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TEMPERATURE AND ENERGY SECURITY: WILL FOREST BIOMASS HELP IN THE FUTURE?

ALICE FAVERO[*,¶], JONGHYUN YOO[†,||], ADAM DAIGNEAULT[‡,**] and JUSTIN BAKER[§,††]

[*]*RTI International, Research Triangle Park*
NC 27709-2194, USA

[†]*Department of Urban Planning and Design, University of Seoul*
Seoul 02504, Republic of Korea

[‡]*School of Forest Resources, University of Maine*
Orono, ME 04469, USA

[§]*Department of Forestry and Environmental Resources*
North Carolina State University, Raleigh, NC 27607, USA
[¶]*afavero@rti.org*
[||]*jyoo@uos.ac.kr*
[**]*adam.daigneault@maine.edu*
[††]*jsbaker4@ncsu.edu*

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Despite the numerous technical, logistical, and policy challenges associated with the use of bioenergy to mitigate climate change, the latest IPCC report identifies bioenergy as a high-value and large-scale mitigation option to support the transition to a cleaner energy system. This paper links a climate-economic-energy model and a land model to measure the net mitigation effect of using forest biomass for electricity generation and corresponding implications on global temperature. Through the soft-link, the energy model provides to the land model the cost-effective regional consumption of forest biomass under nine carbon price scenarios and measures the effects of its use on fossil fuel emissions and carbon sequestered in carbon capture and storage (CCS). The land model provides the dynamic supply of forest biomass and measures the change in land management/use under each demand scenario and corresponding changes in carbon sequestered in forests. Results suggest that forest biomass should be part of global mitigation efforts despite the expected small share of electricity sourced from it. The net climate benefits of forest biomass energy vary across scenarios and temporally — in most scenarios increased biomass demand results in near term reductions in global forest carbon stocks, but at carbon prices starting at \$40/tCO_2e or greater, results show positive net sequestration by 2030. This increased sequestration, coupled with energy emissions displacement and bioenergy with carbon capture and storage (BECCS) implies substantial long-term mitigation potential for forest biomass energy. Our results suggest that high forest biomass demand pathways could also help reduce the magnitude of future temperature growth. Further, we explore the regional effects on

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[||]Corresponding author.

energy security of using forest biomass. Results show that its use can have potential large effects on trade dynamics and regional energy security issues, with 4 of the 17 global regions found to be net exporters of forest biomass.

Keywords: Integrated assessment model; BECCS; global average temperature; energy security; forest biomass.

1. Introduction

Despite the challenges associated with bioenergy expansion as climate change mitigation strategy (Galik, 2020), in the most recent Assessment Report of the IPCC (AR6), bioenergy still represents a high-value and large-scale mitigation option that could support the transition to a cleaner energy system. Common net-zero energy system pathways in line with a temperature target of 1.5°C are expected to include alternative energy sources such as bioenergy and the use of CO_2 removals such as bioenergy combined with carbon capture and storage (BECCS). Specifically, based on recent projections and information on existing energy technologies, it is *very unlikely* that net-zero carbon goal can be reached without implementing any carbon dioxide removal (CDR) options, such as BECCS. Across the integrated assessment model (IAM) scenarios reviewed by the IPCC, BECCS is the dominant form of CDR with a total of 91–127 GtC cumulative sequestration from 2020 to 2100 for a temperature target of 1.5°C and 79 GtC for a temperature target of 2°C. Cumulative CDR via afforestation, reforestation, and other land management trails closely behind BECCS. The estimated cumulative sequestration from direct air capture technologies (DAC) is 8–30 Gt under the 1.5°C target and 5 GtC under the 2°C target. Total CDR from all technology options is expected to remove between 55 GtC and 327 GtC by 2100 (Riahi *et al.*, 2022).

Moreover, bioenergy has the potential to be a high-value and large-scale mitigation option to support many different parts of the energy system, particularly in sectors with limited alternatives to fossil fuels such as aviation. A review of 29 runs from IAMs and across different policy scenarios shows that the average share of global energy supply sourced by bioenergy is 30% under the scenarios limiting warming to 1.5°C in 2050 and 35% in 2100. Moreover, biomass is expected to supply an average of 8% of electric power in 2050 with a max of 30% and in 2100 — with electricity demands growing over time commensurate with socioeconomic growth and electrification of transportation and industry. Four specific IAMs (REMIND, MESSAGE, IMAGE, and POLES) provide results under the 1.5°C and 2°C targets with and without a limitation on bioenergy supply, enabling the generation of comparable marginal cost curves necessary to determine the effects of BECCS availability on the mitigation cost. Under the 1.5°C target, the constraint on bioenergy use triples the price of carbon in 2050 and in 2100 while under the 2°C the price increases by 100% in 2050 and 110% in 2100. Finally, one of the key advantages of using bioenergy is the replacement of fossil fuels. Specifically, the same four models show that greenhouse gas (GHG) emissions from fossil fuels in the electricity sector will increase by 43% in 2050 and 53% in 2100 if the use of biomass is limited under the 1.5°C target (Huppmann *et al.*, 2019).

While on one side, bioenergy is recognized for its mitigation potential, on the other side, the last IPCC report also acknowledges possible issues related to substantial bioenergy expansion, including potential trade-offs with food and water systems, and concerns that forest biomass utilization in the energy system may not be carbon beneficial (see Abt *et al.*, 2022; Favero *et al.*, 2023a,b). In the past, studies have identified issues related to the loss of land carbon when energy crops are ill-deployed or they drive deforestation and land degradation (Hanssen *et al.*, 2020). Moreover, demand for bioenergy can place pressure on food systems and biodiversity through the use of land and water for managed forests and energy crops (Henry *et al.*, 2018; Xu *et al.*, 2019). These negative implications might increase in the future or under more stringent climate policy scenarios when the demand is likely to increase (Fujimori *et al.*, 2018; Ohashi *et al.*, 2019; Roelfsema *et al.*, 2020). Finally, biomass trade can play an important role in meeting regional demands for bioenergy with the actual production of bioenergy feedstock, but it might also introduce further challenges due to energy security implications, regional sustainability criteria, and accountability issues of land emissions (Fajardy and Mac Dowell, 2018; Lamers *et al.*, 2016; Funk *et al.*, 2021).

