BIOENERGY

Forests: Carbon sequestration, biomass energy, or both?

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There is a continuing debate over the role that woody bioenergy plays in climate mitigation. This paper clarifies this controversy and illustrates the impacts of woody biomass demand on forest harvests, prices, timber management investments and intensity, forest area, and the resulting carbon balance under different climate mitigation policies. Increased bioenergy demand increases forest carbon stocks thanks to afforestation activities and more intensive management relative to a no-bioenergy case. Some natural forests, however, are converted to more intensive management, with potential biodiversity losses. Incentivizing both wood-based bioenergy and forest sequestration could increase carbon sequestration and conserve natural forests simultaneously. We conclude that the expanded use of wood for bioenergy will result in net carbon benefits, but an efficient policy also needs to regulate forest carbon sequestration.

INTRODUCTION

A long literature establishes that forests are an efficient carbon sink through actions such as afforestation, forest management, and reduced deforestation (*1*–*5*). In recent years, forest-based actions have gained additional policy relevance as many countries have included forest sequestration activities in their nationally determined contributions toward reducing net carbon emissions as part of the Paris Agreement (*6*, *7*). At the same time, there have been increasing efforts in the United States and Europe to use wood as a source of biomass energy, under the assumption that wood-based energy is "carbon neutral" (*8*, *9*). Last, most pathways that aim to restrict global average temperature to 1.5°C by 2100 rely on large-scale deployment of afforestation actions and biomass used in power plants with carbon capture and storage (BECCS) (*10*).

The role that forests should play in mitigating climate change is still widely debated. Some researchers have argued that forest-based biomass energy is not carbon neutral (*11*–*13*) and, thus, that forest-based bioenergy should not be allowed to offset other energy sources under renewable energy standards. These assessments have suggested that when forest biomass energy is generated, it creates a carbon emission to the atmosphere that may, or may not, be taken back up by trees that grow in the future. Even if regrowth does occur, it occurs slowly over time, increasing global climate damages during the period when the released carbon is in the atmosphere. Given these concerns, some have argued that society should focus on enhancing carbon sinks rather than encouraging biomass energy (*11*, *13*–*15*). Assessing whether forest biomass energy is carbon neutral is complex and sensitive to assumptions about the spatial and temporal scale of the analysis, feedstocks used, and supply chain emissions. Buchholz *et al.*'s (*16*) meta-analysis found that the payback period (i.e., the time required by the forest to recover through sequestration the carbon dioxide from biomass combusted for energy) ranged from zero to more than 1000 years. Birdsey *et al.* (*17*) conclude that increasing bioenergy production and pellet exports often increases net emissions of greenhouse gases (GHGs) for decades or longer, depending on source of feedstock and its alternate fate, time horizon of analysis, energy emissions associated with the supply chain and fuel substitution, and impacts on carbon cycling of forest ecosystems. The studies examined in these two reviews, however, ignore economic analysis that accounts for the interactions between demand and supply and forest management (*18*–*23*). These interactions include assessment of the opportunity costs of intensified harvesting and management, as well as expansion of intensive timber harvesting activities into extensive (e.g., unmanaged) regions.

This paper examines key issues related to the consequences of bioenergy policies on forests and carbon emissions, namely, management response, the efficiency of the policy, and the impacts of increasing biomass demand on forest ecosystem services. To analyze these issues, we use a dynamic global forest model that accounts for the biological and economic responses to various policy incentives on forest management and carbon fluxes in all regions of the world (*22*, *23*). Such integrated assessment modeling of the forest sector provides important insights into the temporal and spatial scale of forest management efforts that must be undertaken to increase wood flow in the face of large, new biomass energy demands, as well as their interactions with carbon policies. The analysis clarifies how various policy incentives for biomass energy and carbon sequestration influence the net exchange of carbon between the atmosphere and forested ecosystems. Last, a sensitivity analysis tests the results under different assumptions on land constraints and economic parameters.

RESULTS

The debate behind woody biomass for energy

Three critical issues have arisen in the literature related to the use of woody biomass for energy. First, the impact of biomass energy policies on carbon depends on the supply response, which include investments in new forests, increased management of existing forests, harvests of inaccessible and unmanaged forests in the extensive margin, conversion of those forests to more intensive uses, and substitution across product uses. Studies that assume there is little to no management response, or consider only use of the extensive margin, predict that bioenergy demand will increase carbon emissions (*16*, *17*). Studies that allow efficient investments in forestry management find that bioenergy policies lead to a net increase in forest sequestration (*18*–*22*). A key determinant rests on the response of land use and management

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to the price changes induced by bioenergy policy. If models include management responses, higher prices invariably encourage more management and forest area, and thus, biomass energy policies reduce net emissions over time. Alternatively, if forest land area and forest management do not change or decline with biomass energy policies, and there is additional harvesting of unmanaged stocks, then the policies typically result in net emissions. It is, thus, important to isolate the role of management on forest carbon stocks.

Second, studies suggesting that biomass energy should be taxed have ignored the literature showing the efficient economic treatment of carbon fluxes between the atmosphere and forests in the broader carbon cycle (*4*). From the perspective of the atmosphere, a ton of CO_2 in forests is a ton not in the atmosphere, suggesting that the social cost of carbon can be used to value carbon exchanges, or fluxes, between the atmosphere and ecosystems (*24*). Two equally efficient schemes have been proposed in the literature to credit carbon fluxes between the atmosphere and forests: a carbon rental approach (*4*) and a carbon tax and subsidy approach (*25*). Under both approaches, the efficient climate policy counts emissions when forests are used for energy or wood products as an increase in atmospheric carbon, but they also count sequestration that occurs when forests grow. Bioenergy emissions can be taxed like other GHGs under an efficient approach to credit carbon fluxes, but only if the benefits of storing carbon in forested ecosystem are also recognized and subsidized (*25*). That is, a policy that taxes forest-based bioenergy without recognizing that forests also sequester carbon through growth [the Schlesinger proposition (*26*)] is inefficient and will lead to too little carbon in forests and too much carbon in the atmosphere.

Third, there are concerns that ecosystem services and biodiversity provided by primary forests could be affected if harvests are diverted from traditional wood products to bioenergy (*13*, *14*) or the level and quality of standing biomass on managed forests are diminished due to higher levels of residue removals (*27*), shorter rotations (*28*, *29*), or more land moved from no/low management to more intensive management. Concerns with ecosystem services, however, tend to focus on the effects of biomass harvests at individual sites (*13*, *14*). While more intensive harvesting will be a consequence of any biomass energy policy that increases the demand for wood, intensification will not occur at a few selected sites, but across forests, especially under widespread biomass energy or carbon neutrality mandates. To gauge the full impacts of policies, models must be able to analyze the full spatial and temporal consequences on the global forest ecosystem.

In numbers: pro and cons of woody biomass demand

We use the dynamic global timber model (GTM) to assess how bioenergy demand affects the forestry sector, forestland, and carbon sequestration (*4*, *30*). GTM compares timber harvesting and management in more than 200 managed and natural forest ecosystems across 16 world regions (fig. S1) under different bioenergy demand scenarios to a no-bioenergy demand scenario (*22*). The model used the Shared Socioeconomic Pathway (SSP) 2 marker scenario projections of gross domestic product (GDP) and population (*31*–*33*) to simulate forest product demand, while bioenergy demand projections [following the assumptions presented in Lauri *et al.* (*34*) that 9% to 12% of total bioenergy demand is sourced by dedicated forest plantation; bioenergy is converted from gigajoules (GJ) to cubic meters (m^3) of forest biomass using constant conversion factors of 7.2 GJ/m^3] and carbon price paths under the same SSP2 scenario for each Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) are used to simulate the future demand for woody biomass and the value of CO_2 (fig. S2).

