WORLD RESOURCES INSTITUTE

THE GLOBAL LAND SQUEEZE: MANAGING THE GROWING COMPETITION FOR LAND

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Foreword

Competition for the world's finite land resources is rapidly intensifying. Around 85% of the world's usable land—ice-free and non-desert—has already been heavily harvested for wood or converted to agriculture. This conversion has contributed roughly a quarter of the carbon that humanity has added to the atmosphere and explains most of the planet's vast loss of biodiversity.

Human demand for food, wood, and space continues to rise even as the climate science makes it clear that preserving forests and other habitats is more vital than ever. Due to rising populations and incomes, WRI models find the world is on course to demand more than 50% more food and wood in 2050 than in 2010. At present rates of rising yields, the world will convert an area of natural habitat up to two times the size of India for agriculture to supply this food. Meeting rising wood demands will also likely lead to decades of carbon losses on par with effects of agricultural land expansion in recent years.

This global land squeeze is a pressing challenge, one that requires thinking differently about humanity's use of land.

Governments, companies, organizations and people everywhere must start by understanding that every hectare of productive land is valuable, whether for producing food or wood or storing carbon and supporting biodiversity. Every hectare of land used to supply human consumption comes with a high "carbon opportunity cost." Despite this inherent cost, some government policies are deliberately increasing demand for land by creating incentives to harvest more trees or grow crops for bioenergy. These policies could more than double the demands people place on land, destroying habitats and releasing vast stores of carbon into the air.

We need a systems approach that stops treating land as "free" and successfully evaluates how the burdens of meeting human needs might be transferred from one place to another. In short, we need an approach that recognizes how land may be our most limited resource.

With this core assumption in place, the path forward becomes clearer. This report frames the broad challenge, exploring our options for solutions. The "Produce, Protect, Reduce and Restore" framework offers a holistic solution to land in both our consumption and production practices.

First, we must find a way to Produce more food and wood on existing agriculture and timber lands. If done right, these changes can also boost incomes and reduce hunger. At the same time, the world must also move to Protect native habitats and their precious carbon and biodiversity through governance. This requires that people around the world Reduce our consumption of land-intensive products – for example by eating less meat, wasting less food, reusing more wood, and dedicating less land to bioenergy. Finally, we must Restore forests and wetlands on those agricultural lands where carbon and biodiversity benefits are exceptional, or where food production potential is low.

With populations rising and climate change accelerating, the world is becoming an ever-tighter place. Luckily, we already know numerous technological and social solutions and have valuable innovations that are ready to be pursued. By pursuing the right set of solutions, humankind can not only fit on the world's land, but thrive together with nature and a healthy climate.

Ani Dasgupta

President and CEO
World Resources Institute

Executive Summary

The world faces a global land squeeze as the world population grows to 10 billion by 2050. Human demands for food, wood products, and urban uses will expand as the population grows and incomes rise. These demands will lead to more conversion of native habitats to agricultural and urban uses; in addition, more natural forests will be converted to wood plantations and increasing amounts of wood will be harvested from relatively natural forests. This growing demand for land-based products will compete with the ability of the remaining native habitats to store carbon and support biodiversity.

Highlights

- The world faces a "global land squeeze" with population and income growth threatening climate and biodiversity goals. We project business-as-usual (BAU) increases in demand for crops (56 percent), meat and milk (70 percent), and wood (54 percent) between 2010 and 2050, requiring an additional 600 million hectares (Mha) of agricultural land, 80 Mha of urban land, and harvests of 800 Mha of forests.
- We project 6.0 gigatons of carbon dioxide equivalent ($GtCO_2e$) in annual land-use-change emissions to satisfy global food demand, 0.7 $GtCO_2e$ per year for urban expansion, and 3.5–4.2 $GtCO_2e$ in annualized time-discounted emissions for meeting wood demand, or 2.6-3.2 $GtCO_2e$ when including 1 Gt of substitution benefits for reduced concrete and steel.
- Initiatives to increase demands for bioenergy and mass timber for construction would vastly increase land-use competition.
- Wood use is not "carbon neutral," even if forests are managed sustainably once one accounts for the loss in forest carbon from harvests. In most scenarios, harvesting additional wood, even for construction, will likely increase atmospheric carbon for decades.
- Solutions require strategies that produce, protect, reduce, and restore: produce more food and wood on already managed land, protect native habitats, reduce demand for land-intensive products, and, if successful, restore forests and other habitats.
- In general, policies should not increase demand for land-based products until the world shows that it can meet rising food and wood demands without additional land conversion.

The growing demand for land-based products, such as food and wood, presents a great environmental challenge. Virtually all climate change pathways that keep global temperature rise below 1.5°C require quickly ending net deforestation and reducing agricultural land use and achieving net reforestation by 2050. The world already is facing a species extinction whose primary drivers are the conversion of native habitats to other uses and the management of forests for wood supply. Scenarios that meet future food needs and expected levels of increased wood demand—without further conversion or net disturbance of the world's forests—are likely possible but highly challenging. Scenarios to meet these needs and also free up land to restore forests and other native habitats to provide biodiversity and store carbon require unprecedented action, technological progress, and political will.

Even as the world faces this land squeeze, many policymakers and researchers are proposing policies that add to these human demands for land-based products. For example, policies to increase the use of bioenergy or wood in construction potentially increase demand beyond business as usual (BAU) growth. Proponents claim these additional land uses will help address climate change. Yet how much could these policies increase global competition for land? And would adding these demands help reduce or exacerbate global warming? If so, under what conditions?

This analysis builds on the World Resources Report *Creating a Sustainable Food Future* to assess the global land squeeze and options to manage it in the coming decades to meet human and environmental needs (Searchinger et al. 2019). Using the academic literature, a variety of data sources, prior World Resources Institute (WRI) analyses, and detailed new forestry modeling, this report summarizes the extent of global land-use competition, analyzes the implications of increasing land-use demands, and describes the suite of strategies to meet rising human needs while preserving biodiversity and carbon stored in vegetation and soils. The analysis builds on work undertaken for *Creating a Sustainable Food Future* by WRI with the

World Bank, the United Nations Development Programme, United Nations Environment Programme, the French Agricultural Research Center for International Development, and the French National Institute for Agricultural Research. To analyze the land and carbon implications of forest product demand, WRI developed the new biophysical Carbon Harvest Model (CHARM) for this report.

Global Land Conversion, Carbon Losses, and Ongoing Changes

The world's lands are already heavily used. Based on our review and analysis of the literature, people had converted nearly half of all vegetated land to agriculture and had harvested or manipulated 60–85 percent of the world's remaining forests by 2010. Between 1700 and 2000, humans also converted or heavily transformed more than 90 percent of the world's native grasslands and 80 percent of its native shrublands and savannas. These changes are the primary drivers of biodiversity loss and have contributed between one-quarter and one-third of the carbon people have added to the atmosphere.

Land-use change is continuing apace. Although estimates vary, according to Global Forest Watch data, people are likely responsible for the gross loss of roughly 15 Mha of forest cover per year since 2000. The best evidence of cropland expansion from a satellite study (Potapov et al. 2022) shows that the net conversion of land to annual cropland has increased from around 5 Mha per year for annual crops between 2004 and 2007 to 10 Mha per year between 2013 and 2019, with other evidence suggesting another 1 Mha per year for expansion of perennial crops such as oil palm and rubber. Gross conversion is nearly twice the net. Because of limitations in how satellites read pasture and some reported declines in very dry pasture, net pasture expansion by area is uncertain. But gross pasture expansion is the primary driver of tropical forest loss overall, which strongly suggests that more carbon and biodiversity is being lost from changes in pasture overall.

Estimated Land-Use Demands (2010–2050) without Major New Policies

Agricultural Land Expansion

Growing food demand is likely to lead to 600 Mha of agricultural expansion between 2010 and 2050. Under BAU, WRI estimated in the report *Creating a Sustainable Food Future* that crop calorie demand will grow by 56 percent during that period, and demand for meat and dairy by 68 percent. Assuming that crop yields and meat and milk output per hectare of pasture continue to grow roughly at historical (linear) rates since 1960, we estimate that cropland will expand on a net basis by about 200 Mha—roughly 5 Mha per year—and pasture by 400 Mha between 2010 and 2050. Collectively, these 600 Mha of agricultural expansion are nearly twice the size of India.

BAU agricultural expansion would lead to ongoing land-use change and unacceptably high greenhouse gas (GHG) emissions. According to our modeling, agricultural expansion at the expense of forests and woody savannas, along with ongoing degradation of peatlands, would release roughly 240 $GtCO_2e$ into the atmosphere over the 40-year period, or 6 $GtCO_2e$ per year. These emissions are 25–40 percent of the maximum cumulative carbon dioxide emissions "budget," as estimated by various studies, between 2010 and 2050 to limit warming to 1.5°C–2°C.

Evidence from the 2010s shows that agricultural expansion and related land-use change remain key challenges. Since our 2019 projections, which relied on data available only through 2011, growth in crop production, and overall production of livestock products, has roughly tracked our projected rates out to 2050. One exception is that growth in ruminant meat production has occurred at roughly half our projected rate. Although that is good news in one way, our analysis of data from the Food and Agriculture Organization of the United Nations (FAO) shows that this lower growth rate has occurred due to almost no growth in per capita consumption in the world's poor countries rather than from a sharp drop in per capita consumption among the world's wealthy. Limited income growth during the 2010s in sub-Saharan Africa may be a major factor. Furthermore, as discussed above, direct estimates of cropland expansion are now occurring at annual rates that are almost double our projected annual rates over 40 years.

Urban Land Expansion

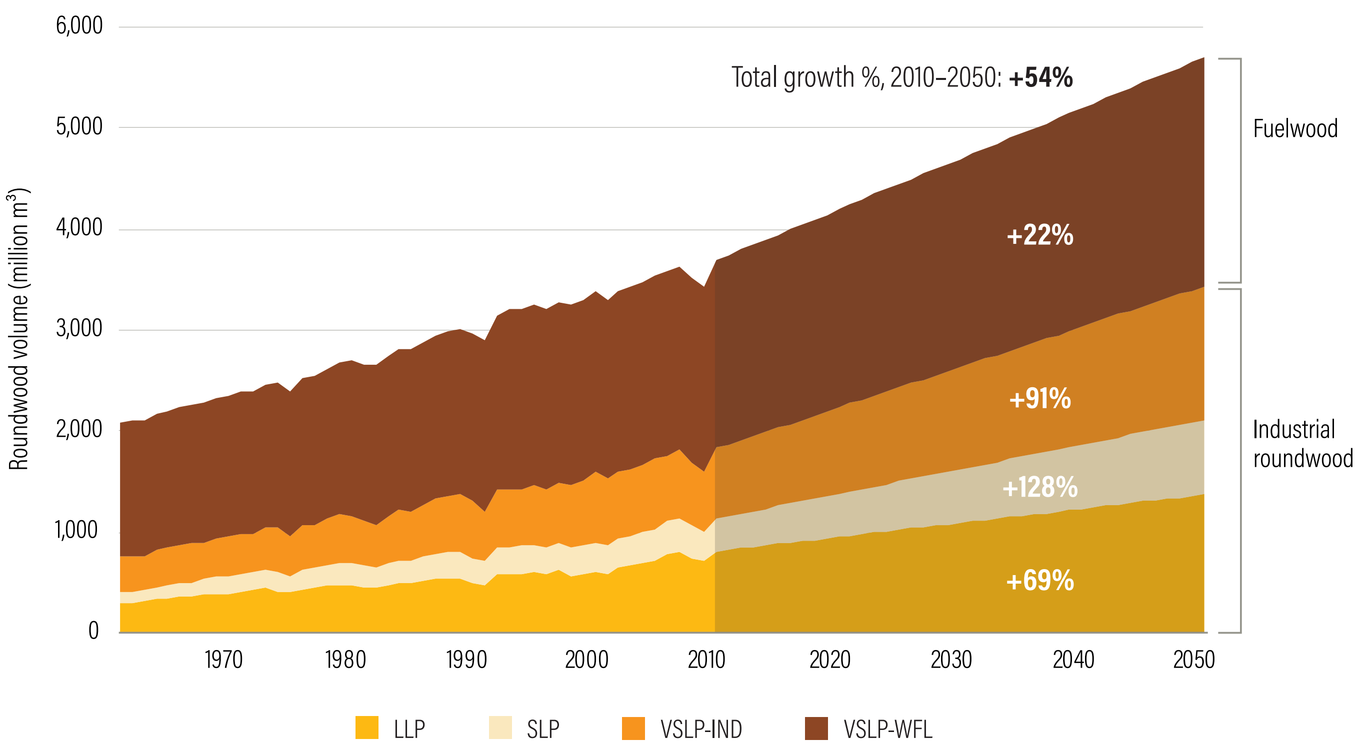
Urban land expansion will further add to human land demands. Based on our literature review, midrange estimates for urban land expansion are roughly 80 Mha between 2010 and 2050. Our modeling indicates that expansion will contribute to land demands that would cause 27 $GtCO_2e$ of additional carbon dioxide emissions during the 40-year period, or about 0.7 $GtCO_2e$ per year, further adding to the climate challenge.

Forestry Effects

In addition to agricultural and urban expansion, wood harvesting from forests is also likely to increase, adding to human land demands and effects on climate and biodiversity. Forestry impacts are often left out of global land-use analyses, but wood harvesting also causes impacts on biodiversity and reduces carbon stored in forests for decades or more.

We project a BAU 54 percent increase in overall wood demand between 2010 and 2050, including an 88 percent growth in the industrial wood harvest and a 22 percent growth in fuelwood (Figure ES-1).

Figure ES-1 | We project a 54 percent increase in total wood production between 2010 and 2050 under "business as usual"



Note: LLP = long-lived product (such as wood timber and panels); SLP = short-lived product (mainly paper products); VSLP-IND = very-short-lived product (mainly wood burned for energy as a by-product of other wood production); VSLP-WFL = very-short-lived product for traditional fuelwood use (such as firewood, charcoal, and wood pellets). The projected percentage increases from 2010 to 2050 are listed for total products and each category.

Source: Authors' estimates.

The industrial wood harvest includes solid timber, various wood panels, and paper and cardboard products. These estimates are moderately higher than those projected by a recent FAO model, partly because of newer, higher estimates of global gross domestic product (GDP) per capita and population growth in developing countries.

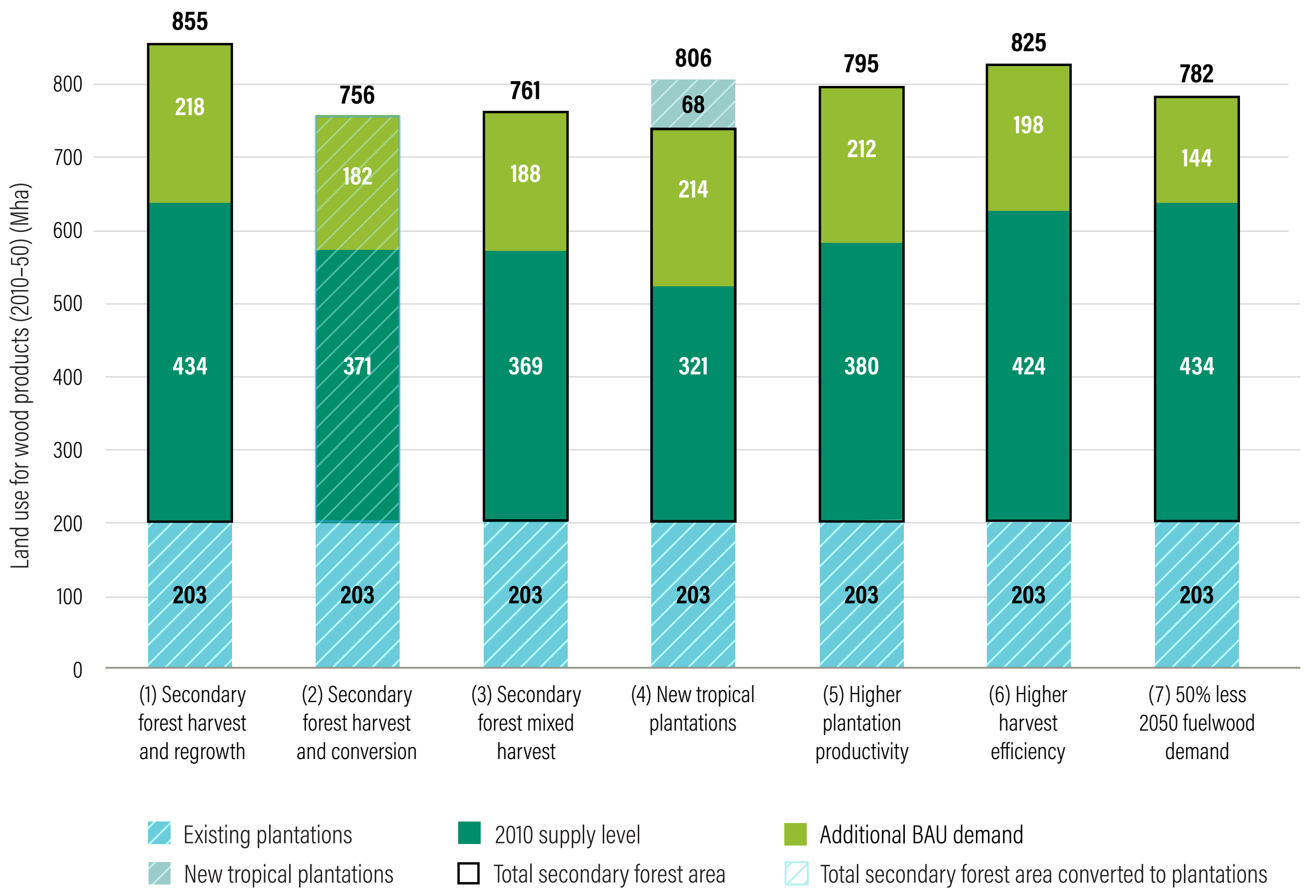
Meeting wood demand would likely require harvesting about 600 Mha of secondary forest between 2010 and 2050, in addition to 200 Mha of existing plantations. Because this growth in wood demand could be met in different ways, we analyze a variety of scenarios. We assume that future wood harvests will use the 200 Mha of tree plantations that existed in 2010, and we project that, based on other wood sources, an area of secondary or primary forests equal to 530-650 Mha must also be harvested. Figure ES-2 shows the results according to scenarios described in Table ES-1. Areas shown are in "clear-cut" equivalents—in other words, the hectares of forest that would be harvested if all wood were supplied by clear-cuts. (Selective harvests reduce impacts per hectare harvested but require more hectares.) The variation depends on the location and productivity of the natural forests, the extent to which they are converted to plantations, and the extent to which new plantations are established on agricultural land.

Table ES-1 | Description of Modeled Scenarios for Future Wood Supply

SCENARIO NAME	DESCRIPTION OF SOURCES OF WOOD	ADDITIONAL ASSUMPTIONS
(1) Secondary forest harvest and regrowth	Existing plantations and secondary forest harvest and regrowth	The portion of wood supply from secondary forests is 100% from middle-aged stands
(2) Secondary forest and conversion	Existing plantations and secondary forest harvest and then converted to productive plantations	The portion of wood supply from secondary forests is 100% from middle-aged stands
(3) Secondary forest mixed harvest	Existing plantations and secondary forest mixed harvest and regrowth	The portion of wood supply is 50% from middle-aged and 50% from mature secondary forest
(4) New tropical plantations	Existing plantations, secondary forest harvest and regrowth, and tropical agricultural land gradually converted to plantation	Rotation length of new tropical plantations is 7 years; 2 million hectares per year of tropical agricultural lands are converted to plantations each year
(5) Higher plantation productivity	Existing plantations with 25% increase in plantation growth rates and secondary forest harvest and regrowth	The portion of wood supply from secondary forests is 100% from middle-aged stands
(6) Higher harvest efficiency	Existing plantations with 25% increase in plantation growth rates and secondary forest harvest and regrowth	The portion of wood supply from secondary forests is 100% from middle-aged stands
(7) 50% less 2050 fuelwood demand	Fuelwood demand decreases linearly to reach 50% of 2050 baseline demand, existing plantations, and secondary forest harvest and regrowth	The portion of wood supply from secondary forests is 100% from middle-aged stands

Source: Authors' calculations.

Figure ES-2 | We project 756-855 Mha of wood harvest for 2010–2050 (clear-cut equivalents)



Note: BAU = business as usual.

Source: Carbon Harvest Model.

Harvests reduce carbon storage in forests both because wood is removed from the forest and much of the wood felled is left to decompose. Much of the removed wood is quickly burned, releasing its carbon, and other wood-based carbon is temporarily stored in short- or long-lived products. Forests then regrow. For at least a few years, they are likely to grow more slowly than forests left unharvested, but then they start to grow faster. Over enough time, they recoup much to nearly all of the carbon lost. The carbon "cost" is therefore in part a time-limited increase in carbon in the atmosphere. If forests are repeatedly harvested, they will also store less carbon on average.

To analyze these costs, we developed a new model, CHARM, which follows a long-established approach to track the carbon across all "pools" of carbon storage. Any carbon not stored in some pool is by definition emitted to the air.

Reflecting the added value of immediately reducing emissions, we also value the importance of earlier mitigation more than later mitigation. Restraining emissions in the next few decades not only reduces climate damage during that time but also creates more time for the world to mobilize the technology and resources to permanently stabilize the climate.

To reflect the value of time, our primary analysis applies a discount rate (4 percent); thus, if a ton of carbon is emitted in the first year, then even if it is reabsorbed 40 years later, the loss of carbon in the interim is still treated as a cost to climate change. (All tons are metric tons unless otherwise indicated. The discount rate is not discounting emissions per se but rather the cost of emissions and, therefore, the value of mitigation at different times.) We also apply other approaches to reflect the cost of short- to medium-term increases in carbon, including focusing on the change in carbon in the atmosphere after 40 years.

Our accounting approach differs from many others that either fail to account for future forest regrowth or inappropriately view harvests as carbon neutral so long as forest carbon stocks remain stable on average. Some papers, such as Houghton and Nassikas (2018), have estimated the gross carbon costs of annual wood harvests, which is the carbon released by each year's wood harvests. This approach captures the effect of a harvest but does not factor in the faster forest regrowth in the future. As we show in an extensive literature review, other papers treat the harvest of wood as carbon neutral (i.e., as doing nothing to increase carbon in the air) so long as wood is harvested sustainably. *Sustainably* typically means that harvests of trees are limited to match the forest's annual growth so that the existing "carbon stock" in the forest is maintained. We consider this approach incorrect. If forests would increase in carbon in the absence of harvesting, then harvesting and only maintaining their carbon stocks decreases the carbon that otherwise would have been stored in the forest, thereby increasing carbon in the air compared to leaving the forest alone.

