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Economic factors influence net carbon emissions of forest bioenergy expansion

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There is considerable concern that consuming forest biomass for energy will increase net carbon emissions from forests, which is defined as carbon debt. Using a market-based economic model, we test the effects of 51 demand pathways for forest bioenergy on future forest carbon stocks to assess the likelihood of incurring a sustained carbon debt lasting for several decades. We show that potential forest carbon debt from bioenergy expansion, measured as a near-term decrease in forest carbon sequestration relative to a baseline, occurs and persists only under a specific set of assumptions about carbon accounting, markets, policies, and future biomass demands. Finally, we evaluate whether forest regulations restricting biomass sourcing could influence the scale of carbon debt and/or reduce the time needed to recover the carbon debt (payback period). We show that under similar demand pathways and in the absence of direct carbon policies, imposing limits to supply is likely to reduce the payback period but does not avoid initial carbon debt.

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Forest biomass demand has increased due to renewable energy and climate policies¹ and recent climate commitments suggest it will grow further^{2,3}. Bioenergy from land systems will likely be critical in meeting global de-carbonization targets⁴. Despite its potential as a climate solution, there is a lengthy debate in the literature about the sustainability of forest bioenergy production and its effects on forest carbon balance⁵.

Studies of isolated forest systems argue that using forest biomass for energy generation results in a terrestrial carbon debt that can take decades to repay⁶. From the perspective of an existing forest stand of a given age (be it relatively young or nearing/past its age of economic or biological maturity), the carbon debt hypothesis argues that harvesting and allocating biomass to a new demand pull from the energy system displaces emissions for many years when a new stand has grown to take its place (see Nabuurs et al. (2017)⁷ and Bentsen (2017)⁸ for a more comprehensive discussion of forest carbon debts and factors driving their potential likelihood). The concept sows doubt that forest bioenergy mitigates climate change in the short to medium term, but it ignores physical realities of disturbance risks and diminished carbon sequestration capacity of stands over time, as well as market realities (that stands may be harvested for alternative uses)⁹. Other studies indicate similar effects at market scale, with increasing demands for forest products diminishing carbon sequestration^{10–12}. While such analyses capture demands for different end uses of forest biomass, these studies ignore key interactions between markets and forest management investments that can expand carbon sequestration¹³. Conversely, other economic studies have shown that increased forest bioenergy demand increases forest carbon storage, and impacts depend on private forest investments, policies, and land use change^{14–17}.

One critical methodological difference involves the role of price expectations. Traditional single-stand models of carbon debt (e.g., refs. 6,9) are forward-looking because they replant the site post-harvest, but they are myopic by assuming constant prices that are unaffected by market or policy changes. Static equilibrium forest sector models (FSM) (e.g., refs. 10,11,18) track landscape harvesting decisions through timber prices, wood product allocation, and replanting but they often assume a fixed forested land base and the inability for landowners to respond to market signals (e.g., invest in softwood plantation management). Dynamic FSMs (e.g., refs. 15–17) also account for landscape-level decisions and product substitution, but also allow landowners to adjust their management in response to prices.

An important question that emerges from a single-site model is whether carbon debt is an appropriate measure of carbon neutrality for an allocation of harvested biomass to the energy system. Carbon neutrality is often measured across space, or emission points, not across time, especially in national accounting methodologies¹⁹. Single-site models do not measure carbon neutrality because they focus on changes over time at a single point. Landowners with multiple stands would not quantify carbon neutrality by only measuring carbon emissions at a harvest site, but rather the net flux across all their stands. Similar logic flows to the market scale when assessing the regional impacts of a bioenergy policy impact—quantification of net impacts requires an assessment of all flux changes within a region as well as market reallocations that occur due to the bioenergy demand change (e.g., reduced pulpwood or sawtimber harvests). Furthermore, it is likely that stand-level models do not capture the complexities of alternative fate (e.g., product substitution) and net energy sector emissions.

Leaving aside the single-site models, the treatment of forest investments clearly influences outcomes in FSMs. Static models make assumptions about forest investments through replanting trees after harvest—but replanting is an assumed outcome

following the harvest decision. When presented with an increase in current and future wood demand (due to, e.g., bioenergy policy), static FSMs do not replant or manage forests more intensively due to higher prices. Thus, the planting intensity in the reference and biomass scenarios are the same. In contrast, dynamic models with endogenous land use and management will respond to higher market prices from expanded biomass demands by replanting and managing forests more intensively in the biomass scenario, thereby resulting in larger and more rapid aboveground carbon sequestration^{13,17}.

Historical market data supports the forward-looking behavior of the timber market. For instance, forest owners began planting timber in the 1950s in anticipation of a “timber shortage” that was predicted by the 1990s²⁰. Sweden offers another good example where forest expansion together with increasing forest management has both doubled the standing volume of forest since 1800s and also increased harvest⁵. Similarly, evidence from the 2020 FAO Forest Resources Assessment²¹ shows continued growth in forest plantations globally, indicating broad economic incentives to invest in planted systems. These trends are supported by recent empirical modeling at the global scale on the relationship between income growth (a key driver of forest product demand) and forest planting²². Empirical estimates in the Western US highlight how increased relative returns to forestry (driven by either policy or environmental change) can drive forest management decisions, including tree planting or forest type change²³. This relationship between market growth, management, and carbon is also supported by recent analyses^{24,25}.

In this study, we assess the concept of forest carbon debt and payback period with the dynamic global economic FSM (GTM)^{17,26,27}, highlighting economic factors that influence the size and duration of forest carbon debt. Since the dynamic model used for this study models all forests in the world, we expand the definition of carbon debt to measure an aggregate outcome associated with the global forest carbon stock. Specifically, forest carbon debt occurs when forest carbon stock in any period in a biomass demand scenario is lower than the carbon stock in the same period in the reference (baseline) scenario without forest biomass demand. Moreover, payback period is measured as the number of years required to move from a situation in which forest carbon stock is below the baseline to a situation in which the stock is above the baseline since the introduction of the new demand. For instance, if the demand is introduced in the model in 2020 and until 2070 forest carbon stock under the demand scenario is lower than the baseline, then the payback period is 50 years. That is, the forest carbon debt has been recovered after 50 years. Using this analytical definition of carbon debt, we then simulate 51 biomass demand pathways assuming different initial quantities (ranging from 50 million m³ to 1.2 billion m³yr⁻¹) and different average annual demand growth rates ranging from 0 to 5% (Fig. 1).

