands placed on land in a decarbonizing society. This analysis finds that some biomass, including wastes and residues, has a role to play in decarbonizing the US economy, but accurate carbon accounting is essential, and guardrails must be placed on biomass use.

The impact of policies like the RFS and California's LCFS demonstrate the power of US policy to shape biomass use. This analysis shows that there are opportunities for US policy incentives to support biomass use that provides efficient climate mitigation benefits and to channel investment toward new and innovative biomass uses.

Policy incentives such as tax credits or low-carbon fuel standards should place a premium on the use of biomass feedstocks for end uses that are most beneficial to decarbonization and should not incentivize feedstocks like first-generation biofuels that lead to increased, not reduced, greenhouse gas emissions.

APPENDIX A: BIOMASS SOURCES AND RESTRICTIONS

For more complete information on biomass sourcing and sustainability constraints, please refer to the DOE's *BT16* and *2023 Billion-Ton Report* (BT23) and LLNL's *R2R* report (DOE 2016, 2024; Pett-Ridge et al. 2023).

Wastes and residues

Biomass wastes and residues can come from agriculture, forestry, and municipal operations. The *R2R* report's "zero cropland change" scenario (Pett-Ridge et al. 2023), which this study uses for the adjusted *R2R* scenario, applies spatial constraints so that the demand for agricultural wastes cannot trigger cropland expansion or further displacement of food production beyond the area already used for biofuels and crops. Woody feedstocks include unused residues from existing mill and forestry operations. No material from small-diameter trees nor virgin marketable wood is used in the adjusted *R2R* scenario. Restrictions on forestry residues reduce the risk of damage to sensitive ecosystems and can help maintain forest carbon stock over time. The *R2R* report's projection of woody biomass from wildfire management in western US states was also used across all scenarios. The *Billion-Ton* scenario includes 100 percent of the projected forest residues from the USFS's wildfire crisis strategy; this includes forest thinning on approximately 70 million acres of USFS lands and other federal, state, tribal, and private lands. The adjusted *R2R* scenario uses 50 percent of the projected forest residues from wildfire treatment, which matches biomass availability from treatment levels that reflect the current area of acres treated (US Forest Service 2022, 2024).[6]

Certain categories of wastes could not be clearly and consistently compared between the *BT16* and *R2R* reports, so for clarity of analysis and to avoid the possibility of double counting feedstocks, the same source was used across scenarios. This includes municipal wastes and forestry residues, for which the *R2R* projection was used across all model scenarios. For forestry biomass, the *R2R* projections were used, unmodified, for the *Billion-Ton* scenario, including currently unused mill and logging residues from existing harvests as well as small-diameter trees that may be harvested as part of precommercial thinning within sustainability and production limits from existing plantation forests. For the adjusted *R2R* scenario, precommercial thinning was excluded to eliminate any possible dedicated land use.

Municipal waste includes woody debris from construction and demolition, food waste, and other biogenic waste that is otherwise destined for the municipal landfill. This analysis does not include lipids, rubber, leather, textiles, or plastics because these categories do not contain solely biogenic materials.

Biogas from animal manure is included as a feedstock in the *Billion-Ton* supply but not in the adjusted *R2R* supply because of environmental justice concerns surrounding subsidies for concentrated agricultural feeding operations (CAFOs). Advocacy groups and agricultural economists have voiced concerns that California's LCFS has inadvertently subsidized polluting CAFOs by overestimating the climate benefit of biodigesters producing natural gas and over-crediting producers (Waterman and Armus 2024). This does not significantly affect the total amount of biomass used in the adjusted *R2R* scenario. More of the potential municipal solid waste supply is used in the adjusted *R2R* scenario as other biomass sources become more limited.

Biomass crops

Biomass crops are herbaceous plants and trees that are grown primarily for energy production and/or carbon dioxide removal and cannot otherwise be used for food production. The *BT16* and *R2R* reports both include projections of such crops, referred to as "energy crops" in *BT16* and as "carbon crops" in *R2R*.

The adjusted *R2R* scenario builds upon the *R2R* report's restrictions to protect crop prices and food production and prevent any conversion of current cropland to biomass crop production. In this scenario, biomass crops are limited to switchgrass and native grasses established through grassland restoration, and they are only allowed on CRP land to avoid risk of competition with food production. For the purposes of this analysis, it is assumed that there is no COC to grow native grasses for biomass on CRP land because these lands are purposefully retired from crop production for conservation purposes. The *R2R* report also includes a projection of biomass crops on former ethanol production land that would be "freed up" by increasing adoption of electric vehicles, but this supply is not included in this paper's analysis because it projects that ethanol will be diverted to aviation fuel, absent additional safeguards, or phased out in favor of food production if the COC of land is accounted for. This analysis does not include miscanthus due to biodiversity concerns related to introducing non-native species. Moreover, the land restrictions exclude the consideration of woody biomass crops in this scenario.

The *Billion-Ton* scenario reflects the potential future cultivation of biomass crops in a mature market that incentivizes biomass production but triggers the conversion of food croplands to biomass croplands and causes commodity prices to increase (DOE 2016). Biomass crops in this scenario include switchgrass, miscanthus, biomass sorghum, energy cane, and some fast-growing tree species (eucalyptus, willow, poplar, and pine). The *BT16* report's modeling of the supply and availability of these crops is constrained to the area of total cropland and pastureland in the United States according to the 2010–13 US Department of Agriculture (USDA) inventory. In addition, there are annual constraints on the amount of each land class (permanent pasture, cropland pasture, and cropland) that can be converted to energy crops.

Corn and soy crops

The third category of biomass in this analysis is food crops used to make first-generation biofuels, which includes corn for ethanol and soy for bio-based diesel (including both biodiesel and renewable diesel). Instead of restricting these feedstocks, as was done with wastes and biomass crops, the limitations placed on corn and soy in this analysis are in the form of the COC of dedicating land to energy production (Fehrenbach and Bürck 2022; Searchinger et al. 2018), which is an additional emissions factor applied per unit of corn and soy selected in the RIO model. This is different from the restrictions applied to wastes and biomass crops discussed above, which are restrictions on the amount and types of biomass that are available.

APPENDIX B: SENSITIVITY ANALYSIS

In addition to the primary scenarios, sensitivity scenarios were run to shed light on policy questions and test the sensitivity of model results to key variables. Most sensitivity scenarios were variations of a baseline scenario that included a high electrification rate, a partially restricted biomass supply, and the COC on corn and soy.

Sensitivity analysis baseline scenario

The sensitivity analysis baseline scenario includes the *R2R* report's restrictions on wastes and energy crops as well as a COC applied to corn- and soy-based biofuels. Woody biomass crops were not included in the sensitivity baseline scenario for the same reasoning described above in Appendix A, but some of the other feedstocks excluded from the adjusted *R2R* scenario were included in the sensitivity baseline, including 100 percent of wildfire treatment residues, precommercial thinning of small-diameter trees, and grasses on 'marginal lands.' Other biomass feedstock included are agricultural wastes, forestry residues, and municipal waste. This scenario was not highlighted in the body of the paper above, but it was used as a baseline to which sensitivity scenarios, described below, were compared.

The following sensitivity cases shed light on policy questions:

- **100 percent renewable energy:** Removes all fossil fuels, including oil, natural gas, and coal, by 2050 while still meeting the projected energy demand and reaching modeled net zero emissions. For a full description of this scenario's assumptions, see the "100% Renewables" scenario in EER's 2023 *Annual Decarbonization Perspective* (ADP) (Haley et al. 2023).
- **Lowered consumer demand for energy:** Lowers consumer demand for energy across all primary sources by increasing energy efficiency and changing consumer behavior. For a full description of how the demand reduction affects different technologies across the energy sector, see EER's ADP technical documentation (Haley et al. 2023).
- **DAC breakthrough:** Assumes a 50 percent drop in the cost of DAC by 2050.
- **Slow electrification (slow E):** In contrast with the baseline electrification rate assumptions, this sensitivity case assumes slower electrification rates across many energy technologies throughout the US economy. For a full description of assumed electrification rates, both baseline and slow, see EER's ADP technical documentation (Haley et al. 2023).