This study assesses some of these challenges and explores new ones by linking the IAM World Induced Technical Change Hybrid (WITCH) with a partial equilibrium model of the global forest sector global timber model (GTM). The integration of the two models is used to provide new insights into the bioenergy debate. First, we measure the net effect of using forest biomass for the global power sector on the emissions balance and corresponding implications on temperature. We address the accounting issue by measuring land emissions from forests in GTM as the change in emissions from the scenario with forest biomass production relative to the Baseline without biomass. Emissions from the power sector are measured using the WITCH output by comparing the scenario with the same carbon price with and without forest biomass availability. Since the two models jointly provide the cost-effective demand for forest biomass (WITCH) and supply of forest biomass (GTM), we can map where emissions will occur for both systems (forest and energy). Moreover, each model provides the regional cost-effective production of forest biomass (GTM) and consumption (WITCH) which depends on the regional attributes of the land and the power sector systems. Therefore, building on Favero and Massetti (2014), we are able to measure the effects of biomass trade on regional energy security and test our results under different scenarios. Finally, we introduce an energy security indicator to estimate the amount of electricity sourced by imported forest biomass under future climate change scenarios and discuss if this is a potential challenge associated with the large-scale use of this technology.

2. Methods

Soft-link. For this study, we link the global forest sector model GTM (Sohngen *et al.*, 1999; Sohngen and Mendelsohn, 2003) and the global IAM WITCH (Bosetti *et al.*, 2006, 2007, 2009). GTM is a global model that combines the spatially and temporally detailed predictions of the dynamic global vegetation model BIOME3 (Haxeltine and Prentice, 1996) with an economic model that intertemporally optimizes forest management, harvest, and land use decisions on a decadal basis. GTM provides the supply function for forest biomass (global and regional) and information about changes in forest carbon stocks and market conditions. The IAM WITCH examines a host of mitigation alternatives under each carbon price scenario and generates the cost-effective package of mitigation technologies across regions over time. WITCH also provides a set of marginal abatement costs for energy technology-related mitigation.

The soft-link between the two models allows us to equate global forest biomass supply and global forest biomass demand over time under different climate mitigation policy scenarios (Fig. 1). Given a carbon price pathway (policy scenario), WITCH finds the optimal portfolio of mitigation strategies to reduce emissions at the point in which their marginal abatement costs are equal to the carbon price and calculates forest biomass demand given the 10-year average price of biomass from GTM. In WITCH, two types of electricity use forest biomass as an input: the traditional direct combustion plants and the integrated gasification combined cycle (IGCC) power plants with CCS (BECCS). For this study, only biomass from forests including forestry residues is available for the power sector. That is, biomass power plants can use only forest biomass from the international market at the market clearing price. Introducing a carbon price in WITCH alters the optimal energy mix and energy demand with direct effects on forest biomass demand. Specifically, biomass-based power can have competitive prices over fossil-fueled power generation facilities, as it embodies relatively lower or zero carbon (though one contribution of this study is that we directly assess carbon impacts of bioenergy in land use systems via GTM). Moreover, WITCH does not allow the winner-takes-all system. Rising demand for clean energy under a carbon

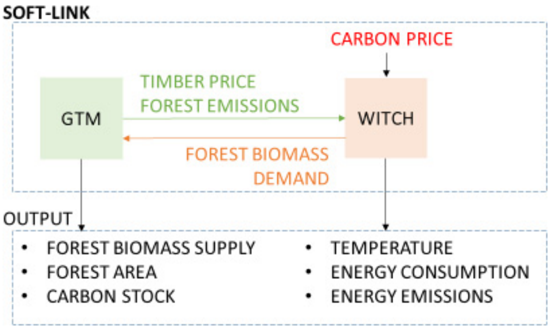


Figure 1. Soft link between WITCH and GTM.

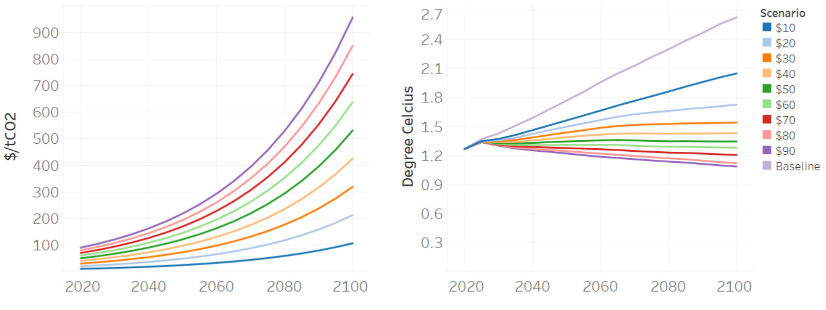
price is satisfied with a bundle of energy options, such as solar, wind, fossil fuel plants with carbon capture and storage (CCS), and BECCS.

The resulting path of forest biomass demand is then entered into GTM, which then calculates the regional cost-effective forest planting, harvesting, and management intensity to meet the demand. Moreover, GTM provides information on forest carbon stocks across four different pools (above ground, soil, slash and market) and takes into account market dynamics with other timber products (pulpwood and sawtimber). The resulting price of biomass over time is then entered back into WITCH and the model finds the new demand path for forest biomass. This process is continued until the adjustments between iterations become very small (i.e., lower than 5%). The resulting equilibrium reveals a dynamic path of timberland, management intensity, harvests, prices, forest biomass supply and forest carbon sequestration in the GTM model, and a path of carbon mitigation and energy mix in WITCH. Under every carbon price scenario, the mitigation policy begins in 2020 and the results are examined through 2100. All decision makers face the same worldwide carbon price.

This soft-link approach has been used before to link GTM with IAMs to calculate optimal sequestration programs (Sohngen and Mendelsohn, 2003; Tavoni *et al.*, 2007) and to estimate the optimal use of forest biomass and the effective mix of forest biomass production and forest carbon sequestration under climate mitigation scenarios (Favero *et al.*, 2014, 2017, 2020). However, this is the first analysis that combines the different effects of forest biomass consumption on the emissions balance and temperature effect and provides regional results of changes in energy and forest system emissions. These additions allow us to assess the role of forest biomass in achieving specific temperature targets by the end of the century. Finally, we discuss the role of trading forest biomass on a large scale and the energy security challenge — a renewed focus in recent energy policy deliberations.