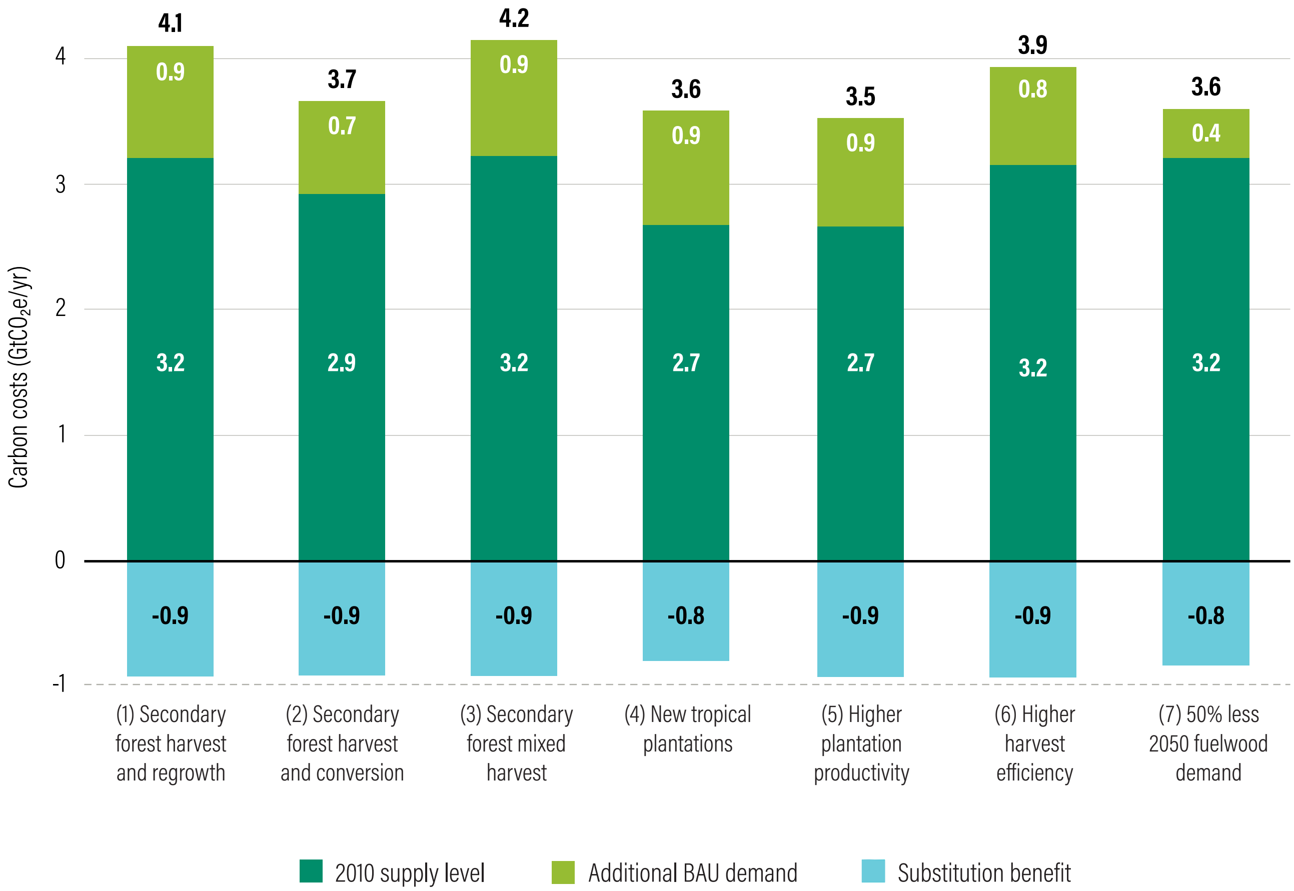
This accounting also ignores the fact that although many countries' forests are regrowing due to heavy prior harvests, this regrowth of previously cut forests would occur anyway (i.e., regardless of whether new harvests are occurring). As a result, this forest regrowth is not caused by the new harvests and does not alter the climate consequences of the new harvests. In fact, forests all over the world are growing faster because of higher carbon dioxide in the atmosphere and climate change itself. These are beneficial feedback effects of climate change that already are factored into scientific "baseline" estimates of future climates; without this forest carbon sink, climate change would be far worse. This sink is not disposable if the world is to achieve its climate goals. Removing the sink through harvest means more carbon in the air.

Using our time-discounted approach, we estimate that forest harvests between 2010 and 2050 will cause annual emissions of 3.5–4.2 $GtCO_2e$ across different scenarios (as described in Table ES-1) for meeting future wood demand (Figure ES-3). Even without any future growth in wood demand, we estimate that these forestry-related emissions would likely be roughly 3.2 $GtCO_2e$ per year. These emissions are increases in carbon in the atmosphere.

There is also value in estimating the "net" effects of forestry if we factor in the lower fossil and related emissions in making wood for construction compared to concrete and steel. When we factor in our best global estimate of the global substitution value of wood for concrete and steel of roughly 0.9 $GtCO_2e$ avoided per year, the annual net effect of forestry is therefore 2.6-3.2 $GtCO_2e$.

These estimates of the climate impacts of forest harvests are calculated using time discounting and a 4 percent discount rate, but the undiscounted results after 40 years are similar. Substitution effects do not alter the absolute emissions from wood harvest, but they do allow a comparison of wood use versus nonwood use if nothing is done in the future to reduce emissions from concrete and steel. (In the same way, driving a small car emits carbon even if its emissions are lower than driving a large car.)

Figure ES-3 | We estimate 3.5–4.2 Gt per year of carbon emissions from global wood harvest (2010–2050) with roughly a 0.9 Gt per year benefit from replacing concrete and steel



Note: BAU = business as usual. These estimates show the time-discounted approach at 4 percent assuming all forests are allowed to regrow for 40 years after harvest.

Source: Carbon Harvest Model.

Beyond BAU: The Implications of Policy-Induced Increases in Land and Wood Demand (2010–2050)

Policymakers have enacted or are considering policies to increase demand for wood or crop-based products, which would require use of additional land, based on the theory that increasing use of these products helps to combat climate change. One set of policies promotes liquid biofuels from food and energy crops or the burning of wood for electricity or heat. Policy examples include biofuel blending mandates and renewable energy standards in the United States and Europe. Other contemplated policies, such as those generally proposed by the European Commission in its Forest Strategy for 2030, would promote increased harvesting of wood for construction, including use of wood in tall buildings, an approach known as "mass timber." Such a strategy often relies on new types of thick wood panels formed by gluing thinner boards in perpendicular shapes, of which the main example is cross-laminated timber.

Policy ideas that increase demand for land-based products raise important questions around climate benefits and land availability. Will bioenergy or mass timber policies reduce net GHG emissions? They can only reduce emissions if the reductions in the energy or construction sectors exceed any increased emissions from loss of carbon in the land-use sector. Furthermore, even if harvesting additional land-based products would be advantageous for a single project, is land available for the additional energy or construction products if they are demanded at a large scale? For example, if a hectare of existing forest plantation were diverted to produce wood products for tall buildings in a way that provided climate benefits, that diversion might require even more natural forest to be harvested or converted into a plantation elsewhere to replace the diverted wood for furniture and paper products. Similarly, unless the demand for global agricultural land can be reduced overall, diverting a hectare of grazing land in South America to another use (e.g., to forest plantation) would require clearing of another hectare of forest or savanna for agriculture elsewhere to replace the lost food production.

Land Demands and Carbon Implications of Bioenergy Expansion

Policies to support bioenergy could result in vast increases in wood harvests or in the use of land to generate biofuels. For example, providing just 10 percent of transportation fuels from crop-based biofuels by 2050 would likely provide only 2 percent of global energy use in 2050 on a net basis; however, it would require roughly 30 percent of the energy in all the world's crops as of 2010. Doing so would increase agricultural land area by an additional 100 Mha (beyond BAU expansion) and release an additional 1.3 $GtCO_2e$ annually from land-use change over 40 years. Furthermore, meeting an additional 2 percent of global energy demand through solid biomass from wood would require roughly doubling the present global commercial wood harvest. The gross emissions would exceed 3 $GtCO_2e$ per year.

Analyses that find large benefits from bioenergy typically (and incorrectly) treat biomass as "carbon neutral," which means they do not count as emissions the carbon dioxide emitted by burning or decomposing biomass. The typical justification for doing so is that the carbon emitted by biomass burning was absorbed from the atmosphere by growing plants. The theory, in effect, is that bioenergy just recycles atmospheric carbon unlike burning fossil fuels, which adds carbon to the air otherwise stored underground.

However, analyses that treat biomass as inherently carbon neutral are incomplete because it takes land to grow plants for bioenergy. Using this land to produce plants for bioenergy is a benefit of using land, but the climate cost is not using the land for other valuable purposes. Those purposes can include storing carbon directly in forests. They can also include producing food or fiber, which frees up other global land to store more carbon while still meeting food demands. The assumption of carbon neutrality of biomass in effect treats land from a climate perspective as having no opportunity cost. That means, from a climate perspective, that the analysis treats land as "free."

Factoring in an opportunity cost of land fundamentally changes the analysis of bioenergy and shows that dedicating land to bioenergy production is harmful for the climate. One way of estimating the opportunity cost of land when producing a liter of biofuels is to estimate the average quantity of carbon lost from vegetation and soils to yield the amount of the crop used to produce. This quantity can then be amortized over a number of years of bioenergy production, which policymakers have typically chosen as 20 or 30 years. Using 30 years, analysis shows that the GHG emissions from using grain ethanol for bioenergy are double those of using gasoline, and the emissions from vegetable oil-based bioenergy are triple those of gasoline.

Another "opportunity cost" approach would compare the emissions from fossil fuels avoided by using a hectare of land to produce bioenergy with the quantity of carbon that would likely be sequestered allowing that land to reforest. Reforestation typically would reduce atmospheric carbon more (versus the fossil fuel savings). As a result, even if there were surplus farmland, the net climate effect of biofuels would still be adverse compared to this alternative use of even surplus land.

Even dedicating land to inedible bioenergy feedstocks, such as grasses or trees, is inadvisable from a climate standpoint because the land used still has an opportunity cost. Biofuels from perennial energy crops, such as switchgrass, miscanthus, and willow trees, would have some advantages over food crops because they use less fertilizer and appear to sequester some soil carbon. But their land-use requirements are likely to be similar (after accounting for food crop by-products). Even if land becomes available, and even using highly optimistic technical assumptions, such "second-generation" biofuels still fall far short of achieving carbon-neutral energy when factoring in the opportunity costs of land.

In the case of using wood for power or heat, multiple studies have shown that harvesting wood, instead of leaving trees unharvested in the forest, will increase net emissions in the atmosphere for decades to centuries, even when replacing coal or natural gas. These studies have analyzed these wood uses in a wide variety of scenarios, including scenarios with the wood coming from different forests, using different harvesting systems, having different ultimate energy uses, and replacing different fossil fuels. The result always has the same bottom-line result: producing any meaningful quantity of bioenergy (even from inedible feedstocks) greatly exacerbates competition for land and has high carbon costs.

Land Demands for Wood Construction

From a climate perspective, using wood for construction has obvious advantages over burning it for bioenergy but still has high costs. The advantage occurs because the portion of the tree stored as wood in buildings persists, storing its carbon and keeping it from the atmosphere for years. However, only some of the wood affected by forest harvest is stored, and only for some time. Much of the wood and other vegetation affected is lost through the decay of roots and some tops, branches, and bark from harvest residues. Typically, between 40 and 50 percent of wood sent to sawmills or paper mills is burned as waste, and much harvested wood is used for more temporary products such as paper.

Under a scenario of significant increase in mass timber use, the areas and quantities of additional wood harvested could be large. For example, providing 10 percent of the world's new urban construction material from wood between 2010 and 2050 would require 50 Mha of secondary forest (in clear-cut equivalents). Providing 50 percent of new urban construction material from wood between 2010 and 2050 would require harvesting an additional 200-250 Mha of secondary forest.

The Carbon Implications of Wood Construction Expansion

Most published analyses that find climate benefits from mass timber assume that wood is carbon neutral so long as wood is harvested sustainably, which we consider incomplete. We analyzed 60 published studies with conflicting scientific claims. We found that the vast majority of the studies that find net climate benefits from mass timber in construction—such as the incomplete bioenergy studies—assume that all wood is carbon neutral, which means that the carbon lost from the forest and emitted to the air when wood is burned or decayed is not counted. These studies come in different varieties. Some not only ignore these releases of carbon but count all the carbon stored in forests used to supply wood as part of the benefit, presumably on the theory that those forests would not exist without these wood uses and that the harvested land would otherwise generate no other climate benefits. This is the same assumption used to justify using wood for bioenergy and is incorrect for the same reason discussed above.

A limited number of published studies have analyzed the climate implications of mass timber using what we call the all-carbon-pools approach—a climate analysis that tracks the quantity of carbon stored in various uses as they change over time. These "pools" include carbon in live vegetation in the forest, carbon in roots and slash left behind to decompose in the forest, carbon in wood products, and carbon in landfills. Any carbon lost from the forest but not stored in another pool is by definition lost to the atmosphere. These all-carbon-pools analyses—like other analyses of the climate benefits of wood in construction—can also calculate the "substitution" benefits of using wood to replace concrete and steel. These studies generally have found that most wood harvests increase carbon in the atmosphere for many decades if they assume the typical real-world distribution of the harvested wood into furniture, construction, paper, and

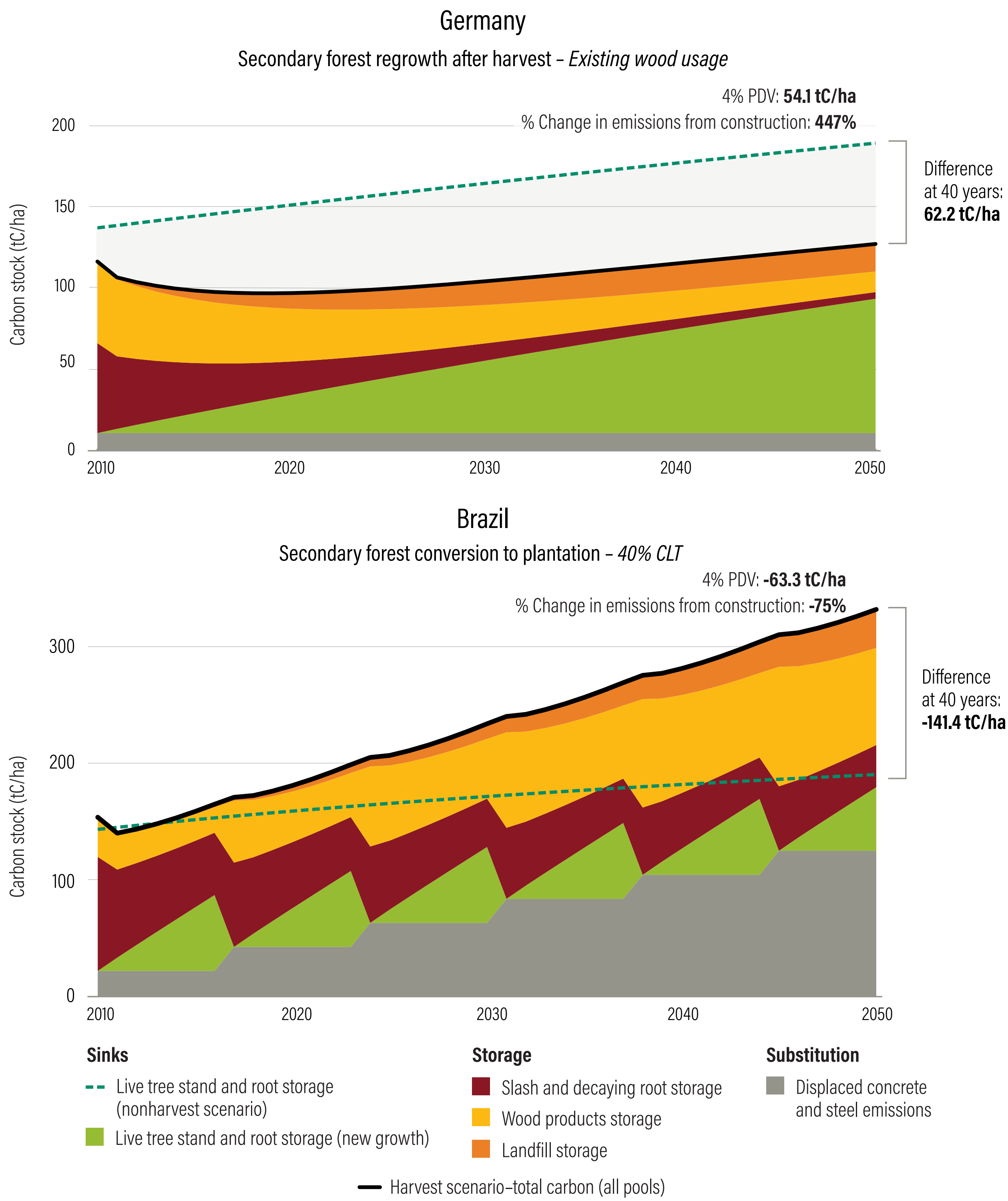
energy. Based on observations to date, only a small percentage of the harvested wood actually substitutes for steel and concrete.

Some studies have found that if forests are harvested with relatively low slash rates, and if a very high percentage of harvested wood is turned into a construction product that substitutes for concrete and steel, the harvest and use can generate GHG benefits within a few decades or sometimes even immediately. Assumptions about several parameters, such as the percentage of wood used for construction, the substitution value, and forest growth rates, significantly influence these results.

To explore the potential implications of wood supply and demand scenarios on land use and the climate in more depth, we applied CHARM to a range of different scenarios. Although other papers have used a similar all-carbon-pools approach, CHARM can summarize the change in carbon over time using a single, time-discounted number. We also calculate the undiscounted net result after 40 years, which typically turns out to be similar. The analysis first generates the effect on GHG emissions per hectare of wood harvested. Figure ES-4 shows how carbon flows between different pools after harvest, the present discount value of the changes, and the absolute change in carbon after 40 years.

CHARM also adds another calculation that is nearly always left out of other papers: the net percentage change in emissions from construction materials when wood is used to replace concrete and steel. This percentage-change calculation is common in other climate contexts, such as comparing a renewable energy source versus a fossil fuel. In policy analysis, it is important for many reasons. For example, a reduction in emissions substantially less than 100 percent would suggest the need to pursue additional solutions. Such emissions reductions might also be eliminated if progress is made in reducing emissions from the "conventional" activity—in this case, the production and construction use of concrete and steel. Furthermore, a finding of a small emissions reduction might also justify less attention and resources devoted to the use of mass timber, particularly since other environmental and social costs, such as biodiversity loss, are not included in the climate analysis. In the scenarios in ES-4, one results in a 447 percent increase in construction emissions while the other results in a 75 percent decrease.

Figure ES-4 | CHARM Model Analysis of Changes in Carbon Pools and Carbon Consequences of Wood Harvest and Use Scenarios



Notes: **PDV:** present discount value of carbon cost per hectare. When the PDV per hectare is positive, there is a net disadvantage to the wood harvest scenario; when negative, there is a net carbon benefit to the wood harvest scenario. **% Change in emissions from construction:** the net percentage change in emissions from construction materials when wood is used to replace concrete and steel. **Difference at 40 years:** the difference at 40 years from the first harvest between the nonharvest scenario carbon stock (green dashed line) and the harvest scenario carbon stock (black line). **Existing wood usage:** a supply scenario where the wood is harvested and follows the existing patterns of wood use. **40% CLT:** a supply scenario where 40% of the wood is used as construction timber that replaces steel and concrete.

Source: Carbon Harvest Model.

Our analysis of wood harvest scenarios for construction (Table ES-2) roughly confirms the implication of other studies that count all carbon pools:

- So long as additional wood harvests follow existing patterns of wood use, an increase in the harvesting of secondary forests for construction use is likely to result in a net increase in GHG emissions, even when accounting for the effects of substituting wood for concrete and steel. One reason is that only a small proportion of harvested wood (and therefore the forest carbon lost due to increased wood harvesting) is typically incorporated into a long-lived wood product and stored in buildings. If we assume that 40 percent of wood harvested will be used to replace concrete and steel, the results are still adverse.
- In some warm, wet regions, converting secondary forests to plantations could result in more favorable climate results if 40 percent of the wood harvest could be used to replace concrete and steel. For forests in Indonesia, construction material savings of 24 percent would be possible, and that would rise potentially to 75 percent in Brazil (if technology can evolve to use its plantation wood). Using existing plantations in Indonesia and Brazil could generate larger savings of roughly 70 percent and 110 percent, respectively. But all this plantation wood is already needed to meet other wood needs.
- Studies have estimated the effects if 70 percent of wood harvested were turned into construction material, so we analyze this scenario as well, although we doubt it would be technically feasible. If this is possible, and with a significant substitution benefit, many harvests could produce small net percentage savings, such as 18 percent in Germany. In a few examples using plantations, savings could be high, reaching 65 percent when natural forests are converted to loblolly pine in the southeastern United States and reaching 95 percent for conversion of natural forests to plantations in Brazil.
- If agricultural land is abandoned and at least 40 percent of wood harvested can be used to replace concrete and steel, we find that fast-growing tropical forest plantations can be more beneficial for the climate than simply allowing these secondary forests to regrow. To avoid clearing more land elsewhere, however, these opportunities require overall measures to reduce the need for agricultural land. In addition, unless the first use of such plantations would be to meet rising demand for other wood uses, using them to meet additional demand to replace construction would require harvesting more wood from natural forests, making them the true source of the wood.

Table ES-2 | Percentage change in emissions when harvesting wood for construction versus using concrete and steel (selected wood harvest scenarios)

WOOD USAGE SCENARIO	EXISTING WOOD USAGE	40% WOOD FOR MASS TIMBER	70% WOOD FOR MASS TIMBER	EXISTING WOOD USAGE	40% WOOD FOR MASS TIMBER	70% WOOD FOR MASS TIMBER
SUBSTITUTION FACTOR	0.44 tC/tC			1.2 tC/tC		
U.S. Pacific Northwest Hemlock-Sitka spruce						
Secondary forest and regrowth	+1,419	+235	+73	+622	+59	-18
Secondary forest and conversion to plantation	+1,299	+207	+56	+565	+46	-26
Existing plantation	+1,121	+162	+29	+480	+24	-39
U.S. Pacific Northwest Douglas Fir						
Secondary forest and regrowth	+1,532	+263	+88	+676	+72	-11
Secondary forest and conversion to plantation	+1,386	+228	+68	+606	+56	-20
Existing plantation	+1,101	+157	+27	+471	+22	-40
U.S. Southeast Oak-hickory						
Secondary forest and regrowth	+898	+111	+1	+374	0	-52
Secondary forest & conversion to loblolly plantation	+709	+65	-26	+285	-22	-65
U.S. Southeast Loblolly-shortleaf pine						
Existing plantation	+653	+50	-35	+258	-29	-69
Brazil						
Secondary forest and regrowth	+1,203	+162	+40	+519	+25	-33
Secondary forest and conversion to plantation	+303	-47	-89	+92	-75	-95
Existing plantation	-77	-128	-136	-89	-113	-117

Table ES-2 | Percentage change in emissions when harvesting wood for construction versus using concrete and steel (selected wood harvest scenarios) (cont.)

WOOD USAGE SCENARIO	EXISTING WOOD USAGE	40% WOOD FOR MASS TIMBER	70% WOOD FOR MASS TIMBER	EXISTING WOOD USAGE	40% WOOD FOR MASS TIMBER	70% WOOD FOR MASS TIMBER
SUBSTITUTION FACTOR	0.44 tC/tC			1.2 tC/tC		
Indonesia						
Secondary forest and regrowth	+609	+269	+110	+237	+75	0
Secondary forest and conversion to plantation	+182	+61	-26	+34	-24	-65
Existing plantation	-33	-32	-81	-68	-68	-91
Germany						
Secondary forest and regrowth	+1,050	+231	+72	+447	+57	-18
Secondary forest and conversion to plantation	+1,005	+219	+65	+425	+51	-21
Existing plantation	+1,696	+395	+165	+754	+135	+26

Source: Carbon Harvest Model.

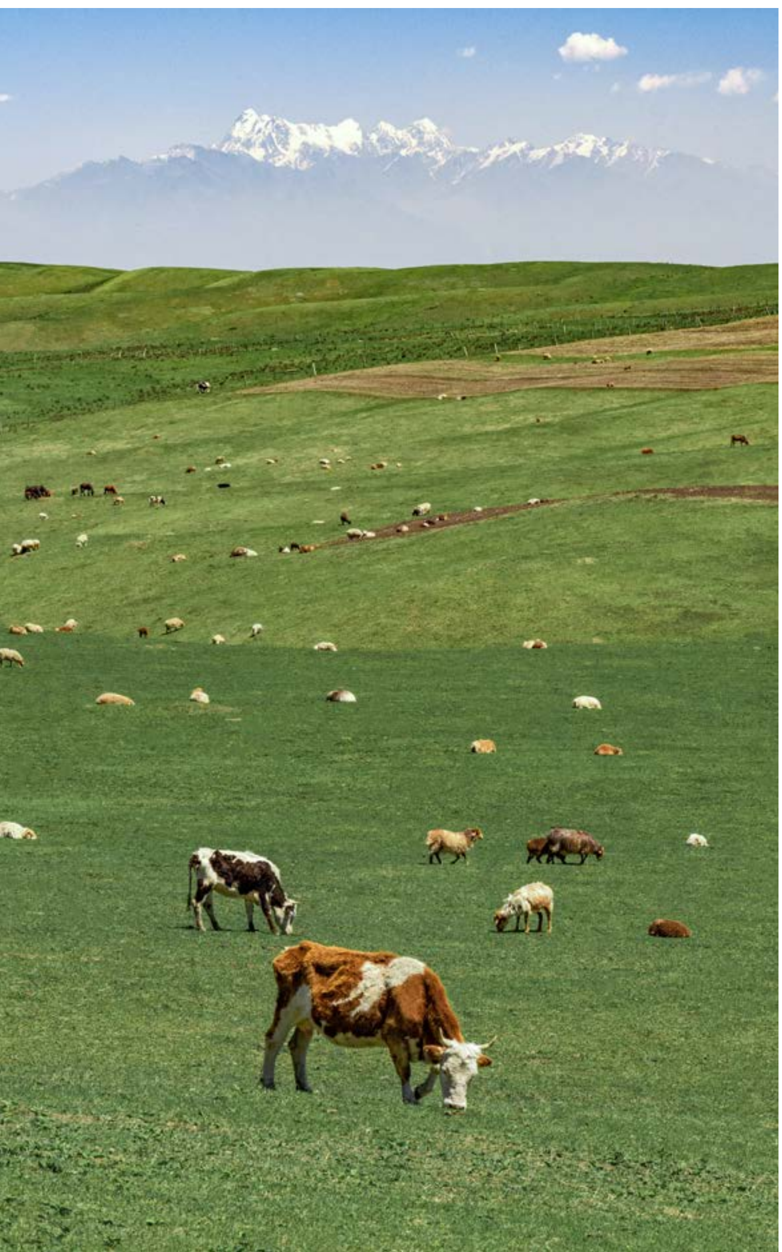
Although many of the estimates and assumptions that go into our calculations have significant uncertainties and would benefit from improved data and analysis, we believe the broad implications of this analysis are likely to remain valid. Among the scientific organizations in agreement is the European Commission's Joint Research Centre, which has concluded that the "material substitution" benefits of harvesting more wood are likely to be less than the costs in reduced forest carbon storage "even assuming the highest substitution values." (Grassi et al. 2021).