The following sensitivity cases test the sensitivity of model results to key variables:

- **Removal of land protection for wind and solar (all land):** Allows renewable siting on all suitable land in the United States to understand how social and environmental restrictions affect model results. All other scenarios employ The Nature Conservancy's *Power of Place* (TNC 2023) 70 percent impact reduction land protections when siting wind and solar.
- **No direct biomass sequestration:** Removes direct biomass sequestration as a possible end use to understand how biomass use may change if direct sequestration is not an option. All other scenarios have an end use option of direct biomass sequestration.
- ***Billion-Ton* with COC:** This scenario illuminates how sensitive model results are to the inclusion of the COC alone. Run with both fast and slow electrification, these scenarios apply the COC to corn ethanol and soybean oil biodiesel but use least-restricted biomass supply curves. Comparison of these scenarios with the *Billion-Ton* scenarios described above allow the analysis to isolate the impact of accounting for the COC on crop-based biofuels.

Like the cases above, the "all land" and "no direct biomass sequestration" cases were compared to the sensitivity baseline scenario. The "*Billion-Ton* with COC" case, however, was a variation of the *Billion-Ton* scenario.

APPENDIX C: BIOMASS USE IN 2050 ACROSS SCENARIOS

Table C-1 shows the estimates of biomass quantities, by feedstock category, utilized in 2050 in each scenario. It is important to note that these are estimates of the biomass chosen to be used by the model, not the supply amount available. In other words, these represent the output of the model scenarios rather than the input. These estimates are calculated from model results, which are presented in energy units, exajoules, and converted to tons of biomass via standard conversion factors, shown in the Table C-2. Tonnage of biomass used is not a direct output of the model, and these estimates are very sensitive to rounding and conversion. Because of these sensitivities, it should be emphasized that these are approximations and not direct, precise findings of the model.

Table C-1 | **Biomass use in 2050 across scenarios (million tons)**

	AG. WASTES AND RESIDUES	FORESTRY WASTES AND RESIDUES	WOODY ENERGY CROP	WOODY	MUNICIPAL WASTES AND RESIDUES	VEGETABLE OIL	HERBACEOUS ENERGY CROP	FOOD CROP	TOTALS
a. Primary scenarios									
Current policy	7	32	0	65	32	0	0	174	**311**
Billion-Ton	227	66	21	297	54	8	261	178	**1,112**
Adjusted *R2R*	187	38	0	155	88	0	32	5	**504**
b. Sensitivity analysis base case									
Sensitivity base case: partially restricted, COC, baseline E	184	67	0	298	62	0	166	0	**778**
c. Sensitivity cases that shed light on policy questions									
100 percent renewable energy	185	68	0	298	91	17	171	357	**1,188**
Lowered consumer demand for energy	181	67	0	298	54	0	99	0	**699**
DAC breakthrough	184	68	0	298	58	0	149	0	**756**
DAC breakthrough, slow E	186	68	0	298	74	0	169	24	**819**
Slow E, *Billion-Ton*	273	67	83	298	76	19	481	179	**1,476**
Slow E, adjusted *R2R*	185	68	0	298	84	0	173	53	**861**
Slow E, sensitivity base case	275	67	83	298	76	0	481	18	**1,299**
d. Sensitivity cases that test sensitivity of model results to key variables									
All land	183	67	0	298	58	0	159	0	**766**
No direct biomass sequestration	185	67	0	298	56	0	166	0	**772**
Billion-Ton with COC	238	67	24	298	54	0	316	0	**997**

Notes: Sensitivity analysis base case biomass availability assumptions are used in the sensitivity cases except where otherwise noted.
Source: WRI authors.

Table C-2 | **Conversion factors from gigajoule of energy to ton of biomass**

CONVERSION FACTORS	GJ/TON
Agricultural wastes and residues	15
Food crop	15
Forestry wastes and residues	19
Herbaceous energy crop	15
Municipal wastes and residues	15
Vegetable oil	15
Woody	19
Woody energy crop	19

Source: Pett-Ridge et al. 2023.

APPENDIX D: DIRECT AND TOTAL LAND USE

Table D1 | **Direct and total land area use in 2050 across scenarios**

	DIRECT AREA LAND USE (MILLION ACRES)				TOTAL AREA LAND USE[a] (MILLION ACRES)			
Scenario name[b]	**Purpose-grown biomass for energy**	**Onshore wind**	**Solar PV**	**Grand total**	**Purpose-grown biomass for energy**	**Onshore wind**	**Solar PV**	**Grand total**
Current policy	54.0	1.5	4.1	**59.6**	54.0	49.9	4.5	**108.4**
Billion-Ton	103.0	1.9	6.8	**111.8**	103.0	65.0	7.4	**175.5**
Sensitivity base case	39.1	1.9	7.0	**48.0**	39.1	64.5	7.7	**111.3**
100 percent renewable energy	134.5	1.7	16.9	**153.1**	134.5	58.0	18.6	**211.1**
Lowered consumer demand for energy	28.5	2.0	5.1	**35.6**	28.5	65.4	5.6	**99.5**
DAC breakthrough	36.3	1.9	6.9	**45.2**	36.3	65.0	7.6	**108.9**
DAC breakthrough, slow E	45.5	2.0	6.3	**53.8**	45.5	65.6	7.0	**118.1**
***Billion-Ton*, slow E**	139.1	2.0	5.3	**146.4**	139.1	65.5	5.9	**210.5**
Sensitivity base case, slow E	53.9	2.0	6.3	**62.1**	53.9	65.6	6.9	**126.4**
All land	38.2	3.6	6.2	**48.0**	38.2	120.6	6.8	**165.6**
No direct biomass sequestration	39.1	1.9	7.2	**48.2**	39.1	64.4	8.0	**111.4**
***Billion-Ton*, COC**	62.4	1.9	6.7	**71.0**	62.4	64.9	7.4	**134.6**
***Billion-Ton*, COC, slow E**	96.6	2.0	5.4	**104.0**	96.6	65.3	6.0	**167.9**

Notes: COC = carbon opportunity cost; DAC = direct air capture; E = electrification; PV = photovoltaic.
a. Total area accounts for land surrounding wind turbines and solar panels.
b. Land area calculations were not performed for the adjusted R2R scenario.
Source: WRI authors.

APPENDIX E: BIOMASS SYNTHESIS PATHWAYS

Fast pyrolysis

Fast pyrolysis breaks down biomass into bio-oil (main product) and biochar and gases (by-products) (Bridgwater and Peacocke 2000; Pett-Ridge et al. 2023; Sandalow et al. 2021). It is a process that quickly heats biomass in the absence of oxygen, causing its decomposition into vapors, aerosols, and charcoal, which are further cooled and transformed into bio-oil and by-products (Bridgwater and Peacocke 2000; Pett-Ridge et al. 2023).Bio-oil can be further processed and turned into hydrogen or transportation fuels, or it can even be blended with fossil asphalt, creating bio-asphalt (Pett-Ridge et al. 2023).

Slow pyrolysis

Slow pyrolysis breaks down biomass into biochar (main product) and bio-oil and gases (by-products) (Premchand et al. 2023). It heats biomass at a low heating rate in the absence of oxygen, causing its decomposition into vapors, tar, and char, followed by a second heating step that creates more char. Finally, the products are cooled and transformed into bio-char and by-products (Premchand et al. 2023). Biochar can be applied in bio-asphalt production (Zhou et al. 2020), carbon storage, soil conditioner, and as a source of heat and energy (Pett-Ridge et al. 2023; Roberts et al. 2010).