In general, bioenergy consumption is expected to increase with the stringency of the RCP target. For reference, under RCP 1.9—the scenario most consistent with a 1.5°C target—about 30% of the total energy supply through 2100 is estimated to be sourced from bioenergy with carbon capture and storage (BECCS) (*33*). Because bioenergy demand is expected to come from a variety of sources, we assume about one-third of the supply is provided by forests, which is consistent with other global analyses (*34*). The model assumes a homogenous form of woody biomass energy demand without distinguishing types of woody biomass production. From the perspective of our model, this means that each type of wood that could be used as an input into biomass energy production is paid the same price.

Increasing demand for woody biomass will have noticeable impacts on the global forest sector compared with a no-policy baseline case (tables S2 to S4). Timber prices could more than triple if woody biomass consumption reaches 4.3 billion m^3/year by the end of this century, as in the RCP 1.9 scenario (Fig. 1A). The model does account for the substitution between wood products and biomass, and the increasing demand for woody bioenergy negatively affects the industrial timber market. That is, there is a decline of between 30 and 80% in the production of industrial timber over the century projected across the RCPs, with the largest reduction under RCP 1.9.

Higher timber prices incentivize afforestation across the globe (Fig. 1B). However, higher timber prices also encourage harvesting of natural forest areas (forest types are defined as follows: "plantation" = intensively managed plantations; "managed" = extensively managed, often naturally regenerating forests; "natural" = inaccessible, unmanaged natural forests) (Fig. 1C), which are replanted as a mix of low-managed forests and intensive plantations (Fig. 1D). Total global forest carbon sequestration is projected to increase only when the demand for woody biomass is large enough to encourage consumption greater than 1.1 billion m^3/year by 2100, i.e., an RCP of less than 4.5 (Fig. 1E). When biomass demand is lower than this level, it does not generate high enough timber prices to generate enough investments in forests or plantations to offset carbon losses that occur when forests are harvested. The carbon losses occur primarily in regions dominated by large areas of remaining inaccessible forests, namely, Latin America, Southeast Asia, Canada, and Russia. Older forests have substantial carbon stocks that are not compensated. Eventually, if biomass energy demand is strong enough, investments in forests will outweigh losses, and carbon turns positive. The expenditure on forest management, as measured by dollars per hectare invested in replanting, also matters, as it increases with more stringent climate policy (Fig. 1F).

The model accounts for carbon stored in four different pools. The increase in carbon stocks is primarily driven by improvements in aboveground carbon, while more forestland marginally increases soil carbon due to afforestation relative to the baseline scenario. Carbon stored in harvested wood products is projected to decline under all policy scenarios because the increasing demand for woody biomass reduces the quantity of noncombusted wood products (fig. S4).

Expanding woody biomass energy could result in a 286 (RCP 6.0) to 1931 (RCP 1.9) m^3/year increase in total timber harvesting compared with the baseline scenario. Increases in harvests are not equally distributed across the globe though (Fig. 2), with the largest harvest increases expected in places where industrial wood harvesting is already an important part of the landscape and regional economy. For instance,

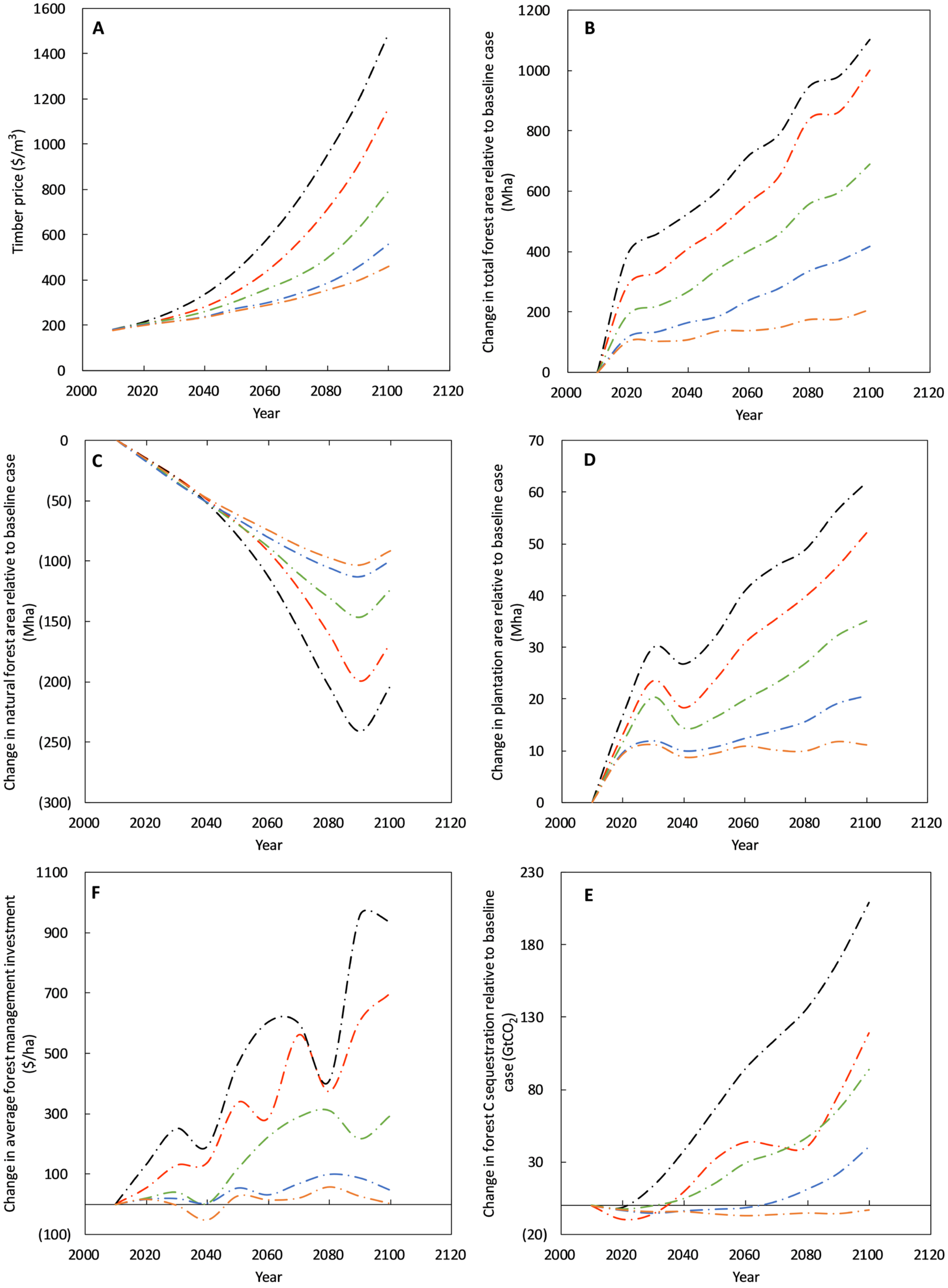

Fig. 1. Global impacts for increased wood-based bioenergy demand, 2010–2100. (**A**) Timber prices, (**B**) total forest area, (**C**) natural unmanaged forest area, (**D**) plantation forest area, (**E**) total forest carbon stock (includes all the four carbon pools presented in fig S3), and (**F**) management investment relative to the baseline (no bioenergy demand). Black, RCP 1.9; red, RCP 2.6; green, RCP 3.4; blue, RCP 4.5; orange, RCP 6.0.