Produce, Protect, Reduce, and Restore: Potential Solutions to Reduce Land Competition

Avoiding harsh impacts on climate and biodiversity from the global land squeeze requires strategies to produce, protect, reduce, and restore. The overall strategy is to meet human needs for food, wood, and shelter while reducing the demand for land for human uses and increasing the costs of converting natural lands to those uses. This strategy means *producing* more food and wood on the same land while encouraging denser cities; *protecting* forests and other natural ecosystems; *reducing* demands for land-intensive foods, wood, and other products; and *restoring* forests and other native habitats where few land-based products are produced, where there is a high biodiversity need, or if agricultural land use can be reduced in the future.

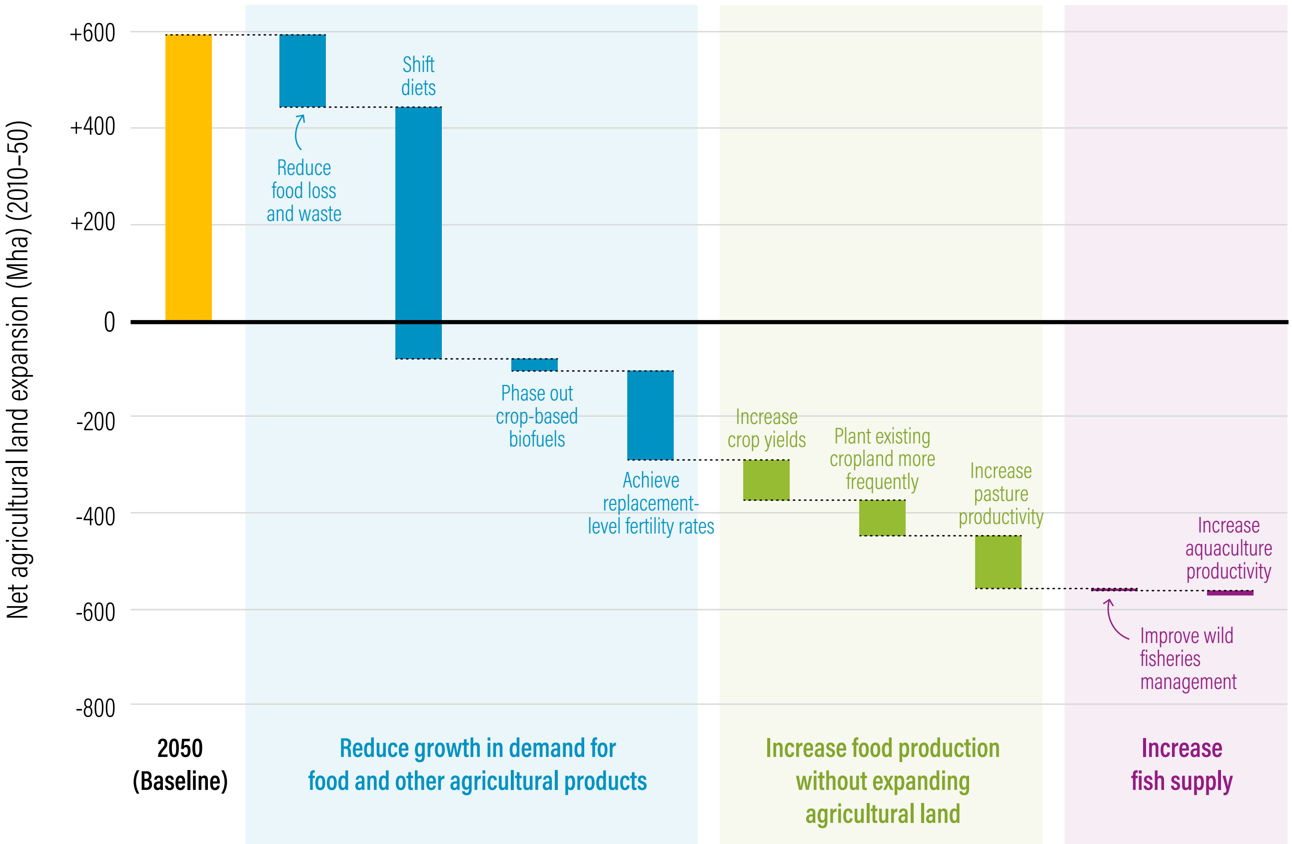
- For agriculture, this strategy involves dramatically increasing crop and grazing yields. It also means reducing food loss and waste and consuming less land-inefficient foods (for example, by shifting diets away from meat and milk, especially beef, towards plant-based foods). Productivity gains should be explicitly linked with efforts to simultaneously protect and restore forests and other natural areas.

- Vast changes are necessary just to avoid further clearing of forests and other natural ecosystems. With massive improvements in all these measures—at the outer edges of what might be technologically and politically feasible by 2050—reducing agricultural land area by 800 Mha between 2010 and 2050 is conceivable (Figure ES-5). Achieving such a goal could free up some lands for both natural forest restoration and forest plantations in a sustainable food and forest future.
- For urban areas, the needs are for a variety of policies to concentrate development.
- For wood products, strategies to reduce consumption include expanded recycling and reduced use of materials for packaging, more efficient wood-burning stoves, and transitions to solar-based electric heating systems in developing countries. This includes using more existing wood harvests for longer-lived uses and then making cascading uses of the wood for shorter-lived purposes. Despite the high environmental costs of plantation forests, there is also a case for providing more of the world's wood from plantations because it would reduce the need to harvest from natural forests. And where natural forests are harvested, a key need is to reduce the large quantities of vegetation destroyed for each ton of wood harvested in tropical forests and to avoid extending roads that open up new areas for harvesting.



- At this time—because the world has not yet demonstrated it can peak and reduce demand for land-based products—any policies that would further increase demand for land-based products should be avoided. This principle is true whether those additional demands are for bioenergy (from sources other than wastes) or increased wood for construction. These expanded uses have the potential to dramatically escalate land-use competition, potentially increasing overall human uses of land several-fold and greatly increasing pressure on the world's remaining forests and other natural ecosystems. When factoring in the opportunity costs of land, these land uses will also typically increase emissions in at least the medium term (through 2050).
- Despite the need for land for human uses, some lands in agricultural use should be restored to natural ecosystems either because of their large carbon costs, such as drained peatlands, or their limited food production combined with high potential for carbon and biodiversity benefits. Examples of the latter include highly sloped tropical pasture lands that can be restored to tropical forests.
- In the future, if strategies to produce, protect, and reduce are highly successful and agricultural land demand is reduced, there are multiple potential competing uses of that "liberated" land, ranging from reforestation and other forms of habitat restoration to bioenergy to timber plantations for construction. These competing uses can be evaluated at that time based on what will likely be new information on the efficacy and alternatives to each.

Figure ES-5 | An ambitious menu of food solutions could theoretically reduce agricultural land demand by 800 million hectares while feeding 10 billion people in 2050



Source: GlobAgri-WRR model in Searchinger et al. 2019.

1. Introduction

The world faces a "global land squeeze" due to rising competition for land. This competition exists between growing demands for land to supply human consumption of plant material—whether for food, wood, or industrial products—and land uses to store carbon and provide habitat in forests, savannas, or some other form of relatively native vegetation.

Already today, nearly half of all vegetated land is in some kind of agricultural use, and 60–85 percent of forests are at least occasionally harvested or manipulated by people in some other way (Erb et al. 2007, 2018; Shukla et al. 2019). As the global population grows to 10 billion people by 2050 (UNDESA 2019a), incomes rise, and the world seeks to make progress against the Sustainable Development Goals (UNDESA n.d.), competition for finite land resources is intensifying.

Growing demands for land to supply products for human consumption pose a major challenge to the climate and biodiversity. Land-use change, including reductions of wood and therefore carbon in remaining forests and savannas, likely has contributed one-quarter to one-third of the carbon that human beings have added to the air (Le Quéré et al. 2016). Habitat loss from the conversion to agriculture and forestry has been the single dominant driver of biodiversity loss (Pimm et al. 2014). Although urban areas occupy a much smaller percentage of land than agriculture and forestry, the projected growth of urban areas in coming decades significantly adds to the land-use challenge; two-thirds of the global population is likely to live in cities by midcentury, up from 55 percent in 2018 (UNDESA 2019b).

Even as these pressures to increase food production, wood use, and urban areas threaten natural habitats, many proposed strategies for addressing climate change make additional demands for land, such as using more biomass for energy and more wood to replace concrete or steel in construction. At the same time, competing climate strategies, often the core of “natural climate solutions,” call for not only protecting remaining forests but also restoring large areas of forest.

How vast is this land use competition? This paper examines the scope of the combined land-use challenges and their implications for carbon and biodiversity.

- Section 2 looks at recent land-use trends and their effects on carbon and biodiversity. For carbon in particular, this section explains the different ways of tracking land-related carbon emissions and what we do and do not know.
- Section 3 projects land demands and carbon implications for agriculture, urban expansion, and forestry. For agriculture and forestry, we provide projections from our own biophysical models and put those projections in perspective with other researchers' estimates. We examine different scenarios: business-as-usual (BAU), high- and low-demand, and scenarios with different sources of supply. The purpose is to provide a "first-order" sense of the challenges and to examine the relative significance of possible changes in demand for and supply of land-based products.
- Section 4 examines some potential implications of climate-related policies that would increase land demands, including bioenergy and long-lived forest products.
- Section 5 examines more deeply the climate consequences of using wood for construction, given competing demands for land, and explores different wood demand scenarios and assumptions.
- Section 6 offers guiding principles for addressing these challenges, including some overall scenarios that could preserve and even restore existing natural areas.

One theme that emerges from this analysis is that climate and biodiversity strategies have frequently failed to appreciate both the scope of global land use competition and the even more basic fact that no use of land is "free" from the perspective of carbon or biodiversity. Solutions that benefit the climate and protect biodiversity require reducing the demand for land for human purposes. Given growing demands for all human land uses, and a fixed area of land, successful protection and restoration of natural ecosystems means both more land-efficient consumption and more land-efficient production. People must try to consume foods and forestry products that require less land, and people must produce more of those products on each hectare of land they use.

2. Global Land-Use Change, Recent Trends, and the Effects on Carbon and Biodiversity

The world has a fixed area of total land that, excluding Antarctica, amounts to 13.3 billion hectares (Bha). Of that, 22 percent is barren or sparsely vegetated (i.e., covered by ice, desert, or almost desert). Another 2 percent consists of rivers and lakes, and around 1 percent is in urban use. That means about 75 percent of the world's land (about 10 Bha) is vegetated.

2.1 Global Land Use Today and the Historical Effects on Carbon

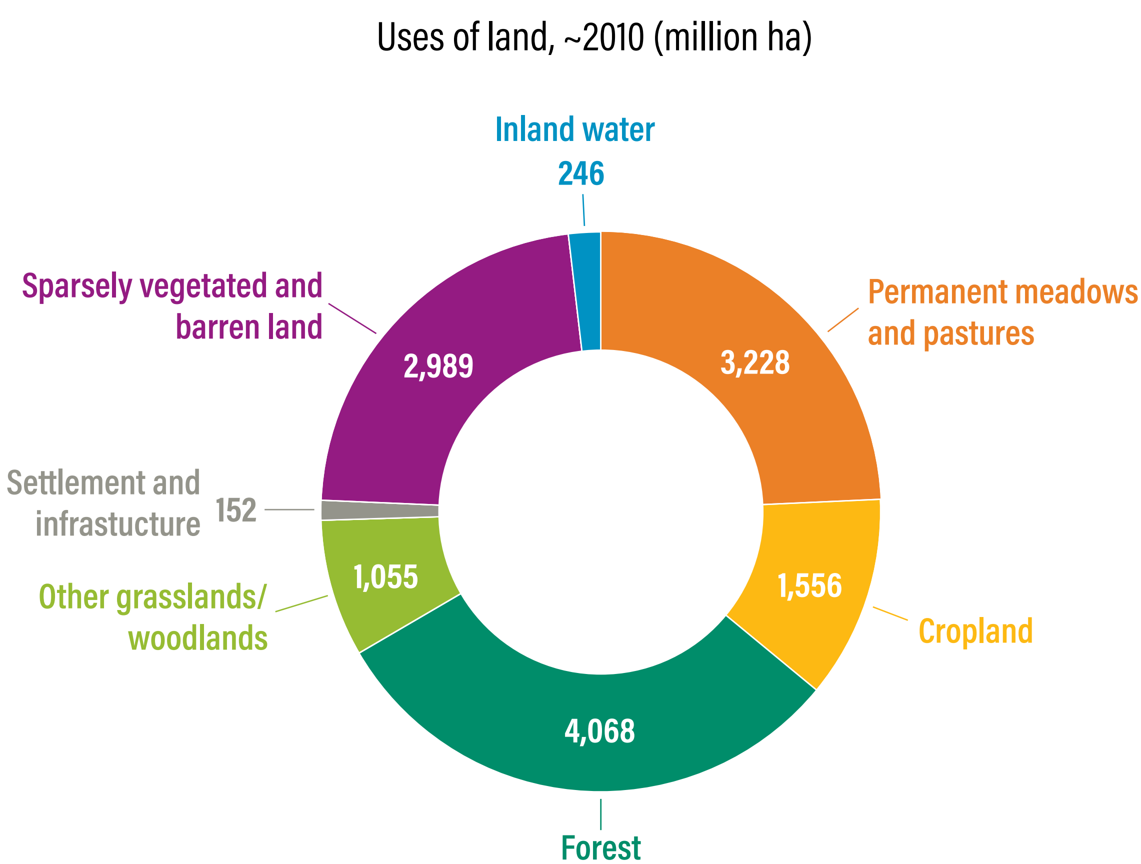
People heavily manipulate the vast majority of the world's vegetated land (Figure 1). Around half has already been converted to agricultural use (probably around 5 Bha depending on different pasture definitions and estimates; Fetzel et al. 2017; Searchinger et al. 2019). Two-thirds of that agricultural use is pasture, and one-third is cropland. According to one estimate, agricultural land area grew by more than 40 percent between 1850 and 2015 (Houghton and Nassikas 2017).

This expansion of agriculture has led to vast losses of forests and native grasslands. Primarily as a result of agricultural expansion, the world has lost 35 percent of its forests (Watson et al. 2018).

Between 1700 and 2000, the world also converted to cropland or otherwise heavily transformed more than 90 percent of its native grasslands (Shukla et al. 2019) and more than 80 percent of its shrublands (Ellis et al. 2010). The rate of loss has also accelerated. According to the Food and Agriculture Organization of the United Nations (FAO), just between 1990 and 2020, global forest area declined by 420 million hectares (Mha), or roughly 10 percent. That 1990–2020 forest loss included 81 Mha of primary forests, which FAO defines as forests with little sign of human impact (FAO 2020b).

Most of the remaining areas are also manipulated by humans. Estimates are that 60–85 percent of forests are regularly manipulated by human uses in the form of harvests or changed plantings, and that is also true of 70–90 percent of woody savannas (Shukla et al. 2019).

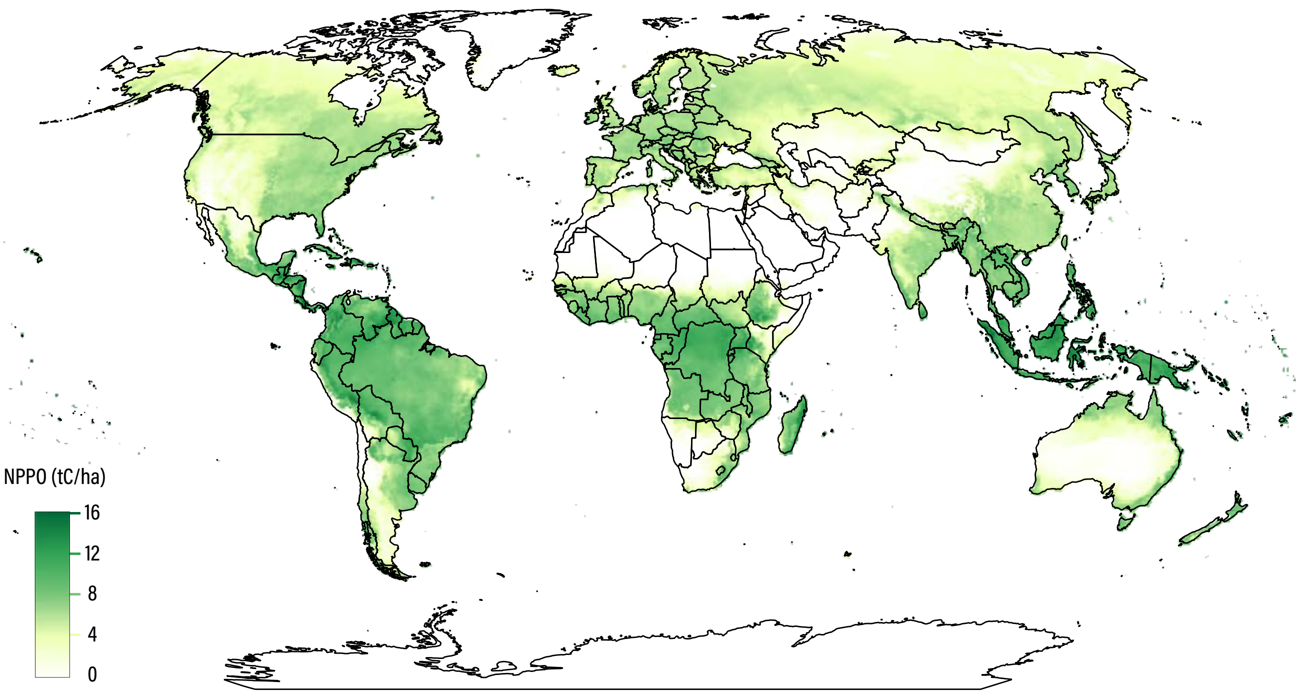
Figure 1 | The Global Land Budget



Source: FAO 2011; GlobAgri-WRR model in Searchinger et al. 2019.

One way to measure the limited productive capacity of managed land is to estimate the likely potential carbon absorbed into aboveground vegetation each year by plant growth (or net primary productivity) if native plants still covered the planet. These estimates are in the range of 65 gigatons of carbon (GtC) per year (Haberl et al. 2007) and vary greatly across the landscape, as illustrated by Figure 2. Although there are limited locations in which human activity has increased total plant growth versus native vegetation, mainly through irrigation, human activity has overall reduced total plant growth per year (Haberl et al. 2007), with more recent estimates placing actual plant growth at around 55 GtC per year (Running 2014). Each year, people directly consume almost 25 percent of this plant-productive potential by harvesting it as crops or wood, feeding it to farm animals, or reducing total plant growth, and human activity also greatly alters most of the remainder (Haberl et al. 2007). Although humanity has greatly increased the efficiency with which it uses land since 1900 (Krausmann et al. 2013), most notably by increasing crop yields, the global capacity to produce plants is a highly limited, although not entirely fixed, resource.

Figure 2 | The world's potential to generate plants is roughly represented by the carbon in native vegetation



Note: NPP0 = net primary productivity of native vegetation.

Source: Calculations using Lund-Potsdam-Jena managed Land model (LPJmL) and reproduced from Searchinger, Wirsenius, et al. 2018.

Land-use changes have been a major cause of global warming. The estimate that historical land-use change is responsible for one-quarter to one-third of the carbon human activity has added to the air since 1750 (Le Quéré et al. 2018) may even be an underestimate. It is based on estimates of total cumulative losses from land conversion and wood harvests of roughly 150 GtC from studies that use so-called bookkeeping methods, such as Houghton and Nassikas (2017).[1] Another recent paper estimated a much larger mean figure of losses of 450 GtC from soils and vegetation (Erb et al. 2018). Although its estimates of conversion due to agriculture were similar to the smaller estimates, it estimated far higher losses due to forest harvests or native vegetation loss in savannas and shrublands.

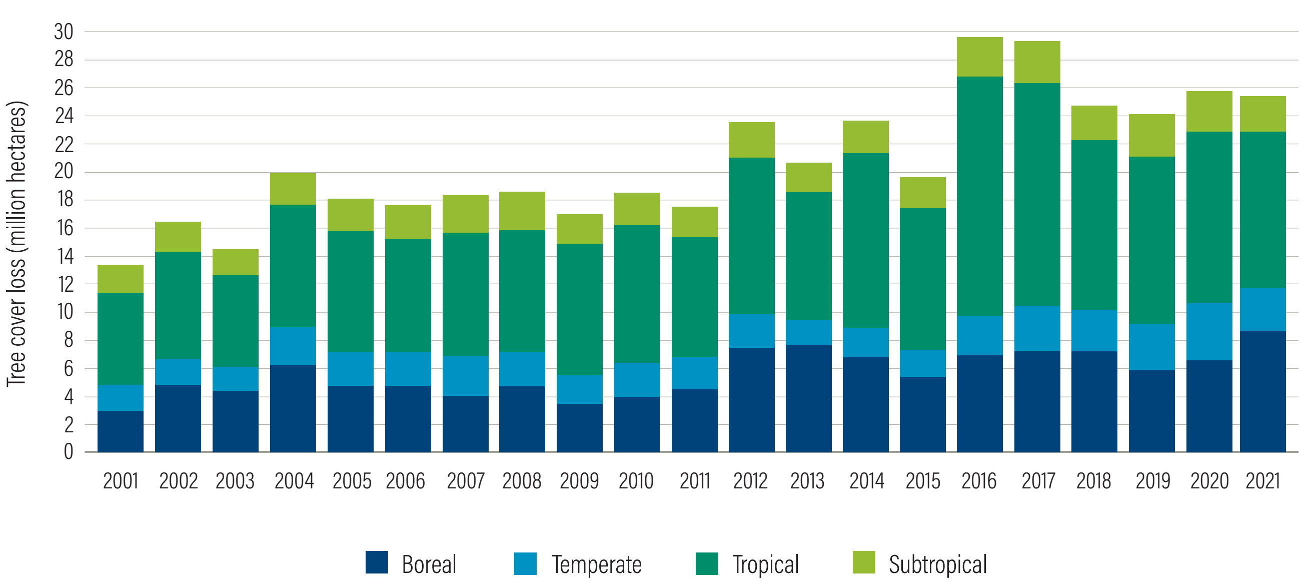
2.2 Ongoing Land-Use Change

Greenhouse gas (GHG) emissions and biodiversity loss from land-use change are ongoing. The different ways of counting this change, and the different meanings of *land-use change* can be confusing. As used by both the Intergovernmental Panel on Climate Change (IPCC) and this report, the term *land-use change* includes both conversions of land permanently to another use and changes, such as forest harvests, that affect carbon storage on land remaining in the same basic use. The overall evidence supports high levels of both gross land-use change and net land-use change. And the difference between gross and net land-use change, which represents shifts in where agriculture occurs, presents its own climate and biodiversity challenges.

2.2.1 Evidence of gross and net forest loss

One form of land-use change arises from the gross loss of forest cover; this refers to the total area of land covered with forest that is cleared for one reason or another. By this measure, human activity was responsible for roughly 15 Mha of gross forest clearing per year from 2001 to 2015 (Curtis et al. 2018), with another 5 Mha due to forest fires. The immediate drivers of this clearing were almost evenly divided between large-scale agriculture, small-scale agriculture, and forestry. Gross deforestation (defined here as tree cover loss, whether permanent or not) has been growing, rising from an average of roughly 15 Mha in 2001–03 to 26 Mha in 2017–21 (Global Forest Watch 2022; Figure 3).

Figure 3 | Gross forest cover loss has averaged 20 Mha per year since 2001



Source: Global Forest Watch 2022.

However, the 20 Mha per year of gross deforestation does not account for areas that reforest. Determining net deforestation is challenging because there have yet to be satisfactory methods of counting net changes globally using satellites. Relying instead on country-reported area changes, FAO reports an annual net loss of 8 Mha of natural forests between 2010 and 2020 and a net annual increase of 3 Mha of planted forests for a net total annual loss of 5 Mha (FAO 2020b). The FAO analysis does not count clear-cuts of forests as forest losses if those forests will be allowed to regrow.