The demand pathways with zero or low growth closely mimic site-level LCA frameworks that assume a constant and lasting reallocation of forest biomass to a new demand source while limiting a dynamic framework's (or forest manager's) ability to respond to demand shifts and anticipated market changes through new investments. On the other hand, bioenergy demand pathways with growth rates between 1 and 5% are in line with the growth rates projected by integrated assessment models (IAMs) in response to a rising carbon price. Forest biomass demand quantity and expected growth rates are driven by the stringency of the climate policy target. For instance, under scenarios with a stringent temperature target (e.g., 1.5 °C, RCP 1.9), the demand is expected to grow at a higher rate than under a less stringent target (e.g., RCP 4.5)²⁸.

We simulate bioenergy demand pathways relative to a Reference (i.e., “Baseline”) scenario that represents a “middle of the

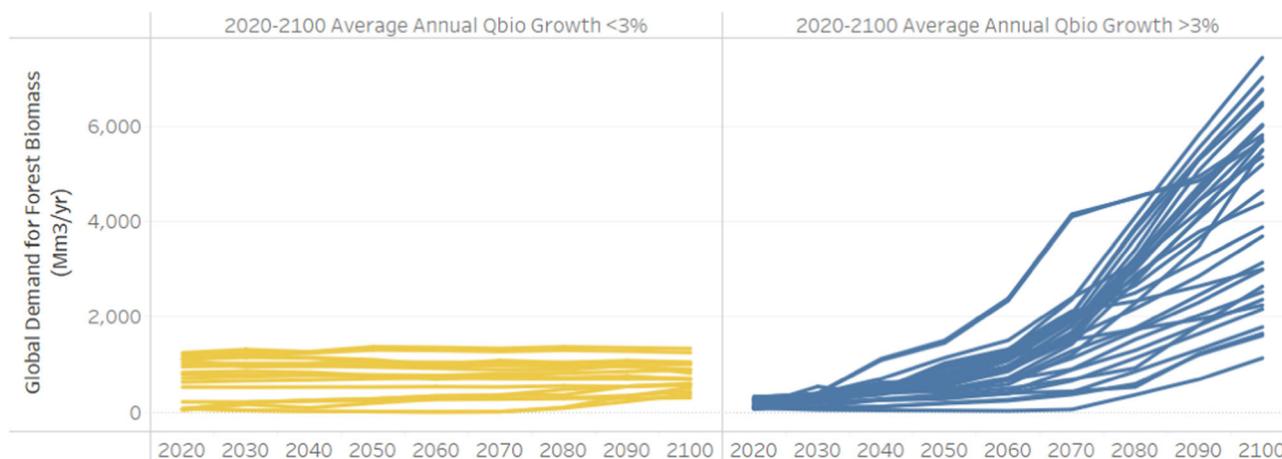


Fig. 1 Fifty-one forest biomass demand pathways in million m^3 (Mm^3) per year broken out by 2020–2100 average demand growth rate (2020–2100). Yellow lines show forest biomass demand pathways in million m^3 per year with a 2020–2100 average demand growth rate below or equal to 3%. Blue lines show forest biomass demand pathways in million m^3 per year with a 2020–2100 average demand growth rate greater than 3%.

road” narrative of future socioeconomic trends as part of the global Shared Socioeconomic Pathways (SSP) framework²⁹ without bioenergy demand or other climate policies (e.g., carbon price incentives on forest carbon sequestration). Under the Reference scenario, we do not assume additional biomass demand growth driven by policy change, but pulpwood and sawtimber demands do grow over time commensurate with projected changes in global population and income under SSP2. That is, under the SSP2, pulpwood and sawtimber demands are expected to increase as global consumption per capita (the main driver of these demands, the Z in the objective function in Eq. 1 in Methods) is expected to increase. As a result, timber prices increase over time, driving more investments per hectare and the conversion of unmanaged forests into managed forest (both naturally regenerated and plantation). Forestland is predicted to decrease overall because unmanaged forestland will be converted to cropland. On the other hand, more investments and more plantations together with more timber products in the future will drive an increase in forest carbon stock that is expected to raise from 958 GtC (current values) to 981 GtC in 2100 (Supplementary Table 1 and Supplementary Fig. 1).

We use our results to highlight important methodological differences that have contributed to a divergence in carbon debt estimates in the literature. Specifically, we use our simulation results to illustrate the importance of accounting for dynamic interactions between physical and economic systems when simulating both near- and long-term effects of forest bioenergy expansion. Our analysis supports the use of systems modeling frameworks for estimating both market and terrestrial carbon responses to forest biomass consumption in lieu of site-specific life-cycle analyses that ignore economic decisions related to forest harvest, management, and expansion. Furthermore, our analysis provides new insight into how economic drivers affect bioenergy carbon debts, which has implications for climate, renewable energy, and conservation policy design and global climate change policy discussion.

Results

The dynamic global forest sector model, GTM, endogenously selects the cost-effective composition of supply for each demand. In the case of forest biomass demand, there are three different sources of material: forest residues from harvesting (Forest residues are a byproduct of forest harvesting or mill operations that have relatively lower commercial value compared to industrial

roundwood. Logging residues include branches, tops, and stumps, while mill residues include bark, shavings, and sawdust. For this study, a maximum of 30% of total forest yield can be forest residues.), substitution from industrial timber products, and new harvesting (Supplementary Fig. 2). The new harvesting will come from both more land converted into forestland (extensification) and changes in forest management (intensification). In GTM, land and intensification of management are substitutes, such that when land is limited, there are larger increases in forest management intensity over time. The distribution of the supply sources differs as we move from the low-demand to the high-demand scenarios. In the very low-demand scenarios (i.e., average biomass demand below $500 \text{ Mm}^3/\text{yr}$ and demand growth of less than $0.5\%/yr$), forestry residues are almost enough to meet all the incoming demand, supplying an average of 93% of total bioenergy consumption. The role of residues declines as the demand increases, highlighting that the composition of the woody biomass supply is likely to affect the resulting changes in forest carbon.