Carbon capture and storage

Carbon capture and storage (CCS) involves technologies used in industrial facilities to capture carbon dioxide before it enters the atmosphere (Lebling et al. 2023) and sequester it permanently underground. CCS can be used to capture carbon from ethanol, biomass hydrogen, and slow and fast pyrolysis processes. The capture approach will depend on the process being considered (Sandalow et al. 2021).

Direct biomass sequestration

Direct biomass sequestration covers different methods for storing biomass and delaying or permanently preventing the release of carbon via decomposition (Denvir and Leslie-Bole 2024). This can include using biomass in long-lived building materials or other products (Denvir and Leslie-Bole 2024; Pett-Ridge et al. 2023; Sandalow et al. 2021) and in wood burial or wood “vaulting,” which is a process in which woody biomass is processed to enhance its stability and storage potential and is then buried (Ellery 2023; Sandalow et al. 2021).

Gasification: Fisher-Tropsch

Fischer-Tropsch gasification is a thermochemical technology that converts biomass into renewable liquid fuels (Pett-Ridge et al. 2023). The process consists of first breaking down biomass into syngas (carbon monoxide, hydrogen, carbon dioxide, and methane), followed by removing impurities, and finally synthesizing it into biofuel by the Fischer-Tropsch synthesis (Hu et al. 2012; Pett-Ridge et al. 2023). This synthesis consists of creating larger hydrocarbon chains (liquid fuels) from the synthesis of carbon molecules from syngas via catalytic processes (Hu et al. 2012).

Gasification: Hydrogen

Hydrogen gasification is a thermochemical technology that converts biomass into hydrogen (Pett-Ridge et al. 2023). Biomass is broken down into syngas (carbon monoxide, hydrogen, carbon dioxide, and methane), its impurities are removed, the hydrogen concentration is increased (hydrogen purification), and, lastly, the hydrogen is separated from other gases (Meramo-Hurtado et al. 2020; Pett-Ridge et al. 2023). Hydrogen can be used as a source of heating in industry (high-heat processes), residential, and commercial buildings, as a feedstock for industrial processes, as a transportation fuel, and for electricity generation (FCHEA 2020).

HEFA and FAME

Hydroprocessed esters and fatty acids (HEFA) are fuels produced by hydroprocessing (ETIP n.d.a; Pett-Ridge et al. 2023). This method converts oils such as vegetable oils, waste oils or fat into fuel by hydrogenation (oxygen removal) at high temperatures and pressures. The resulting material is then cracked and isomerized to be turned into renewable diesel and/or biojet fuel (ETIP n.d.a; IEA 2022; Pett-Ridge et al. 2023).

Fatty acid methyl esters (FAME) are fuels made from vegetable oils and animal fat, made via transesterification. The triglycerides (oils) react with alcohol in the presence of a catalyst and form esters (fuel) and glycerol (Mumtaz et al. 2017; Yan et al. 2014). The esters are then separated from glycerol and further purified, composing the biofuel (Karatzos et al. 2014).

Both HEFA and FAME can be used as biodiesel, and HEFA specifically can be used as an aviation fuel (ETIP n.d.b; Karatzos et al. 2014).

APPENDIX F: ENERGYPATHWAYS AND RIO METHODOLOGY

The approach couples two models: EnergyPATHWAYS and RIO. EnergyPATHWAYS produces demand-side scenarios that result in fuel demand (daily) and electricity demand (hourly). RIO then optimizes supply-side energy decisions subject to emissions and clean energy constraints to meet these demands for a coherent whole-economy pathway that includes a full accounting of all potential energy system decisions.

EnergyPATHWAYS focuses on detailed and explicit accounting of energy system decisions. These decisions are made by the user and are inputs to the model as a set of potential future scenarios. In contrast, the RIO platform is an optimization that finds the set of energy system decisions that are least cost (minimizes the present-value energy system cost across all zones).

These models do not explicitly include nonenergy uses of biomass (e.g., wood for timber); consequently, the biomass resources allocated to these applications are omitted from the supply curves. However, residues and waste streams from nonenergy applications are included. Combining the biomass resources analyzed in this study with those used for other purposes would provide a comprehensive view of biomass consumption in the US economy.

EnergyPATHWAYS

EnergyPATHWAYS is used to analyze energy system transformation (2014 US Deep Decarbonization Pathways Project, Risky Business, the National Renewable Energy Laboratory [NREL] Electrification Futures Study, the Princeton Net-Zero America and Rapid Energy Policy Evaluation & Analysis Toolkit, and many others).

EnergyPATHWAYS is a bottom-up stock-rollover model of all energy-using technologies in the economy, employed to represent how energy is used today and how it may be used in the future. It performs a full accounting of all energy demands in the economy, including feedstocks, and can be used to represent both current fossil-based energy systems and transformed, low-carbon energy systems.

Inputs to determine final energy demand include the following:

- **Demand drivers:** The characteristics of the energy economy that determine how people consume energy and in what quantity over time. Examples include population, square footage of commercial building types, and vehicle miles traveled. Demand drivers are the basis for forecasting future demand for energy services.
- **Service demand:** Energy is not consumed for its own sake but to accomplish a service, such as heating homes, moving vehicles, and manufacturing goods.
- **Technology efficiency:** How efficiently technologies convert fuel or electricity into energy services; for example, how efficiently a vehicle can convert gallons of gasoline into miles traveled.
- **Technology stock:** What quantity of each type of technology is present in the population and how that stock changes over time, including constraints on how quickly the stock can change. For example, how many gasoline, diesel, and electric cars are on the road each year.

The model has high levels of regional granularity, with detailed representations of existing energy infrastructure (e.g., power plants, refineries, biorefineries, demand-side equipment stocks) and resource potential.

EnergyPATHWAYS determines sectoral energy demand for every year over the model time horizon by dividing service demand by technology efficiency, taking into account the stock composition. Service demand and technology stocks are tracked separately for each zone, and the aggregate final energy demand must be met by supply-side energy production and delivery, modeled in RIO.

EnergyPATHWAYS was used to forecast energy demand of all types, including electricity and fuels, as the stocks of energy-consuming technology in the economy change with assumptions about electrification and efficiency. The forecasted energy demands were then put into the RIO platform to solve how to supply that energy over the next 30 years.

RIO

On the supply side, least-cost investments in electricity and fuel production to meet carbon and other constraints are determined using a capacity expansion model called RIO. RIO is a linear program model that optimizes investments and operations starting with current energy system infrastructure. It incorporates final energy demand in future years, the future technology and fuel options available (including their efficiency, operating, and cost characteristics), and clean energy goals (such as renewable portfolio standard, clean energy standards, and carbon intensity). Operational and capacity expansion decisions are co-optimized across 27 US zones (see Haley et al. [2023], Figure 1, for a map of zones).

Multiple timescales are simultaneously relevant in energy system planning and operations, and the emerging importance of variable generation (wind and solar) in future power systems means that high temporal fidelity in electricity operations has increased in importance. RIO decision variables and temporal scales are shown in Figure F-1.

The most important distinction between RIO and other capacity expansion models is the inclusion of the fuels system, making it possible to co-optimize across the entire supply side of the energy system, while enforcing economy-wide emissions constraints within each zone. This is important for accurately representing the economics when electricity is used for the production of fuels; for example, when renewable overgeneration is used for the production of hydrogen.

RIO utilizes the 8,760 hourly profiles for electricity demand and generation from EnergyPATHWAYS but optimizes operations for a subset of representative days ("sample days") before mapping them back to the full year. Operations are performed over sequential hourly timesteps. Clustering of days using several dozen features or diurnal "characteristics" is used with careful attention to ensure that the sampled days represent the full range of conditions encountered in the historical weather year. The clustering process is designed to identify days that represent a diverse set of potential system conditions, including different fixed generation profiles and load shapes. The number of sample days impacts the total runtime of the model and trades off with the ability to represent a range of historical conditions. Across the zones, a total of 40 sample days was found to strike the right balance, giving both good day sampling statistics and reasonable model runtimes.