2.2.2 Evidence of other native habitat loss

In addition to forest loss, woody savannas and other native habitats are likely declining. Global Forest Watch (2022) does not count a variety of woody savannas (with less than 30 percent tree canopy cover). There is no global assessment of nonforest lands converted to agriculture, but there have been assessments of loss in particular areas. For example, studies have found large areas of savanna loss in the Brazilian Cerrado (Beuchle et al. 2015; Rausch et al. 2019) and even recent conversion of native prairie in the U.S. Great Plains (Hong et al. 2021; Lark et al. 2015; Molinario et al. 2017; Popp et al. 2014; Wright et al. 2017). Data from both FAO (2020a) and Potapov et al. (2022) suggest that Nigeria has had millions of hectares of agricultural land expansion over the last decade, but only 1 Mha of that land expansion could be explained even by gross forest cover loss, probably because it is occurring in savannas.

2.2.3 Expansion of agricultural area

Mirroring the gross and net losses in forest cover are gross and net increases in agricultural land area. Although satellite data and self-reported country data contain some discrepancies explained by methodological differences and challenges in definitions and reporting, it is clear that large-scale gross agricultural expansion is ongoing and significant net agricultural expansion is occurring, although the amount of net expansion is more uncertain (Box 1).

One important recent study by Potapov et al. (2022) provides evidence that not only gross but also net agricultural land is expanding at a high, accelerating rate. The Potapov study tracked annual cropland changes by carefully training high-resolution satellite data. It estimated that the net expansion of cropland grew from 5.1 Mha per year in 2004–7 to 10.0 Mha per year in 2012–19. To put this figure in perspective, it is roughly six times FAO's reported expansion of annual cropland during this period. Because separating permanent croplands such as tree crops from natural lands is much less reliable, this study could only count annually cropped land. In addition, FAO estimates roughly a 1.0 Mha per year expansion of permanent cropland, such as oil palm, coffee, and rubber, and the Potapov study finds some support for that type of expansion. The combination would bring recent net cropland expansion up to 11.0 Mha per year.

Net changes in pasture are even harder to estimate, but as discussed in Box 1, the evidence of gross pasture expansion into forests is clear; likewise, strong satellite evidence is emerging that clearing of woodland and forests for pasture is also occurring at a large scale on a net basis. Put together, despite significant uncertainties, the evidence suggests that agricultural land is expanding at a very high and likely expanding rate.

Put together, despite significant uncertainties, the evidence suggests that agricultural land is expanding at a very high and likely expanding rate.

BOX 1 | Assessing Agricultural Expansion

Papers such as Curtis et al. (2018) use satellite images to estimate the gross conversion of forests to agriculture.[a] Curtis et al. estimate that roughly 10 million hectares (Mha) have been converted per year in recent decades, but these estimates do not fully estimate net agricultural expansion. On the one hand, estimates of forest cover loss underestimate agricultural expansion because they do not include large-scale conversion of savannas to agriculture. On the other hand, they overstate net losses of forest because they do not assess the abandonment of agricultural land (and reversion to forest).

Data from the Food and Agriculture Organization of the United Nations (FAO), which mostly rely on self-reporting by countries, ideally should count all gross and net changes. FAO reports that cropland area has been expanding in recent years. However, as discussed in *Creating a Sustainable Food Future*, the precise quantities are not reliable. FAO has reported large increases in "harvested area" in recent years (e.g., increases of 15 Mha/year between 2002 and 2016), but reported increases in "cropland" of only 4 Mha/year during this period. Of that cropland, moreover, roughly half is permanent crops such as oil palm, and only 2 Mha/year are in annual crops. In theory, both estimates could be accurate because there is a difference between "harvested area" and "cropland" as defined by FAO. Harvested area counts the number of harvests that occur in a year, so if a hectare is harvested twice in a year, it counts as 2 hectares of harvested area. For this reason, if the quantity of land harvested twice per year increases (double cropping), or if croplands are left fallow in fewer years, harvested area could increase without an increase in total area used for cropland. However, using more detailed sources for some countries in *Creating a Sustainable Food Future*, we did not find that enough increases in double cropping or decreases in fallow land to justify these differences in FAO estimates of harvested area and cropland. Underlying these problems is the large uncertainty in national reports of cropland area, which is matched by significant variations, even in estimates by different satellite studies.

As discussed in the main text, a recent study by Potapov et al. (2022) now provides strong evidence that annual cropland is expanding at a far higher rate than estimated by FAO cropland data.[b] It found a net expansion of 10 Mha/year between 2013 and 2019, roughly six times the FAO estimates for those years. When combined with FAO estimates of permanent crop expansion, that brings the total to 11 Mha/year. It also found that gross expansion was roughly twice the rate of net expansion. This gross expansion is significant because even if other land is restored—and Potapov et al. found only some land regrew some kind of native vegetation in this period—the exchange still likely results in a greater loss of carbon and biodiversity and an increased quantity of carbon in the atmosphere for many years.

Assessing changes to net pasture area remains somewhat confusing, but the evidence is strong that vast areas of forest and woodlands are being converted to pasture on a gross basis. Overall, satellite imagery suggests that most of the conversion of tropical forest is to pasture.[c]

The confusion is due to FAO data. FAO, using country-supplied data, reports a decline of net pasture area between 1976 and 2019. A closer look, however, suggests that this may largely be a matter of definitions; much of the area that was previously reported as "pasture" was very dry or very little used. For example, Australia has reported a decline in pasture between 1976 and 2019 of 155 Mha, reducing reported pasture from 63 percent to 43 percent of the country's land mass. But the great majority of Australia is extremely dry. Australia has essentially been changing its designation of very dry, semidesert. At the same time, pasture is expanding rapidly in the wetter areas. One recent paper, using very detailed satellite imagery, found a conversion of 0.6 Mha of woodland to pasture in just one state in Australia (Queensland) in just one year (2018–19).[d] Similarly, Brazil has reported to FAO a 6 Mha decline in pasture between 1985 and 2018, but a new report using satellites finds a net increase in pasture of 55 Mha during this period.[e] The difference is likely because Brazil has long reported native Cerrado and similar vegetation as grazing land even though it is only occasionally grazed whereas satellite images can capture the clearing of the woodland and the transformation into truly managed pasture. In other words, the satellite imagery seems to show that vast areas of woodland and forest are being converted to pasture on both a gross and net basis.

Overall, the picture that emerges is of vast agricultural expansion at rates that even appear to exceed prior model projections cited in the main text.

Sources: a. Curtis et al. 2018; b. Potapov et al. 2022; c. Gibbs et al. 2010; Graesser et al. 2015; Weisse and Goldman 2021; d. Queensland Government 2021; e. Parente et al. 2021.

2.2.4 Shifting agricultural land

The difference between gross and net agricultural expansion represents the different ways in which the location of the world's agricultural land can shift from one location to another. Some agricultural shifting can be characterized as traditional swidden agriculture, sometimes known as slash-and-burn agriculture. In this system, farmers rotate agriculture among neighboring fields over several years to allow fields to replenish their nutrients. But even where farmers practice swidden agriculture, deforestation is still occurring overall because swidden agriculture is expanding into new forested lands (Molinario et al. 2017). In addition, swidden agriculture is shifting to shorter-term rotations, which means that on average even preexisting swidden landscapes store less carbon. For example, although there is evidence that much of the new agricultural land in Africa will later be abandoned and rotated as part of swidden agriculture (Curtis et al. 2018), the evidence shows that this swidden agriculture in Africa, and therefore overall agricultural land, is expanding rapidly (Potapov et al. 2022).

Shifting agricultural land from one place to another is also occurring over larger areas than just one farm. Within regions (e.g., Latin America) and countries (e.g., the United States), studies have found agricultural land expansion occurring in some areas while agriculture is being abandoned and forests are recovering in other areas (Aide et al. 2013; Lark et al. 2015; Lindquist et al. 2012; de Sy et al. 2015). This shifting could be encouraged by land-use degradation but also by new roads, crop varieties, and increased mechanization, which can make farming new lands more economical than prior lands. For example, in the first decade of the 21st century, there appeared to be a general shift from higher elevation and drier lands in Latin America towards wetter, flatter lands (Aide et al. 2013). On a global scale, FAO and other data show that agricultural lands are also shifting from the Global North to the Global South (Searchinger et al. 2019). This global shift will likely continue partially because the bulk of future food demand growth is likely to occur in the Global South. In addition, this global shift represents a shift in the economics of where to profitably produce food. This shifting means that reforestation in some countries is related to deforestation in others.

China provides a good example of recent shifts in agricultural land demand. Through deliberate policies, China has reforested roughly 30 Mha of mostly hilly land in western China (Hua et al. 2016) and 70 Mha of the country overall since 1973, primarily in forest plantations (Zeng et al. 2015). However, beginning around 1995, China froze its domestic production of soybeans at around 10–15 million tons, even as its meat production and need for soybean-based feeds greatly expanded. By 2017–19, Chinese soybean imports reached an annual average of 95 million tons. Assuming these imports come only from high-yielding countries, that level of import demand represents a need for roughly an additional 30 Mha of soybean production in foreign countries, primarily in Latin America. (In 2019 and 2020, China bought 4 percent of soybeans produced in the Brazilian Amazon.[2]) China also greatly increased its imports of beef, another extremely land-intensive product, probably using an additional 12 Mha or more of Latin American land.[3] These recent increases in agricultural land to supply soybean and beef imports offset much of the forest areas and carbon sequestration gained by reforesting land in China. Germany and the United Kingdom are other examples of "reforesting" countries whose deforestation associated with imported commodities likely exceeds their reforestation (Pendrill, Persson, Godar, and Kastner 2019).

The shifting of agricultural land locations is significant. On the one hand, it means that reforesting abandoned agricultural land plays an important role in maintaining forest cover because net deforestation would otherwise greatly increase. On the other hand, the trade-off between a gradual regrowth of abandoned agricultural lands and an abrupt clearing of forests and savannas for new agricultural lands is nearly always poor from a carbon and biodiversity perspective (Searchinger, Estes, et al. 2015; Wheeler et al. 2016). Carbon losses occur quickly from conversion of forests to agricultural land in one location while the carbon gains from forest regrowth in other locations occur slowly. In addition, much of the agricultural land expansion is occurring in highly biologically diverse tropical forests even as regrowth occurs in less diverse temperate zones (Chen et al. 2019; Schierhorn et al. 2013)—and often with plantation forests that support little biodiversity (Hua et al. 2016).

2.2.5 Other forms of land-use change

In addition to agricultural land expansion, the growth of plantation forest extent is itself a major change in global land use. For example, assuming FAO statistics are accurate, there has been a net change from natural to plantation forests of roughly 3 Mha per year between 2010 and 2020 and expansion of plantation areas of roughly 6 Mha per year between 2000 and 2015. Growth in agricultural crops such as rubber and oil palm, which together grew by 1.3 Mha per year on average from 2005 to 2019, also commonly appears in satellite imagery as forest growth.

Net changes in land use also do not capture other forms of habitat degradation and related carbon loss. For example, once lands are cleared, there is strong evidence that adjacent lands are degraded by a variety of forces, including hunting, invasive species, water and air pollution, and reduced size of contiguous habitat (Gibson et al. 2011; Haddad et al. 2015; Laurance et al. 2012; Laurance et al. 2014). Forest degradation also occurs from selectively harvesting wood. Selective harvest is the dominant form of forestry in tropical and neotropical areas, which explains why papers tracking forest clearing assign little forest cover loss to forestry in these areas (Curtis et al. 2018). Even in temperate zones, a substantial quantity of forestry is probably not captured by satellite images of forest cover loss. One of the most detailed studies in the United States suggested that for each ton of wood removed in land completely cleared, another ton is removed in areas that satellite images continue to identify as forests (Harris et al. 2016).

2.3 Carbon Implications of Ongoing Land-Use Change

Continuing land-use change through both land conversions and ongoing forestry causes additional carbon losses. In general, conversion of forest or savanna to cropland results in loss of nearly all the carbon in native vegetation and around 25 percent of the carbon in the top meter of soil (Searchinger, Wirsenius, et al. 2018). Conversion to grazing land also results in a large loss of carbon in vegetation, although typically with less soil carbon loss—and in some situations can actually build soil carbon—but recent estimates also indicate large carbon losses from grazing land overall (Sanderman et al. 2017).

As summarized in *Creating a Sustainable Food Future*, typical annual emissions estimates from net land-use change are roughly 4 Gt of carbon dioxide equivalent (CO_2e) from ongoing changes in land use and around 1 $GtCO_2e$ from the continuing degradation of soils in peatlands for a total of 5 $GtCO_2e$ (Searchinger et al. 2019). This estimate is similar to other researchers' estimates of annual land-use change emissions for the past decade, including Le Quéré et al. (2018) and Houghton and Nassikas (2017), and is similar to estimated losses per year over the past 50 years (Friedlingstein et al. 2019). Land-use change is therefore responsible for roughly 10 percent of total annual global GHG emissions (Le Quéré et al. 2018).

Although these estimates include a wide variety of data uncertainties, there are some specific reasons to believe they may be low. They are based on so-called bookkeeping methods that do not factor in a range of carbon losses from land adjacent to forest clearings. One paper estimated that for each hectare of forest cleared, six times as much carbon is lost on adjacent land due to a variety of disturbances, only some of which could be captured by the standard carbon bookkeeping methods (Maxwell et al. 2019).[4]

These methods of estimating carbon loss also underestimate the effects of "ongoing" forestry activities. In studies typically used by the IPCC, land-use change includes the carbon losses from ongoing forestry, both the wood removed from the forest and the decomposition of the substantial quantities of wood (termed *slash*) that are left to decompose in the forest. These carbon losses are caused by ongoing wood harvests and have been commonly estimated in recent years at somewhat more than 1 Gt per year. But to calculate the net effects of land-use change, these methods also estimate the carbon gains from the regrowth of forest, which nearly offsets the carbon losses from harvesting. Houghton and Nassikas (2017) estimated that regrowth offset 83 percent of the original carbon losses from forest harvests since 1750 and on an annual basis in recent years by roughly 1 GtC per year. To estimate the net effect of both historical and ongoing human activity, this method makes sense. The regrowth of forests from previous harvests would not occur without those previous harvests.

Yet as we discuss in more depth below, regrowth from previous forest harvests is not a result of *present* forest harvests. If all wood harvesting suddenly ceased, the losses of carbon from the world's forests would greatly decline and the recovery of forests from previous harvests would continue, providing a reduction in atmospheric carbon that would continue for many years. Current harvests influence forest regrowth in the future; as forests harvested today recover, the forests will start to take out of the atmosphere the carbon added by the harvests, paying off a so-called carbon debt. Counting recovery from previous harvests as land-use change accurately accounts for past human activity, but it does not accurately represent the consequences of current forest harvests. It understates the effect of current, ongoing harvests. In Section 3, we separately estimate both the gross emissions from harvesting and using wood and introduce a method of simultaneously counting the climate effects of current harvests with future regrowth and with the persistence of some of the harvested wood in wood products.

Beyond the direct effects of land-use change, there is a large increase in the uptake of carbon by global forests and other terrestrial systems through the indirect human effects of increased carbon and nitrogen pollution. Plants are more efficient at photosynthesis when the air from which they draw their carbon has higher concentrations of carbon dioxide, and they also can use water more efficiently by losing less water through transpiration. Plants overall also grow more with increased nitrogen. Fossil fuel combustion and agricultural activities have increased both carbon dioxide and "reactive" nitrogen concentrations in the air, with much of that nitrogen redepositing on the earth, and the two forces together have led to a large increase in forest and possibly grassland growth. This growth can be measured, among other ways, by the faster growth of trees in "intact forests" (Magnani et al. 2007; Malhi 2010), although there is some indication that this growth effect on intact forests is weakening (Hubau et al. 2020). In colder areas, warming allows forests to grow longer. This absorption of carbon is separate from the regrowth of forests due to prior harvests or agricultural land abandonment.

Although uncertain, the best estimates now show that whereas land-use and land cover changes are causing a net increase in atmospheric carbon of around 5 $GtCO_2$/year, absorption of carbon by vegetation is responsible for removing around 12–13 $GtCO_2$/year according to commonly used estimates (Friedlingstein et al. 2019; Li et al. 2016). Although the precise magnitude is uncertain, the effect is both a physical reality and is built into climate models in predicting future change.

Understanding these different flows of carbon into and out of plants and soils is important because the different ways in which researchers "net" one flow of carbon against another can create the impression that some sources of emissions do not "count" or even exist (Box 2). That "netting" in turn can lead to distortions in public policy. These distortions include encouraging policymakers and others to implicitly treat forest harvests as carbon neutral or having limited carbon costs. Netting has also incorrectly conveyed that emissions from land-use change are not occurring in most temperate countries. In our view, each land-use action that increases atmospheric carbon should be judged for its own, separate effects.

BOX 2 | The Implications of Land-Use Netting Approaches for Measuring Carbon Effects of Land Use

Researchers have tended to report their estimated emissions from land-use change in ways that involve some implicit netting of some emissions but not others. Guidance for national inventories from the Intergovernmental Panel on Climate Change (IPCC) also allows some netting. These forms of netting have important consequences.

First, when reporting emissions from land-use change, many researchers tend to report the effects of forestry on a net basis, in which carbon gains from the recovery of forests from prior harvests is netted out against the carbon losses from new harvests. The result implies that present forestry has no (or greatly reduced) carbon consequences even though it has no effect on recovery from prior harvests. A further implication of this approach is that there is no reason to focus climate policy on reducing emissions from forestry, even though doing so would avoid real emissions.

Second, researchers, including the IPCC, often report emissions on a net basis from regions or countries. For example, in a key summary chart in a prominent 2011 paper in *Science*, the authors only reported temperate emissions on a net basis, and they showed a net carbon gain due to reforestation and regrowth of forests from prior clearing.[a] As a result, even though land clearing is still occurring in temperate zones, it is not identified as a source of emissions from land-use change. Instead, the focus is on reducing emissions from land-use change for agriculture in the tropics, and little attention is given to reducing such land clearing in temperate zones.

Third, under IPCC guidance for national inventories, countries are allowed to report the net emissions from all "managed forests."[b] In countries that had heavily cut their natural forests decades ago, including the United States, Europe, and China, that net emissions amount is strongly influenced by the more recent recovery of those previously cleared forests. That recent regrowth also includes the effect of the carbon dioxide and nitrogen fertilization.[c] IPCC guidance does not allow this netting out of any policy rationale. Instead, the IPCC adopted this rule only because it failed to identify a viable, alternative method for segregating the effect of direct human management after 1990 (when the first climate treaty was signed) from the effects of higher carbon dioxide and nitrogen fertilization and regrowth from pre-1990 forest clearing.[d] In many countries in the Global North, including the United States, virtually all forests are considered to be "managed." This method therefore allows these countries to "take credit" for both forest recoveries from harvests before 1990 and from the effect of carbon dioxide and nitrogen fertilization. For those who are not fully informed, it can create the impression that no activities in the United States are causing land-use change emissions, and perhaps even that U.S. agriculture and forestry activities are a net benefit to the climate.

Sources: a. Pan et al. 2011; b. IPCC 2006; c. Grassi et al. 2018; d. IPCC 2010.

2.4 Biodiversity Effects of Ongoing Land-Use Change

Ongoing land-use change poses grave threats to biodiversity. A major UN report recently found that 1 million species are threatened with extinction (IPBES 2019), a rate of extinction now being called Earth's sixth mass extinction event (Ceballos et al. 2015). There is broad agreement that the main driver is habitat loss due both to permanent land conversion and to the loss of primary forests (IPBES 2019; Pimm et al. 2014). One recent paper found that 80 percent of all threatened terrestrial bird and mammal species are imperiled by agriculture-driven habitat loss (Tilman et al. 2017). Another paper found that bird species with impending extinctions due to land-use activities ranged from 74 to 121 in 2011 (depending on the conservativeness of the estimate), which could nearly double the 140 bird species estimated to have been lost since the year 1500 (Marques et al. 2019). The loss of plant and insect species is even more directly attributable to land conversion.

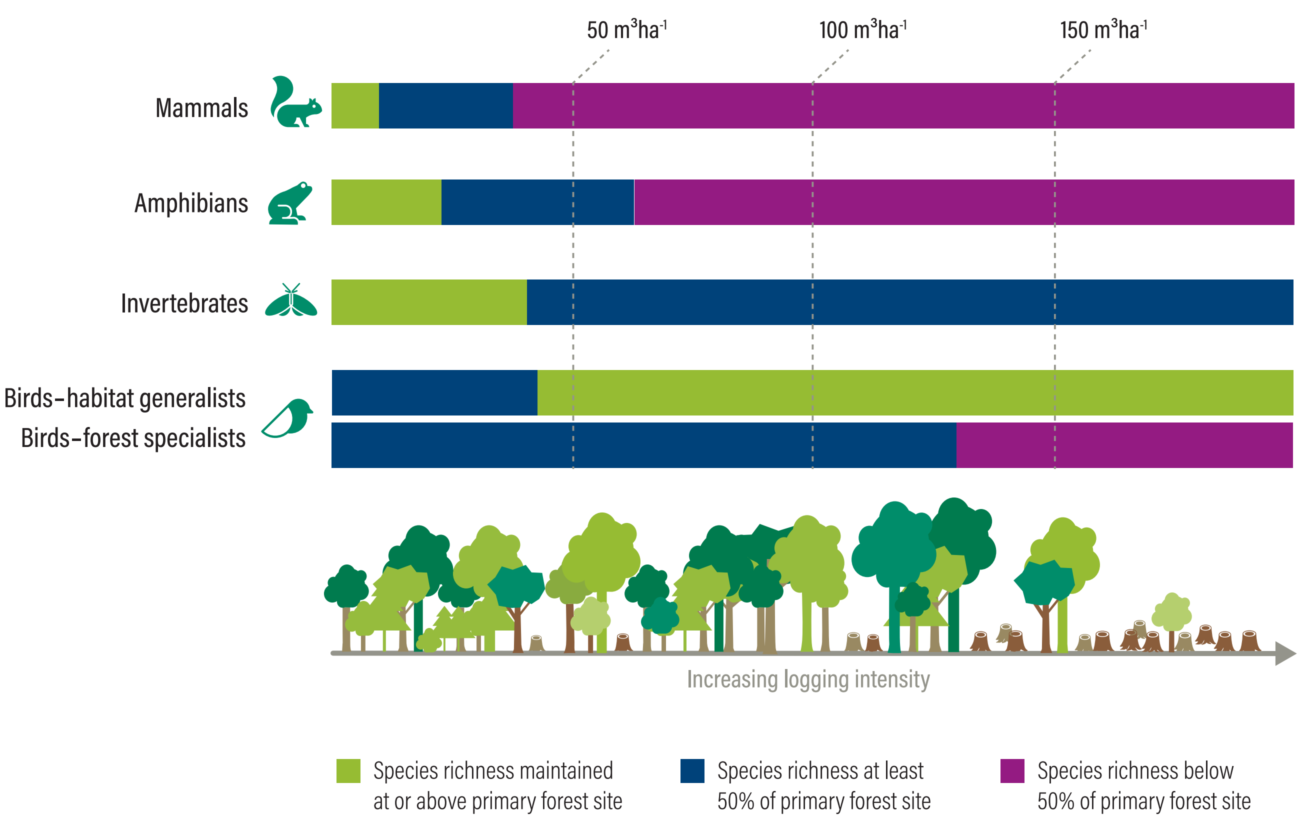
In addition to agricultural conversion, forestry activities have largely adverse effects on biodiversity. Biodiversity is based on complexity. As forests mature, many tend to develop a diversity of vegetation filling different niches, and it is common for different insect species to evolve to take advantage of these differences. The loss of truly primary forests, either through agricultural clearing or forestry, typically has enormous consequences for biodiversity even if forests are eventually allowed to regrow naturally (Gibson et al. 2011), although the results in particular areas can depend on the taxa of species (Barlow et al. 2007).