The introduction of new biomass demand in the system increases total timber production relative to the baseline: on average, supplying 100 million m^3 of forest biomass for the energy sector will increase timber production by 60 million m^3 . The new demand produces an initial increase in the average price of all timber products (including forest biomass for energy) from the Baseline scenario. However, in the long run, the average price is expected to grow more than the Baseline only under the scenarios with high ($>3\%$) forest biomass demand growth. This is driven by the fact that under demand scenarios with a low or zero growth rate, forest biomass is mainly supplied by the substitution of other timber products (mainly pulp) in the early periods, and forest residues later. That is, for the same average global demand between 2020 and 2100, more residues are consumed and more industrial timber products are used under the scenarios with zero/low-demand growth than the scenarios with high-demand growth. Moreover, the same quantity of demand is expected to increase the average timber price more in the early periods than in the long term because fewer options are available in the short term to supply the new demand. For instance, a demand of $700 \text{ Mm}^3/\text{yr}$ of forest biomass is projected to increase the average timber price by 16% over 2020–2050, but (only) by 6% between 2050 and 2100.

Higher timber prices resulting from new demand drive changes in land use and land management decisions in the model. Specifically, an increase in the value of timber due to new demand for

biomass encourages more land to be devoted to forests and more investments in forest management than in the baseline. The increase is greater in scenarios with high-demand growth (Supplementary Fig. 3). On average, producing 1 m³ under high biomass demand growth (greater than 3%) increases forestland by 0.0015%, production intensity (m³/ha) by 5%, and forest management investments (\$/ha) by 0.4% relative to the baseline. On the other hand, under the low-demand growth scenarios (<3%), 1 m³ increases forestland by 0.0002%, production intensity by 3%, and forest management investments by 0.06% relative to the baseline.

The changes in land use and management together with the composition of forest biomass supply (residues, substitution and new harvesting) explain the projected changes in the amount of carbon sequestered in forests and forest products. Expectations of demand growth acceleration shift the sector toward both intensive and extensive management adjustments that improve the long-term climate benefits of the biomass policy. Forest carbon stocks in GTM are measured as the sum of carbon stock in four different carbon pools (above, soil, market, and slash). Above-ground carbon accounts for the carbon in all tree components. Soil carbon includes carbon stored in mineral and organic soils (including peat). Market carbon stock measures carbon stored in harvested wood products under assumed rates of product turnover in markets and resulting oxidization and decay. Finally, slash carbon measures carbon stored in residues that remain on site, resulting from timber harvesting operations (see Methods).

Results show that there is an initial reduction in forest carbon stock relative to the baseline under all 51 biomass demand scenarios, thereby resulting in at least a slight forest carbon debt in the decade in which an exogenous biomass policy is implemented (Fig. 2). Carbon debts range from modest to approximately 1 GtCO_{2e} yr⁻¹, commensurate with the level of removals for low-demand growth scenarios. Under the scenarios with biomass demand growth below 3%, this carbon debt is never fully recovered, and even increases slightly over the simulation horizon under some scenarios. On the other hand, scenarios with demand growth rates higher than 3% always recover the initial carbon debt. Some of the faster growth scenarios show high increases in long-term carbon storage, resulting in 0.2–5.5 GtCO_{2e} yr⁻¹ of additional forest C stocks by end-of-century (Supplementary Fig. 4).

The primary attribute for scenarios with sustained carbon debt is a low biomass demand growth rate (<1% yr⁻¹) and corresponding low relative price growth. Figure 3 captures these

dynamics by showing the relationship between the carbon debt period (colors), the average size of the biomass demand (circle size), the biomass demand growth rate (*x*-axis), and the change in average price growth for all forest-based products (weighted average of sawtimber, pulpwood, and biomass price growth) from the Baseline scenario (*y*-axis). Scenarios with higher biomass demand growth rates (>3%) show either full carbon debt recovery between mid and end-of-century (demand growth <3.5%), or a carbon debt that is recovered within 20 years (demand growth >4%). In some scenarios, the carbon debt is not recovered when the initial biomass demand is low, even when the growth rate is between 2 and 3%. In such scenarios, the price growth is not sufficient to incentivize forest investments. That is, forest biomass pathways with long-term growth >3% drive higher expected growth in the average timber price (all products incl. forest biomass) than the baseline. Furthermore, timber prices that grow faster than the baseline recover forest carbon debt because they drive more land to be converted into forests and more investments in forest management. When the average timber price (incl. forest biomass price) grows faster than the baseline, it is very likely that forest carbon debt is recovered in 70 years or less. Moreover, in the scenarios with a growth rate higher than 3% and, high average values of forest biomass consumption drive a quicker recovery of the debt.

By decomposing the stock of carbon in forest and forest products in four pools, we can measure the main drivers of the debt, and then assess whether the accounting approach might affect the results.