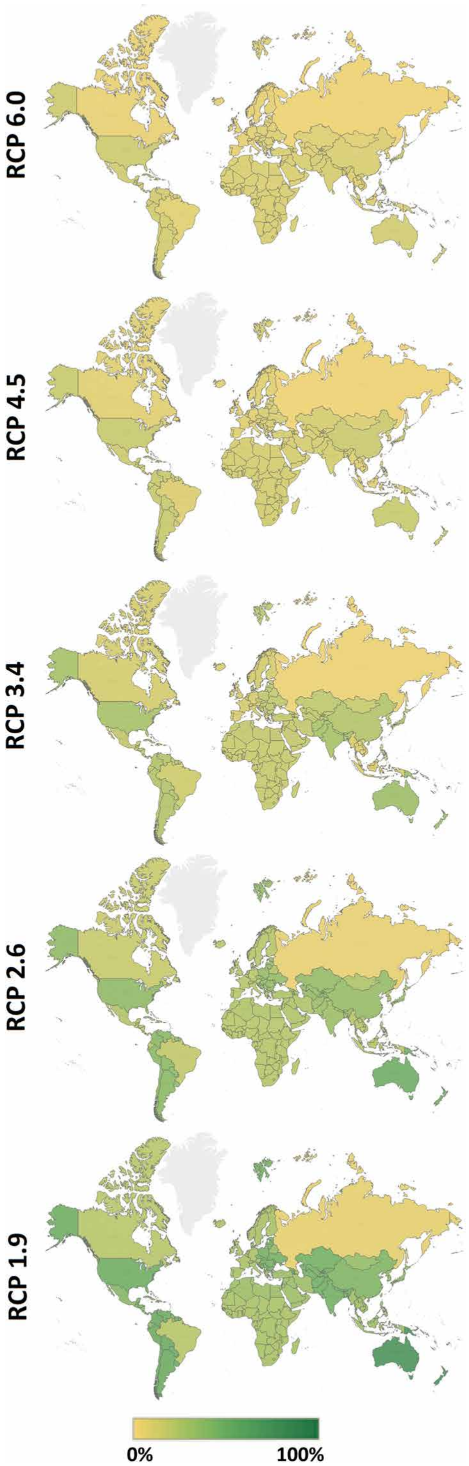

Fig. 2. Mean change in total regional harvests relative to the baseline, 2010–2100.

in the RCP 3.4 case, U.S. harvests increase by an average of 27% over a 100-year period, while harvests in Southeast Asia and Russia only increase by 6 and 2%, respectively.

The increased demand for woody biomass encourages changes in forest management along several margins that are typically ignored in traditional life cycle analyses. First, the area of intensively managed plantations increases by up to 61 million hectares (Mha), or 60%, over the baseline (Fig. 1C). These plantations have rotation ages ranging from 10 to 30 years and, thus, can be used to ramp up timber and biomass supply relatively quickly. We calculate that for every 1% increase in timber price, the area of plantations increases by 0.32% globally.

Second, forests that currently have limited management become more intensively managed via increased investment in harvesting and replanting, thinning, fertilizing, and other actions. Every 100 million m^3 of additional woody biomass energy supply could create 5.6 Mha of more intensively managed forests. Higher prices provide a market signal to landowners, who will take steps to increase their forest stocks via expanding the area in managed forests and/or improving management activities (*18*, *35*). Expenditures on forest management could increase by an average of $230 per hectare on managed forests due to the increase in woody biomass demand, nearly 70% greater than the mean baseline expenditure estimate (Fig. 1F). Some of the land that we project that will become intensively managed is currently ecologically sensitive and/or high in biodiversity. Assuming that there are no other forest carbon sequestration incentives or forest conservation policies in effect, we estimate that if woody biomass demand rises to 4 billion m^3/year, as under RCP 1.9, about 15% of global natural forest area, or 250 Mha, could be converted to a more intensive management regime (fig. S5). These results confirm that "standard" bioenergy policy targeting woody biomass generally has a negative impact on the world's natural unmanaged or inaccessible forests. However, these natural forests will not be converted to agriculture, as economic incentives offset losses through planting forests managed at different degrees of intensity and avoided deforestation of managed forests (fig. S5).

Third, other land will be converted to forests and, thus, increase the absolute area of forests globally. The largest demand scenario (RCP 1.9) estimates a potential increase in forest area by 1.1 billion ha, 30% more than the current forest cover by 2100 (Fig. 1B). This is within the bounds of the recent paper by Bastin *et al.* (*36*), who identify an area of 1.6 billion ha of additional land that could support forests, of which 0.9 billion ha are located outside valuable cropland and urban regions. For this study, we used the 1.6 billion ha as an upper bound for our simulations, and in the sensitivity analysis, we tested the results under the more stringent 0.9 billion limit. The 1.1 billion ha estimate is large but not an outlier (fig. S6). Our results are confirmed by integrated assessment models (IAMs) with land modules and crop prices, which suggest that global forest area could increase by up to 1.0 billion and that about 5.4 billion ha could be covered by forests under the RCP 1.9 stabilization scenario with approximately 1.9 billion ha new forestland (*31*, *33*).

While we do not explicitly model crop production or prices, our model incorporates land rental functions that require paying higher prices to rent land as more land is used for forests. The increases in rents that we project are consistent with other studies in the literature. Under the RCP 1.9 scenario, our global average land rents between now and 2100 are estimated to be four times higher than the baseline rents. Popp *et al.* (*37*) similarly shows that agricultural land for food and feed production declines as more land is used for bioenergy and carbon sequestration. They do not present estimates of land rents, but they do show that crop prices could be between two to six times higher than the baseline under a high mitigation scenario.

An efficient approach to carbon management

This section illustrates the difference between an efficient carbon management approach, which incentivizes both sequestration and avoidance of emissions, and an inefficient approach that only uses a carbon tax to incentivize the avoidance of emissions from woody biomass production. An efficient approach to manage carbon exchanges between the atmosphere and the biosphere can be accomplished by using either a carbon rental (*4*) or a carbon tax and subsidy approach (*25*). Both of these efficient approaches recognize that emissions from biomass energy are like all other GHG emissions and that forest growth removes carbon from the atmosphere. On the other hand, a tax on emissions from bioenergy demand (penalty scenario) without an offsetting subsidy for carbon accumulation is an inefficient approach because it creates relatively less demand for forest products, depresses timber prices (Fig. 3A) and forest area (Fig. 3, B to D),