Watson et al. (2018) provide a good summary of forestry effects on biodiversity:

> *Beyond outright forest clearance (which is the greatest threat facing biodiversity), forest degradation from logging is the most pervasive threat facing species inhabiting intact forests. Many species are sensitive to logging, and studies across many taxonomic groups have shown impacts increasing with the intensity of logging and with the number of times a forest has been logged. Fragmentation of intact forest blocks (and associated edge effects) is also a severe threat to forest-dependent species, especially those requiring large areas to maintain viable populations (for example, wide-ranging predators and tree species that occur naturally at very low densities). In temperate, boreal, and tropical forest regions, the loss of large contiguous tracts of forest has meant wide-ranging forest-dependent species have either retreated to the last remaining intact forest systems or are extinct. Furthermore, there is evidence that—even for some forest species that may persist for a time in degraded fragments—intact forests are necessary to ensure their persistence over the long term.*

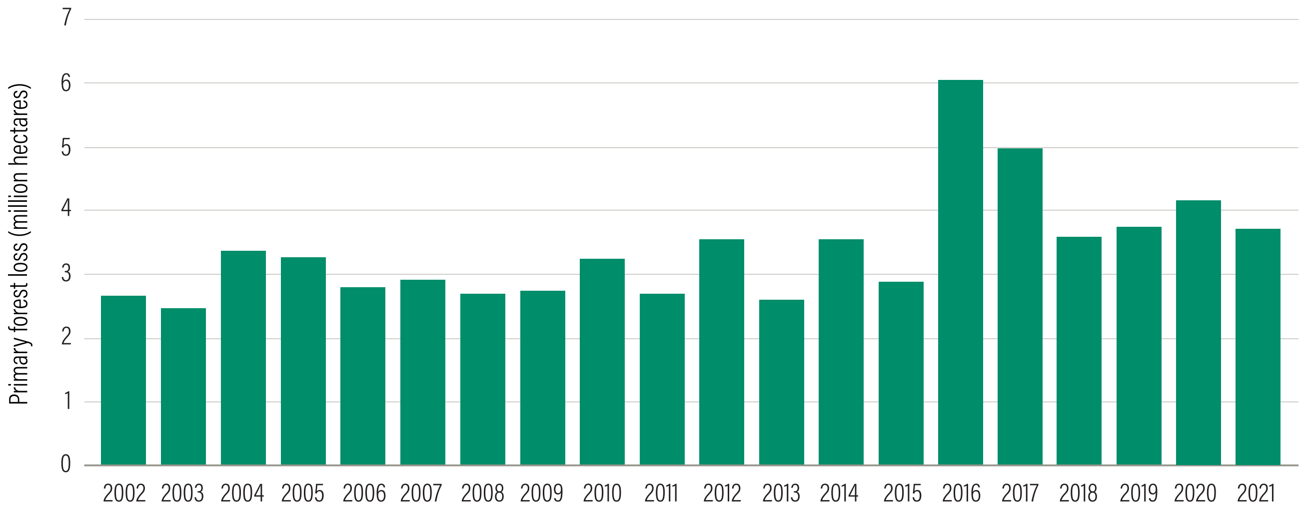
In general, more intensive logging means larger effects on biodiversity, as illustrated by Figure 4. The "generalist" bird species—birds that are relatively common anyway because of their ability to use a variety of habitats—may make greater use of heavily logged forests, but there are

Figure 4 | More intensively logged forest areas have larger effects on biodiversity



Source: Burivalova et al. 2014.

Figure 5 | Between 2002 and 2021, the world lost more than 60 Mha of humid primary forest



Source: Global Forest Watch 2022.

typically declines in the bird species that are of greater conservation concern because they rely on intact forests.

These differences in the biodiversity composition of forests due to forestry activities make the loss of intact forests a particular concern. Satellite data indicate a steady loss of roughly 3 Mha of intact tropical forests per year from 2002 to 2015 and an increase in loss of 4–5 Mha per year from 2016 to 2021 (Global Forest Watch 2022; Figure 5).

Even as they hold less biodiversity than primary forests, secondary forests can still harbor substantial biodiversity if allowed to recover naturally (Barlow et al. 2007; Chazdon et al. 2009; Koh and Wilcove 2008; Watson et al. 2018). Converting forests to forest plantations, however, nearly always causes large biodiversity habitat losses, with greater loss typically increasing with more intensive management (Brockerhoff et al. 2008; Paquette and Messier 2010; Pawson et al. 2013). One study in China's Shanghai Province found that plantations supported even less biodiversity (as measured by birds and bees) than agricultural lands (Hua et al. 2016). Specifically in the southeastern United States, one study found that loblolly pine plantations of any age had significantly less diversity amongst bird species relative to the native tree species (Haskell et al. 2006). Even in agricultural landscapes, natural forest patches may increase local biodiversity—for example, of pollinators—while plantation forests may not (Taki et al. 2011).

The conversion of native grasslands and savannas, many of which can support high plant diversity, also has large biodiversity consequences. The tallgrass prairies of the United States, which once typically harbored 300 more grass and herbaceous species per hectare, have been almost completely eliminated (Wilcove 2000). When replaced with pasture, typically only 1 or 2 grass species are present. The result has been large declines in grassland bird species and vast numbers of insect species, many of which we will never know about. The Brazilian Cerrado is one of the world's most biologically diverse ecosystems with more than 12,000 species of plants, of which 4,400 are found nowhere else (Silva et al. 2006). Most of the native Cerrado has been converted to agricultural use (Beuchle et al. 2015), including pasture that uses a single African grass species. Bengtsson et al. (2019) summarize:

In southern Africa, more than 20% of the grassland biome has been cultivated, 60% is irreversibly transformed to other land uses, and most of the remainder is used as rangeland for livestock. Over 90% of the semi-natural grasslands in northern Europe have been lost since the 1930s. In North America, 80% of the central grasslands has been converted to cropland. Similarly, more than 43 Mha of the Eurasian steppe have been converted into cropland, and 60–80% of the grassland area in South America is degraded.

2.5 The Importance of Reversing Habitat Loss Going Forward

Even as land-use change is ongoing, most strategies to solve climate change and to preserve biodiversity require that net land-use change stop and that some quantity of forests and other habitats be restored. For climate purposes, virtually all strategies that map out solutions to climate change require an almost immediate elimination of emissions from deforestation and other land-use change. Climate mitigation strategies generally focus on two alternative targets: a global average warming of 2°C or 1.5°C. Scientists have estimated a total, cumulative quantity of CO_2 emissions that can occur before exceeding these goals. By 2020, the remaining cumulative emissions allowable would have been around 400 $GtCO_2$ from all sources.[5] At ongoing rates of annual emissions, the emissions from land-use change alone would constitute more than a third of this cumulative emissions budget, leaving too little room for emissions from other sectors (energy, concrete, and waste). To hold warming to 1.5°C, most strategies rely on decreasing agricultural area to allow for reforestation or other land uses to take carbon out of the air (Rogelj et al. 2018; Sanderson et al. 2016).

Although much focus has been on protecting forests, climate and biodiversity are also greatly threatened by the ongoing conversion of the world's tropical woody savannas. These areas of scattered trees and grasses are roughly as extensive as the world's tropical forests (Popp et al. 2014). Although they hold less carbon than tropical forests, their conversion would still cause large releases of carbon, particularly relative to their potential agricultural yields, as well as high effects on biodiversity (Searchinger, Estes, et al. 2015).

Biodiversity protection requires the same goals. The United Nations found that not only does habitat loss threaten extinctions, but without habitat restoration, 500,000 species are likely to go extinct (IPBES 2019).

Among the reasons for immediate action, scientists believe that the Amazon rain forest is at a tipping point. Additional clearing of forest is likely to reduce the Amazon's internal generation of clouds and rainwater necessary for it to remain a rain forest (Barkhordarian et al. 2019; Lovejoy and Nobre 2019). If deforestation continues at present rates for even 10 more years, the Amazon could inexorably transform into a savanna, losing much of its present carbon.

Even as land-use change is ongoing, most strategies to solve climate change and to preserve biodiversity require that net land-use change stop and that some quantity of forests and other habitats be restored.

3. Projected Future Demands for Land and Carbon Implications

Increasing human demands for land are driven by rising populations and rising incomes. As of 2020, the global population was 7.8 billion. By 2050, according to the midrange UN projection, the population will likely rise to 9.7 billion (UNDESA 2019a).

Although global incomes remain highly unequal, there is likely to be a large increase in the number of people entering the "global middle class." For example, by defining *middle class* as the capacity to spend US$11 per person per day, the global middle class reached 3.8 billion in 2018 and is likely to reach 5.3 billion by 2030 (Kharas and Hamel 2018). Although vast numbers of people are living in poverty, the percentage of the population living in poverty is also generally declining (although it has increased during the COVID-19 pandemic).[6] People with higher incomes demand more food (and more land-intensive foods), more wood products, and more urban areas. In this section, we focus on projected increases in land use for these three purposes.

We examine scenarios with different levels of demand (e.g., BAU, high-demand, low-demand), and with different sources of supply. All future projections have uncertainties and all data about global land use and demands for food, wood, and other land-based products have serious limitations, so any projections of this type are rough. The purpose is to provide a "first order" sense of the challenges and to examine the relative significance of possible changes in demand and supply.

For this type of analysis, we use biophysical accounting models. Such models can estimate what the land use and carbon implications will be if a given number of people eat a given diet and consume a certain amount of wood. These kinds of models also make it possible to determine the necessary mixtures of demand and production systems, such as levels of diets and crop yields, to achieve any land-use and climate goal while meeting projected future human needs. Biophysical models do not tell policymakers how to achieve these levels of demand and production systems, but they take the first step towards determining what those levels ought to be to meet an environmental goal.

In biophysical models, including those used in this report, economics can still play a role in the background for estimating future baselines, such as future food and wood demands under BAU. For example, estimated relationships between levels and types of consumption and both incomes and population play a role in the estimates incorporated into our modeling of future demands. The use of trend-line relationships also implicitly incorporates economic factors in a crude way: to the extent that past changes in prices have played a role influencing demand and supply, a trend-line analysis implicitly assumes that these price effects will, in aggregate, have the same continuing effect. These estimates, however, become inputs to the biophysical models to estimate land-use and GHG implications.

For our purposes, biophysical models have at least two advantages over economic models:

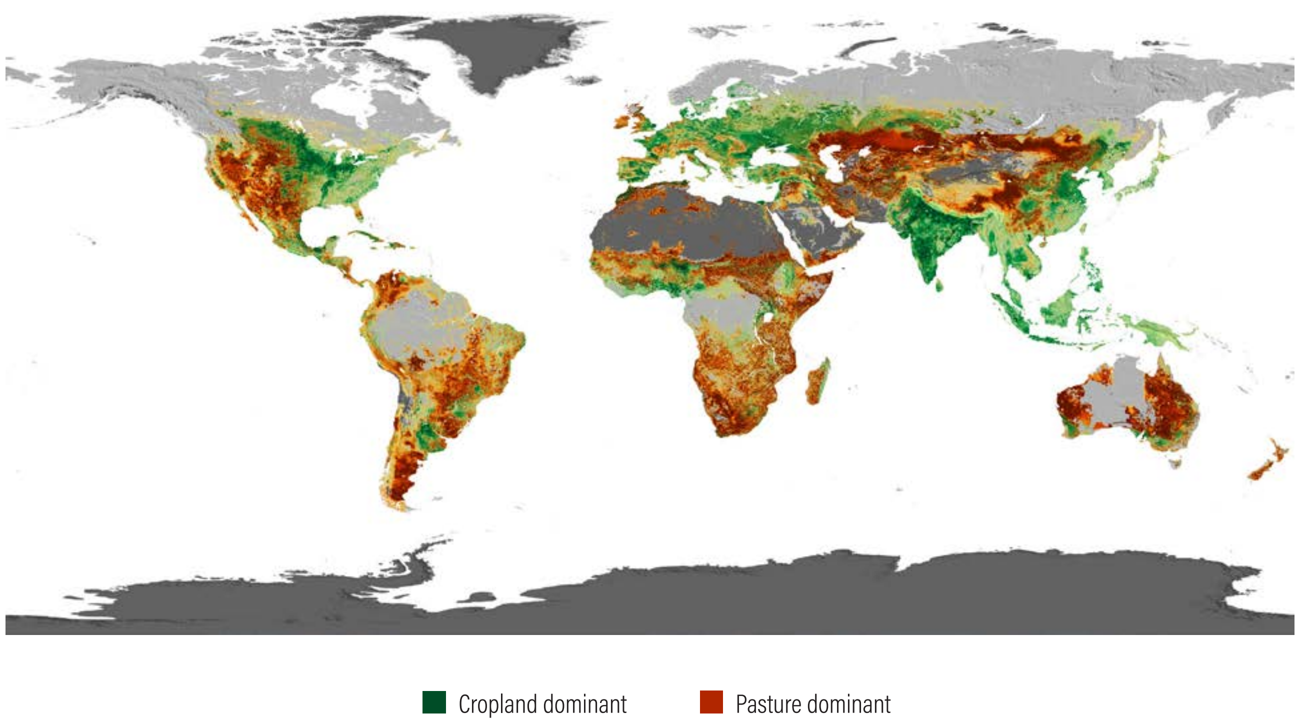
- Although they do not attempt to analyze economic feedbacks, biophysical models can provide answers with greater certainty. Economic models have to start with the same biophysical relationships, but they then add economic relationships (such as demand and supply elasticities) that are extremely hard to estimate at global scales. Long-run elasticities are particularly hard to estimate, as are future elasticities, which will change with unknown technological and social developments. Leaving out economic impacts does not mean they cannot be important for policy. But it at least allows for a more straightforward analysis of certain questions, like how much land would be converted to uses for food production if demand and yields grow by certain percentages. Economic responses might influence how much demand and yields change, but they are not necessary to determine what the land-use consequences are of those changes.
- Using economic models to determine goals can cause confusion. For example, an economic model might project that if policymakers increase demand for wood or crops (e.g., for bioenergy), land use might not expand fully to meet the new demand because higher prices would cause other people to eat less or governments to adopt policies that would lead to farmer increases in yields (Searchinger,

Edwards, et al. 2015). If reliable, such information can be informative for some purposes, but it could also misinform. By assuming changes in government policy, such a model result could also fail to communicate the need for governments to actually change policies. Biophysical accounting models communicate what combinations of changes in production and consumption are necessary, which then can inform policymaking.

3.1 Projected Agricultural Expansion and Carbon Implications

At around 5 Bha, agriculture—including both cropland and pastureland—is the dominant human use of land, occupying nearly half of the world's vegetated land (Figure 6). Agriculture is also the primary historical and ongoing driver of deforestation (Curtis et al. 2018; Millennium Ecosystem Assessment 2005). In addition to rising population, as poverty rates decline and the global middle class increases, people are likely to shift from eating mostly staple crops to diets with greater shares of vegetable oils, fruits and vegetables, and more animal-based foods (meat, fish, eggs, and dairy; Tilman and Clark 2014; Valin et al. 2014). All of these foods require more land per calorie (and/or per gram of protein) relative to staple crops (Ranganathan et al. 2016; Searchinger, Wirsenius, et al. 2018; Tilman and Clark 2014; Willett et al. 2019). Meat and milk are particularly land intensive. Per gram of edible protein, typical estimates are that pulses require around 3 times less land than chicken and pork (as a global average), 5 times less than dairy, and around 20 times less than beef (Ranganathan et al. 2016; Searchinger, Wirsenius, et al. 2018).

Figure 6 | Cropland and pastureland occupy nearly half of the world's vegetated land



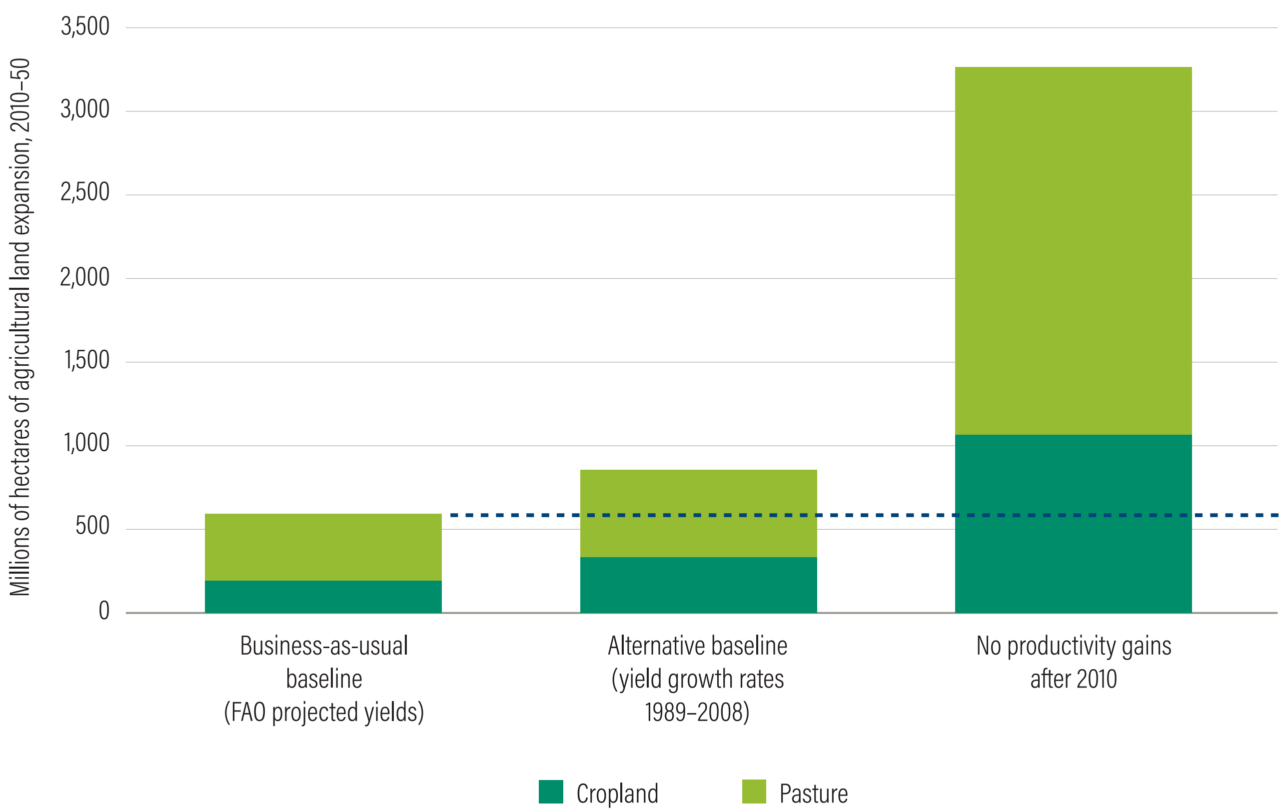
Note: Areas in gray contain neither cropland nor pastureland.

Sources: Ramankutty et al. 2008; map from Navin Ramankutty, University of British Columbia.

One way of viewing the land-use challenge is to estimate agricultural land-use requirements to meet projected future food demands with today's crop yields and livestock feeding efficiencies. WRI used a biophysical model called GlobAgri-WRR (Box 3) to do so in the *Creating a Sustainable Food Future* report. The report estimated that BAU food demand (as measured in crop calories) would rise by 56 percent between 2010 and 2050, with meat and dairy demand rising by 68 percent. Keeping 2010 food production systems constant, we found that global agricultural land use would have to increase by 3.3 Bha between 2010 and 2050 to meet that level of food demand (Searchinger et al. 2019). Bringing 3.3 Bha of additional lands into food production would require the conversion of most of the world's remaining tropical and temperate forests and woody savannas, and it would release an amount of carbon from land-use change that, by itself, would make it impossible to reach climate targets. This number means that a combination of yield gains, livestock efficiency improvements, and reductions in demand growth are needed to avoid this massive land clearing (Figure 7).

Another way to estimate the agricultural land-use challenge is to assume that crop yields will continue to grow into the future as they have in the recent past and to project reasonable improvement in livestock efficiencies as well. Figure 7 shows WRI's estimates. The BAU baseline scenario assumes that yields grow at their average rates from 1961 to 2008, and the alternative baseline scenario assumes that yield growth rates from 1989 to 2008

Figure 7 | Depending on assumptions, agricultural land in the 2050 baseline could grow by hundreds of millions or even billions of hectares compared to 2010



Notes: FAO = Food and Agriculture Organization of the United Nations. The cropland increase includes a 20 million hectare (Mha) increase in aquaculture ponds under the two projected baselines and a 24 Mha increase in the projection with no productivity gains after 2010.

Source: GlobAgri-WRR model in Searchinger et al. 2019.

will prevail into the future. The BAU baseline scenario estimates the need to expand cropland by roughly 200 Mha and pastureland by 400 Mha, for a total of nearly 600 Mha between 2010 and 2050—an area nearly twice the size of India. The alternative baseline scenario, which uses more recent yield growth rates, estimates a need to clear more than 850 Mha (Searchinger et al. 2019).

Even our main BAU baseline scenario in Figure 7, with nearly 600 Mha of agricultural expansion at the expense of forests and woody savannas, along with ongoing degradation of peatlands, would release roughly 240 $GtCO_2e$ into the atmosphere over the 40-year period, or 6 $GtCO_2e$ per year (Searchinger et al. 2019). To put that level of emissions in perspective, it is equal to 25–40 percent of the estimated maximum cumulative carbon dioxide emissions "budget" from all human sources between 2010 and 2050 to limit warming to 1.5°C–2°C; such a result would make it very difficult, if not impossible, to hit these climate targets given the large emissions cuts also needed in the energy sector. More recent papers have concurred that ongoing emissions from land-use change threaten the world's ability to meet Paris Agreement climate goals, especially given projected future food demand growth (Clark et al. 2020; Hong et al. 2021).

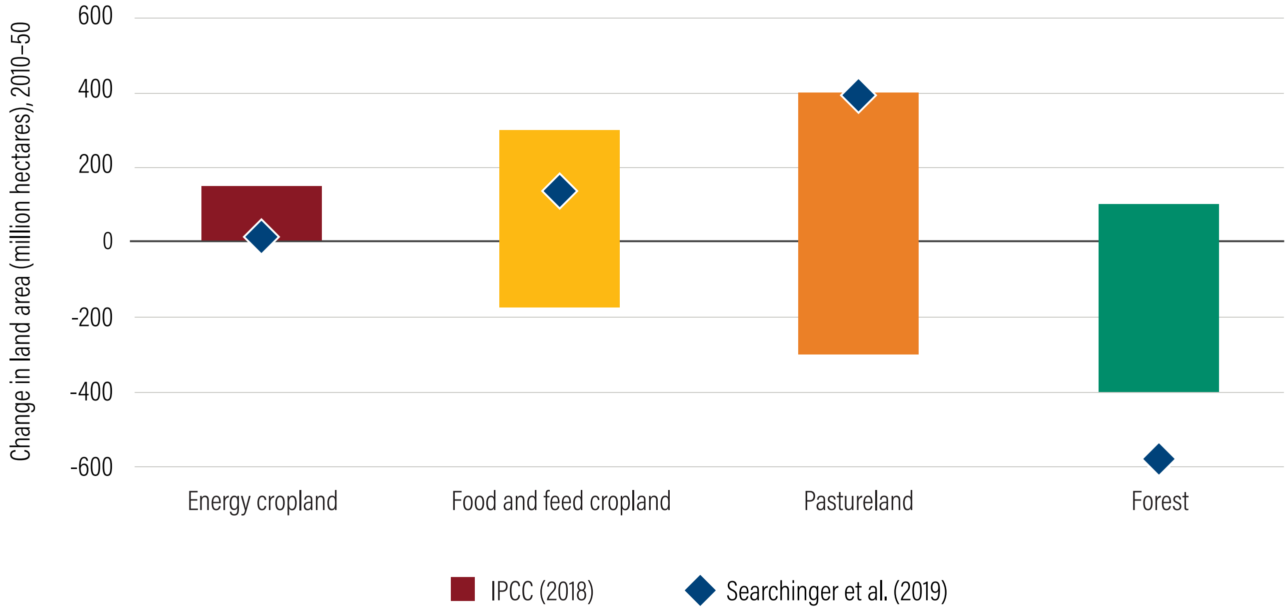
Other researchers have also projected a large growth in agricultural land demand by 2050 to feed a growing population, using both biophysical and economic models. For example, a majority of the agro-economic models reviewed in Schmitz et al. (2014) project increases in cropland and pasture area, with 6 of the 10 models reviewed projecting a cropland increase at least as large as that in *Creating a Sustainable Food Future*. The IPCC (Rogelj et al. 2018) recently summarized a wider range of models (Figure 8), and the *Creating a Sustainable Food Future* report's BAU baseline agricultural land demand projections mostly fall within these ranges. Biophysical-only models tend to project even larger growth in agricultural land demand. Bajželj et al. (2014) projected an increase in cropland and pastureland of more than 1 Bha between 2009 and 2050, and Tilman and Clark (2014) projected an increase in cropland alone of 600 Mha. And although certain analyses are more optimistic and project smaller growth or even declines in agricultural area out to 2050 (e.g., the lower estimates in Figure 8), Searchinger et al. (2019) noted that such analyses tend to rely on overly optimistic estimates. For example, they tend to assume that yields grow in a compound rather than linear fashion, or they use lower, out-of-date 2050 population estimates. That said, the majority of the IPCC's point estimates project BAU forest loss in the hundreds of millions of hectares between 2010 and 2050 (Rogelj et al. 2018).