Figure F-1 | **RIO decision variables and temporal scales**

	Decision variables	Key results
Hours 24 hours x 66 sample days = 1,584 hours	• Generator dispatch • Transmission flows • Operating reserves • Curtailment • Load flexibility	• Hourly dispatch • Transmission flows • Market prices • Curtailment
Days 365 days x 1 weather year = 365 days	• Fuel energy balance and storage • Long duration electricity storage • Dual fuel generator blends	• Daily electricity balances • Daily fuel balances
Years Modeled years: 2023, 2026, 2030, 2035, 2040, 2045, 2050	• Emissions from operations • CES supply and demand • Capacity build, retirement and repower	• Total annual emissions • CES composition • Incremental build, retirement and repower • Thermal capacity factors • Annual average market prices • Marginal cost of fuel supply

Note: CES = clean energy standard.
Source: Evolved Energy Research.

APPENDIX G: DOWNSCALING METHODOLOGY

Biomass downscaling

The process of downscaling biomass requirements reported at the RIO zone level can be simplified as the proportional allocation of projected biomass demand using the potential biomass supply estimated from states and counties. The complexities of this process result from the sheer number of sources but primarily are rooted in the fact that biomass demand values are modeled based on RIO zones within the United States, which often fail to follow state and county borders. To estimate how much of each biomass feedstock each state and county should produce under each scenario, the supply and demand data need to be aligned, which requires considerable alteration. Below, the data cleaning processes are outlined for both the demand and supply data and describe how those results are combined to generate the final downscaled results.

Mapping jurisdictions to RIO zones. First, counties and states were mapped to their respective RIO zones. The resulting data include Federal Information Process System (FIPS) code, county name, state, zone, and square mileage. Counties that are split across multiple zones will appear multiple times, with different zone names and square mileages. From here, the analysis generated variables for the proportion of the county's area within the zone and the proportion of the state's area within the zone. These proportions are utilized later once the supply and demand data are joined.

Biomass feedstock demand data processing. The results of the RIO scenarios are reported as the modeled demand of biomass in tons for each feedstock, for each year, at various costs (bins), for each RIO zone. These values are then joined one to many with the mapped county data from above using the zone column to join. This operation greatly increases the size of the data to about 12 million rows. For every zone, feedstock, year, and cost combination, there is an increase of rows equivalent to how many counties exist in that zone. Although county data have successfully been connected to the demand data at this point, the values for projected tons of biomass were still representative of the entire zone.

Biomass feedstock supply data processing. The biomass supply data come from a variety of sources in order to cover all the required feedstocks across the modeled scenarios. Sources include the International Council for Clean Transport (ICCT), LLNL's R2R, and the DOE's BT16. Note that LLNL's R2R and DOE's BT16 are county-level data, but the ICCT data were only available at the state level, so those feedstocks (canola oil, soybean oil, and corn oil) can only be downscaled to the state level. The goal for the supply data processing is to calculate the proportional contribution of each state or county toward the total supply in each RIO zone. The process for preparing state- and county-level supply are similar, with some minor contextual differences. Based on the demand scenario, supply data were sourced from the three previously mentioned sources. First, values for county supply were scaled by its RIO zone overlap proportion to reflect that county's contribution relative to each zone it falls in. Next, values for total zone supply were calculated and subsequently used to calculate the proportion that each county contributes to the overall zone. The final step aligned the cost (bin) column to match the ranges for demand.

Combining supply and demand data. Supply and demand were then combined by joining, and final dry metric ton values were calculated by multiplying total zone demand by each county's proportional contribution to the zone total. At this point, results were still separated by different cost bins, so to get final demand by county or state, tons were summed across cost bins. There were some instances in which no supply was available to fulfill demand. In these instances, demand was spread evenly across all counties in the RIO zone proportional to their square mileage. There were also instances in which no supply was recorded for a subset of costs in a RIO Zone, leading to demand not being met. In these cases, the proportion that each county contributes across all known cost brackets was used as a proxy to estimate the missing ones. These edge cases do not occur with much frequency and are the final steps in ensuring that demand is sufficiently met.

Tons were converted to land area requirements using average yields for purpose-grown feedstocks using values in Wu et al. (2023, Table S14) as well as 4.155 dry tons per acre for corn and 0.270 tons/acre for soybean oil. These conversion factors are based on the following information:

Corn:

- USDA National Agricultural Statistics Service (NASS)[7] for 2023 states a national average corn production of 177.3 bushels per acre.
- Of sources surveyed, Barchart[8] had the most precise listed conversion from bushels to metric tons: 39.3679 bushels of corn per metric ton.
- The U.S. Grains Council's *2023/2024 Corn Harvest Quality Report*[9] lists the moisture content of corn as 16.3 percent, so the factor 0.837 converts to dry metric tons.
- 1 metric ton = 1.10231 US ton

Corn result: 4.155 dry tons per acre

Soybean oil:

- USDA NASS[10] for 2023 shows a national average soybean production of 50.6 bushels per acre.
- Of sources surveyed, Barchart[11] again had the most precise conversion of 36.7437 bushels of soybeans per metric ton.
- U.S. Soybean Export Council[12] listed soybeans as having 17.8 percent oil content.
- 1 metric ton = 1.10231 US ton

Soybean oil result: 0.270 tons per acre

Onshore wind and solar PV downscaling

Because RIO portfolios, which include the installed capacity of wind and solar PV, are reported at the RIO zone level (similar to US Environmental Protection Agency's Emissions & Generation Resource Integrated Database subregions), selected wind and solar capacity was downscaled to specific ~0.5 square kilometer (km^2) geographic units, what we refer to as "candidate project areas," across the contiguous United States. There are three main inputs in this analysis: (1) RIO portfolios for each scenario; (2) siting prediction score surfaces for where wind and solar are likely to be developed given where past projects have been sited; and (3) candidate project areas (CPAs) that represent suitable locations for wind and solar projects. After spatially averaging the siting prediction score within each CPA, the analysis sorted CPAs by prediction score within each resource bin for each RIO Zone, calculated the cumulative capacity, and selected the number of CPAs whose cumulative capacity would be greater or equal to the target (selected) capacity in that resource bin and RIO zone. This process was repeated for each combination of RIO scenario and year. The process for generating inputs 2 (siting prediction score surfaces) and 3 (candidate project areas) is described below.

CPAs for onshore wind and solar PV. The CPAs developed for the *Power of Place: National* study (TNC 2023) were used and improved upon. Please refer to the *Power of Place* technical slide deck and Wu et al. (2023) for details on the methodology on how CPAs were identified. As a brief overview, CPAs are approximately 0.5 km^2 units that are suitable for developing onshore wind, solar PV, or both technologies, given industry-standard technical (e.g., slope), economic (e.g., minimum wind capacity factor), social (e.g., recreational areas, protected viewsheds), and environmental (e.g., protected areas) siting constraints. Improvements made to the CPAs include removing onshore wind CPAs with relative elevation less than 8 meters below sea level, which removes potential in areas that are unlikely to be sited due to topography.