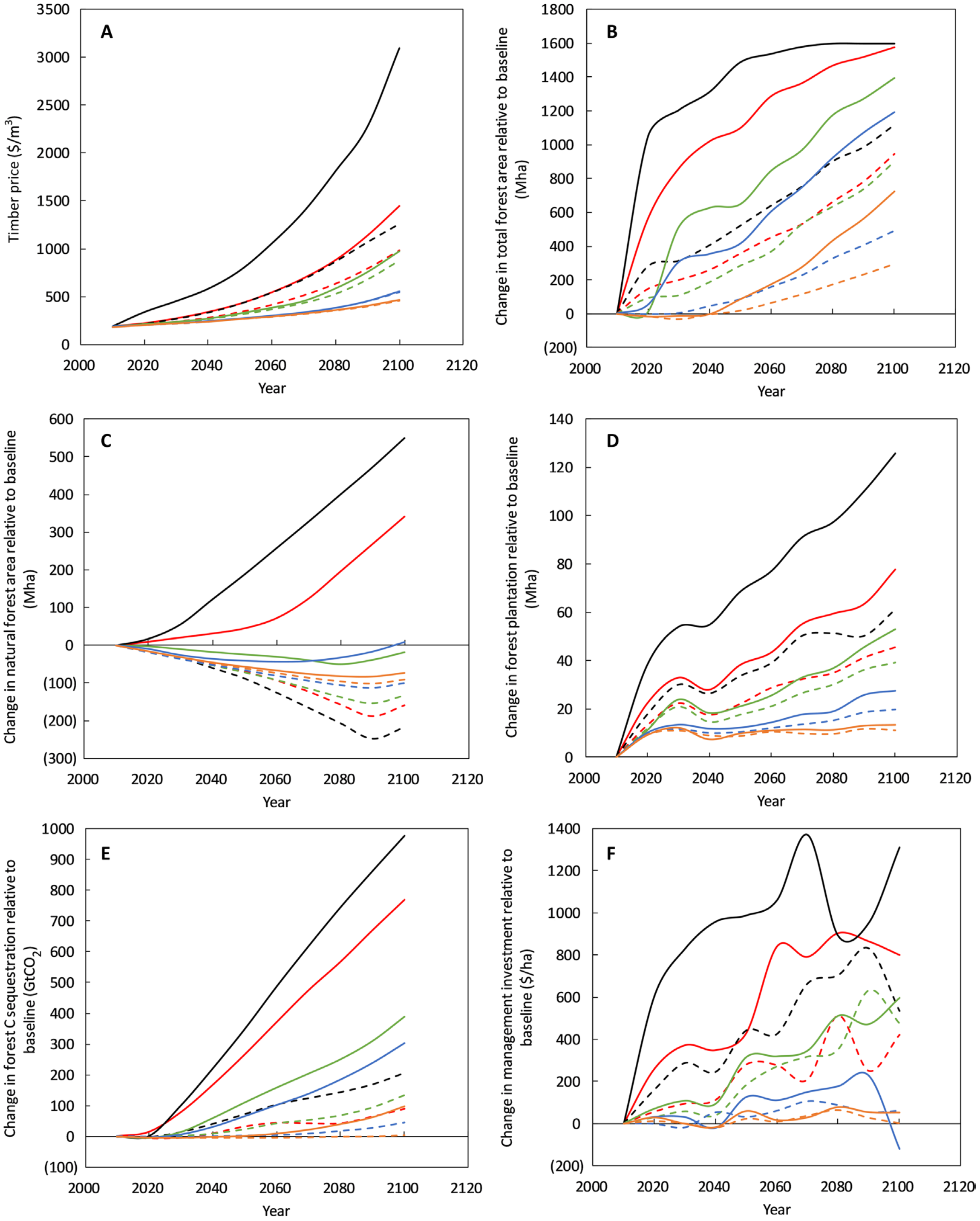

Fig. 3. Global impacts for alternative wood-based bioenergy policies, 2010–2100. (**A**) Timber price and changes in (**B**) total forest area, (**C**) natural forest area, (**D**) forest plantation area, (**E**) total forest carbon stock, and (**F**) management investment relative to the baseline (no bioenergy demand). Dashed, carbon penalty; solid, forest carbon rental; black, RCP 1.9; red, RCP 2.6; green, RCP 3.4; blue, RCP 4.5; orange, RCP 6.0.

lowers investment in forest management (Fig. 3F), and, thus, leads to lower forest carbon stocks (Fig. 3E) compared with the efficient approach (carbon rental scenario). That is, under any given demand for woody biomass, an approach that only penalizes emissions will deliver less carbon sequestration than the efficient rental approach. Moreover, timber prices are higher under the rental scenario because there are additional benefits associated with holding carbon in forests, thereby potentially reducing the annual timber supply.

Critically, the penalty approach, as suggested by Searchinger *et al.* (*13*), could cause a large reduction in the area of natural inaccessible forests of up to 200 Mha under the strong biomass energy demand of RCP 1.9 or 2.6 (Figs. 3C and 4). Without valuing standing stocks of forests through a subsidy for forest carbon sequestration, higher timber prices (Fig. 3A) provide a substantial incentive to convert natural forests to other forest types (Fig. 3B). The tax cannot avoid this outcome. The largest declines in natural forest areas under a penalty approach will occur under biomass demand higher than 1.5 billion m^3/year, mainly in the tropics, followed by the temperate zone (Fig. 4). In contrast, a carbon rental approach encourages protection of standing natural forests by valuing the standing stock, such as old growth harvests in boreal regions and unmanaged forests in the tropics. In particular, a combination of the high carbon prices and bioenergy demands (RCPs 2.6 and 1.9) will avoid future deforestation of tropical natural forests relative to the baseline. That is, opportunity costs of land are relatively low in the tropics, so there is a reduction in forestland conversion to cropland. Second, the carbon gains in the tropics are relatively fast and large, such that the rental values encourage substantial carbon sequestration comparing to temperate and boreal forests.

Each of the policy approaches leads to more forestland globally over the next century, but estimates vary at the regional level (Fig. 5). In the cases where there is a penalty imposed on harvesting biomass, even with the relatively low carbon prices of RCPs 6.0 and 4.5, there could be 10 to 25% less forest cover in parts of the tropics by 2100 compared with the forest carbon rent policy. The forest carbon rental payment approach is expected to increase forest cover across the globe, with the more stringent mitigation scenarios leading to increases of 50% or more in many parts of the world.

A forest carbon rental approach has sometimes been considered an infeasible climate change mitigation policy option because of the complexities with measuring and verifying changes in carbon stocks and possible governance issues in developing countries (*35*, *38*). However, placing a tax on woody bioenergy could exacerbate one of the issues the policy is intended to prevent, namely, the loss of natural forests and associated ecosystem services. Despite this, we find that increasing the demand for wood-based bioenergy, regardless of the policy approach, will increase the total forest carbon in nearly all scenarios (Fig. 3E). Under the penalty scenario, average stocks could increase by 34 gigatonnes carbon dioxide eqiuvalent ($GtCO_2e$) or about 1% compared with the baseline. This is equivalent to 0.4 $GtCO_2e$/year or 1.1% of 2018 global CO_2 emissions (*39*). Including payments for forest carbon sequestration has additional benefits. Forest area could expand by 500 Mha or more, and total carbon stocks could increase by an average of 2.3 $GtCO_2e$/year, offsetting 7.1% of current annual emissions (Fig. 3E). In nearly all scenarios, a majority of this net increase in carbon stocks is due to increases in aboveground carbon, while the substitution of some timber to bioenergy has a somewhat negative effect (fig. S7).

Growing wood-based bioenergy demand will positively affect forest management investment regardless of the policy approach, averaging about 80% above baseline investment. Demand for wood products in general will stimulate investment as landowners are expected to accrue a higher return. However, a forest carbon rental and increased biomass demand policy could double investment compared with the biomass penalty approach (Fig. 3F). Management decisions affect the amount of carbon stored in forests in different ways. First, GTM controls rotation ages, which influences carbon stocks on sites, with higher rotation ages leading to greater timber supply and more carbon, and vice versa. Second, under high bioenergy demand and/or carbon prices, the model projects more replanting, which, compared with natural regeneration, will increase average carbon on a site over a rotation. Third, GTM shifts species types over time in response to prices and land rental values. Fourth, the model shifts species from no management to modest management (harvesting with natural regeneration or harvesting with replanting in some cases, depending on value). In nearly all cases, this conversion of older forests to younger forests leads to more timber output but less carbon. Last, GTM includes management intensity on replanted land. This type of management intensity, which could include genetic selection, fertilizing, density controls, and other approaches, increases both carbon stocks and the value of timber. This type of management intensity is monitored in the model by the expenditure per hectare of forestland, with higher expenditures leading to more timber and more carbon.

Sensitivity test

We tested the effects of bioenergy demand on forestland and carbon sequestration and the efficiency of the rental approach relative to the penalty approach under a scenario in which forestland additions are limited to 0.9 billion ha, following Bastin *et al.* (*36*). Even under this constrained scenario, our findings are confirmed: Bioenergy demand will increase total forestland and forest carbon sequestration compared with a no-bioenergy (baseline) scenario (Fig. 6, A and C), and the carbon rental policy provides an efficient approach to regulate the increasing demand for bioenergy by protecting natural forestland while providing woody biomass for energy at the same time (Fig. 6B). Although forest area does not expand as much with the tighter constraint, it is around 50% lower; forest carbon storage declines by only 20 to 30%. Carbon declines proportionally less than forest area because forests are managed more intensively to increase timber production, and this in turn enhances carbon storage. Any time there is a conversion in natural forest areas from inaccessible to accessible and lightly managed forests, there is lower total carbon stored over time. Thus, the efficient carbon rental climate policy leads to more carbon by protecting more natural forests from conversion.