Scenarios. For this study, we simulate a baseline scenario without mitigation policy in WITCH and GTM. Under this scenario, WITCH's socio-economic assumptions from the SSP2-RCP4.5 pathway (Riahi *et al.*, 2022) and land use emissions from GTM lead to an increase of 2.7°C in the temperature by 2100. Moreover, socio-economic assumptions from the SSP2 (e.g., population and GDP growth) drive the demand for timber products (outside of forest biomass for energy) in GTM.

In order to test the demand for forest biomass in WITCH, we simulated nine different global carbon prices in WITCH that apply to the energy and industrial sectors (i.e., no land sector) globally. The price paths start at \$10–90/tCO_2e in 2020 and rise at rates of 3%, before reaching \$110–958/tCO_2e in 2100 (Fig. 2(a)). These carbon price pathways are associated with an increase in global average temperature in 2100 between 1.2°C and 2.1°C compared to pre-industrial levels (Fig. 2(b)). Finally, to estimate the effect of forest biomass on the emissions from the power sector, we run the nine carbon price pathways without forest biomass available and compare them with the same carbon price scenario with forest biomass available. In this way, we measure the reduction in fossil fuel emissions attributable to the biomass energy emissions



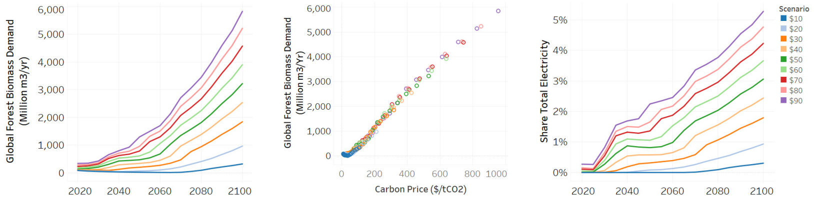
(a) (b)

Figure 2. (a) Carbon prices and (b) temperature pathways under baseline and carbon price scenarios with forest biomass available ($ values show the starting price in 2020 for each scenario).

displacement together with the indirect changes in land use emissions driven by the increased demand for forest biomass in GTM and use of CCS and their collective effects on global average temperature.

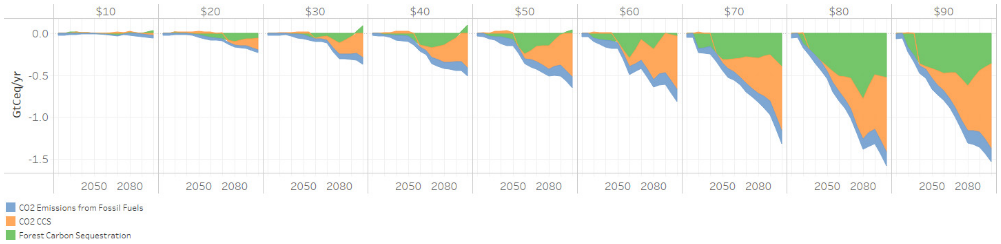
3. Results

Forest Biomass Demand. Under the carbon price scenarios, the demand for forest biomass in WITCH is expected to increase from 320 million m^3/yr under the low carbon price scenario to about 6000 million m^3/yr in 2100 (Fig. 3(a)). These quantities are in the range of other forest biomass energy projections (e.g., Lauri *et al.*, 2017). In the early periods, forest biomass is primarily used in existing traditional biomass power plants while future forest biomass will be mainly allocated to power plants with BECCS. Moreover, global forest biomass consumption is expected to increase as the carbon price increases (Fig. 3(b)), peaking at around 5,000 TWh electricity generation in 2100, which covers around 5% of total electricity generation (Fig. 3(c)). For reference, under the same year and scenario, solar is expected to supply 25% and wind 50% of the total global electricity.



(a) (b) (c)

Figure 3. (a) Global consumption of forest biomass; (b) carbon price versus global biomass consumption; and (c) share of total global electricity supplied by forest biomass under each carbon price scenario.



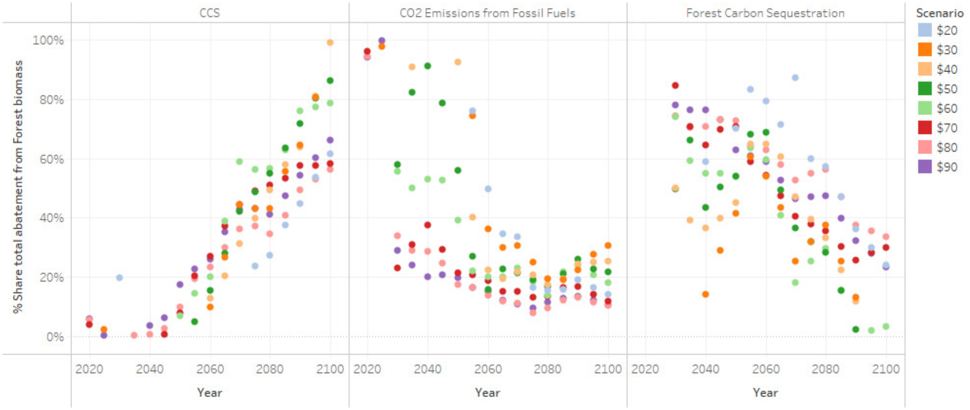
Notes: Negative values = sequestration; Positive values = emissions.

Figure 4. Change in annual CO_2 emissions from fossil fuels; CCS and annual forest carbon sequestration under carbon price scenarios relative to the same price scenarios without forest biomass available.

Energy emissions. By simulating the same carbon price scenarios with and without forest biomass available, we can measure both the effects on the GHG emissions from the energy sector and the effects on land emissions (Fig. 4). Results show that under all the carbon price pathways, the use of forest biomass reduces fossil fuels emissions (blue area in Fig. 4) because it is cost-effective in the power sector to displace a portion of fossil fuels with forest biomass. Moreover, the displacement is higher under scenarios with high carbon prices (i.e., more stringent temperature targets) when the use of forest biomass increases. On average, for every MWh of forest biomass electricity used at the global level, 0.07 tons of C are reduced through the replacement of fossil fuels. Additionally, the availability of forest biomass increases in the long term via the use of CCS in WITCH relative to the scenario in which only natural gas and coal can be used in power plants with CCS. Consequently, for every MWh of forest biomass electricity, 0.05 tons of C will be stored underground via CCS. Finally, as WITCH considers a portfolio of mitigation options available and their corresponding costs (solar, wind, energy efficiency, etc.), this result shows that when forest biomass is not available, it is not cost-effective to fully replace the feedstock with other clean options resulting in more emissions under the same carbon price. For instance, by 2050, emissions from fossil fuels will be 15% lower under the 90 $/t$CO_2$e scenario with biomass than the same scenario without biomass. By the end of the century, GHGs will be between 25% less under the same scenario