Siting prediction surfaces for onshore wind and solar PV. This analysis built upon the methods first presented in the *Power of Place: West* study (TNC 2022) and later improved in the *Power of Place: National* study (TNC 2023), which use statistical and machine learning approaches for estimating the probability (on a scale of 0–100) that any parcel of land would be suitable for development based on locations of existing wind and solar power plants and a set of predictor variables (siting criteria). Predictor variables include the following:

- Capacity factors estimated using NREL's System Advisory Model
- Slope
- Substation locations (Homeland Infrastructure Foundation-Level Data)
- Transmission line locations (Homeland Infrastructure Foundation-Level Data)
- Roads (OpenStreetMap)
- Population density (LandScan)
- Land acquisition cost (Nolte 2020)
- Environmental sensitivity (TNC 2023)
- Land use and land cover type (Landscape Fire and Resource Management Planning Tools)
- Renewable portfolio standards (N.C. Clean Energy Technology Center 2022)
- Several socioeconomic variables (poverty, minority, unemployment) from the Centers for Disease Control and Prevention's 2018 Social Vulnerability Index

Existing wind locations are from the U.S. Wind Turbine Database (Hoen et al. 2024) and existing solar PV locations are from the U.S. Large-Scale Solar Photovoltaic Database (Fujita et al. 2024). "Pseudo-absence" locations were generated for each technology by randomly sampling points within CPAs. The predictor variable datasets were then sampled at these existing and pseudo-absence locations. The dataset was then randomly split into training and test sets to assess the performance of several predictive models: logistic regression, lasso regression, MaxEnt, and random forest. Performance (receiver operating curve) was highest for random forest; thus, the random forest prediction score surface was used in subsequent downscaling (CPA selection). A manuscript detailing these updated methods is currently in preparation (Wu et al. in prep).

Abbreviations

ADP	Annual Decarbonization Perspective
BECCS	biomass hydrogen energy with carbon capture and storage
BT16	*2016 Billion-Ton Report*
BT23	*2023 Billion-Ton Report*
CAFO	concentrated agricultural feeding operation
CCS	carbon capture and storage
CES	clean energy standard
COC	carbon opportunity cost
CPA	candidate project area
CRP	Conservation Reserve Program
DAC	direct air capture
DOE	US Department of Energy
EER	Evolved Energy Research
FAME	fatty acid methyl esters
GTAP	Global Trade Analysis Project
HEFA	hydroprocessed esters and fatty acids
ICCT	International Council for Clean Transport
ILUC	indirect land use change
LCA	life cycle assessment
LLNL	Lawrence Livermore National Laboratory
MRV	monitoring, reporting, and verification
NASS	National Agricultural Statistics Service
NREL	National Renewable Energy Laboratory
PV	photovoltaic
RFS	US Renewable Fuel Standard
RIO	Regional Investment and Operations
R2R	*Roads to Removal*
SAF	sustainable aviation fuel
slow E	slow electrification
USDA	US Department of Agriculture
USFS	US Forest Service

Endnotes

1. Oregon, Washington, and New Mexico also have policies incentivizing low-carbon transportation fuels, but thus far these policies have had a smaller impact on biofuel use because they were passed more recently and these state economies are smaller.
2. The RIO model is a partial equilibrium framework with perfect foresight, meaning the whole time period is optimized at once, so decisions in the present are impacted by information about conditions in the future.
3. The inclusion of a category of biomass feedstocks in our "low biomass" scenario does not guarantee a priori that a certain source of biomass will be environmentally friendly or provide climate benefits when used in a project context. The impact of using a given feedstock will vary by region, local climate, land management practices, and by existing uses of biomass that may be displaced. It will be necessary for project developers to conduct analyses to identify likely counterfactual uses for specific biomass resources and conduct robust life cycle assessments to quantify the greenhouse gas emissions and removals associated with the harvesting and refining of all biomass, including wastes and residues.
4. While the COC is applied to biofuels here and in Searchinger et al. (2018), similar concepts have been applied in other contexts to evaluate the relative efficiency of land uses and agricultural systems (Blaustein-Rejto et al. 2023; Erb et al. 2018; Yang and Tan 2021). Note that there are many other papers that have utilized the COC concept, often called something different.
5. Current corn production in the United States is approximately 90 million acres and soy productions is approximately 86.5 million acres (USDA NASS 2024).
6. For more information on quantifying available biomass from wildfire mitigation treatments, please see Chapter 6 of the *R2R* report (Pett-Ridge et al. 2023).
7. USDA NASS, https://quickstats.nass.usda.gov/results/A9F64DAE-B8E4-3A7F-8129-40C32A3F5CEA.
8. Barchart, https://www.barchart.com/education/commodity-conversions#:~:text=1%20Tonne%20(metric%20ton)%20Equals,bushels%20of%20Wheat%20or%20Soybeans.
9. U.S. Grains Council, *2023/2024 Corn Harvest Quality Report*, https://grains.org/wp-content/uploads/2023/11/2023-24-USGC-Corn-Harvest-Report-compressed.pdf.
10. USDA NASS, https://quickstats.nass.usda.gov/results/71F34B17-013D-3B67-8D73-07449F40FBFF.
11. Barchart, https://www.barchart.com/education/commodity-conversions#:~:text=1%20Tonne%20(metric%20ton)%20Equals,22.046%20hundredweight.
12. U.S. Soybean Export Council, https://ussec.org/resources/conversion-table/.

REFERENCES

Austin, K.G., J.P.H. Jones, and C.M. Clark. 2022. "A Review of Domestic Land Use Change Attributable to U.S. Biofuel Policy." *Renewable and Sustainable Energy Reviews* 159 (May): 112181. https://doi.org/10.1016/j.rser.2022.112181.

Banerjee, T. 2020. "Impacts of Forest Thinning on Wildland Fire Behavior." *Forests* 11 (9): 918. https://doi.org/10.3390/f11090918.

Berry, S., T. Searchinger, and A. Yang. 2024. "Biofuels, Deforestation, and the GTAP Model." Tobin Center Working Paper. New Haven, CT: Yale University, Tobin Center. https://tobin.yale.edu/sites/default/files/2024-12/Biofuels%2C%20Deforestation%2C%20and%20the%20GTAP%20Model_December%202024.pdf.

Blaustein-Rejto, D., N. Soltis, and L. Blomqvist. 2023. "Carbon Opportunity Cost Increases Carbon Footprint Advantage of Grain-Finished Beef." *PLoS ONE* 18 (12): e0295035. https://doi.org/10.1371/journal.pone.0295035.

Booth, M.S. 2018. "Not Carbon Neutral: Assessing the Net Emissions Impact of Residues Burned for Bioenergy." *Environmental Research Letters* 13 (3): 035001. https://doi.org/10.1088/1748-9326/aaac88.

Bos, J. 2024. "Biofuel Blunders: Time to Fix Two Decades of EU Policies Driving Food Insecurity." Briefing Paper. Nairobi: Oxfam International. https://policy-practice.oxfam.org/resources/biofuel-blunders-time-to-fix-two-decades-of-eu-policies-driving-food-insecurity-621622/.

Brack, D., R. Birdsey, and W. Walker. 2021. "Greenhouse Gas Emissions from Burning US-Sourced Woody Biomass in the EU and UK." Environment and Society Programme Research Paper. London: Chatham House. https://www.chathamhouse.org/2021/10/greenhouse-gas-emissions-burning-us-sourced-woody-biomass-eu-and-uk.

Bradley, C.M., C.T. Hanson, and D.A. DellaSala. 2016. "Does Increased Forest Protection Correspond to Higher Fire Severity in Frequent-Fire Forests of the Western United States?" *Ecosphere* 7 (10): e01492. https://doi.org/10.1002/ecs2.1492.

Bridgwater, A.V., and G.V.C. Peacocke. 2000. "Fast Pyrolysis Processes for Biomass." *Renewable and Sustainable Energy Reviews* 4 (1): 1–73. https://doi.org/10.1016/S1364-0321(99)00007-6.

Camia, A., J. Giuntoli, R. Jonsson, N. Robert, N.E. Cazzaniga, G. Jasinevičius, V. Avitabile, G. Grassi, J.I. Barredo, and S. Mubareka. 2021. *The Use of Woody Biomass for Energy Production in the EU*. Report EUR 30548 EN. Luxembourg: European Commission, Joint Research Centre. https://doi.org/10.2760/831621.

CARB (California Air Resources Board). 2020. "Low Carbon Fuel Standard." Unofficial electronic version. Sacramento: CARB. https://ww2.arb.ca.gov/sites/default/files/2020-07/2020_lcfs_fro_oal-approved_unofficial_06302020.pdf.