Additional sensitivity analysis that adjusts key model parameters such as the land supply elasticity, management response to forest investment, and the cost of accessing and clearing natural forests to half and double their original values indicates that our general findings still hold (fig. S8). That is, higher biomass demand will increase the value of timberland, incentivize additional investment in forest management and afforestation, and result in greater forest carbon stocks over time, even if our model includes more pessimistic (i.e., less responsive) parameter values. However, the relative impact that each parameter has on the estimates varies. For example, a low land supply elasticity results in about half the afforestation rate of the high land supply elasticity case, simulating the potential effect if landowners are more resistant to converting their agricultural lands to forests. As a result, forest carbon stocks would still increase over

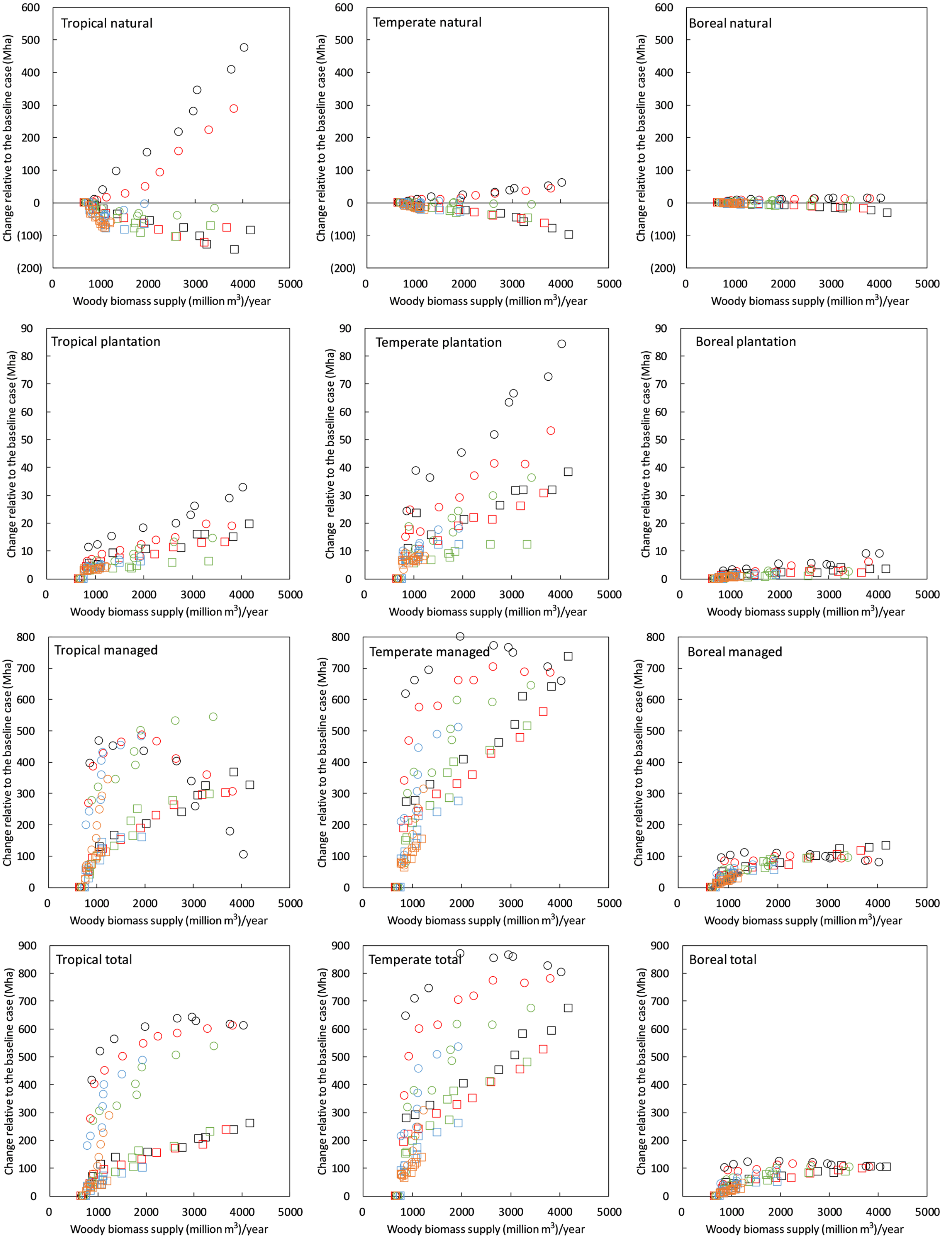

Fig. 4. Changes in global forest area by major ecosystem relative to baseline case under alternative wood-based bioenergy policies. Square, carbon penalty; circle, forest carbon rental; black, RCP 1.9; red, RCP 2.6; green, RCP 3.4; blue, RCP 4.5; orange, RCP 6.0.

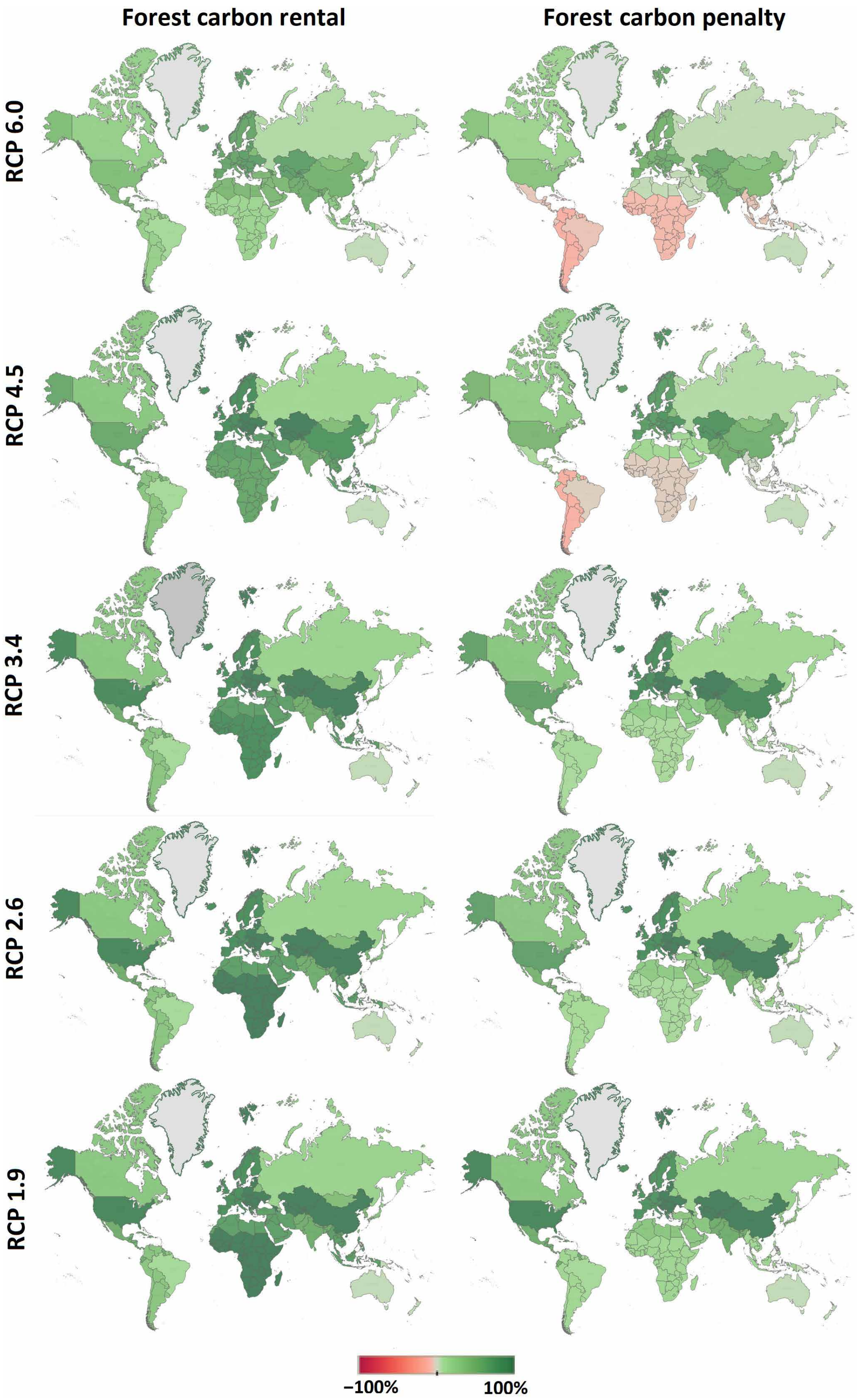

Fig. 5. Regional changes in forest area relative to 2010 for forest carbon rental and carbon penalty scenarios.

the next century, but at a rate that is about 40% less than most of the other sensitivity cases. Furthermore, our sensitivity analysis indicated that estimates were most sensitive to the forest carbon rental scenarios, especially in the cases with high carbon prices that incentivize more competition between carbon, bioenergy, and timber production.