Land emissions. Across the nine carbon price scenarios, 95% of the tested scenarios show that there will be an initial reduction in forest carbon stocks from the Baseline. That is, less carbon will be sequestered by forest under the carbon price scenarios than the scenarios without forest biomass demand (Fig. 4). Under the very low carbon price scenario, carbon losses are *very likely* to persist for several decades because the demand for forest biomass is not high enough to generate large new investments in forests but only a substitution with other timber products and more harvesting. On the other hand, forests under the medium carbon price scenarios (between 30 $/t$CO_2$e and 50 $/t$CO_2$e) are projected to increase sequestration in the short-medium term as more trees are planted in response to future biomass demand, but more harvesting in the long term will lead to a decline in carbon sequestered than the baseline. Finally, carbon price scenarios that start at \$60/tCO$_2$e or higher lead to increased management of existing forests and establishment of new forests, which lead to an overall increase in global carbon stocks of around 0.6 GtCe/yr in 2100. Under these scenarios, as the carbon price increases, sequestration is expected to expand and then stabilized.

Total net mitigation and temperature effects. By aggregating all the emissions categories in WITCH across each scenario, we measure the net mitigation effect of using forest biomass from 2020 to 2100 (Fig. 5). Results show that under the scenarios with low carbon prices and corresponding low demand for forest biomass, the effect of forest biomass availability is insignificant because the abatement from fossil fuel substitution and the expanded use of CCS is offset by less forest carbon sequestration. On the other hand, carbon price scenarios starting at \$40/tCO$_2$e show a positive effect on net mitigation driven by more carbon sequestered in land and CCS as well as a larger substitution of fossil fuels when biomass is available. Moreover, in the short term (2020–2050) fossil fuel substitution and forest carbon sequestration cover the largest share of mitigation from forest biomass. On the other hand, in the long term (after 2050), carbon sequestration via CCS is the dominant mitigation activity. Finally, despite the uncertainty in carbon sequestered via forests under different scenarios, net mitigation is always positive in the long term (Fig. 5). In the most stringent carbon price scenarios, the mitigation achieved with the use of forest biomass reaches a maximum of 0.67 GtCe in 2050 and 1.58 GtCe in 2100 under with the largest share coming from additional carbon stored underground by CCS (56%) followed by carbon sequestered in forests (33%). In cumulative terms this is around 70 GtCe between 2020 and 2100 which is in line with the IPCC mitigation estimates of BECCS discussed in the Introduction (Fig. 6).



Notes: The \$10 scenario has been removed because the amount of abatement was not significant.

Figure 5. Percentage share of total forest biomass abatement by category across scenarios.

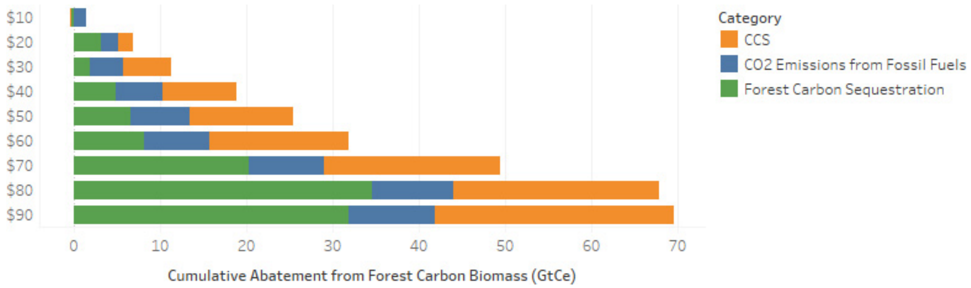


Figure 6. 2020–2100 Cumulative abatement from Forest biomass consumption.

These results show that forest biomass availability starts affecting temperature significantly only under high carbon price scenarios. Because forest biomass is still an expensive input, and it is not cost-effective to use it on a large scale under low carbon price scenarios, its effect on temperature is minimal. On the other hand, under the highest carbon price scenario — which translates into the most stringent temperature targets — the use of forest biomass reduces the change in the global average temperature by up to 11% by the end of the century relative to the same carbon price scenario without forest biomass. That is, forest biomass mainly used with CCS (BECCS) helps the world reach a temperature target of around 1.09°C instead of 1.23°C by 2100 under the 90\$/tCO_2e carbon price scenario. Finally, despite the decline in forest carbon sequestration under the very low carbon price scenario (starting at 10\$/tCO_2e), temperature is not expected to change relative to the same carbon price scenario without forest biomass available, thereby remaining at around 2.05°C. That is, under this scenario, the mitigation benefits of fossil fuel substitution are not high enough to offset the reduction in forest carbon sequestration driven by the production of forest biomass. From a different perspective, results show that it is much more likely to produce global climate benefits from the use of forest biomass than from the feedstock used to create climate damages. Specifically, under each carbon price scenario tested, temperature is either unchanged or decreased relative to the same price scenario without biomass (Table 1).

Regional Consumption, Production and Trade. WITCH does not only project global forest biomass demand under each carbon price scenario, but also its cost-effective regional composition. As in the global results, when the carbon price increases, there is a shift towards using more carbon-free energies and less fossil-based energies in all regions, which translates into more forest biomass consumption in several of them. Moreover, each region chooses the energy mix that minimizes energy costs taking into account regional energy demand, energy prices (with carbon price), and the capacity for producing each type of energy. This results in varying levels of forest biomass consumption. For instance, in the short term (2020–2050), Europe and the US are the two largest consumers on average of forest biomass due to their existing infrastructure for producing traditional biomass-based electricity (Fig. 7(a)). This