Much of the carbon debt results from the reduction in the stock of carbon in long-lived wood products (market C), rather than from a reduction in forest carbon stocks (Supplementary Fig. 5). Our analysis highlights the effect of forest product substitution: when new timber product demand (e.g., forest biomass for the power sector) is constant over time, the increased demand will mainly drive substitution between products, without increasing the overall value of forest-based products. As a result, carbon sequestered in forest products declines because of the immediate need to substitute timber from traditional wood product markets to biomass markets. On the other hand, above-ground carbon gains are the main driver of forest carbon debt recovery. Aboveground carbon is explained largely by forest area (extensive margin) and forest management intensity (intensive margin). When forest biomass demand increases at rates higher

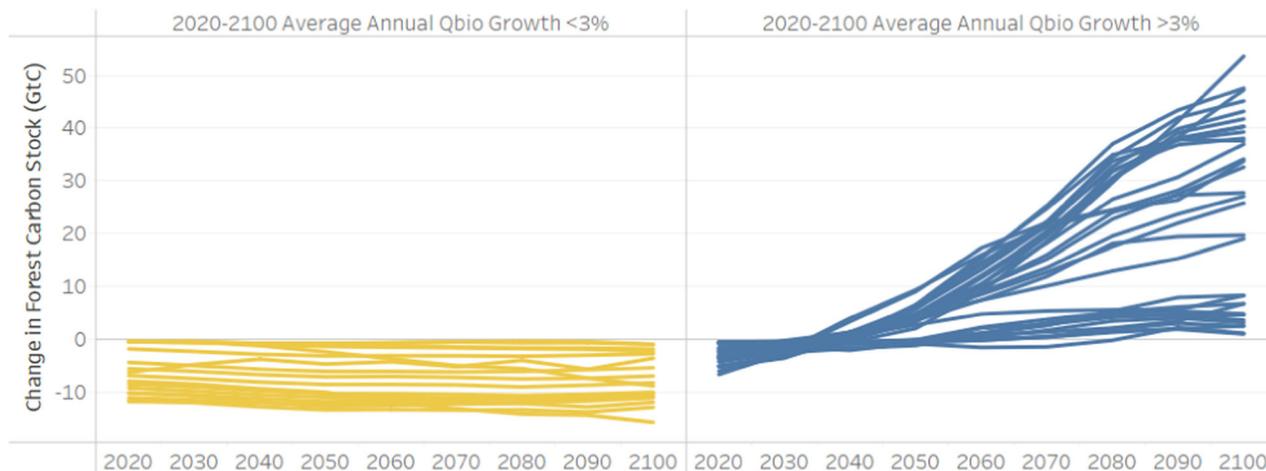


Fig. 2 Projected change in forest carbon stock in Giga tons of carbon (GtC) from baseline under the 51 forest biomass demand pathways (2020–2100). Yellow lines show the change in forest carbon stock from baseline under the demand scenarios with a growth rate below or equal to 3%. Blue lines show the change in forest carbon stock from baseline under the demand scenarios with an average growth rate greater than 3%. Positive values = more sequestration than the baseline (net sequestration), Negative value = less sequestration than the baseline (net emissions).

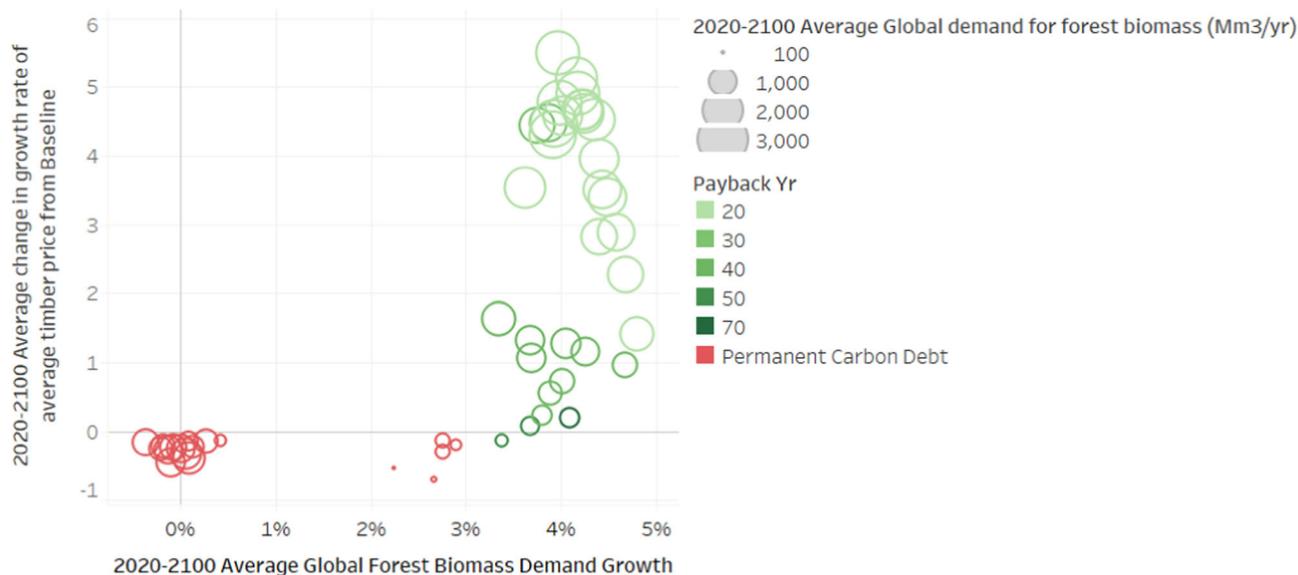


Fig. 3 Payback period of forest carbon debt under 51 demand scenarios divided by annual average forest biomass demand growth rate and change in average timber price growth from baseline, 2020–2100 (all carbon pools included). Each circle shows the payback period of the forest carbon debt per scenario according to the annual average forest biomass demand growth rate (x-axis) and change in average timber price growth from baseline (y-axis). All carbon pools are included in the carbon debt calculation. The color of the circle identifies the payback period: scenarios that never recover the carbon debt are in red (permanent carbon debt), while scenarios that recover it between 20 and 70 years are in green. The size of the circle represents the global annual average biomass quantity supplied between 2020 and 2100 and it ranges from 100 to 3000 Mm³/yr.

than 3% per year, the resulting investments and land conversion can offset the forest product substitution effect. For instance, for the same share of forest biomass supplied by wood products substitution (40%), demand growth <3% results in a perpetual carbon debt while this debt is recovered in 40–70 years when demand growth rates are higher than 3%. On the other hand, carbon debt scenarios are associated with low average management intensity (m³/ha) (<30% increase from Baseline) and low increase in average forest area (<1% increase from Baseline).