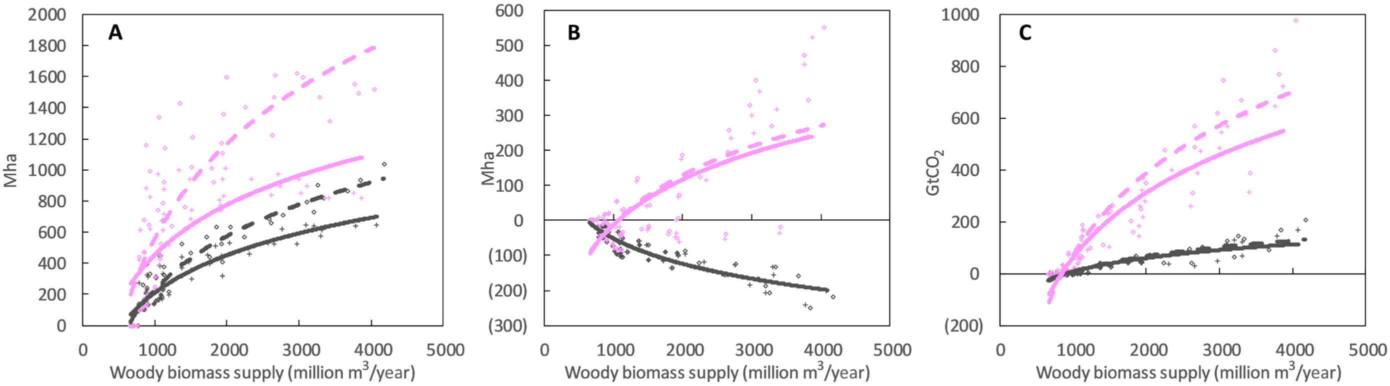

Fig. 6. Estimated impacts for alternative land constraint scenarios under all RCPs. (**A**) Total forest area; (**B**) natural forestland and (**C**) forest carbon sequestration versus woody biomass production relative to the baseline (no bioenergy demand) for alternative land constrained scenarios and policy scenarios under all the RCPs. Diamond, 1.6 billion ha additional forestland limit; plus, 0.9 billion ha additional forestland limit; gray, carbon penalty; pink, forest carbon rental. Trend lines: dashed, 1.6 billion ha; solid, 0.9 billion ha additional forestland limit.

DISCUSSION

Projections using IAMs show that bioenergy demand is very likely to dominate under the 1.5° to 2°C target scenarios (*10*). Our study provides a comprehensive outlook of how this bioenergy future will affect forest harvests, prices, timber management investments, the area of forest, and forest carbon balance when market interactions and management responses are considered. Dynamic market and management responses are usually ignored in many environmental studies that provide only a partial view of the ongoing debate about benefits and risks of increasing global bioenergy demand (*12*–*17*, *36*).

The results show that lower levels of bioenergy demand, consistent with RCPs 4.5 and 6.0, can lead to net carbon emissions if the higher prices encourage more harvesting of natural forests but not enough of an increase in investments in forest regeneration. For RCPs more stringent than 4.5, bioenergy demand is sufficiently high that it encourages strong enough investments in forest management to offset the negative effects of harvesting inaccessible and natural forests. Thus, for these higher levels of bioenergy demand, there are net positive effects on the global carbon balance, although there are notable impacts on natural forests. Across all ranges of bioenergy demand, efficient forest carbon sequestration policies can be deployed to ensure that forests are carbon neutral and that forest carbon stocks are maintained. Further, these efficient policies can significantly reduce the loss of inaccessible and natural forests. In contrast, inefficient policy proposals, such as taxing carbon emissions from biofuels without also accounting for the gains that accrue to forest growth, cause potentially large losses of natural and inaccessible forests and lead to carbon emissions in some circumstances.

There are two important reasons why stocks are enhanced in the face of strongly growing demand. First, when demand grows, prices rise and landowners with growing forests will typically hold trees to take advantage of the rising prices, as there is a higher opportunity cost of felling them prematurely. If the demand for biomass energy turns out to be short-lived, lasting only a couple years, then landowners would be encouraged to harvest trees earlier than otherwise, which would reduce carbon stocks and lead to net emissions. However, biomass energy projections associated with long-run phenomenon like climate change suggest that the demand for wood-based biomass energy will grow over time.

Second, rising prices incentivize foresters to increase regeneration and management expenditures. These include replanting, fertilizing, managing for competition, and other practices aimed at increasing the value of and size of the growing stock. Expansion of biomass energy production would increase management over a wide swath of forests around the world, but most intensification would occur in places that are already intensively managed. For context, the stock of forests has increased steadily in the southern United States and has stabilized in the Pacific Northwest since 1950, despite old growth harvesting that continued up to the 1990s (*40*).

These findings advance the policy discussion by capturing several dynamics of how landowners respond to incentives, namely, that economic incentives promote more forest management. This outcome is different than that of Schlesinger *et al.* (*26*) and others, who do acknowledge regrowth of forests but argue that emissions in the near term are particularly harmful because they cause damages during the entire time it takes for forests to regrow. This stance ignores the benefits of the past accumulation of carbon embodied in current forest stocks, which is an important component of the global carbon budget. The argument can also be extended to the future: Is it fair to hold landowners accountable for today's emissions without considering the benefits of their future regrowth, especially given that the future carbon storage is more valuable than even today's emission?

In addition to increasing the stock of forests, higher prices make forests more resilient to land use change. The real price of forest products has increased since the 1940s, while the real price of crops has fallen. As a result, the area of land in forests in the many parts of the United States and Europe has increased over the same time frame due to afforestation and the abandonment of low-productivity agricultural land (*41*, *42*). Rising prices, however, can encourage landowners with unmanaged, or natural forests, to liquidate their stock sooner than otherwise. If a policy that accounts for forest sequestration, such as the carbon rental policy, is not implemented, bioenergy demand could harm natural forests and the ecosystem and the biodiversity services that they provide. Further, as long as policies are implemented efficiently, large areas of natural forests would remain intact.

This study provides an improved understanding of the benefits and risks of increasing global bioenergy demand on forest area and forest carbon mitigation potential under alternative policy scenarios. However, there are at least two other factors that could be integrated in future research to provide a more complete analysis of these issues in a dynamic framework: first, estimating the effects of climate change on forest growth, merchantable yields, dieback, and biome shifts on regional biomass supply; and second, analyzing how emerging technological and/or social transformation processes may affect the projected demand for woody biomass, especially over a long time horizon. Taking this more complex and integrated approach might not change our overall findings but rather provide more insight into additional risks that could be considered when designing efficient bioenergy and forest carbon sequestration policies.

MATERIALS AND METHODS

The forestry model used in this analysis is the GTM, which was initially developed to study dynamic forest markets and policies (*4*, *30*). GTM combines the spatially detailed data on forests with an economic model that weighs optimal forest management alternatives. This version of the model does not include climate change impacts, but the land classes in the model can be linked to vegetation types represented in ecosystem models such as BIOME/LPX-Bern (*43*, *44*) or MC2 (*45*, *46*). The baseline scenario used in this study is consistent with current climatic conditions. Moreover, GTM incorporates overall constraints on land areas derived from the ecological models, such that only land that is capable of naturally supporting forests can be converted to forestland (*44*). For this specific study, we included more restricted limitations on regional land that can be converted to forest following the estimates presented in Bastin *et al.* (*36*) of 1.6 billion ha and 0.9 billion ha.