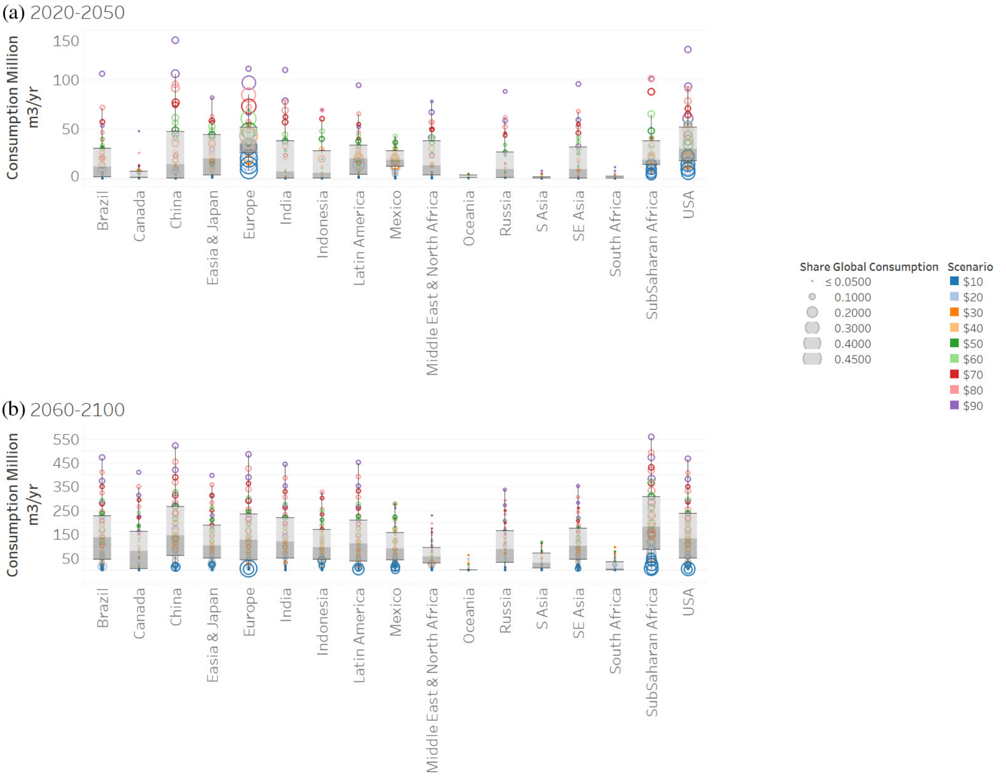
Table 1. Change in global average temperature from pre-industrial level under each carbon price scenario with and without forest biomass availability in 2100.

Carbon Price Scenario $/tCO$_2$e	Scenario: With forest biomass	Scenario: Without forest biomass	% change with forest biomass
$10	2.05°C	2.05°C	—
$20	1.73°C	1.74°C	−0.6%
$30	1.54°C	1.56°C	−1%
$40	1.43°C	1.46°C	−2%
$50	1.35°C	1.39°C	−3%
$60	1.28°C	1.34°C	−4%
$70	1.21°C	1.29°C	−7%
$80	1.12°C	1.25°C	−10%
$90	1.09°C	1.23°C	−11%

infrastructure allows them to meet the increasing demand for energy driven by population and economic growth. In the long run (2060–2100), the share of biomass-based electricity is similar across regions, at around 5%, with the majority of this coming from BECCS (Fig. 7(b)). Since BECCS is a new technology, most regions are expected to invest in it early on as a forward-looking strategy, given that they are not constrained by existing capital assets.

For each global biomass demand estimate from WITCH, GTM projects the regional 10-year average supply by taking into account land availability, the cost of harvesting and the cost of converting land into forestland. GTM results show that Europe and the US are not only the main consumers of forest biomass, but also its main producers. On average these two countries will produce in the short term 16% and 17% and in the long term 30% and 28% of global supply respectively (Figs. 8(a) and 8(b)). That is, GTM shows that it is cost-effective to meet a large portion of global forest biomass demand with biomass produced in these two temperate regions. In the long term, the third largest supplier is Brazil where most of the Amazon rainforests lie. Despite the significant increase in regional production in Brazil, with a share that can go up to 60%, the area of natural forests converted into managed forests in Brazil is below 2% for all scenarios. On the contrary, Sub-Saharan Africa, one of the major consumers of biomass, demands much more than its domestic production. For instance, in 2100 the region is expected to use around 51–557 million m^3 of forest biomass but to produce only 7–12 million m^3 of it.

Under the carbon price scenarios, forest biomass trade is indeed projected to increase in the future as regional cost-effective production (from GTM) does not match regional cost-effective consumption (from WITCH) and the market of forest biomass emerges as a major global commodity market, both in terms of volume and of value



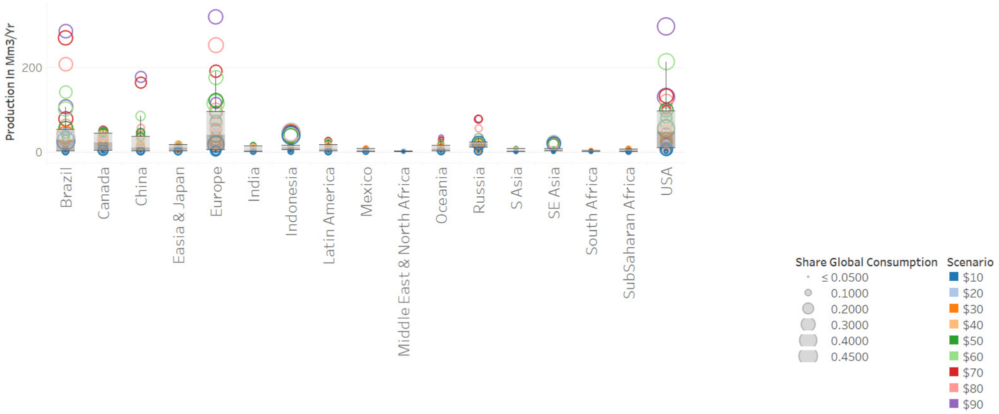
Notes: Box Plot shows the mean regional consumption, and the whisker shows 1.5 the IQR.

Figure 7. Regional forest biomass consumption (million m^3/yr) and share of global consumption (bubble size) (a) in the short term and (b) in the long term under each carbon price scenario.

traded. For instance, under the most stringent carbon price scenarios, the value of the market for forest biomass will be around 700 $ billion by 2100.