Chen, L., D. Debnath, J. Zhong, K. Ferin, A. VanLoocke, and M. Khanna. 2021. "The Economic and Environmental Costs and Benefits of the Renewable Fuel Standard." *Environmental Research Letters* 16 (3): 034021. https://doi.org/10.1088/1748-9326/abd7af.

Daioglou, V., G. Woltjer, B. Strengers, B. Elbersen, G. Barberena Ibañez, D. Sánchez Gonzalez, J.G. Barno, and D.P. van Vuuren. 2020. "Progress and Barriers in Understanding and Preventing Indirect Land-Use Change." *Biofuels, Bioproducts and Biorefining* 14 (5): 924–34. https://doi.org/10.1002/bbb.2124.

Davis, K.T., J. Peeler, J. Fargione, R.D. Haugo, K.L. Metlen, M.D. Robles, and T. Woolley. 2024. "Tamm Review: A Meta-analysis of Thinning, Prescribed Fire, and Wildfire Effects on Subsequent Wildfire Severity in Conifer Dominated Forests of the Western US." *Forest Ecology and Management* 561 (June): 121885. https://doi.org/10.1016/j.foreco.2024.121885.

Denvir, A., and H. Leslie-Bole. 2024. "Biomass Can Fight Climate Change, but Only If You Do It Right." *Insights* (blog), January 16. https://www.wri.org/insights/sustainable-biomass-carbon-removal.

DOE (US Department of Energy). 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. M.H. Langholtz, B.J. Stokes, and L.M. Eaton, leads. Report ORNL/TM-2016/160. Oak Ridge, TN: Oak Ridge National Laboratory. https://www.energy.gov/eere/bioenergy/articles/2016-billion-ton-report-advancing-domestic-resources-thriving-bioeconomy.

DOE. 2024. *2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources*. M.H. Langholtz, lead. Report ORNL/SPR-2024/3103. Oak Ridge, TN: Oak Ridge National Laboratory. https://doi.org/10.23720/BT2023/2316165.

EIA (US Energy Information Administration). 2022. "State Energy Data System (SEDS): 1960–2022 (Complete)." https://www.eia.gov/state/seds/seds-data-complete.php?sid=US.

EIA. 2024. "Biofuels Explained." February 28. https://www.eia.gov/energyexplained/biofuels/.

Ellery, M. 2023. "To More Effectively Sequester Biomass and Carbon, Just Add Salt." Berkeley News, April 11. https://news.berkeley.edu/2023/04/11/to-more-effectively-sequester-biomass-and-carbon-just-add-salt/.

EPA (US Environmental Protection Agency). 2010. “Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program.” 40 CFR Part 80. *Federal Register* 75 (58): 14670–904. https://www.govinfo.gov/content/pkg/FR-2010-03-26/pdf/2010-3851.pdf.

Erb, K.-H., T. Kastner, C. Plutzar, A.L.S. Bais, N. Carvalhais, T. Fetzel, S. Gingrich, et al. 2018. “Unexpectedly Large Impact of Forest Management and Grazing on Global Vegetation Biomass.” *Nature* 553 (7686): 73–76. https://doi.org/10.1038/nature25138.

ETIP (European Technology and Innovation Platform). n.d.a. “Biodiesel (FAME) Production and Use in Europe.” https://old.etipbioenergy.eu/value-chains/products-end-use/products/fame-biodiesel. Accessed July 17, 2024.

ETIP. n.d.b. “HVO/HEFA.” https://old.etipbioenergy.eu/value-chains/products-end-use/products/hvo-hefa. Accessed July 17, 2024.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. “Land Clearing and the Biofuel Carbon Debt.” *Science* 319 (5867): 1235–38. https://doi.org/10.1126/science.1152747.

FCHEA (Fuel Cell and Hydrogen Energy Association). 2020. *US Hydrogen Road Map: Reducing Emissions and Driving Growth across the Nation*. Washington, DC: FCHEA. https://www.fchea.org/us-hydrogen-study.

Fehrenbach, H., and S. Bürck. 2022. “Carbon Opportunity Costs of Biofuels in Germany: An Extended Perspective on the Greenhouse Gas Balance Including Foregone Carbon Storage.” *Frontiers in Climate 4* (October). https://doi.org/10.3389/fclim.2022.941386.

Fujita, K.S., Z.H. Ancona, L.A. Kramer, M. Straka, T.E. Gautreau, C.P. Garrity, D. Robson, J.E. Diffendorfer, and B. Hoen. 2024. “United States Large-Scale Solar Photovoltaic Database.” U.S. Geological Survey and Lawrence Berkeley National Laboratory data release, Version 2.0, August. https://doi.org/10.5066/P9IA3TUS.

Glauber, J., and C. Hebebrand. 2023. “Food versus Fuel v2.0: Biofuel Policies and the Current Food Crisis.” *IFPRI Blog*, April 11. https://www.ifpri.org/blog/food-versus-fuel-v20-biofuel-policies-and-current-food-crisis/.

Gonzalez, C.G. 2018. “An Environmental Justice Critique of Biofuels.” In *Energy Justice*, edited by R. Salter, C.G. Gonzalez, and E.A. Kronk Warner. Cheltenham, UK: Edward Elgar. https://doi.org/10.4337/978 1786431769.00010.

Haley, B., R.A. Jones, J.H. Williams, G. Kwok, J. Farbes, D. Bentz, G. Schivley, and J. Jenkins. 2023. *Annual Decarbonization Perspective: Carbon Neutral Pathways for the United States 2023*. San Francisco: Evolved Energy Research. https://www.evolved.energy/us-adp-2024.

Hoen, B.D., J.E. Diffendorfer, J.T Rand, L.A. Kramer, C.P. Garrity, and H.E. Hunt. 2024. “United States Wind Turbine Database.” U.S. Geological Survey, American Clean Power Association, and Lawrence Berkeley National Laboratory data release, Version 8.0, February 25. https://doi.org/10.5066/F7TX3DN0.

Hu, J., F. Yu, and Y. Lu. 2012. “Application of Fischer–Tropsch Synthesis in Biomass to Liquid Conversion.” *Catalysts* 2 (2): 303–26. https://doi.org/10.3390/catal2020303.

IEA (International Energy Agency). 2022. *World Energy Outlook 2022*. Paris: IEA. https://www.iea.org/reports/world-energy-outlook-2022.

Karatzos, S., J.D. McMillan, and J.N. Saddler. 2014. *The Potential and Challenges of Drop-in Biofuels*. IEA Bioenergy Task 39. Paris: IEA Bioenergy, International Energy Agency. https://task39.sites.olt.ubc.ca/files/2014/01/Task-39-Drop-in-Biofuels-Report-FINAL-2-Oct-2014-ecopy.pdf.

Lark, T.J., N.P. Hendricks, A. Smith, N. Pates, S.A. Spawn-Lee, M. Bougie, E.G. Booth, C.J. Kucharik, and H.K. Gibbs. 2022. “Environmental Outcomes of the US Renewable Fuel Standard.” *Proceedings of the National Academy of Sciences of the United States of America* 119 (9): e2101084119. https://doi.org/10.1073/pnas.2101084119.

Lebling, K., D. Riedl, and H. Leslie-Bole. 2024. “Measurement, Reporting, and Verification for Novel Carbon Dioxide Removal in US Federal Policy.” Working Paper. Washington, DC: World Resources Institute. https://www.wri.org/research/measurement-reporting-and-verification-novel-carbon-dioxide-removal.

Liska, A.J., H. Yang, M. Milner, S. Goddard, H. Blanco-Canqui, M.P. Pelton, X.X. Fang, H. Zhu, and A.E. Suyker. 2014. “Biofuels from Crop Residue Can Reduce Soil Carbon and Increase CO_2 Emissions.” *Nature Climate Change* 4 (5): 398–401. https://doi.org/10.1038/nclimate2187.