GTM was recently used in a validation exercise to provide a historical assessment of global and regional timber harvesting, timber management, and carbon stocks from 1900 to 2010 in Mendelsohn and Sohngen (*47*). Thus, our first simulation period (a decade) overlaps with the historical decade. Furthermore, Sohngen *et al.* (*48*) conducted a Monte Carlo analysis with the model to assess how uncertainty in the land supply elasticity and forest biomass (yield) parameters would affect timber supply and carbon outcomes. The historical validation illustrates that the model can reproduce forestry management, land areas, timber prices, and timber stocks. The Monte Carlo illustrates that the model is most sensitive to the yield function parameters in terms of the carbon outcomes and timber supply outcomes. Land supply elasticity is uncertain, but given that the elasticity parameter is likely not to vary systematically, uncertainty in the land supply elasticity does not have strong effects on carbon or timber supply.

GTM contains 200 forest types i in 16 regions. Figure S1 shows the regional disaggregation. Forest resources are differentiated by ecological productivity and by management and cost characteristics. To account for differences in ecological productivity, different land classes in different regions have different yield functions for timber, derived from the underlying inventory data. Moreover, forests are broken into different types of management classes. The first type is moderately valued forests; these are forests managed in rotations and located primarily in temperate regions. The second type is natural inaccessible forests, located in regions that are costly to access. To be conservative, inaccessible forests are assumed to be in equilibrium, such that they are neither accumulating nor releasing carbon. Inaccessible forests are unmanaged and located in places that are costly to access for timber market reasons. Over time, some of them in our model become accessible due to economic reasons, e.g., timber prices rise, making additional hectares economically efficient to harvest. If they become accessible, they are harvested, and when regrown, they are subject to applicable forest growth functions. The third type is low-value forests located in temperate and boreal areas that are lightly managed, if they are managed at all. The fourth category includes low-value timberland in inaccessible and semi-accessible regions of the tropical zones. The fifth type includes the high-valued timber plantation that is managed intensively; these forests can principally be found in subtropical regions of the United States, South America, southern Africa, the Iberian Peninsula, Indonesia, and Oceania.

GTM is an economic model of forests that maximizes the net present value of consumers' and producers' surplus in the forestry sector. By maximizing the net present value, the model optimizes the age of harvesting timber a and the intensity of regenerating and managing forests m_t^i. It is an optimal control problem, given the aggregate demand function, starting stock, costs, and growth functions of forest stocks.

GTM relies on forward-looking behavior and solves all time periods at the same time; this means that when land owners make decisions today about forest management, they do so by considering the implications of their actions today on forests in the future with complete information. The result is a forecast of what a competitive market would also do with forestland.

Mathematically, this optimization problem is written as

$$\max \sum_0^\infty \rho^t \left\{ \begin{array}{c} \int_0^{Q_t^{\text{tot}}} \left\{ D(Q_t^{\text{ind}}, Z_{t,\text{RCP}}) + D(Q_{t,\text{RCP}}^{\text{wbio}}) - C(Q_t^{\text{tot}}) \right\} \mathrm{d}Q_t^{\text{tot}} - \\ \sum_i C_G^i(m_t^i, G_t^i) - \sum_i C_N^i(m_t^i, N_t^i) - \sum_i R_t^i\left(\sum_a X_{a,t}^i\right) + \text{CC}_{t,\text{RCP},\text{policy}} \end{array} \right\} \quad (1)$$

In Eq. 1, ρ^t is a discount factor, $D(Q_t^{\text{ind}}, Z_{t,\text{RCP}})$ is a global demand function for industrial wood products Q_t^{ind} and average global consumption per capita $Z_{t,\text{RCP}}$ from the International Institute of Applied Systems Analysis (IIASA) SSP database (*33*). In particular, we use the SSP2 IAM marker scenario from MESSAGE GLOBIOM under each of the five IPCC RCPs [according to the IIASA SSP database (*33*), the global consumption per capita under the SSP2 IAM marker scenario does not change across RCPs].

Industrial timber demand follows the general functional form $Q_t^{\text{ind}} = A_t (Z_{t,\text{RCP}})^\theta P_t^\omega$, where A_t is a constant, θ is the income elasticity, P_t is the timber price, and ω is the price elasticity. The global demand function is for industrial round wood, which is itself an input into products like lumber, paper, plywood, and other manufactured wood products.

Wood demand for bioenergy production $Q_{t,\text{RCP}}^{\text{wbio}}$ is estimated by adjusting the total bioenergy consumption in the IIASA SSP database $Q_{t,\text{RCP}}^{\text{bio}}$ with the proportion of global biomass energy produced from wood by following similar assumption as in Lauri *et al.* (*34*). Figure S2 (A and B) shows total bioenergy consumption and total woody biomass supply under each RCP for the SSP2.

We assume 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 will be traded internationally (*49*). Competition for supply will equilibrate their prices.

Equation 2 shows that the total quantity of wood depends on 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_t^i and management intensity $m_{a,t}^i$.

$$Q_t^{\text{tot}} = \sum_i \left(\sum_a H_{a,t}^i V_{a,t}^i(\theta_t^i, m_{a,t}^i) \right) \quad (2)$$

The functional form for the yield function is

$$V^i_{a,t}(\mathrm{m}^i_{a,t}) = h * \left[\exp\left(\delta^i - \frac{\pi^i}{a}\right)\right] \tag{3}$$

Per equation $h = \varphi^i\,(1 + \mathrm{m}^i_{a,t})^{\tau^i}$, h is the stocking density, which can be adjusted depending on the intensity of management, $m^i_{a=1,t}$. We restrict stocking elasticity, τ, to be positive and less than 1. The τ^i affects the elasticity of management inputs in forestry to account for technology change. Initial stocking is denoted by φ^i. Increase in $m^i_{a=1,t}$ will increase h, e.g., $dh/dZ > 0$, but the increase diminishes as $m^i_{a=1,t}$ rises, e.g., $d^2h/dZ^2 < 0$. The model chooses management intensity by optimally choosing $m^i_{a=1,t}$. Increases in management intensity will increase yield and shift the entire yield function upward. Forests are assumed to grow according to $V^i_{a,t}(Z^i_{a=1,t})$, where δ and π are species-dependent growth parameters (fig. S3 shows a representative yield function assuming $h = 1.32$, $\delta = 5.2$, and $\pi = 30$). $C(Q^{\mathrm{tot}}_t)$ is the cost function for harvesting and transporting logs to the center (mills or power plants) from each of timber type.

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

$$X^i_{a,t} = X^i_{a-1,t-1} - H^i_{a-1,t-1} + G^i_{a=0,t-1} + N^i_{a=0,t-1} \tag{4}$$

The initial stocks of land X^i_t are given, and all choice variables are constrained to be greater than or equal to zero, and the area of timber harvested $H^i_{a,t}$ does not exceed the total timber area. G^i_t is the area of timber regenerated land planted, and N^i_t is the new forest planted. $C^i_G(\cdot)$ is the cost function for planting land in temperate and previously inaccessible forests, while $C^i_N(\cdot)$ is the cost function for planting forests in subtropical plantation regions.

GTM takes into account the competition of forestland with crops and livestock using a rental supply function for land (*2*). In Eq. 1, $R^i_t(\cdot)$ is the rental cost function for the opportunity costs of holding timberland $X^i_{a,t}$. For example, if timber prices rise relative to agricultural land prices, the model predicts that timber owners will rent suitable farmland for at least a rotation. Similarly, if timber prices fall relatively to agricultural land prices, suitable forest land will be converted back to farmland upon harvest. In addition, the model accounts for the aggregate global effects of moving land between forests and agriculture by shifting all of the land supply functions for individual forest types as a function of the aggregate global area of forestland. As more land globally moves from agriculture to forests, all rental functions shift inward, making it more costly to convert any land from agriculture to forestry. This captures the effect that having less land in agriculture would have on land prices. We have assumed that the elasticity of land supply is 0.25, such that a 0.25% reduction in the global area of agricultural land would cause all land rents to rise by 1%. Note also that the 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 sendogenous.