Moreover, the incentive to trade forest biomass is expected to grow as the stringency of the target increases (Fig. 9). Trade enables world regions to efficiently distribute forest biomass, significantly altering the energy mix, and thus increasing the efficiency of carbon price policies. At a regional level, trade dynamics are explained by the endowment of land suitable for forests, forest biomass production costs, and the carbon intensity of the economy. On the one hand, biomass importers have either low domestic capacity to meet their domestic demand, low biomass potential, more expensive clean energy sources or high production costs. On the other hand, exporters are countries with either large biomass potential, low production costs, or relatively small domestic demand. The USA and Europe are the two largest biomass exporters, representing more than 50% of exports in 2100 in all scenarios (Fig. 10). Further, these regions have high relative forest inventories and are key timber-producing regions, with low relative supply costs for forest products and biomass. Canada appears to be a

(a) 2020-2050



(b) 2060-2100

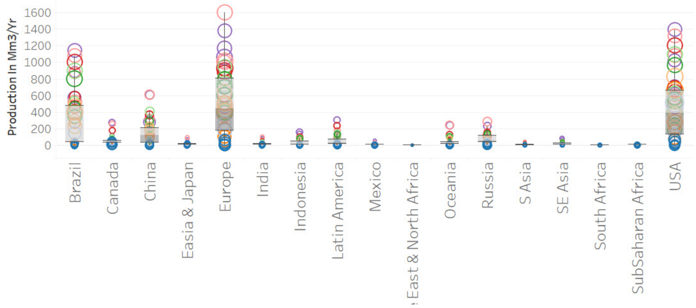
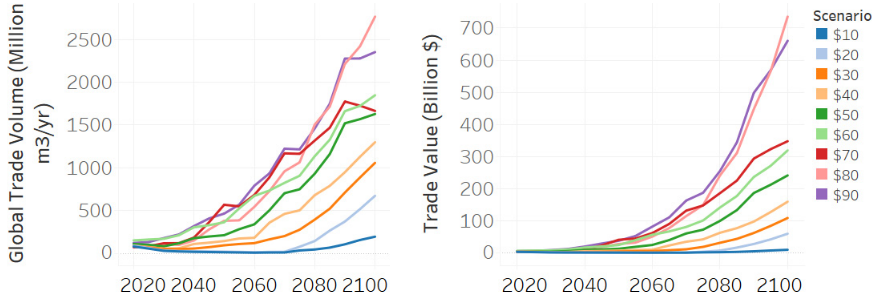


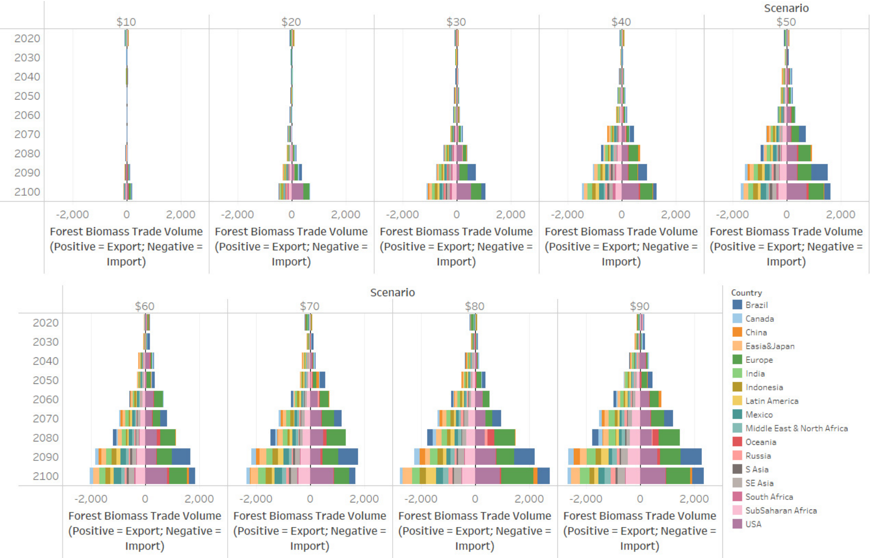
Figure 8. Regional forest biomass production (million m^3/yr) and share of global consumption (bubble size) (a) in the short term and (b) in the long term under each carbon price scenario.

main exporter under low demand scenarios while Oceania and China are only likely to become exporters in the long run under high carbon price scenarios. Overall, the regional distribution of exporters and importers does not change much under different price scenarios, with the most noticeable change being the increased share of exports from Brazil over time as carbon prices rise.



(a) (b)

Figure 9. Global forest biomass trade (a) volume (million m^3/yr) and (b) value (billion $/yr) by carbon price scenario, 2020–2100.



*Notes:*Trade = Regional Production — Regional Consumption; if trade > 0, region = exporter; if trade < 0, region = importer.

Figure 10. Regional forest biomass trade across scenarios (2020–2100).

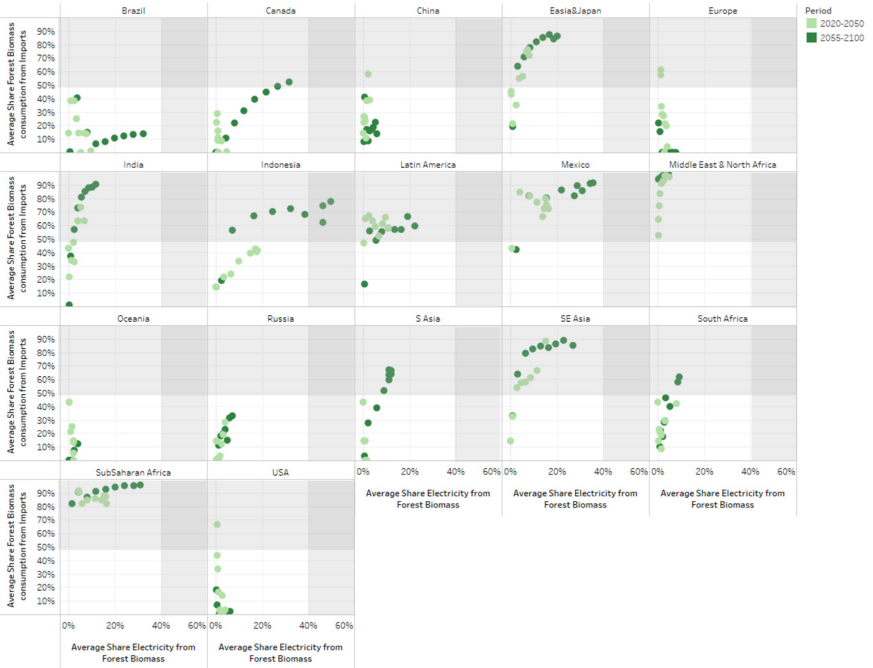


Figure 11. Share of forest biomass consumption from imported wood versus share of electricity sourced by forest biomass across all carbon price scenarios, light colors = short term (2020–2050); dark colors = long term (2050–2100).