Soil C generally increases with forest area since more land will be converted into forests under the scenarios with high growth. Finally, slash C is expected to decline under all the demand pathways since more forest residues will be removed to supply forest biomass demand than the baseline. On average, we estimate that 1 m³ of forest residues consumed for forest biomass will release 0.2–0.7 tons of C.

Since carbon sequestered in industrial timber products is the main driver of carbon debt, we tested the effect of removing it from the payback period calculation. Our results show that the accounting rule affects the estimated payback period: if we remove market carbon, fewer scenarios experience carbon debt. Specifically, only the scenarios with a fixed level of biomass demand over time ($n = 11$) result in long-term carbon debt while all other scenarios ($n = 39$) have carbon debt for only 0–10 years (Fig. 4).

Finally, following the approach discussed in a recent study³⁰, we tested how different regulations or constraints on forest biomass supply (described in Supplementary Table 2) can influence carbon debt and the payback periods under the scenarios with demand growth higher than 2%. Results show that under similar demand growth pathways, imposing limits on the supply is likely to reduce the payback period but does not avoid initial carbon debt. For instance, regulations that limit the use of natural forests or limit the expansion of plantations to supply biomass reduce the payback period from 20 to 10 years under the scenarios with a high growth rate. Moreover, scenarios with a growth rate below the 3% threshold persist showing a carbon debt, even when supply is constrained (Fig. 5).

Discussion

These results have implications for bioenergy, climate and complementary forest carbon policy design. On the policy interpretation of our carbon debt results, it is important to reiterate that these projections are only capturing changes in forest and wood product C storage and do not account for potential energy system emissions displacement of expanded wood-based bioenergy globally. Thus, it is not appropriate to interpret a sustained carbon debt as a definitive net negative for the climate, especially if emissions from forest bioenergy combustion are captured and geologically sequestered (BECCS), or if bioenergy base load power facilitates other low-carbon renewables with intermittency challenges (e.g., wind and solar).

A full recovery and positive net forest carbon stock change over time is indicative of a bioenergy source that already exhibits net negative emissions over the long term. That is, regardless of how biomass is used (i.e., what fossil energy source it replaces), a long-term increase in forest carbon stock would almost certainly indicate a net climate benefit as our modeling assumes full emissions from biomass energy (see other studies^{2,16,17} for more discussion of how we model bioenergy demand and associated emissions impacts in our modeling framework). This result holds with exception of the unlikely scenario in which biomass transport, processing, and storage emissions outweigh the net change in landscape carbon storage, though these emissions sources are typically relatively small. While we do not provide a full life-cycle assessment of bioenergy pathways with connections to the energy system, our results illustrate that under certain conditions, biomass energy provides climate benefits.

We find that even in the absence of carbon capture and sequestration from bioenergy systems (a widely cited negative emissions technology), a positive net change in total forest carbon storage post-carbon debt can be interpreted as a bioenergy source that is not only carbon neutral, but exhibits net negative emissions. Notably, our results also indicate that alternative market expansion pathways for forest biomass (e.g., expanded production of long-lived wood products) instead of bioenergy demand

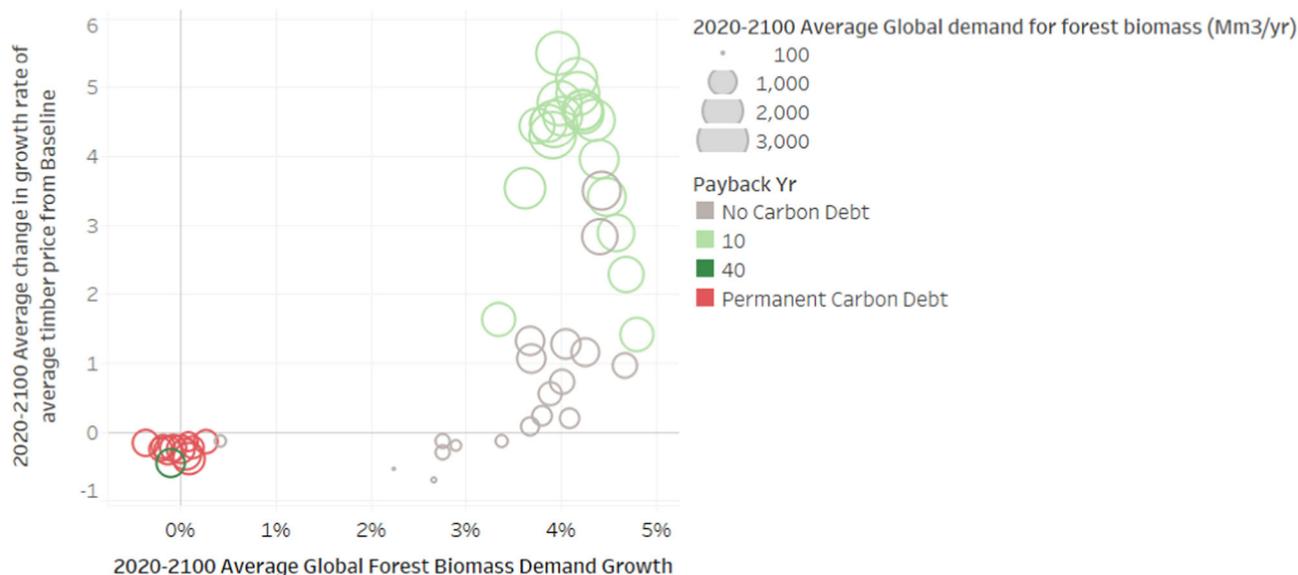


Fig. 4 Payback period of forest carbon debt under 51 demand scenarios divided by annual average forest biomass demand growth rate and change in average timber price growth from baseline, 2020–2100 (market C excluded). Each circle shows the payback period of the forest carbon debt per scenario according to the annual average forest biomass demand growth rate (x-axis) and change in average timber price growth from baseline (y-axis). All carbon pools with the exception of market carbon are included in the carbon debt calculation. The color of the circle identifies the payback period: scenarios that never recover the carbon debt are in red (permanent carbon debt), scenarios that recover it between 20 and 40 years are in green while scenarios that do not experience the carbon debt are in gray. The size of the circle represents the global annual average biomass quantity supplied between 2020 and 2100 and it ranges from 100 to 3000 Mm³/yr.