BOX 3 | Overview of the GlobAgri-WRR Model

GlobAgri-WRR is a global accounting and biophysical model developed by researchers with the Centre de coopération internationale en recherche agronomique pour le développement (CIRAD) and Institut national de la recherche agronomique (INRA), World Resources Institute, and Princeton University. The model estimates land-use demands and greenhouse gas emissions related to food production and consumption scenarios, including emissions from land-use change, as agricultural land demand grows or shrinks. It links two data sets from the Food and Agriculture Organization of the United Nations on agricultural production and food supply/consumption (Food Balance Sheets) and accounts for the multiple products (e.g., food, feed, energy) generated by the world's crops. Production-side parameters, such as yields and emissions intensity, can be altered, along with consumption-side parameters, such as human population, dietary patterns, trade patterns, and levels of waste.

Like the Carbon Harvest Model developed for this paper, GlobAgri-WRR does not try to estimate economic feedback effects (e.g., changes in demand for products as prices change). This focus on biophysical relationships helps make the model more transparent as it does not need to include the many econometric assumptions of such models, which would otherwise introduce a high quantity of complexity, especially when projecting three decades into the future. Economic relationships are not necessary to estimate the land-use and climate consequences of a set of production and consumption practices by themselves, which is the focus of this report.

Figure 8 | BAU projections of land-use change between 2010 and 2050 suggest additional large-scale conversion of forest to cropland and pastureland



Note: The forest loss estimate in Searchinger et al. (2019) is not necessarily comparable because it includes the loss of woody savannas. These estimates also do not consider changes in land extent of forestry activities.

Sources: Rogelj et al. 2018, Figure 2.24; Searchinger et al. 2019.

Although future projections are inherently uncertain, these differences in projections do not alter the scope of the land-use challenge; they just reflect different judgments about the likelihood of meeting these challenges under some concept of BAU. Differences in future projections depend mainly on differences in projected future diets or different projected increases in crop yields, pasture output, or livestock efficiencies.[7] Even if a model projects less land-use change, that result still depends on such factors as moderating growth in demand for meat and milk and achieving high increases in output of food per hectare.

The biggest differences in model results are in projected pasture areas. These differences are important because pastures are commonly identified as an available source of land for a wide range of other uses, from cropland to wood plantations to bioenergy plantations. Pasture area projections face a variety of data uncertainties; even estimates of present pasture area are highly variable, as are the quantities and the quality of the forages they provide and the feed uses of most of the world's cattle.[8]

These uncertainties, however, do not dramatically alter our understanding of the challenge. Forages of some kind, whether from pasture or cut-and-carry grasses, are the largest source of feed for cattle (Herrero et al. 2013). There is broad agreement of the technical potential to increase efficiency of production based on wide disparities in production efficiencies (Cardoso et al. 2016; Herrero et al. 2013; Strassburg et al. 2014). However, absent government protection, it is also cheap to convert forests to pasture (Searchinger et al. 2019), which helps explain why it is occurring extensively in

Brazil, Bolivia, Colombia, and Paraguay, among other countries (Aide et al. 2013; Rausch et al. 2019). Major institutional barriers also prevent many farmers from investing in improved technologies, such as the lack of a clear title, which is pervasive in Colombia. These obstacles must be overcome at a vast scale to meet rising demand without clearing more land. *Creating a Sustainable Food Future* estimated that every improvable hectare of pasture in Latin America would likely need to triple its yield to meet FAO projections for global beef and dairy consumption in 2050 without further pasture expansion.

The land demand projections in *Creating a Sustainable Food Future* were based on FAO diet and yield projections from 2012 and applied from 2010 to 2050, so it is possible now to compare those projections with more recent trends (Lebling et al. 2020). Those recent trends have both bad news and good news. In general, demand for overall meat and dairy has been growing closely in line with our projections. There is no global sign of moderation in the growth of these key food items, which play a disproportionate role in driving agricultural demand for land. The main source of good news is that our projected 88 percent increase in total global ruminant meat consumption—the most land-intensive type of food—so far appears high. Between 2012 and 2017, per capita ruminant meat consumption actually slightly declined (FAO 2020a), setting a global pace closer to 35 percent total global consumption growth between 2010 and 2050. Unfortunately, this change did not occur because of major declines in high-consuming developed countries. Instead, it resulted from small declines in high-consuming countries and a stagnation in per capita consumption at very low levels in low-income countries. In fact, per capita consumption decreased from already low baselines in sub-Saharan Africa.

As we discuss above, the overall result of demand and yield changes has been an accelerating expansion of cropland in ways that are consistent with our prior projections.

3.2 Projected Urban Expansion and Carbon Implications

Growth in areas of human settlement presents another large source of increased future demand for land. The estimates of current global urban area range from less than 1 percent to almost 3 percent of global land area, excluding Antarctica and Greenland because of different definitions, classification methods, and spatial resolutions (Liu et al. 2014).[9] Estimates of actual artificial surfaces are on the order of 30–60 Mha, or 0.23–0.50 percent of global land area. Most global-scale urban area expansion projections preferred to use "built-up area" data sets as their base map (Seto et al. 2012), such as MODIS v5, due to their higher levels of accuracy (Potere et al. 2009; Schneider et al. 2009). As indicated in these references, estimates of city or urban administrative areas that incorporate other vegetated and barren land around the built-up areas can reach 2.64 percent of global land area.

The urban percentage of the world's population is projected to increase from 55 percent in 2018 to 68 percent in 2050 (UNDESA 2019b), suggesting that around 2.5 billion more people will be living in urban areas by 2050 compared to 2018. This large population increase implies a large expansion in urban land area and infrastructure in the next three decades.

A number of studies use different statistical tools to project urban area growth in the coming decades. At the low end, Angel et al. (2005) estimated 100 Mha of total urban area in 2030, but that still represented a more than doubling in area from their estimate of urban area in 2000, which focused mainly on artificial surfaces. Later, Angel et al. (2011) estimated an urban area of 216 Mha in 2040 under an assumption, based on observed trends, that the average density of the urban population is decreasing 1 percent per year because of sprawling development. Table 1 lists the projections, methods, and inputs for different urban area projections, and Figure 9 shows the current and future urban area estimates from these studies. Overall, the mean estimates are for a roughly 100 Mha increase in urban area between 2000 and 2050. When scaled to our 2010–50 study period, the increase would be 80 Mha.

Table 1 | Projections of Global Urban Area in 2030, 2040, and 2050

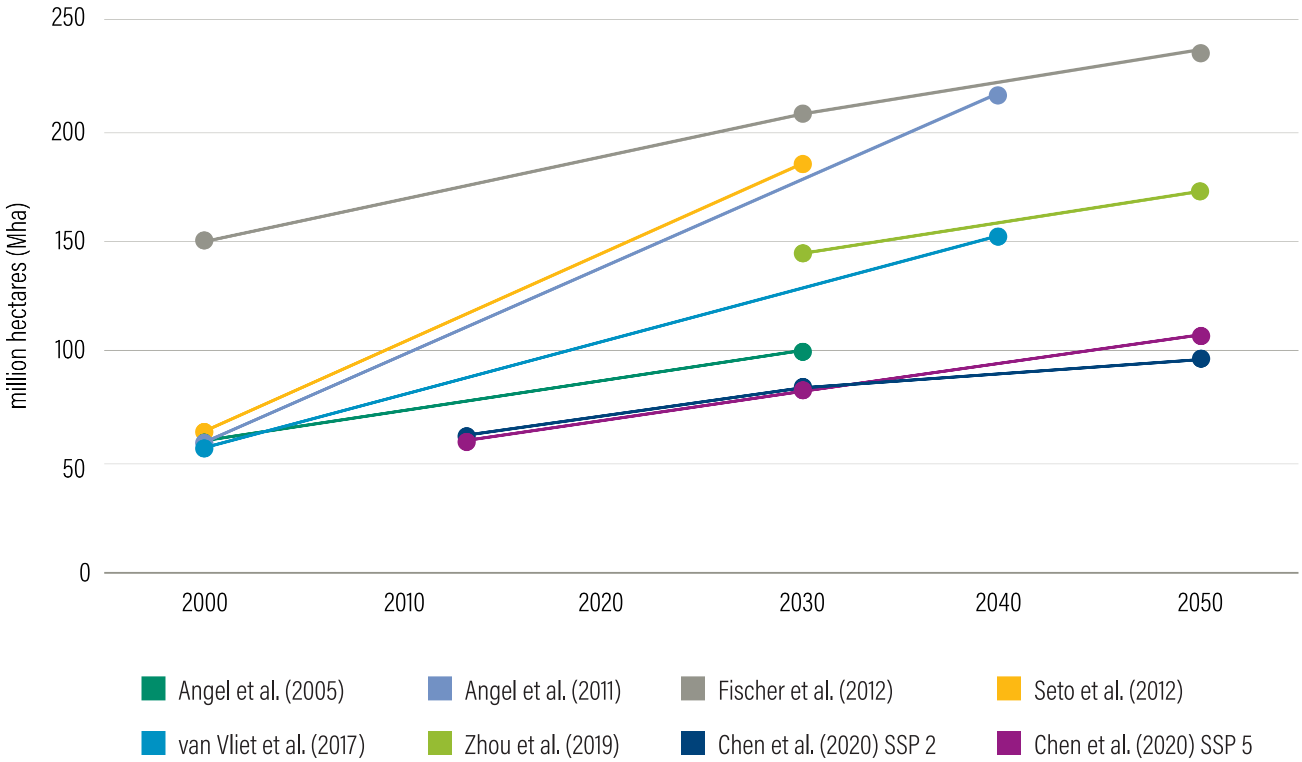
	PRESENT URBAN AREA (MHA)	PROJECTED FUTURE URBAN AREA (MHA)	METHODS	INPUTS
Angel et al. 2005	**2000** 41	**2030** 100	Logarithmic regression model	UN urban population, income, agricultural rent, climate, exclusion area
Angel et al. 2011	**2000** 60	**2040** 216	Logarithmic regression model	UN urban population, 3 realistic density change scenarios
Fischer et al. 2012	**2000** 152	**2030** 206 **2050** 233	IIASA world food system model (general equilibrium)	Climate model, production, demand, trade parameters[a]
Seto et al. 2012	**2000** 65	**2030** 186	Probabilistic forecasts with GDP and urban population, land-change model GEOMOD	UN GDP and population projection, GRUMP population density, slope, distance to roads, population density land cover
van Vliet et al. 2017	**2000** 58	**2040** 154	Urban demand model IMAGE, land-change model CLUMondo	UN population medium scenario, land system maps
Zhou et al. 2019		**2030** 147 **2050** 173	Urban growth model SLEUTH (cellular automata)	LandScan population, slope, exclusion area, hill shade, transportation, historical urban distribution
Chen et al. 2020, SSP2	**2010** 60	**2030** 80 **2050** 97	Panel data regression for land demand with GDP per capita and urbanization, land-use model FLUS (artificial neural networks)	SSP GDP and population projection, distance to city center, distance to road network, distance to airport, elevation, slope, eco-region, and water resource condition
Chen et al. 2020, SSP5	**2010** 60	**2030** 85 **2050** 108		

Notes: FLUS = Future Land Use Simulation; GDP = gross domestic product; GRUMP = Global Rural-Urban Mapping Project; IIASA = International Institute for Applied Systems Analysis; SSP = Shared Socioeconomic Pathway.

a. Fischer 2009.

In assessing global land-use competition, one study found that 64 percent of urban expansion between 1992 and 2015 displaced croplands; 9 percent, forests; 13 percent, shrublands; and 10 percent, grasslands (van Vliet 2019). Since urban land is often located in areas suitable for crop production, and food demand is still growing, a shift from croplands to urban areas means that crops will need to be produced in other areas, potentially with higher elevations and steeper slopes, which can reduce crop yields. Van Vliet et al. (2017) estimated a potential displacement of crop production at 65 million tons between 2000 and 2040 due to urban expansion.

Figure 9 | Studies have different estimates and projections for urban areas



Note: SSP = Shared Socioeconomic Pathway.

Because urban expansion affects native habitats and their carbon not only directly but also by displacing and pushing croplands into those habitats, an average carbon cost per hectare of new cropland can provide a reasonable basis for estimating the global carbon costs of this urban expansion, holding agricultural land uses constant. (For urban area expansion to result in less loss of native habitats, it would have to cause some combination of reduced food consumption and higher land-use efficiency gains in agriculture than those incorporated into our baselines. Any effect of urban expansion on agricultural land area is implicitly incorporated into our independent agricultural projections because they are based on trend lines.) Urban areas can continue to hold some carbon stocks, such as in parks and people's yards. That amount obviously depends on the precise definition of urban areas used by each projection. For example, in the United States, one study found average vegetative carbon stocks of 0.4–0.5 tons of carbon (tC) per hectare in heavily urban areas of Seattle and 12–18 tons per hectare in medium urban areas (Hutyra et al. 2011). Overall, we estimate that additional urban expansion of 80 Mha between 2010 and 2050 is likely to directly cause carbon losses of 27.0 $GtCO_2e$, or 0.7 $GtCO_2e$/year.[10]

3.3 Projected Expansion of Forestry and Carbon Implications

Analyses of the land-use and carbon implications of wood harvests inherently differ from those of agriculture and urban land expansion. The conversion to agriculture and urban use, as we and others analyze it, involves a one-time change in carbon stored on each hectare. The assumption behind forestry activity is that some kinds of trees will regrow on harvested lands. All land uses tend to have indirect effects on adjacent lands, but the direct effects differ in this fundamental way.

Even though some kind of forest will typically regrow, forest harvests cause immediate losses of both carbon and biodiversity. Over time, both can significantly recover, but that recovery typically takes decades at least (and cutting old-growth forests can have permanent effects on biodiversity). Some tropical savannas may recover relatively quickly while harvesting temperate, old-growth rain forests (of which only remnants now remain) would take many hundreds of years to fully recover (Rozendaal et al. 2019).

One common way to evaluate the effects of forestry is to compare the average carbon stock and biodiversity of regularly harvested forests with that of an unharvested forest. In other words, if forests are harvested every 50 years, a carbon or biodiversity analysis would compare the average carbon stock and biodiversity of the forest over the entire rotation with that of an unharvested forest. We do not follow this approach for carbon because it understates the significance of time. GHG emissions need to be constrained heavily in the coming decades to avoid crossing critical climate thresholds. Ambitious climate targets for 2050 adopted by the Paris Agreement largely reflect that idea. A judgment of climate effects should reflect the need for short-term GHG reductions, which also imply costs for short-term GHG increases.

We address the effects of future forestry in two ways:

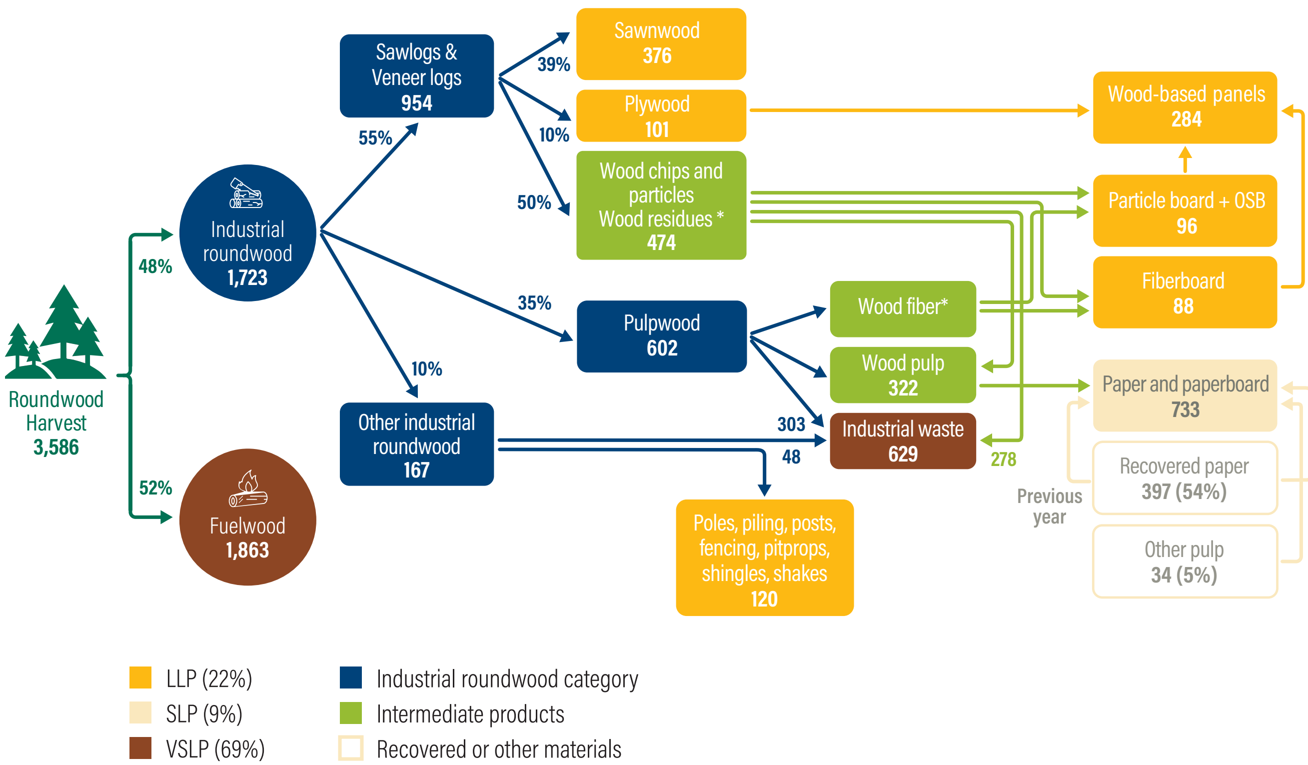
- First, we estimate the area likely to be directly affected by forest harvests. Most of these forest areas are likely to have been harvested in the past, but the ongoing harvesting continues to cause carbon losses and biodiversity effects, as discussed above. We analyze these forest areas using different scenarios of potential future harvests.
- Second, we estimate the carbon consequences of these future harvest scenarios. In doing so, we use a time-discounting value (described below) to value the carbon losses between 2010 and 2050. Unlike agricultural expansion, there are far fewer efforts to estimate the future scope and consequences of forestry on land use and the climate; to our knowledge, none of these efforts uses our time-discounting approach. We therefore start by analyzing future demand for wood products.

3.4 Projected Future Demand for Wood Products

Using FAO's widely adopted approach, global wood harvests are divided into two categories: industrial roundwood and fuelwood. Industrial roundwood is essentially any wood harvested for commercial purposes, and fuelwood is generally wood harvested by individuals or small groups for their own fuel uses. Fuelwood is primarily harvested in developing countries and includes wood used for charcoal (Houghton and Nassikas 2017). Some fuelwood has also been harvested in more developed countries, primarily for heating, and in recent years, government policies have caused an expansion of industrial wood harvests of logs for electricity and other energy uses. Industrial roundwood itself falls into three categories: generally larger logs that are sawn into timber or peeled to provide veneer, typically called sawlogs and veneer logs; generally smaller logs harvested for paper, particleboard, and paperboard (e.g., cardboard), called pulpwood; and other industrial roundwood. Figure 10 shows the initial breakdown of roundwood production in 2010 (FAO 2020a): fuelwood (1.9 billion cubic meters [m^3], or 52 percent), sawlogs and veneer logs (954 million m^3, or 26 percent), and pulpwood (602 million m^3, or 17 percent).

Although harvested wood initially falls into these three major categories, the production of wood products generates wastes along the way, and those wastes in turn contribute to other products. For example, the production of sawn wood, such as wood boards, and plywood generates smaller wood chips and particles, which in turn are mostly used for making some wood-based panels or paper products or are burned for energy. (Overall, wood-based panels include plywood and oriented strand board [OSB] often used in construction and particleboards used for furniture.) Much of the wood used to make paper products is also burned for energy in the production process. Tracking these different wastes and flows is necessary to estimate future quantities of wood harvests to meet rising demand for final products and to estimate how long the carbon in this wood remains stored in some use or is emitted to the atmosphere.

Figure 10 | Harvested wood flows into different products (production by volume, million cubic meters, 2010)



Notes: LLP = long-lived product; OSB = oriented strand board, SLP = short-lived product; VSLP = very-short-lived product. Wood chips and particles and wood residues exclude the chips in production of pulp, particleboard, fiberboard, and chips counted as pulpwood, fuelwood, and other industrial roundwood. The quantity of wood fiber (source materials for fiberboard, particle board, OSB) is not reported by FAO. The unit of wood pulp is converted from tons (10 percent moisture content) to cubic meters (m^3) by multiplying 1.87 m^3/ton. This conversion factor is determined as (1–10 percent moisture)/wood basic density, where we used a global average density 0.48 tons/m^3 derived from the forestry products conversion guideline of the Food and Agriculture Organization of the United Nations. The shrinkage of total roundwood is neglected due to lack of information. Numbers may not add to 100% due to rounding.

Source: FAO 2020a.

Although FAO's data do not directly track this flow of wood, and its reporting includes many overlapping categories, we used a combination of FAO data and reported production parameters to construct the flow of wood harvests into different uses both globally and by country. We ultimately tracked this wood into four major categories based on the source and how long the product remains before being thrown out or burned (Table 2):

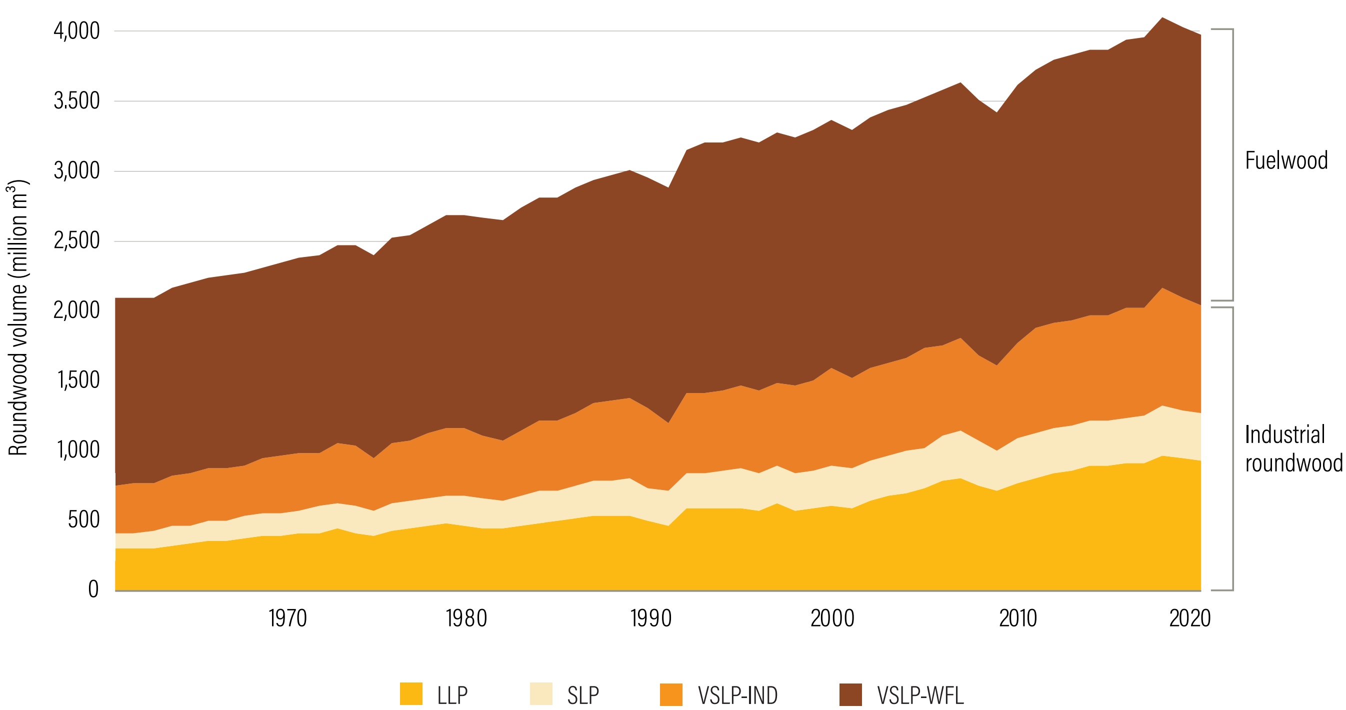
- Long-lived product (LLP) used for construction and furniture
- Short-lived product (SLP) used for paper and cardboard products
- Very-short-lived product used immediately for fuelwood (VSLP-WFL)
- Very-short-lived product burned for energy as a by-product of other wood production (VSLP-IND)

In 2010, LLPs constituted 22 percent of total roundwood, including sawn wood, wood-based panels, and other industrial roundwood. The production of paper and paperboard is supplied by wood pulp (43 percent of the paper products) and recycled paper and other pulp (57 percent). (We used the FAO category "wood pulp" instead of "paper and paperboard" to represent SLPs because that way we can close the material balance of total roundwood harvested.) SLPs constituted about 9 percent of total roundwood. VSLPs-WFL constituted 52 percent of wood harvested, and VSLPs-IND constituted 18 percent. Overall, VSLPs constituted 69 percent of total roundwood, which means that a large majority of all wood harvested is quickly burned, releasing its carbon back into the air. (We discuss our estimates for how long these different products persist below.)