Biomass energy security. Two indicators were developed to assess the level of forest biomass energy security for each region over the short and long terms (Fig. 11). The first indicator measures biomass energy import exposure, which is represented by the share of forest biomass consumption at the regional level sourced from international trade. The second indicator measures the diversification of the electricity mix by estimating the share of total electricity sourced by forest biomass.

Biomass energy import exposure (y-axis) varies greatly across regions and is influenced by many factors such as the domestic resource base and the energy intensity of the economy. The lowest levels of import risk are in Oceania, Russia, China, South Africa, Europe, Brazil and the United States. These countries have few observations in which more than 50% of their average consumption comes from trade, and these occur at very low consumption levels. The other countries show higher risks with more than 50% of their average consumption imported across price scenarios and time.

The electricity generation diversity risk (x-axis) shows less variability across countries. In the long term, about 56% of countries use less than 20% for their electricity generation, while 37% use between 20% and 40%, and finally only Indonesia is projected to have more than 50% of electricity sourced by forest biomass on average. The USA, Oceania, Russia, South Asia, China, and Europe are examples of countries that scored very well in both metrics (less than 10% electricity sourced by biomass and a large share of domestic production of forest biomass consumption) and thus have a low biomass energy security risk. On the other hand, Indonesia, Sub-Saharan Africa and Mexico scored very poorly in both metrics, resulting in a high biomass energy risk especially in the long run when more of their domestic electricity is sourced by imported forest biomass.

4. Conclusions

We link a global land use model and global energy-climate-economic model to estimate impacts of various forest biomass demand scenarios on emissions, temperature, and trade. WITCH provides the cost-effective mix of energy technology across time to achieve specific emissions reduction targets while GTM provides the cost-effective use and management of regional forests to meet the expected demand forest biomass. Key output of this model interaction is the change in emissions from the land and energy sectors. To our knowledge, this is the first study assessing trade dynamics and climate effects of forest biomass at both the global and regional levels.

Results show that including forest biomass as a viable option for energy-based GHG mitigation could increase feedstock demand to as much as 6 billion million m^3/yr by 2100. At the emissions level, increased biomass demand will result in near term reductions in forest carbon stocks for 95% of the modeled scenarios, but carbon prices starting at \$40/tCO_2e or more result in net positive sequestration by 2030. Moreover, forest biomass availability will reduce emissions by displacing fossil fuel and increasing CO_2 sequestration through CCS. This will result in more net carbon sequestration across all carbon price scenarios than the same scenarios without forest biomass. Overall, this reduces the projected change in global average temperature. For instance, under the most ambitious carbon price scenario, forest biomass availability is likely to reduce global average temperature changes by up to 11% (from 1.2°C to 1.1°C) by 2100 compared to policies that exclude the use of forest-based bioenergy.

Moreover, we can use the results to test the contribution of forest biomass to meet specific abatement goals. For very modest mitigation targets, its role is almost undetectable. However, as the target increases its stringency and carbon prices increase, the availability of biomass becomes more important and can affect the cost of the policy. For instance, in order to achieve a temperature increase of 1.3°C, the carbon price has to be equal to 640$/tCO$_2$e in 2100 when forest biomass is not available, while it the same temperature goal can be achieved at an 18% lower price (532 $/tCO$_2$e) with the use of biomass. This result confirms the findings from the integrated assessment modelling community where biomass availability is shown to be a valuable mitigation option (e.g. if it is not available, the cost of meeting a specific temperature target increases significantly). It is important to note that these results do not consider possible effects on surface albedo driven by more land converted to forest to meet the new demand that might alter future temperature (Favero *et al.*, 2018b).

Global consumption of forest biomass is very sensitive to carbon prices and is expected to increase almost linearly to it. For instance, under a carbon price of 100 $/tCO$_2$e, forest biomass demand is projected to be around 600 Mm3/yr while under a carbon of 500 $/tCO$_2$e it is likely to be around 3000 Mm3/yr, regardless of the specific time period that price was imposed. At the regional level, some countries follow a similar trend, with consumption increasing under higher carbon prices, and only a few countries (e.g., Oceania, South Africa) not changing their biomass consumption pathways as carbon rises.

The results strongly suggest that forest biomass should be part of global mitigation efforts despite the expected small share of electricity sourced from it (below 6% globally). That is, the mitigation potential of this technology is mainly driven by its combined use with CCS and the indirect benefit of forest carbon sequestration in the long term. On the other hand, the use of forest biomass can have potential large effects on regional biomass trade and energy security, with 4 of the 17 regions found to be net exporters under all carbon price scenarios. This key finding should be considered if the energy system transitions to a larger use of this source, especially because similar energy security issues are not likely to occur under the use of other renewable energy sources. Furthermore, we did not model the potential increase in land demand for building new solar capacity and its effect on the regional supply of forest biomass.

Finally, there remain some important topics to study in this field that have not been explored in this study and might affect the results. First, climate change effects on the growth of forests around the world and fire risk could alter these results at the global and regional levels (Favero *et al.*, 2018a, 2021). Future research should integrate climate change impacts into the decision to use forests to supply bioenergy feedstocks and store carbon. Second, this study did not include direct payments for forest sequestration that are likely to produce two distinct effects on the results. First, including a price on land use emissions is likely to avoid the initial decline in forest carbon stock driven by increased forest biomass demand. Secondly, they will make the cost of forest biomass higher in the short term and possibly lower in the long term with consequences in the cost-effective portfolio of mitigation options (Favero *et al.*, 2020). Moreover, carbon payments for forest sequestration could preserve natural unmanaged forests from conversion to managed forests driven by biomass demand (Favero *et al.*, 2020). Third, this study does not consider emerging demands for sustainable timber products (e.g., cross-laminated timber) and the potential effects on land competition and prices in the link with WITCH. Future research should explore the effects of demand for different forest-based products and the overall effects on the global mitigation portfolio.

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Supporting Information

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References

Abt, R, C Galik and JS Baker (2022). When burning wood to generate energy makes climate sense. *Bulletin of the Atomic Scientists*, 78(3), 152–157.

Adams, DM, RJ Alig, BA McCarl, JM Callaway and SM Winnett (1999). Minimum cost strategies for sequestering carbon in forests. *Land Economics*, 75, 360–374.