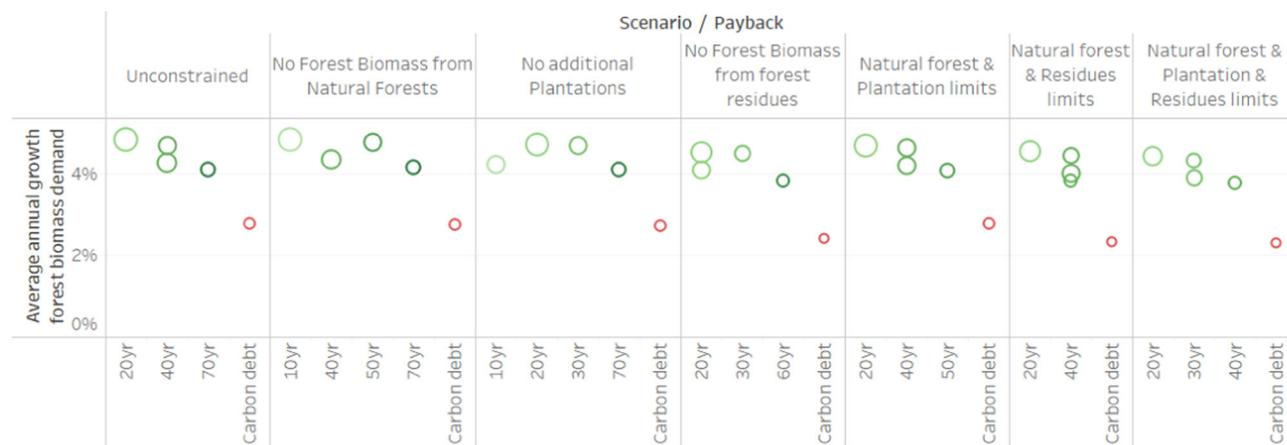


Fig. 5 Payback period of forest carbon debt under 5 representative demand scenarios by annual average forest biomass demand growth rate for 2020–2100 under different constraints on forest biomass supply 2020–2100 (all carbon pools included). Each circle shows the payback period of the forest carbon debt per scenario according to the annual average forest biomass demand growth rate (y-axis) across seven supply scenarios as described in Supplementary Table 2. All carbon pools are included in the carbon debt calculation. The color of the circle identifies the payback period: scenarios that never recover the carbon debt are in red (permanent carbon debt) and scenarios that recover it between 10 and 40 years are in green. The size of the circle represents the global annual average biomass quantity supplied between 2020 and 2100 and it ranges from 100 to 900 Mm³/yr.

expansion could provide dual carbon benefits in both terrestrial and wood product pools, though these pathways would reduce emissions displacement potential in the energy sector relative to biomass demand scenarios.

Our results have several other implications for climate/energy policy and forest management. First, stand-level perspectives that ignore the influence of markets on resource investments may not be appropriate for projecting emissions implications of a policy change or used to assess the carbon benefits of bioenergy production. Moreover, our results show that the timing of forest bioenergy production and consumption is crucial. Mitigation options like forest biomass for the power sector need to be assessed beyond the initial direct effect on emissions balance.

Static analysis often focuses on physical carbon flows, that is, the tradeoff between carbon emissions from biomass energy burning and carbon stored in forests and wood products, both in the near and long term. Economists alternatively consider the value of the ecosystem service flows when evaluating policy alternatives. In the case of biomass energy for instance, economists may evaluate the net value of the carbon emissions to the atmosphere over time using the social cost of carbon³¹, and assess whether the policy diminishes or increases the present value of social damages caused by carbon emissions. The future increase of forest carbon stocks despite the initial decline will be highly valued under these scenarios. Finally, it is important to acknowledge that forests provide other goods and services outside timber products and

carbon sequestration, including ecosystem services like biodiversity protection that are not included in this study and might be affected by the new demand for forest biomass. Specifically, Favero et al. (2022)³⁰ show that new demand for forest products (e.g., bioenergy) is likely to drive the conversion of unmanaged forests into managed forests, and while such a transition could increase carbon sequestration rates, there are possible biodiversity trade-offs to consider, especially in light of the recent global agreements to protect and maintain 30% of land resources (UN Biodiversity Conference COP15)³².

Second, regulating biomass supply sources reduces the payback period, and can be complemented by direct carbon policies such as paying for additional carbon sequestration or indirect policies such as direct payments for forest conservation, tax incentives to maintain natural forest area, or payments (or cost-share programs) to incentivize reforestation or improved forest management projects. Strengthening voluntary markets for carbon offsets can also help avoid unintended consequences of biomass demand pathways by recognizing a market value for forest carbon. Daigneault et al. (2022)²⁴ couples carbon sequestration incentives and forest bioenergy expansion across several socioeconomic and climate policy pathways using three models of the global forest sector, and results show that these policies can result in increases in forest carbon storage when implemented conjunctively.

Third, incentives that increase the productivity of managed forest systems, e.g., through new tree planting, genetic improvement, and silviculture, could complement the climate goals of forest bioenergy policies by increasing the supply of forest biomass per hectare of land. Bioenergy policy design has not always encouraged use of new forest plantations or more intensively managed forest systems as a feedstock source, but our results indicate that investments in industrial plantations to meet growing forest biomass demand can have tangible climate benefits.

Fourth, our analysis focuses largely on the effects of biomass demand on forest area, timber harvests, and carbon sequestration. The shifts in forest management and use that could emerge from these policy shocks will impact a range of other ecosystem services such as wildlife habitat, water and soil regulation, and cultural services. Additional research is needed to assess the implications of biomass markets on these services, particularly with respect to potential changes in the distributions of forest species and harvest intensities.