Malcolm, J.R., B. Holtsmark, and P.W. Piascik. 2020. “Forest Harvesting and the Carbon Debt in Boreal East-Central Canada.” *Climatic Change* 161 (3): 433–49. https://doi.org/10.1007/s10584-020-02711-8.

Malins, C., R. Plevin, and R. Edwards. 2020. “How Robust Are Reductions in Modeled Estimates from GTAP-BIO of the Indirect Land Use Change Induced by Conventional Biofuels?” *Journal of Cleaner Production* 258 (June): 120716. https://doi.org/10.1016/j.jclepro.2020.120716.

Martin, J. 2024. “A Cap on Vegetable Oil-Based Fuels Will Stabilize and Strengthen California’s Low Carbon Fuel Standard.” *The Equation* (blog), January 30. https://blog.ucsusa.org/jeremy-martin/a-cap-on-vegetable-oil-based-fuels-will-stabilize-and-strengthen-californias-low-carbon-fuel-standard/.

Meramo-Hurtado, S.I., P. Puello, and A. Cabarcas. 2020. "Process Analysis of Hydrogen Production via Biomass Gasification under Computer-Aided Safety and Environmental Assessments." *ACS Omega* 5 (31): 19667–81. https://doi.org/10.1021/acsomega.0c02344.

Mumtaz, M.W., A. Adnan, H. Mukhtar, U. Rashid, and M. Danish. 2017. "Biodiesel Production through Chemical and Biochemical Transesterification: Trends, Technicalities, and Future Perspectives." In *Clean Energy for Sustainable Development: Comparisons and Contrasts of New Approaches*, edited by M.G. Rasul, A.K. Azad, and S.C. Sharma, 465–85. Cambridge, MA: Academic. https://doi.org/10.1016/B978-0-12-805423-9.00015-6.

N.C. Clean Energy Technology Center. 2022. "Database of State Incentives for Renewables & Efficiency." https://www.dsireusa.org/.

Nolte, C. 2020. "High-Resolution Land Value Maps Reveal Underestimation of Conservation Costs in the United States." *Proceedings of the National Academy of Sciences of the United States of America*, 117 (47): 29577–83. https://doi.org/10.1073/pnas.2012865117.

O'Brien, P.L., T.J. Sauer, S. Archontoulis, D.L. Karlen, and D. Laird. 2020. "Corn Stover Harvest Reduces Soil CO_2 Fluxes but Increases Overall C Losses." *GCB Bioenergy* 12 (11): 894–909. https://doi.org/10.1111/gcbb.12742.

Peng, L., T.D. Searchinger, J. Zionts, and R. Waite. 2023. "The Carbon Costs of Global Wood Harvests." *Nature* 620 (7972): 110–15. https://doi.org/10.1038/s41586-023-06187-1.

Pett-Ridge, J., S. Kuebbing, A. Mayer, S. Hovorka, H. Pilorgé, S. Baker, S. Pang, et al. 2023. *Roads to Removal: Options for Carbon Dioxide Removal in the United States*. Report LLNL-TR-852901. Livermore, CA: Lawrence Livermore National Laboratory. https://www.osti.gov/servlets/purl/2301853/.

Pollard, J., J. Watson, and S. Smith. 2024. "Wood Pellets Production Boomed to Feed EU Demand. It's Come at a Cost to Black People." *Independent*, July 29. https://www.independent.co.uk/news/world/americas/mississippi-biomass-wood-pellets-pollution-b2587574.html.

Premchand, P., F. Demichelis, D. Chiaramonti, S. Bensaid, and D. Fino. 2023. "Biochar Production from Slow Pyrolysis of Biomass under CO_2 Atmosphere: A Review on the Effect of CO_2 Medium on Biochar Production, Characterisation, and Environmental Applications." *Journal of Environmental Chemical Engineering* 11 (3): 110009. https://doi.org/10.1016/j.jece.2023.110009.

Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, et al. 2021. "Adapting Western North American Forests to Climate Change and Wildfires: 10 Common Questions." *Ecological Applications* 31 (8): e02433. https://doi.org/10.1002/eap.2433.

Roberts, K.G., B.A. Gloy, S. Joseph, N.R. Scott, and J. Lehmann. 2010. "Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential." *Environmental Science & Technology* 44 (2): 827–33. https://doi.org/10.1021/es902266r.

Sandalow, D., R. Aines, J. Friedmann, C. McCormick, and D. Sanchez. 2021. *Biomass Carbon Removal and Storage (BiCRS) Roadmap*. LLNL-TR--815200. Livermore, CA: Lawrence Livermore National Laboratory. https://doi.org/10.2172/1763937.

Santeramo, F.G., and S. Searle. 2019. "Linking Soy Oil Demand from the US Renewable Fuel Standard to Palm Oil Expansion through an Analysis on Vegetable Oil Price Elasticities." *Energy Policy* 127 (April): 19–23. https://doi.org/10.1016/j.enpol.2018.11.054.

Schnoor, J.L. 2011. "Cellulosic Biofuels Disappoint." *Environmental Science & Technology* 45 (17): 7099. https://doi.org/10.1021/es2026032.

Searchinger, T., and R. Heimlich. 2015. "Avoiding Bioenergy Competition for Food Crops and Land." Working Paper. Washington, DC: World Resources Institute. https://www.wri.org/research/avoiding-bioenergy-competition-food-crops-and-land.

Searchinger, T., L. Peng, J. Zionts, and R. Waite. 2023. *The Global Land Squeeze: Managing the Growing Competition for Land*. Washington, DC: World Resources Institute. https://www.wri.org/research/global-land-squeeze-managing-growing-competition-land.

Searchinger, T.D., S. Wirsenius, T. Beringer, and P. Dumas. 2018. "Assessing the Efficiency of Changes in Land Use for Mitigating Climate Change." *Nature* 564 (7735): 249–53. https://doi.org/10.1038/s41586-018-0757-z.

Seber, G. 2024. "The Case for a Lipids Cap in California's Low Carbon Fuel Standard." International Council on Clean Transportation blog, May 29. https://theicct.org/the-case-for-a-lipids-cap-in-californias-low-carbon-fuel-standard-may24/.

Shumway, E. 2023. "Wood Pellet Production in the U.S. South and Exportation for 'Renewable' Energy in Europe: The New Green Sacrifice Zone." *Columbia Journal of Environmental Law* 48 (2): 48. https://doi.org/10.52214/cjel.v48i2.11735.

Soterroni, A.C., F.M. Ramos, A. Mosnier, J. Fargione, P.R. Andrade, L. Baumgarten, J. Pirker, et al. 2019. "Expanding the Soy Moratorium to Brazil's Cerrado." *Science Advances* 5 (7): eaav7336. https://doi.org/10.1126/sciadv.aav7336.

Sparks, J. 2024. *Carbon for Chemicals: How Can Biomass Contribute to the Defossilisation of the Chemicals Sector?* Manchester, UK: Supergen Bioenergy Hub. https://www.supergen-bioenergy.net/output/carbon-for-chemicals-how-can-biomass-contribute-to-the-defossilisation-of-the-chemicals-sector/.

Sterman, J.D., L. Siegel, and J.N. Rooney-Varga. 2018. “Does Replacing Coal with Wood Lower CO_2 Emissions? Dynamic Lifecycle Analysis of Wood Bioenergy.” *Environmental Research Letters* 13 (1): 015007. https://doi.org/10.1088/1748-9326/aaa512.

Swanson, A., and A. Smith. 2024. *Alternative Land-Use Impacts of the Sustainable Aviation Fuel Grand Challenge: Corn Ethanol vs. Soybean Oil Pathways*. Washington, DC: American Enterprise Institute. https://www.jstor.org/stable/resrep58532.

Temkin, A., S. Evans, T. Manidis, C. Campbell, and O.V. Naidenko. 2019. “Exposure-Based Assessment and Economic Valuation of Adverse Birth Outcomes and Cancer Risk due to Nitrate in United States Drinking Water.” *Environmental Research* 176 (September): 108442. https://doi.org/10.1016/j.envres.2019.04.009.