The model is also developed to account for the global forest carbon stocks and flows following a method first presented by Sohngen and Sedjo (*50*) and updated by Daigneault *et al.* (*18*). Carbon is tracked in four pools: aboveground carbon, soil carbon, forest product carbon, and slash.

Aboveground carbon $C^i_{a,t}$ 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

$$C^i_{a,t} = \sigma^i\, V^i_{a,t}(m^i_{t0}) \tag{5}$$

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

$$\mathrm{TFCP}^i_t = \textstyle\sum_a C^i_{a,t} X^i_{a,t} \tag{6}$$

Carbon in harvested forest products HC^i_t is estimated by tracking forest products over time as follows

$$\mathrm{HC}^i_t = (1 - \tau_t)\,\kappa^i \textstyle\sum_a (\beta^i\, V^i_{a,t} H^i_{a,t}) \tag{7}$$

where κ^i is the proportion of harvested timber volume that is carbon stored permanently, and it is estimated to be 0.30 (*51*), β^i is a parameter that converts forest products into carbon (regional and forest type based), while τ_t is the portion of wood used in the energy sector, and it is endogenously selected by the model; that is, HC^i_t accounts only for carbon stored in wood products, not woody biomass used for energy production. Carbon stored in woody biomass used for bioenergy production is calculated as follows

$$\mathrm{BIOC}^i_t = \tau_t \textstyle\sum_a \beta^i\,(V^i_{a,t} H^i_{a,t}) \tag{8}$$

Soil carbon SOLC^i_t is measured as the stock of carbon in forest soils of type i in time t. The value of $\overline{K}$, 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

$$\mathrm{SOLC}^i_{t+1} = \mathrm{SOLC}^i_t + \mathrm{SOLC}^i_t(\mu^i)\left[\frac{(\overline{K} - \mathrm{SOLC}^i_t)}{\mathrm{SOLC}^i_t}\right] \tag{9}$$

Last, we measure slash carbon AS^i_t as the carbon leftover on site after a timber harvest

$$\mathrm{AS}^i_t = \textstyle\sum_a(\omega^i_a\, V^i_{a,t} H^i_{a,t} - \kappa^i\, V^i_{a,t} H^i_{a,t}) \tag{10}$$

Over time, the stock of slash SP^i_t builds up through annual additions and decomposes as follows

$$\mathrm{SP}^i_{t+1} = \mathrm{AS}^i_t + (1 - \vartheta^i\, \mathrm{SP}^i_t) \tag{11}$$

Decomposition rates ϑ^i differ, depending on whether the forest lies in the tropics, temperate, or boreal zone.

Last, in Eq. 1, the term $CC_{t,\,\mathrm{RCP,\,policy}}$ represents the carbon payments/penalties for forest owners according to the policy implemented. For this study, GTM has been enhanced to capture public policy efforts that either penalize bioenergy demand or value climate mitigation benefits of forests sequestration. GTM assumes that the incentives in the timber product, woody biomass, and carbon sequestration system can be implemented efficiently. That is, GTM portrays an ideal world in which the carbon price and/or subsidy is implemented simultaneously everywhere, and there are no trade barriers or other limitations in the use of woody biomass for energy or governance issues. This is an ideal framework: Carbon obviously has not been traded globally, and there are widespread reservations about trading it in the atmosphere as well as in forests. There are measurement, monitoring, and verification problems, as well as concerns about leakage and permanence.

Starting with the scenarios simulated in Favero *et al.* (*22*), this study explores four possible policy scenarios:

1) Reference scenario: No bioenergy demand and carbon price are implemented;

2) Bioenergy scenario: Exogenous bioenergy demands from SSP2 across RCPs $Q^{\mathrm{wbio}}_{t,\mathrm{RCP}}$ are included;

3) Forest carbon rental scenario: Exogenous bioenergy demands from SSP2 across RCPs are included, and forest owners are compensated by annual rent for providing annual carbon sequestration according to the carbon prices from the IIASA SSP database;

4) Carbon penalty scenario: Bioenergy demands from SSP2 across RCPs are included, and carbon emissions upon harvests for energy are taxed.

The policy scenarios are described in Eq. 1 with the term $CC_{t,\mathrm{RCP},\mathrm{policy}}$. Moreover, in the reference and bioenergy scenarios, the term $CC_{t,\mathrm{RCP},\mathrm{policy}}$ is assumed to be equal to zero since no policy efforts are implemented to value or penalize bioenergy demand.

On the other hand, in the forest carbon rental scenario, forest owners receive carbon payments for the carbon permanently stored in wood products and are compensated by annual rent for providing annual carbon sequestration according to the carbon prices $P^{c}_{t,\mathrm{RCP}}$ from the IIASA SSP database (fig. S2C) as follows

$$CC_{t,\mathrm{RCP},\mathrm{carbon\_rental}} = P^{c}_{t,\mathrm{RCP}}\left[\sum_i \mathrm{HC}^{i}_{t} + (\mathrm{SOLC}^{i}_{t+1} - \mathrm{SOLC}^{i}_{t})\right] + R^{c}_{t,\mathrm{RCP}} \sum_i \mathrm{TFCP}^{i}_{t} \tag{12}$$

The first part of Eq. 11 is the carbon transferred to long-lived wood products ($\mathrm{HC}_t{}^{i}$) from each forest *i* valued at the carbon price $P^{c}_{t,\mathrm{RCP}}$. The change in soil carbon (SOLC^{i}_{t}) when land switches between forests and agriculture is also valued at the carbon price (*13*, *15*). The second term is the annual rent, $R^{c}_{t,\mathrm{RCP}}$, whereby the total carbon stocks in forests TFCP^{i}_{t} are rented during the time period that the carbon is stored following Sohngen and Mendelsohn (*4*). The rental value for carbon is

$$R^{c}_{t,\mathrm{RCP}} = P^{c}_{t,\mathrm{RCP}} - P^{c}_{t+1,\mathrm{RCP}}/(1+r)^{t} \tag{13}$$

where *r* is the interest rate. This equation accounts for potential price increases in carbon that occur as carbon accumulates in the atmosphere.

Last, in the carbon penalty scenario, forest owners pay a penalty for the carbon released when timber is harvested to supply bioenergy demand.

$$CC_{t,\mathrm{RCP},\mathrm{penalty}} = -P^{c}_{t,\mathrm{RCP}} \sum_i \mathrm{BIOC}^{i}_{t} \tag{14}$$

Table S1 provides the list of parameter values used to parameterize equations for the simulations presented in this study. More details on the version of GTM used in this analysis are available in (*18*) and (*22*).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/13/eaay6792/DC1
Supplementary Materials and Methods
Model estimates
Fig. S1. GTM—Regional Aggregation.
Fig. S2. Global assumptions for alternative RCP scenarios.
Fig. S3. Yield for representative species in the GTM.
Fig. S4. Estimated changes in global forest carbon stock pools in $\mathrm{GtCO_2}$ relative to the baseline scenario under each RCP.
Fig. S5. Changes in global forest area by major ecosystem versus woody biomass supply under the bioenergy demand scenario relative to the baseline scenario.
Fig. S6. IAMs' estimates of forest areas and crop areas (2010–2100) under the RCP 1.9 and RCP 2.6 from the IIASA SSP database.
Fig. S7. Estimated changes in global forest carbon stock pools in $\mathrm{GtCO_2}$ relative to the baseline scenario under each RCP and the two policy approaches.
Fig. S8. Key parameter sensitivity impacts relative to 2010 for RCP 2.6 Forest Carbon Rental scenario.
Table S1. GTM parameter values.
Table S2. Baseline key GTM estimates, 2010–2100.
Table S3. Baseline global forest area (Mha) by major ecosystem, 2010–2100.
Table S4. Baseline global total forest carbon stocks by major ecosystem, 2010–2100.

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