Finally, it is important to note that we do not link our modeling framework with integrated assessment models to assess optimal pathways for forest biomass utilization in the forest sector. Our results indicate that market expansion in a variety of potential product pools could indirectly increase carbon storage in terrestrial and wood product pools long-term, though reduced bioenergy pathways could lower emissions displacement potential in the energy system. Further research is needed to assess tradeoffs of alternative pathways, including a wide range of demand-side policies supporting growth in the forest industry.

Methods

This analysis uses a dynamic forest sector model, the Global Timber Model (GTM)^{26,27}. GTM is a dynamic partial equilibrium model that maximizes total welfare in timber markets over time across approximately 350 world timber supply regions by managing forest stand ages, compositions, management intensity, and acreage given production and land rental costs over 200 years. Land classes in the model were linked to vegetation types represented in ecosystem models such as BIOME/LPX-Bern^{33,34} or MC2^{3,35,36}. This version of the global timber model does not include climate change impacts that could vary under different GHG emissions pathways, although⁵. Furthermore, the model's baseline scenario does incorporate historical climate change, as the yield functions for the land classes in the model are consistent with current climatic conditions. Moreover, the model incorporates overall land limits on areas derived from the ecological models, such that only land that is capable of naturally supporting forests can be used for timber production. The model is calibrated to regional forest inventory to the extent possible, and

recent analysis indicates that future market and land use projections are robust to parametric uncertainty related to forest growth and land supply parameters³⁷. Finally, another GTM paper provides a historical calibration exercise with the model performing a simulation of a historical time to illustrate the important contributions of management to the evolution of terrestrial carbon stocks historically³⁸. Superimposed on this system is a demand side that anticipates changes in demand levels for industrial sawtimber, pulpwood, and biomass through time, primarily through exogenous changes in population, per capita income, consumer preferences for wood products, and technology.

The supply side of the model consists of forestland with differing biological yield functions estimated from forest inventory data or obtained from the literature. In regions where there is evidence of forest management, the yield functions can be modified through changes in investment as well as the number of hectares planted. Aggregate yield in a region can change over time if rising prices encourage a shift from a less productive to a more productive forest type. Major supply-side influences include forest management, harvest, processing costs, and shifts in annual agricultural land rents at the regional levels.

The model's optimization problem is formally written as:

$$\max \sum_0^\infty \rho^t \left\{ \int_0^{Q_t^{ind}} \{D(Q_t^{ind}, Z_t) + D(Q_t^{bio}) - C_H^i(Q_t^{tot})\} dQ_t^{tot} - \left[\sum_i C_G^i(m_i^t, G_i^t) - \sum_i C_N^i(m_i^t, N_i^t) - \sum_i R_i^i(\sum_a X_{a,t}^i) \right] \right\} \quad (1)$$

The model assumes a global demand function for industrial wood products $D(Q_t^{ind}, Z_t)$ where Q_t^{ind} is the quantity of industrial wood harvested each year t and Z_t is the global GDP per capita from the SSP2²⁹.

Demand uses the following functional form: $Q_t^{ind} = A_t(Z_t)^\theta P_t^\omega$ where A_t is a constant, θ is income elasticity and ω is price elasticity. Total industrial demand incorporates separate demand functions for sawtimber and pulpwood. Future demand for wood products is controlled by income elasticity, which we assume is 0.87 in this model, following Smangunson and Buongiorno (2001)³⁹ and Turner and Buongiorno (2004)⁴⁰ who estimate income elasticity of at least 1.0 in various models. We note that our model is a long-term model, not a short-term model. The forest sector does have inelastic short-term supply and demand functions; however, over the longer run, these are substantially more elastic⁴¹. We use a demand elasticity of -1.0 in the Global Timber Model (which is solved on a decadal basis). Supply is dynamically determined, but we calculate supply elasticity of approximately +0.4 in the short run, increasing to +1.0 in the longer run.

In Eq. 1 ρ^t is the discount factor, Q_t^{bio} represents global forest biomass demand for bioenergy as presented in Fig. 1. Finally, the model aggregates timber demand in a single global demand (Q_t^{tot}). C_H^i is the cost of harvesting and transporting timber to the mill, C_G^i is the cost of managing G_t hectares of forest type i (e.g., plantation, regenerating, natural), at varying intensities m_i , C_N^i is the cost of new forestland N at time t , and $R_i^i(\sum_a X_{a,t}^i)$ is the opportunity cost of land area X in age class a at time t . The objective function in Eq. 1 is nonlinear, and the model assumes that management intensity is determined at the moment of planting, and planting costs vary depending upon management intensity.

Equation (2) shows that the total quantity of wood depends upon the area of land harvested in the timber types in i for each age a and time t ($H_{a,t}^i$) and the yield function ($V_{a,t}^i$) which is itself a function of ecological forest productivity θ_i^t and management intensity m_{i0}^t .

$$Q_t^{tot} = Q_t^{ind} + Q_t^{bio} = \sum_i (\sum_a H_{a,t}^i V_{a,t}^i (\theta_i^t, m_{i0}^t)) \quad (2)$$

The stock of land in each forest type adjusts over time according to:

$$X_{a,t}^i = X_{a-1,t-1}^i - H_{a-1,t-1}^i + G_{a=0,t-1}^i + N_{a=0,t-1}^i \quad (3)$$

The initial stocks of land X_t^i are given and all choice variables are constrained to be greater than or equal to zero and the area of timber harvested $H_{a,t}^i$ does not exceed the total timber area. G_t^i is the area of timber regenerated land planted and N_t^i is the new forest planted. $C_G^i(\cdot)$, is the cost function for planting land in temperate and previously inaccessible forests while $C_N^i(\cdot)$ is the cost function for planting forests in subtropical plantation regions.