Note, however, that the FAO does not map production to uses comprehensively. For example, it does not report VSLP-IND, the waste from wood production that is burned. Due to FAO's great data challenges, we were not surprised to discover inconsistencies between the different categories of product consumption—particularly by country—which required judgments and adjustments to reconcile in a physically sensible way. As described in Appendix A, we reconstructed this flow by adding the VSLP-IND category and adjusted the raw total roundwood estimates for each country.

World wood harvests, production, and consumption have been rising for decades (Figure 11). Researchers examining wood demand, as with food demand, have previously found relationships between the level of demand, population, and gross domestic product (GDP). This relationship suggests that wood consumption will increase in light of projections by the United Nations that global population will increase 40 percent between 2010 and 2050 and that GDP per capita will grow between 60 percent (lower bound based on linear time trend) and 111 percent (upper bound based on the Shared Socioeconomic Pathway 2, or SSP2). We interpreted these as indicative relationships. In theory, the quantity of wood use could drive

Figure 11 | Global total roundwood production increased from 1961 to 2020



Notes: LLP = long-lived product; SLP = short-lived product; VSLP = very-short-lived product.

Source: Authors' estimates based on FAO 2020a.

Table 2 | Wood Demand Categories from FAOSTAT Wood Products

CATEGORY	FAOSTAT ITEM CODE	WOOD PRODUCT	SHORT NAME	UNIT	CONVERSION FACTORS
Long-lived product (LLP)	1872	Sawnwood	SNW	m^3	0.48 dry matter tons/m^3
	1873	Wood-based panels	WBP	m^3	
	1871	Other industrial roundwood	IND-O	m^3	
Short-lived product (SLP)	1875	Wood pulp	WPL	tons (10% moisture)	0.90 dry matter tons/ton
Very-short-lived product (VSLP)	1864	Wood fuel	VSLP-WFL	m^3	0.48 dry matter tons/m^3
		Industrial waste	VSLP-IND	m^3	
Other	1876	Paper and paperboard	PPB	tons (10% moisture)	0.90 dry matter tons/ton

Source: Conversion factors from FAO et al. 2020.

GDP growth rather than the other way around, but because wood consumption is a small part of overall GDP growth, that is unlikely. And even if both wood use and per capita income were driven by a third, unknown factor related to both, per capita income growth could still be a good predictor of future wood use.

However, examination of the different countries' wood use data—even with similar per capita incomes—indicates that wood consumption also varies significantly between countries, probably influenced by the availability of wood. For example, countries such as the United States and Sweden, with abundant forests, use far more wood than Spain, which has few forests. To project future wood demand, we therefore used a "fixed-effects" (FE) model (Wooldridge 2001) based on the relationship between per capita wood consumption and socioeconomic factors (e.g., demographics, income levels, technology). This type of model estimates a common relationship of wood consumption to each country's per capita income growth but applies that trend line to a different baseline level of wood consumption in each country.

We derived separate relationships (12 "models") based on three different types of wood products, two different trend lines in developed and developing countries, and two different regression formulas. We selected sawn wood, wood-based panels, paper and paperboard, and wood fuel for our projection of wood product consumption because their consumption is directly driven by socioeconomic factors and have statistics that can be tracked through trade. (Items such as wood pulp, other industrial roundwood, and industrial waste do not have trade statistics.) Wood consumption, in general, has a positive relationship with GDP per capita. However, some high-income countries, such as Australia, Canada, Japan, and the United States, saw decreases in their historical per capita consumption of sawn wood and wood-based panels and paper consumption as their GDP per capita grew beyond certain levels. We therefore separated the countries into developed and developing countries to avoid overestimating future wood consumption in high-income countries. We used a threshold of USD 40,000 for sawnwood and wood-based panels, and a threshold of USD 12,000 for paper, paperboard, and fuelwood. We

applied two types of formulas, one including the effect of development and policy change after 2000, and the other one excluding the effect.

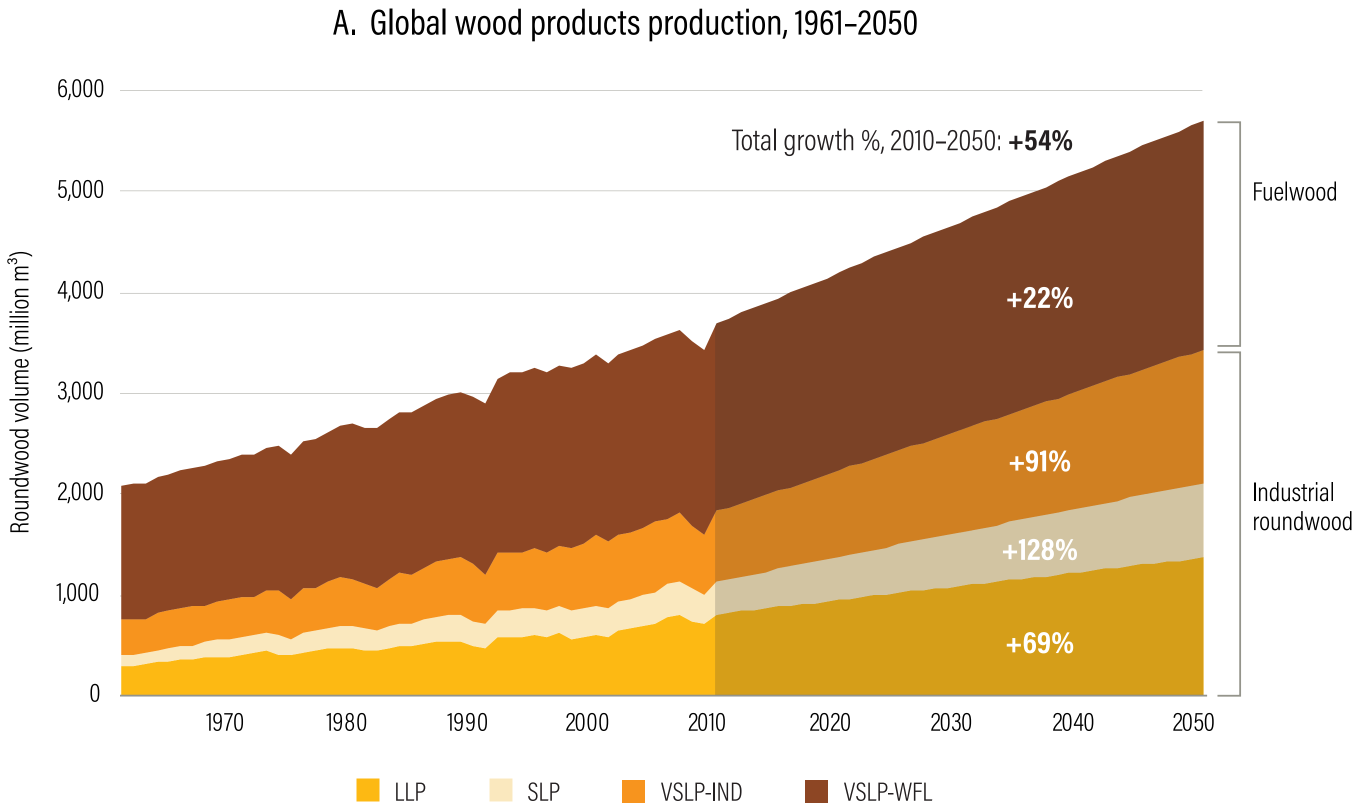
The results of the FE model show that wood consumption generally has a positive relationship with growth in GDP per capita and with population; they also reveal certain time trends that may be used as surrogates for changes in technology (see Appendix A). All the models have reasonable statistical fits, although it is also clear that a number of unobserved factors play roles in wood consumption, which makes future projections uncertain.[11]

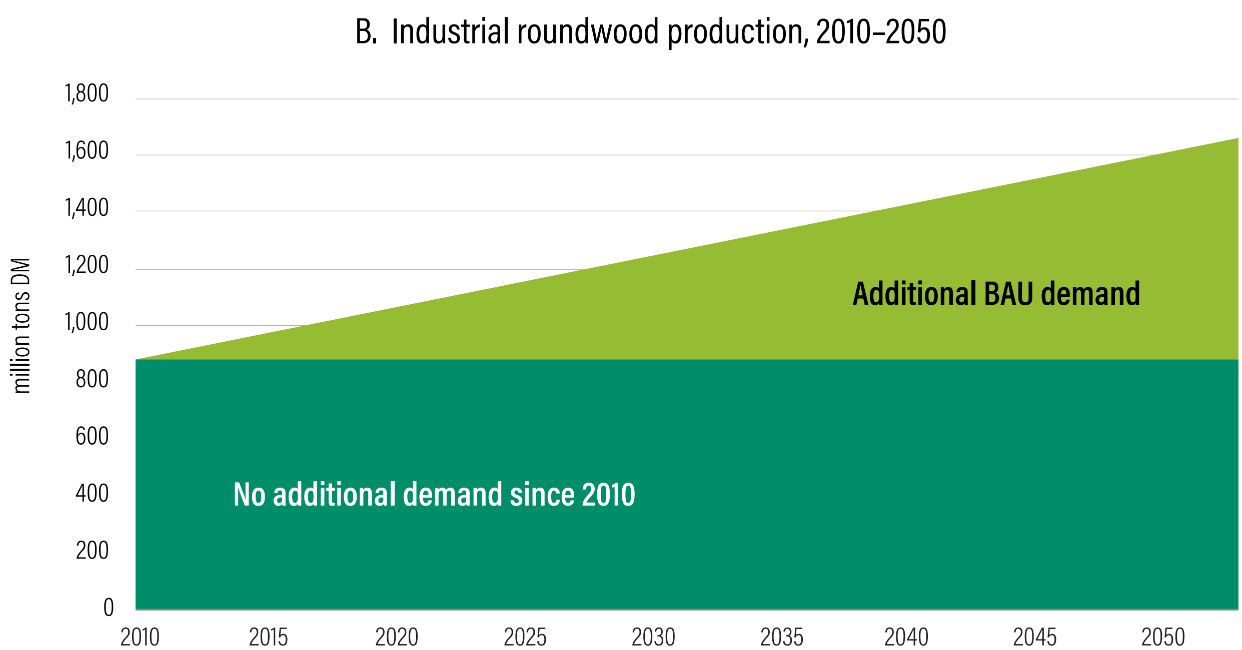
Using these relationships established between 1961 and 2020, we project 2050 consumption based on future populations and GDP per capita and factor in time trend factors (Appendix A).[12] Assuming that trade patterns in 2050 remain the same as in 2010, we estimate 2050 production in each country and globally for LLPs, SLPs, and VSLPs.

Using this modeling approach, we project that total annual global wood production and consumption will increase by 54 percent under a BAU scenario (Figure 12A). We project that LLP production will increase by 69 percent, SLP by 128 percent, and VSLP-WFL by 22 percent. Overall industrial roundwood (LLPs, SLPs, and industrial waste) would increase by 88 percent and fuelwood by 22 percent. Assuming linear increases between 2010 and 2050, we also estimate the cumulative additional industrial roundwood production between those dates as 32,912 million m^3, or 15,860 million tons dry matter (Figure 12B).

Our projections are mostly within the range of other published studies (Table 3). For example, Szabó et al. (2009) projected a 243 percent increase in use of paper and paperboard between 2000 and 2030 in Asia and a 200 percent increase in South America. Over a 40-year period from 2010 to 2050, we project a 180 percent increase in East Asia and 249 percent increase in Latin America. FAO (2009) projected that global consumption of sawn wood and wood-based panels would increase by 41 percent and 116 percent, respectively, from 2005 to 2030, whereas our projections are for an 84 percent increase in sawn wood and wood-based panels from 2010 to 2050, which combines both items and covers 40 years rather than 25 years.

Figure 12 | We project 54 percent growth in total wood production between 2010 and 2050 under "business as usual"





Notes: BAU = business as usual; LLP = long-lived product; SLP = short-lived product; VSLP = very-short-lived product. In panel A, the areas between 1961 and 2010 are adjusted historical data, and post-2010 (shaded areas) are projections. Panel B shows the projected growth in BAU of just industrial roundwood production (million tons in dry matter).

Source: Authors.

Table 3 | Comparison of Different Global and Regional Timber Demand Projections

	LONG-LIVED PRODUCTS (LLP)		SHORT-LIVED PRODUCTS (SLP)	VERY SHORT-LIVED PRODUCTS (VSLP)
	Sawnwood	Wood-based panels	Paper and paperboard	Wood fuel
Kangas and Baudin 2003	**2000–2020**			
Europe	+24% (1.2%)	+38% (1.9%)	+50% (2.5%)	
Szabó 2009	**2000–2030**			
Asia			+243% (8.1%)	
Europe			+44% (1.5%)	
North America			+36% (1.2%)	
South America			+200% (6.7%)	
FAO 2009	**2005–2030**			**2000–2020**
Africa	+117% (4.7%)	+67% (2.7%)	+200% (8.0%)	+34% (1.7%)
East Asia and Pacific	+35% (1.4%)	+199% (7.9%)	+157% (6.3%)	−14% (−0.7%)
Europe	+41% (1.7%)	+74% (3.0%)	+78% (3.1%)	+536% (26.8%)
Latin America	+56% (2.3%)	+67% (2.7%)	+94% (3.8%)	+17% (0.9%)
North America	+34% (1.3%)	+64% (2.6%)	+56% (2.2%)	
Western and Central Asia	+77% (3.1%)	+211% (8.4%)	+150% (6.0%)	−30% (−1.5%)
World	+41% (1.6%)	+116% (4.6%)	+105% (4.2%)	
Buongiorno 2015	**2015–50**			
East Asia and Pacific		+71% (2.0%)	+62% (1.8%)	+9% (0.3%)
Europe and Central Asia		+22% (0.6%)	+33% (0.9%)	+9% (0.3%)
Latin America		+40% (1.2%)	+52% (1.5%)	+8% (0.2%)
Middle East and North Africa		+65% (1.9%)	+49% (1.4%)	+9% (0.3%)
North America		+14% (0.4%)	+29% (0.8%)	+9% (0.3%)
South Asia		+138% (3.9%)	+137% (3.9%)	+5% (0.2%)
Sub-Saharan Africa		+48% (1.4%)	+100% (2.9%)	−13% (−0.4%)
World		+46% (1.3%)	+52% (1.5%)	+1% (0.0%)
This report	**2010–50**			
East Asia and Pacific		+177% (4.4%)	+180% (5.6%)	+5% (0.1%)
Europe and Central Asia		+22% (0.5%)	−7% (−0.2%)	−9% (−0.2%)
Latin America		+110% (2.7%)	+249% (6.2%)	+8% (0.2%)
Middle East and North Africa		+169% (4.2%)	+338% (8.5%)	+38% (0.9%)
North America		−28% (−0.7%)	+3% (0.1%)	5% (0.1%)
South Asia		+277% (6.9%)	+904% (22.6%)	+18% (0.5%)
Sub-Saharan Africa		+317% (7.9%)	+436% (10.9%)	+49% (1.2%)
World		+84% (2.1%)	+128% (3.2%)	+22% (0.5%)

Note: The linear annual growth rate (percentage per year) is in parentheses.

Source: Authors

Buongiorno (2015) projects that the world is likely to demand about 50 percent more industrial roundwood by 2050 relative to 2010, lower than our estimated 88 percent increase. Compared to Buongiorno (2015), we project similar changes for LLPs in Europe and North America, but much higher growth rates in other regions. One explanation may be that we use more recent, higher projections of GDP per capita and population growth rates (rising to 9.7 billion rather than 9.3 billion in Buongiorno [2015]). We also use a fuller length of historical data (1961–2020). Buongiorno (2015) used the shorter period of 1992–2012, which ended in years of recession with depressed wood use. Compared to that study, we also project a larger increase in paper consumption in Africa, Asia, and Latin America and a similar increase in Europe and North America.

Our projection of 22 percent in direct use of wood for fuel compares with only 1 percent in Buongiorno (2015). Fuelwood use has the least consistent relationship with growth in population and GDP per capita. China, for example, mostly shifted from fuelwood to fossil fuels despite a relatively low per capita income, but low-income African countries have continued to rely primarily on fuelwood. Because of this variation, and because future fuelwood use will depend greatly on government energy policies, we consider our fuelwood projection (and any fuelwood projection) to be the least reliable of overall wood consumption projections.

Although our model has reasonably good statistical fits, it is clear that wood consumption depends on many unknown variables, and future wood consumption is likely to depend on factors that cannot be predicted with present information. One unknown is the effect of changing technologies. For example, Hurmekoski and Hetemäki (2013) argued that the structural change driven by digital information technology around 2000 has had large downward impacts on paper demand. Studies using data before 2010 cannot account for these trends and therefore could not project the effects of changing technology. On the other hand, more than 50 percent of paper products are used for packaging (FAO 2020a), and the global rise of internet shopping could fuel increases in paper used for packaging (Chiba et al. 2017). Another uncertainty is possible constraints on supply. In Buongiorno's (2015) model, projected wood price increases depress growth in future wood consumption. These price increases may occur, but to our knowledge, there is no good econometric analysis of the long-term supply and demand elasticities with which to project future wood prices.

Despite these uncertainties, wood demand will likely increase for the same reasons food demand will increase. One reason is that the population is growing. Another is that most of the people in the world consume far less sawn wood and far fewer wood panels and paper products than the world's wealthy. Assuming incomes grow in developing countries, demands for this wood are likely to increase and have the potential to do so in vast quantities.

3.5 Implications of Future Wood Demand Growth on Land-Use Competition

A 54 percent global increase in wood demand between 2010 and 2050 will add to global land-use competition. New plantation forests and agriculture will likely compete with natural land uses, and efforts to harvest forests will likely compete with efforts to leave them unharvested to store more carbon and support more biodiversity. To estimate the overall land-use requirements and carbon implications, we constructed a biophysical accounting model, described in Appendix A, which we call the Carbon Harvest Model (CHARM). To count land use, as others have sometimes done (Ager and Clifton 2005), the model counts clear-cut-equivalent hectares, which estimate the hectares required to produce a quantity of wood assuming the wood comes from a clear-cut. A substantial portion of wood harvests occur through some form of selective harvesting. Because selective harvesting generates less wood per hectare harvested, counting selectively harvested area would increase our estimates of land-use requirements. But knowledge of how much wood is harvested with different forms of selective harvesting in different countries is too incomplete to model globally or even nationally.

Because different forest types and forest management systems could meet rising future demand, we applied the model to different scenarios for meeting future wood supply. For example, harvesting more wood could occur through additional harvests of natural (secondary) forests, which are then allowed to regrow natural vegetation. Alternatively, such harvested forests could be replaced by faster-growing timber plantations. Wood might also be supplied by establishing timber plantations on areas currently in agriculture (assuming that agricultural land could be "liberated" from production through shifting diets, reductions in food loss and waste, and/or sustainable intensification). To explore the various options, we analyzed seven scenarios based on different ways of supplying the needed wood, which are designed to bound the potential results. For example, scenarios that involve converting harvested secondary forests to plantations represent an extreme form of using management intensification to meet rising wood demand (relative to other possible management changes in secondary forests). We also incorporate a scenario with 25 percent increases in plantation forest yields to explore the potential effects of "improved management."

Each scenario assumes that the roughly 200 Mha of existing planted forests in 2010 continue to produce wood at their present typical rotation rates (based on our best estimates of national average rotation rates) and assumes that these areas are fully harvested. We incorporate present estimates of quantities of wood from live vegetation that is killed by the harvest but left unharvested, also referred to as slash. We assume harvested wood is available to meet each of the different types of demand: LLP, SLP, and VSLP. In theory, supplying wood for some uses could become unrealistic because of the different types of wood needed for different uses, but through a combination of trade and our projections for relatively balanced growth in demand for different types of wood products, this assumption is reasonable for this type of analysis.

Our seven scenarios are as follows:

- **Scenario 1 (secondary forest harvest and regrowth)** assumes that the existing plantations are supplying wood at our best estimate of their present growth rates. Additional wood demand is met by the harvesting wood from middle-aged secondary forests, and the forests are allowed to regrow for 40 years. This scenario also assumes that all wood is supplied by at least small clear-cuts, and it measures the area of such clear-cuts.
- **Scenario 2 (secondary forest harvest and conversion)** assumes that the existing plantations are supplying wood at present growth rates and that after secondary forest areas are harvested as in Scenario 1, they are reestablished as plantations (assume at productive locations with at least the present growth rates of secondary forests) to maximize the amount of future wood supplied by plantations. Plantations have substantially higher outputs of wood per hectare per year and are typically harvested more efficiently than natural forests, which means that more of the wood felled is used as wood products. This scenario is designed to examine how much harvest area could be held down by using intensive management.

  Although we assume that the same lands are replanted as plantations, something similar to this scenario would also occur if natural forests continue to be cleared for agriculture in one location while plantations are established on abandoned agricultural land in others. In China and many European countries, as discussed above, the large-scale conversion of less productive agriculture lands to wood plantations is associated with a heavier reliance on imported foods that contribute to large deforestation in Latin America (Pendrill, Persson, Godar, Kastner, et al. 2019). On a global basis, in effect, natural forests are being converted into plantations, although those plantations actually occur at a different location than the clearing of natural forest.
- **Scenario 3 (secondary forest mixed harvest)** is similar to Scenario 1 except that 50 percent of wood demand is provided by middle-aged secondary forests and 50 percent is provided by mature secondary forests (growing for 40 more years than middle-aged secondary forests). Slash rates for both secondary forests are the same.

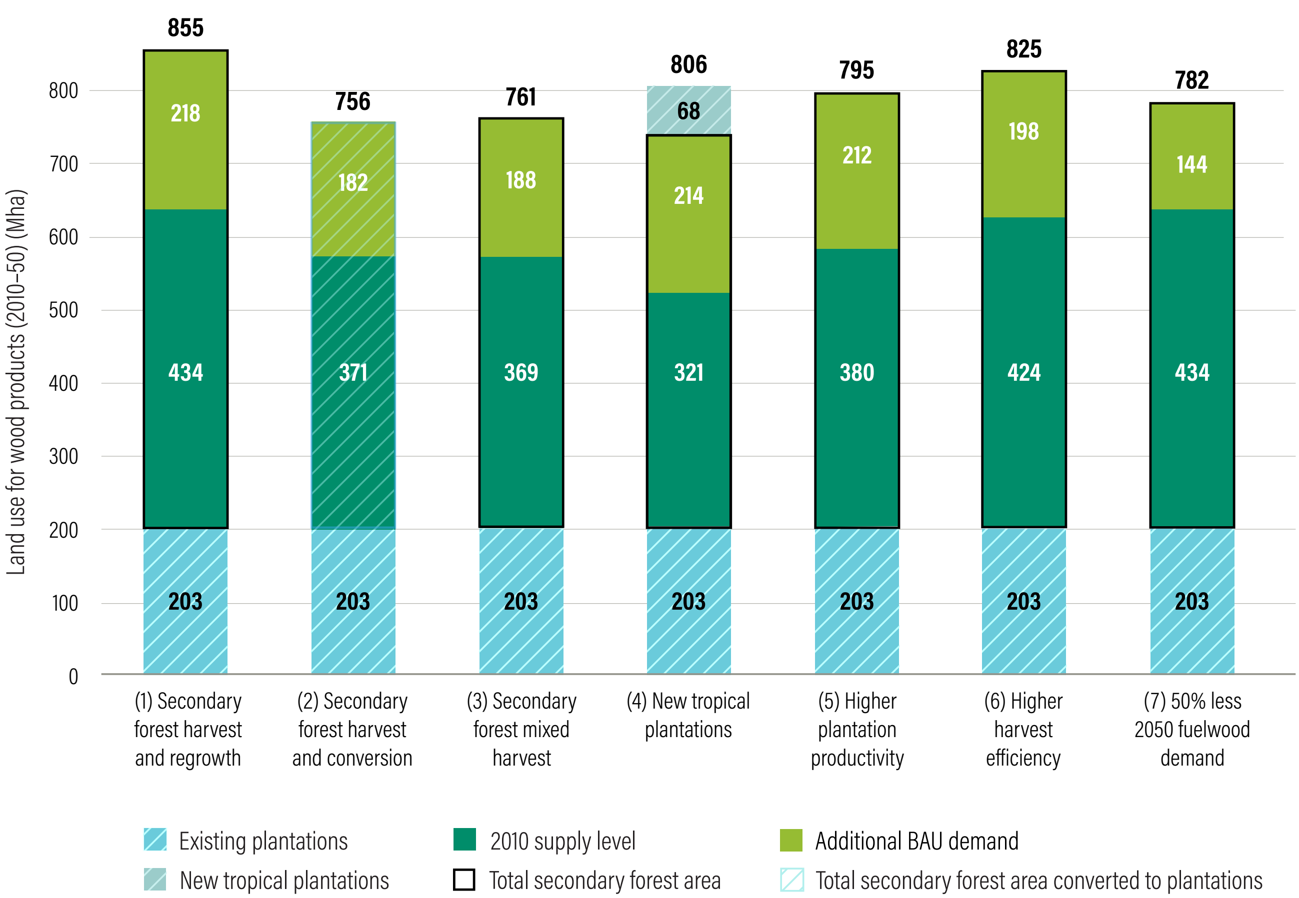
- **Scenario 4 (new tropical plantations)** assumes that 68 Mha of tropical agricultural lands become available for establishing highly productive plantations in the tropics and are harvested evenly between 2020 and 2050 (2 Mha/year since the first harvest occurs after 10 years). All new plantations are located in existing agricultural lands in the tropics and neotropics, where forest yields are higher. The secondary forests are harvested less due to the wood supply from the new tropical plantations. This scenario assumes that these lands are no longer needed to produce food, so although regrowing these lands as plantations sequesters carbon, the carbon cost is not allowing these lands to regrow as secondary forests.
- **Scenario 5 (higher plantation productivity)** is identical to Scenario 1 but assumes that existing plantation forest growth rates increase by 25 percent between 2010 and 2050.
- **Scenario 6 (higher harvest efficiency)** is identical to Scenario 1 but assumes that existing tropical secondary forest harvest efficiency increases so that the slash rate reduces to the level of best practices as described by Ellis et al. (2019).
- **Scenario 7 (50 percent less 2050 fuelwood demand)** is a variant of Scenario 1, in which fuelwood demand in 2050 reduces by half compared to the demand for fuelwood under BAU. It is based on optimistic views of energy transitions in developing countries.