TNC (The Nature Conservancy). 2022. *The Power of Place: West*. Arlington, VA: TNC. https://www.nature.org/content/dam/tnc/nature/en/documents/TNC_Power-of-Place-WEST-Executive_Summary_WEB_LR.pdf.

TNC. 2023. *The Power of Place: National*. Arlington, VA: TNC. https://www.nature.org/en-us/newsroom/power-of-place-national/.

Tran, H., E. Juno, and S. Arunachalam. 2023. “Emissions of Wood Pelletization and Bioenergy Use in the United States.” *Renewable Energy* 219 (December): 119536. https://doi.org/10.1016/j.renene.2023.119536.

United Nations. 2024. “World Population Prospects 2024.” https://population.un.org/wpp/.

USDA ERS (US Department of Agriculture Economic Research Service). 2025. “U.S. Bioenergy Statistics.” March 6. https://www.ers.usda.gov/data-products/us-bioenergy-statistics.

USDA NASS (National Agricultural Statistical Service). 2024. “US Farmers Expect to Plant Less Corn and More Soybean Acres.” Press Release, March 28. https://www.nass.usda.gov/Newsroom/2024/03-28-2024.php.

USFS (US Forest Service). 2022. *Confronting the Wildfire Crisis: A 10-Year Implementation Plan*. FS–1187b. Washington, DC: USFS. https://www.fs.usda.gov/sites/default/files/Wildfire-Crisis-Implementation-Plan.pdf.

USFS. 2024. *A Historic Year: Expanding the Pace and Scale of Wildfire Risk Reduction and Forest Health Treatments*. FS-1187g. Washington, DC: USFS. https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/WCS-Historic-Year.pdf.

Vijay, V., S.L. Pimm, C.N. Jenkins, and S.J. Smith. 2016. “The Impacts of Oil Palm on Recent Deforestation and Biodiversity Loss.” *PLoS ONE* 11 (7): e0159668. https://doi.org/10.1371/journal.pone.0159668.

Walloe, L., A. Baldi, and M. Norton. 2024. “To Protect the Climate, We Need Trees to Grow Not to Burn.” European Academies Science Advisory Council, February 22. https://easac.eu/news/details/to-protect-the-climate-we-need-trees-to-grow-not-to-burn.

Wang, W., and M. Khanna. 2023. “Land Use Effects of Biofuel Production in the US.” *Environmental Research Communications* 5 (5): 055007. https://doi.org/10.1088/2515-7620/acd1d7.

Waterman, C., and M. Armus. 2024. *FactBiogas or Bull****? The Deceptive Promise of Manure Biogas as a Methane Solution*. San Francisco: Friends of the Earth. https://foe.org/wp-content/uploads/2024/03/Factory-Farm-Gas-Brief_final.pdf.

Wilson, A.B., J.M. Baker, E.A. Ainsworth, J. Andresen, J.A. Austin, J.S. Dukes, E. Gibbons, et al. 2023. “Midwest.” In *Fifth National Climate Assessment*, edited by A.R. Crimmins, C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock. Washington, DC: U.S. Global Change Research Program. https://nca2023.globalchange.gov/chapter/24/.

Wu, G.C., R.A. Jones, E. Leslie, J.H. Williams, A. Pascale, E. Brand, S.S. Parker, et al. 2023. “Minimizing Habitat Conflicts in Meeting Net-Zero Energy Targets in the Western United States.” *Proceedings of the National Academy of Sciences of the United States of America* 120 (4): e2204098120. https://doi.org/10.1073/pnas.2204098120.

Yan, Y., X. Li, G. Wang, X. Gui, G. Li, G., F. Su, X. Wang, and T. Liu. 2014. “Biotechnological Preparation of Biodiesel and Its High-Valued Derivatives: A Review.” *Applied Energy* 113: 1614–31. https://doi.org/10.1016/j.apenergy.2013.09.029.

Yang, X., and M. Tan. 2021. “Attributing Global Land Carbon Loss to Regional Agricultural and Forestry Commodity Consumption.” *Environmental Science & Technology* 55 (2): 823–31. https://doi.org/10.1021/acs.est.0c04222.

Zhao, J., and D. Wang. 2022. “Why Hasn’t Biomass-to-Bioethanol Conversion Been Commercialized Yet?” SSRN Scholarly Paper. Rochester, NY: Social Science Research Network. https://doi.org/10.2139/ssrn.4009565.

Zhou, D., S. Q. Zhao, S. Liu, and J. Oeding. 2013. “A Meta-analysis on the Impacts of Partial Cutting on Forest Structure and Carbon Storage.” *Biogeosciences* 10 (6): 3691–3703. https://doi.org/10.5194/bg-10-3691-2013.

Zhou, X., T. Baghaee Moghaddam, M. Chen, S. Wu, S. Adhikari, S. Xu, and C. Yang. 2020. “Life Cycle Assessment of Biochar Modified Bioasphalt Derived from Biomass.” *ACS Sustainable Chemistry & Engineering* 8 (38): 14568–75. https://doi.org/10.1021/acssuschemeng.0c05355.

Acknowledgments

We wish to thank Evolved Energy Research; the Spatial Climate Solutions Lab of the University of California, Santa Barbara; and The Nature Conservancy. We are particularly grateful for the modeling, spatial analysis, and technical advice provided by Ryan Jones, Grace Wu, Henry Strecker, Ben Prenetta, Joe Fargione, and Nels Johnson. The authors are grateful to numerous individuals who provided valuable input, feedback, and support to this work. We thank our reviewers and those whom we consulted for sharing their expertise and insights: Caspar Donnison, Chunjia Ran, Claire Jahns, Daniel Sanchez, Devashree Saha, Jen Wilcox, Jeremy Martin, Joe Fargione, Nels Johnson, Oliver James, Rich Waite, Sarah Baker, and Tim Searchinger.

While the contributions from reviewers are greatly appreciated, the views presented in this paper reflect those of the authors alone. We also wish to thank Renee Pineda, Gregory Taff, Laura Malaguzzi Valeri, and Romain Warnault for editing, design, and production and Carrie Dellesky for communications support. This project was made possible through generous funding from Breakthrough Energy.

About the authors

Haley Leslie-Bole is a Senior Manager with the US Lands team, where she manages WRI's portfolio of research on climate-informed land use in the United States. This includes work on the environmental and economic impacts of biofuels, biomass utilization and biomass carbon removal, and nature-based carbon removal.

Contact: Haley.leslie-bole@wri.org

Audrey Denvir is an Associate on the US Lands team at WRI, where she researches how to best use limited biomass resources given the trade-offs between various demands on land, including energy production, food production, and carbon sequestration and removal.

Contact: audrey.denvir@wri.org

Dan Lashof is a Senior Fellow and former Director of the US Program at WRI, where he focuses on climate and energy policies to achieve net zero emissions, including measures to reduce emissions from industry and aviation and responsibly scale up a portfolio of carbon dioxide removal approaches.

Contact: dan.lashof@wri.org

Angela Scafidi is a Research Analyst with the US Lands team and the Land and Carbon Lab at WRI, where she supports research and analysis on land use change and associated greenhouse gases both in the United States and globally.

Contact: angela.scafidi@wri.org

Caroline Melo Ribeiro is a Research and Administrative Analyst at WRI's Energy Program. She works on clean energy procurement, industrial decarbonization, and related technologies. She is currently supporting the Asia Clean Energy Coalition and WRI's portfolio of energy work in Latin America.

Contact: caroline.meloribeiro@wri.org

About WRI

World Resources Institute works to improve people's lives, protect and restore nature and stabilize the climate. As an independent research organization, we leverage our data, expertise and global reach to influence policy and catalyze change across systems like food, land and water; energy; and cities. Our 2,000+ staff work on the ground in more than a dozen focus countries and with partners in over 50 nations.