GTM takes into account the competition of forestland with farmland using a rental supply function for land (2). In Eq. (1) $R_i^i(\cdot)$ is the rental cost function for the opportunity costs of holding timberland $X_{a,t}^i$. For example, if timber prices rise relative to farmland prices, the model predicts that timber owners will rent suitable farmland for at least a rotation. Similarly, if timber prices fall relative to farm prices, suitable forest land will be converted back to farmland upon harvest. The total amount of forestland is therefore endogenous. This rental supply function is restricted to agricultural land that is naturally suitable for forests. It presumes that the least productive crop- and pasture- land will be converted first and that rental rates increase as more land is converted and thus becomes scarcer².

GTM assumes there is an international market for timber that leads to a global market clearing price. As the price of wood for bioenergy rises to compete with industrial timber, both timber and bioenergy are traded internationally⁴². Competition for supply equilibrates their prices. GTM is programmed into GAMS and solved in decadal time increments using the MINOS solver. Terminal conditions are imposed on the system after 200 years, far enough into the future so as not to affect the study results over the period of interest (2020–2100).

In the forestry model GTM, forest carbon stock is measured as the sum of carbon stock in four different carbon pools: above, soil, market and slash carbon.

Aboveground carbon accounts for the carbon in all tree components, including stem, stump, branches, bark, seeds, and foliage, as well as carbon in the forest understory and the forest floor. Aboveground carbon in the GTM framework does not include dead organic matter such as from slash, which is contained in a separate pool.

Aboveground carbon $C_{a,t}^i$ accounts for the carbon in all components of the living tree, including roots, as well as carbon in the forest understory and the forest floor, but does not include dead organic matter in slash, which is contained in a separate pool. For this analysis, we assume that carbon is proportional to total biomass, such that carbon in any forest of any age class is given as:

$$C_{a,t}^i = \sigma^i V_{a,t}^i (m_{a,t}^i) \quad (4)$$

where σ^i is a species-dependent coefficient that converts biomass to carbon. Given this, the total forest carbon pool $TFCP_t^i$ for each timber type is calculated as:

$$TFCP_t^i = \sum_a C_{a,t}^i X_{a,t}^i \quad (5)$$

Market carbon pool is the GTM classification for carbon stored in harvested wood products under assumed rates of product turnover in markets and resulting oxidation and decay. GTM classification of market carbon is consistent with the US EPA GHG Inventory definition of harvested wood product pools that affect "Changes in forest carbon stocks."

Carbon stock in harvested forest products HC_t^i is estimated by tracking forest products over time as follows:

$$HC_t^i = HC_{t-1}^i (1 - \omega^i) + \sum_a (\kappa^i V_{a,t}^i (1 - \tau_i) H_{a,t}^i) \quad (6)$$

where κ^i is the proportion of harvested timber volume that is carbon stored immediately after harvest. It ranges from 0.75 to 0.8 depending on forest type and location⁴³, τ_i is the portion of wood used in the energy sector and it is endogenously selected by the model. ω^i is the annual decline due to oxidization and decay, which ranges from 0.4% yr^{-1} for sawnwood products in some regions to 2% yr^{-1} for pulpwood products. HC_t^i accounts only for carbon stored in wood products, not forest biomass used for energy production.

Soil carbon includes carbon stored in mineral and organic soils (including peat). GTM models changes in soil carbon storage from forest land use change, but does not capture nuanced soil carbon dynamics associated with forest operations. Soil carbon $SOLC_t^i$ is measured as the stock of carbon in forest soils of type i in time t . The value of \bar{K} , the steady state level of carbon in forest soils, is unique to each region and timber type. The parameter μ^i is the growth rate for soil carbon. In this analysis, we capture the marginal change in carbon value associated with management or land use changes. When land use change occurs, we track net carbon gains or losses over time as follows:

$$SOLC_{t+1}^i = SOLC_t^i + SOLC_t^i (\mu^i) \left[\frac{(\bar{K} - SOLC_t^i)}{SOLC_t^i} \right] \quad (7)$$

Finally, slash carbon AS_t^i measures carbon stored in slash that remains on site, resulting from timber harvesting operations.

$$AS_t^i = \sum_a (C_{a,t}^i H_{a,t}^i - \kappa^i V_{a,t}^i H_{a,t}^i) \quad (8)$$

Over time, the stock of slash SP_t^i builds up through annual additions, and decomposes as follows:

$$SP_{t+1}^i = AS_t^i + (1 - \vartheta^i SP_t^i) \quad (9)$$

Decomposition rates ϑ^i differ, depending on whether the forest lies in the tropics (3%/yr), temperate (5%/yr), or boreal zone (7%/yr).

Total forest carbon stock in each region n at time t is calculated as follows:

$$C_GTM_{t,n} = \sum_i (TFCP_t^i + SOLC_t^i + HC_t^i + SP_t^i) \quad (10)$$

Such that if $C_GTM_{t,n} > C_GTM_{t+1,n}$ forests in region n are releasing emissions at time $t+1$ because forest carbon stock is declining, while if $C_GTM_{t,n} < C_GTM_{t+1,n}$ more sequestration is occurring. Forest carbon debt is measured as the difference in forest carbon stock at any time t from the baseline scenario at the same time.

The carbon payback period is measured as the number of years required to move from a situation in which forest carbon stock is below the baseline to a situation in which the stock is above the baseline since the introduction of the new demand. For instance, if "alternative" biomass demand is introduced in the model in 2020 and forest carbon stock under the "alternative" demand scenario is lower than the baseline until 2070, the payback period is 50 years. That is, after 50 years, the forest carbon debt has been recovered.

Data availability

Data are openly available in a public repository at: <https://public.tableau.com/app/profile/adam.daigneault/viz/RakingitinTheImpactofglobalforestbiomassdemandgrowthoncarbondebt/Overview>.

Code availability

The code that supports the findings of this study is openly available at: <https://u.osu.edu/forest/code-repository/>.

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Author contributions

A.F. designed the study, conducted analysis, interpreted data, and wrote the paper. J.B., B.S., and A.D. interpreted data and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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