Daigneault, A and A Favero (2021). Global forest management, carbon sequestration and bioenergy supply under alternative shared socioeconomic pathways. *Land Use Policy*, 103, 105302.

Fajardy, M and N Mac Dowell (2018). The energy return on investment of BECCS: Is BECCS a threat to energy security? *Energy & Environmental Science*, 11, 1581–1594, doi: 10.1039/C7EE03610H.

Favero, AE and T Massetti (2014). Trade of forest biomass for electricity generation under climate mitigation policy. *Resource and Energy Economics*, 36, 166–190.

Favero, A and R Mendelsohn (2014). Using markets for woody biomass energy to sequester carbon in forests. *Journal of the Association of Environmental and Resource Economists*, 1(1–2), 75–95.

Favero, A, R Mendelsohn and B Sohngen (2017). Using forests for climate mitigation: Sequester carbon or produce forest biomass? *Climate Change*, 144(2), 195–206.

Favero, AR, R Mendelsohn and B Sohngen (2018a). Can the global forest sector survive 11°C warming? *Agric. R. Econ. Rev*, 47, 388–413.

Favero, A, B Sohngen, Y Huang and Y Jin (2018b). Global cost estimates of forest climate mitigation with albedo: a new integrative policy approach. *Environmental Research Letters*, 13(12), 125002.

Favero, A, A Daigneault and B Sohngen (2020). Forests: Carbon sequestration, biomass energy, or both? *Science Advances*, 6(13), eaay6792.

Favero, A, R Mendelsohn, B Sohngen and B Stocker (2021). Assessing the long-term interactions of climate change and timber markets on forest land and carbon storage. *Environmental Research Letters*, 16(1), 014051.

Favero, A, A Daigneault, B Sohngen and J Baker (2023a). A system-wide assessment of forest biomass production, markets, and carbon. *GCB Bioenergy*, 15(2), 154–165.

Favero, A, J Baker, B Sohngen and A Daigneault (2023b). Economic factors influence net carbon emissions of forest bioenergy expansion. *Communications Earth & Environment*, 4(1), 41.

Fujimori, S *et al.* (2018). Inclusive climate change mitigation and food security policy under 1.5°C climate goal. *Environmental Research Letters*, 13(7), 74033, doi: 10.1088/1748-9326/aad0f7.

Galik, CS (2020). A continuing need to revisit BECCS and its potential. *Nature Climate Change*, 10(1), 2–3.

Hanssen, SV, V Daioglou, ZJN Steinmann, JC Doelman, DP van Vuuren and MAJ Huijbregts (2020). The climate change mitigation potential of bioenergy with carbon capture and storage. *Nature Climate Change*, 10, 1023–1029. doi: 10.1038/s41558-020-0885-y.

Haxeltine, A and IC Prentice (1996). BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochemical Cycles*, 10, 693–709.

Henry, RC, K Engström, S Olin, P Alexander, A. Arneth and MDA Rounsevell (2018). Food supply and bioenergy production within the global cropland planetary boundary. *PLoS One*, 13, e0194695, doi: 10.1371/journal.pone.0194695.

Huppmann, D *et al.* (2019). IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. *Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis*. doi: 10.5281/zenodo.3363345, data.ene.iiasa.ac.at/iamc-1.5c-explorer (accessed March 2022).

IPCC (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, JT Houghton, Y Ding, DJ Griggs, M Noguer, PJ van der Linden, X Dai, K Maskell and CA Johnson (eds.), p. 881. New York, NY, USA, Cambridge, UK, Cambridge University Press.

Kim, JB, E Monier, B Sohngen, GS Pitts, R Drapek, J McFarland, S Ohrel and J Cole (2017), Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios. *Environmental Research Letters*, 12, 045001.

Kim, SJ, JS Baker, BL Sohngen and M Shell (2018). Cumulative global forest carbon implications of regional bioenergy expansion policies. *Resource and Energy Economics*, 53, 198–219.

Lamers, P, E Searcy, JR Hess and H Stichnothe (2016). *Developing the Global Bioeconomy: Technical, Market, and Environmental Lessons from Bioenergy.*Academic Press.

Lauri, P, N Forsell, A Korosuo, P Havlík, M Obersteiner and A Nordin (2017). Impact of the 2°C target on global forest biomass use. *Forest Policy and Economics*, 83, 121–130.

Meinshausen, M, SCB Raper and TML Wigley (2011). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, magicc6: Part I — model description and calibration. *Atmospheric Chemistry and Physics*, 11, 1417–1456.

Nordhaus, W and P Sztorc (2013). User's Manual for Dice-2013R.

Riahi, K, R Schaeffer, J Arango, K Calvin, C Guivarch, T Hasegawa, K Jiang, E Kriegler, R Matthews, GP Peters, A Rao, S Robertson, AM Sebbit, J Steinberger, M Tavoni and DP van Vuuren (2022). Mitigation pathways compatible with long-term goals. In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, PR Shukla, J Skea, R Slade, A Al Khourdajie, R van Diemen, D McCollum, M Pathak, S Some, P Vyas, R Fradera, M Belkacemi, A Hasija, G. Lisboa, S Luz and J Malley (eds.). Cambridge, UK, New York, NY, USA: Cambridge University Press, doi: 10.1017/9781009157926.005.

Roelfsema, M *et al.* (2020). Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nature Communications*, 11(1), 2096, doi: 10.1038/s41467-020-15414-6.

Sohngen, BR, R Mendelsohn and R. Sedjo (1999). Forest management, conservation, and global timber markets. *American Journal of Agricultural Economics*, 81, 1–13.

Tian, X, B Sohngen, JB Kim, S Ohrel and J Cole (2016). Global climate change impacts on forests and markets. *Environmental Research Letters*, 11, 035011.

Tian, X, B Sohngen, J Baker, S Ohrel and AA Fawcett (2018). Will U.S. forests continue to be a carbon sink? *Land Economics*, 94, 97–113.

US Environmental Protection Agency (2021). Inventory of US greenhouse gas emissions and sinks: 1990–2019.

Xu, H, M Wu and M Ha (2019). A county-level estimation of renewable surface water and groundwater availability associated with potential large-scale bioenergy feedstock production scenarios in the United States. *GCB Bioenergy*, 11(4), 606–622, doi: 10.1111/gcbb.12576.