Table 4 | Summary of Seven Global Scenarios Analyzed in CHARM to Meet Future Wood Demand

SCENARIO NAME	DESCRIPTION OF SOURCES OF WOOD	ADDITIONAL ASSUMPTIONS
(1) Secondary forest harvest and regrowth	Existing plantations and secondary forest harvest and regrowth	The portion of wood supply from secondary forests is 100% from middle-aged stands
(2) Secondary forest and conversion	Existing plantations and secondary forest harvest and then converted to productive plantations	The portion of wood supply from secondary forests is 100% from middle-aged stands
(3) Secondary forest mixed harvest	Existing plantations and secondary forest mixed harvest and regrowth	The portion of wood supply is 50% from middle-aged and 50% from mature secondary forest
(4) New tropical plantations	Existing plantations, secondary forest harvest and regrowth, and tropical agricultural land gradually converted to plantation	Rotation length of new tropical plantations is 7 years; 2 million hectares per year of tropical agricultural lands are converted to plantations each year
(5) Higher plantation productivity	Existing plantations with 25% increase in plantation growth rates and secondary forest harvest and regrowth	The portion of wood supply from secondary forests is 100% from middle-aged stands
(6) Higher harvest efficiency	Existing plantations with 25% increase in plantation growth rates and secondary forest harvest and regrowth	The portion of wood supply from secondary forests is 100% from middle-aged stands
(7) 50% less 2050 fuelwood demand	Fuelwood demand decrease linearly to reach 50% of 2050 baseline demand, existing plantations, and secondary forest harvest and regrowth	The portion of wood supply from secondary forests is 100% from middle-aged stands

These scenarios are intended to collectively bound the potential land-use and carbon costs of meeting growing wood demand, although none of these pure scenarios may be likely by itself. For example, Scenario 2, which relies more heavily on plantations, would require some shifts in the types of wood used. Most hardwoods would be eliminated (probably with some limited supply coming from hardwood plantations, such as teak plantations), and wood would be supplied mostly by fast-growing trees. In temperate areas, such production would be dominated by fast-growing pine species, and eucalyptus, acacia, and bamboo would dominate plantations in tropical and neotropical areas. This scenario would probably require continued evolution of wood product manufacturing technologies to make more use of fast-growing trees. Scenario 4 requires sufficient dietary changes or increases in agricultural outputs per hectare to free up land to establish forest plantations without triggering land-use change elsewhere. Scenario 5 requires large increases in plantation forests either through more intensive management or new tree varieties. Scenario 6 relies on reducing the amount of felling and destruction of other trees during tropical wood harvests to reduce the overall slash rate. Scenario 7 assumes sufficient technology breakthroughs or income growth to greatly reduce wood energy demands in the developing countries that rely on fuelwood. We suspect future wood

Figure 13 | We project 756-855 Mha of wood harvest (clearcut equivalent) for 2010–2050



Notes: BAU = business as usual. Because the quality of data is less reliable from countries with limited forestry, these global results sum up country-level estimates from the top 30 wood-producing countries that collectively generated 80 percent of production in the 2010 baseline. To scale up from 80 percent to 100 percent of production, we divided the total from the 30 countries by 0.8, which assumes the global average level of land-use efficiency for the remaining 20 percent of production. We also assumed linear phasing in of additional wood demand from 2010 to 2050.

Source: Carbon Harvest Model.

supply will likely result from some mixture of these scenarios, although only sweeping policy or technology changes are likely to result in reductions in agricultural land. Our results therefore show a good range of possible outcomes.

Figure 13 presents the results. The bars show the quantity of land (in Mha) we estimated that would be needed to supply wood products between 2010 and 2050 under our seven different scenarios. The bars show the existing plantation area in 2010 (bottom diagonal lines), the area that would be needed just to maintain the 2010 wood supply if it remained constant to 2050 (dark green), and the additional area needed to meet BAU-projected demand by 2050 (light green).

Scenario 1 shows that meeting projected wood demand in 2050 without expanding plantation areas beyond the 2010 level would require harvesting ~850 Mha of forest between 2010 and 2050, including about 200 Mha of existing plantations and 650 Mha of secondary forests. Harvesting ~430 Mha of secondary forests (53 percent of total harvested area) would be needed to maintain the 2010 wood supply level, and an additional ~220 Mha of secondary forest (51 percent) would be necessary to meet the growth in BAU wood demand to 2050. Instead of harvesting the middle-aged secondary forests only, supplying 50 percent of the additional wood demand from older secondary forests (Scenario 3) would reduce the amount of total secondary forest needed from 650 Mha to 557 Mha because older forests produce more wood with the same hectares.

Scenarios 2 and 4 show that less additional land would be needed if plantation areas increased between 2010 and 2050 because multiple harvests over the 40 years mean that more wood could be produced on fewer hectares. Reestablishing the secondary forests harvested with plantations (Scenario 2) would reduce the amount of total secondary forest needed from 650 Mha to 553 Mha. Establishing plantations on tropical agricultural land at average efficiencies of the high-yielding tropics (Scenario 4) would reduce the land area needed beyond the 2010 plantations to 603 Mha (535 Mha of secondary forests and 68 Mha of new plantations).

Scenarios 5–7 show that productivity increases and technology shifts could help reduce the land area needed. Increasing plantation growth rates by 25 percent (Scenario 5) would reduce the amount of total secondary forest to 592 Mha. Increasing the harvesting efficiency in tropical forests (Scenario 6) would reduce the the amount of total secondary forest to 622 Mha. Decreasing 2050 demand for fuelwood by 50 percent (Scenario 7) would reduce the amount of total secondary forest to 579 Mha.

We found limited other literature providing estimates of land demands from increases in wood demand, but our results appear consistent with those of some other researchers. For example, the World Wide Fund for Nature (WWF 2012) examined scenarios involving a tripling of wood demand and projected that between 242 Mha and 304 Mha of additional natural forest would need to be managed for commercial harvesting by 2050 relative to 2010 (compare this to the light green solid bar in Scenario 1 in Figure 13, with 218 Mha), along with a need for 250 Mha of new tree plantations to be established between 2010 and 2050 (compare this to the light green solid bar in Scenario 2, with 182 Mha). Although these scenarios are not directly comparable with our scenarios, the sum of 304 Mha and 250 Mha is similar to the orders of magnitude of our estimates.

3.6 Implications of Future Wood Demand Growth on Carbon

The additional wood harvests to meet the growth in wood demand between 2010 and 2050 will have substantial implications for carbon and thus for climate impacts. We use CHARM to provide an estimate of these effects that reflects the time-discounted value of earlier rather than later mitigation—or, put another way, that counts early emissions more than later emissions. We also use the model to estimate the net effect on carbon 40 years after each harvest.

Although papers use a wide variety of approaches to account for the GHG costs of forestry, they typically present their results with little discussion or explanation of the method they use (Ter-

Mikaelian et al. 2015). For this paper, we reviewed more than 60 previously published studies (Appendix B) on the climate implications of forestry and wood demand.

Probably the most common approach in the literature to date has been to treat wood harvesting as carbon neutral so long as forests are harvested "sustainably." *Carbon neutral* means that the carbon lost from the forest and emitted to the air as wood decomposes or is burned is not counted as an emission. This is the approach followed for nearly all analyses of the carbon implications of construction timber or other LLPs (Appendix B), and the approach followed in the vast majority of papers finding GHG benefits from harvesting wood for bioenergy (see Ter-Mikaelian et al. 2015; Haberl et al. 2012). *Sustainable forest management* can mean many things, including just practices that allow forests to regrow, and it is often not defined. In its strongest formulation, the term *sustainable forest management* is used to mean that the harvest of forests does not exceed the annual growth of the forest, so that overall existing carbon stocks of the whole forest are maintained. This quantity is sometimes referred to as the "sustainable yield."

Under this approach, if all the world's forests were viewed as one forest, it is possible to view global forest harvests as having no GHG effect because forests are gaining carbon globally. That carbon gain is occurring through a combination of regrowth of previously cut forests and carbon dioxide fertilization and other climate effects. However, if forests were going to gain carbon without new harvests, then harvesting wood in an amount that keeps wood and carbon stocks in the forest the same reduces the forest carbon that would otherwise have been stored. European forests, for example, are increasing in wood and therefore carbon content for a variety of reasons. These reasons include agricultural abandonment (spurred heavily by a reduction in horses and other draft animals)[13] and a variety of biophysical effects primarily linked to increased carbon dioxide and other effects of climate change (Ciais, Schelhaas, et al. 2008; Le Noë et al. 2019). Among other effects, an accounting approach that treats "sustainable" wood harvesting as carbon neutral treats the near-term elimination of the forest carbon through wood harvesting as having no climate consequence even though that sink is critical to restraining climate change (Schimel et al. 2015).

This assumption of carbon neutrality, applied to particular harvests, has similar consequences to that of counting the climate impacts of a country's forestry by netting the effect of new harvests with regrowth from forests cut longer ago (Box 2). In both cases, the accounting reduces the apparent carbon consequences of the new forest harvest by crediting it with carbon uptake in forest regrowth that either did occur or would have occurred anyway and therefore cannot be considered a consequence of harvesting forests more today.

Another approach seen in the literature is to compare an unharvested forest with the average carbon stock of a forest under regular harvest. In other words, if an unharvested forest would have 100 tC, but it is cut and regrows until harvested again at 100 tC, then the average carbon stock held by each hectare of forest may be around 50 tC. This approach could accurately represent the average amount of carbon over time (although there are concerns with whether repeat harvesting can maintain growth rates and soil carbon). Assuming that forests are allowed to regrow, this approach factors in that regrowth. But this approach makes no allowance for the value of time and therefore does not account for the importance of restraining carbon emissions and warming in the short to medium term.

Although these approaches lead to relatively low estimates of the climate impacts of forestry, there are also papers that focus on the gross carbon costs of harvesting wood and that count the losses of carbon in the forest without factoring in future regrowth (Houghton and Nassikas 2018; Ellis et al. 2019). Using such an approach, for example, Pearson et al. (2017) estimated 2.1 $GtCO_2$ per year from forest degradation (rather than conversion), of which 83 percent was due to wood harvests.

Our forestry carbon accounting approach, based on the framework established by Schlamadinger and Marland (1996), starts from the logical fact that harvesting wood today removes carbon from the forest but that the accounting must also factor in the benefits of regrowth. If never harvested, forest growth rates decline over time, so regrowing forests, typically a few years after harvest, can grow faster and rebuild carbon stocks. This regrowth benefit must be factored in. This accounting must also recognize that harvested carbon is not emitted to the air immediately. It persists for highly varying times in different carbon pools, including slash, the different product categories (LLP, SLP, and VSLP), and in landfills. If forests are harvested again, there will be a continuously lower average carbon stock in the forests versus if they are left alone to grow. But if the world values immediate reductions in carbon, then the carbon costs of harvesting wood are higher than even the change in average carbon stocks in the forest over time. The immediate carbon loss to the atmosphere means more carbon in the atmosphere for decades before regrowing forests can reabsorb most of the carbon lost by the harvest.

Counting the loss of carbon due to additional harvests does not require the assumption that any particular hectare would remain unharvested, only that some forests would otherwise remain unharvested. Highly managed forests are likely to be cut at some point, but they are cut to meet forest product demand. What matters is the aggregate demand, and if that demand increases, some more forests must be cut somewhere. In the same way, the gallon of gasoline any one person pumps from a gas station would almost certainly be pumped by another, but that does not make using gasoline carbon neutral. Life cycle analyses are generally focused on increases or decreases in aggregate consumption.

We show results using two approaches to time. One is simply to count the effect on carbon in the atmosphere 40 years after harvest. The other is to use a time-discounting approach that uses a 4 percent annual discount rate, as in Searchinger, Wirsenius, et al. (2018). With such an approach, a ton of carbon withheld from the air in year one is worth 4 percent more than a ton of carbon withheld from the air in year two. Similarly, a ton of carbon added to the air in year one counts 4 percent more than a ton of carbon added to the air in year two. The reason is not that the carbon is more potent in one year than the next but that we value the carbon emissions (and therefore mitigation) differently based on the time this carbon is added (or removed) from the air and use a discount rate to reflect this difference. One obvious reason to assign higher costs to carbon added to the air early, even if removed later, is that it causes damage in the intervening years. Another reason is the desire to reduce emissions immediately, which reduces the risk of crossing tipping points and therefore provides time for technology to evolve and drive down the costs of achieving the necessary full-scale mitigation. As shown rigorously in Daniel et al. (2019), if the world wants to "buy time" to address climate change in this way, it should pay more to mitigate emissions in the short term rather than in the long term.

As discussed in Searchinger, Wirsenius, et al. (2018), a 4 percent discount rate can also be justified if we assume a constant carbon price (that the economic cost of emissions and therefore the economic value of mitigation is equal over time) while using a commonly estimated long-term cost of capital. In addition, discounting carbon changes from terrestrial vegetation by 4 percent generally results in an equivalent result to amortizing emissions over slightly more than 30 years, which is roughly consistent with U.S. government policies for biofuels, which also effectively amortize emissions from land-use change over 30 years. Because discounting focuses effects on 30-year results, this approach is generally consistent with the actual policies endorsed by most of the world's countries through the Paris Agreement, which also aim to achieve vast reductions in emissions by 2050. Appendix C provides some additional explanation and illustration of how the discounting calculation works. As shown in Appendix C, however, the carbon effect factoring in 40 years of regrowth after each harvest changes little using any number from a 2–6 percent discount rate.

CHARM can also calculate carbon "saved" in fossil fuels kept underground or in limestone by substituting wood for other fossil fuel–intensive products, such as steel and concrete used in construction. Many parameters are uncertain, but Appendix A describes the critical parameters used and their sources. (Box 4 describes how disturbance and thinning are addressed.)

BOX 4 | The Effects of Management on Disturbance and Growth Rates

The scenarios analyzed in the Carbon Harvest Model (CHARM) essentially assume two main forms of management: secondary forest harvest and regrowth and plantation management. Disturbance is implicitly factored in because our estimated growth rates for each country (or forest type) borrow from studies that attempt to assess them in the real world, where they are affected by disturbance. We also factor thinnings into our stand-level analyses, but because of data limitations in our global analyses, thinnings are only implicitly incorporated into the analysis through their effects on overall harvest levels and growth rates.

One question is what other effects management may have on growth rates and carbon stocks. Although the results will vary and the literature does not show only one effect, as a general rule, more intensive plantation management is more likely to result in additional carbon losses.

Despite variability,[a] the weight of existing science is generally that intensively managed plantations are more susceptible to disturbance than more natural forests.[b] That is partially because older trees are less susceptible to fire.[c] Studies also generally find that heavily managed (thinned) monocultures are more susceptible to both wind damage and pests.[e] Some forms of management are ambiguous, however.[f] For example, the intensive removal of weeds and underbrush can reduce resilience of a stand to winds[g] and provide opportunities for increased herbivory,[h] but leaving excess biomaterial can provide shelter for other types of pests[i] and can increase the risk of fire.[j] Fresh stumps and logging scars from thinnings might also be conducive to infection from tree diseases and increase the risk of fire if they create slash left in the forest.[k] However, thinnings that reduce the crown volume might improve resilience to fire.[l]

European plantation forests, which compose a large share of European forests, provide an example of the risk faced by some kinds of forest management. Beetle infestations, at a minimum exacerbated by climate change, are causing extensive damage, and there is an emerging view that European forests will need to be diversified to increase the percentage that can survive climate change.[m]

Thinning is sometimes suggested as another strategy to increase carbon sequestration. In general, thinnings boost the percentage of a forest's growth directed into harvestable trees, mostly due to reduced competition for water resources in arid and semiarid regions following a thinning.[n] However, the evidence is also strong that thinning will tend to reduce overall carbon stocks and total plant growth by reducing the leaf area that intercepts light and the roots that can absorb water and other nutrients.[o]

Sources: a. Felton et al. 2016; b. Reyer et al. 2017; c. Botequim et al. 2013; González et al. 2007; d. Valinger and Fridman 2011; e. Björkman et al. 2015; f. Jactel et al. 2009; g. Gardiner et al. 2005; h. Black 1992; Brandeis et al. 2002; i. Björklund et al. 2003; j. Rothermel and Philpot 1973; k. Fettig et al. 2007; Peterson et al. 2005; l. Agee and Skinner 2005; m. Hlásny et al. 2019; n. Olivar et al. 2014; Giuggiola et al. 2013; Sohn et al. 2013; o. Hoover and Stout 2007; Lin et al. 2018.

Here, we present the carbon impacts of forest harvest in $GtCO_2e$ while maintaining 2010 levels of supply and projected increases under BAU scenarios (Figures 14 and 15). We estimate that the harvests and uses of wood causes time-discounted gross emissions from forests affected by harvesting from 3.5–4.2 $GtCO_2e$ per year. (This estimate ignores the indirect effects on adjacent forests, which, according to some analyses, may be many times greater.)

We also estimate results factoring in emissions savings from substituting wood for other products.

The emissions from wood use related to harvesting are real physical additions of carbon to the atmosphere, even if using wood can avoid even greater emissions from using concrete and steel. In the same way, emissions from burning natural gas are real: even if they are lower than burning coal, we do not claim that natural gas has negative emissions. Although wood emissions physically occur, knowing if they save emissions from other substances can also be relevant for public policy.

Our estimate of substitution benefits uses an average emissions savings estimate from different studies that result from using wood for construction rather than concrete and steel (an estimated 1.2 tC saved for each ton of carbon in wood used in construction). We discuss this substitution factor more below. Our substitution estimates also factor in a bioenergy savings for using traditional fuelwood in place of fossil fuels. The vast majority of this wood is used for cooking in developing countries. Although the alternative might really be no energy at all, we assume it would be the use of propane gas. The result is that for 5.7 tC emitted from burning fuelwood saves 1 tC that would be emitted by propane.[14] Including these avoided emissions in our model reduces the calculated global carbon impact by about 0.9 $GtCO_2e$ (25 percent) in each scenario and does not impact whether regrowing secondary forests or converting them to plantations is more favorable. For example, when crediting substitution benefits, the annual carbon cost of forestry using the secondary forest harvest scenario decreases from 4.1 $GtCO_2e$ to 3.2 $GtCO_2e$.

Due to insufficient data, we do not calculate an overall substitution value for other wood uses, which may be negative—that is, there may be net emissions by using wood instead of other materials.

Figure 14 | We estimate 3.5–4.2 Gt per year of present discount value carbon costs from global wood harvest (2010–2050) with roughly 0.9 Gt per year benefit from replacing concrete and steel

Notes: BAU = business as usual. Positive values indicate emissions; negative values indicate avoided emissions. Substitution benefits assume that 64 percent of long-lived products are used for construction and replace concrete and steel at a rate of 1.2 tons of carbon for concrete and steel per 1 ton of carbon for wood. Gross carbon costs (emissions) are without substitution savings (avoided emissions) from concrete, steel, and bioenergy. Costs are discounted carbon changes from year of harvest to 40 years later discounted to year of harvest.

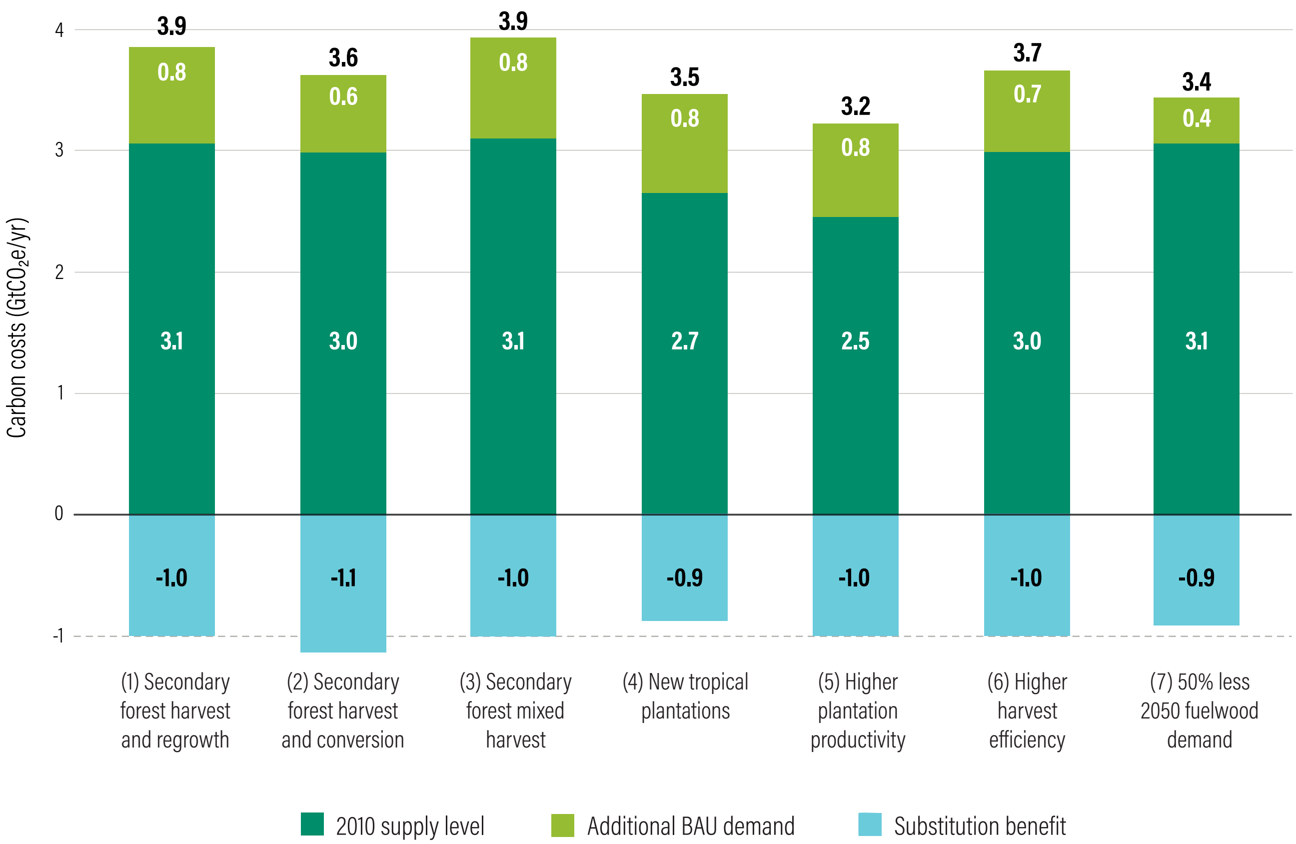
Source: Carbon Harvest Model.

Burning of waste wood generated in making paper and other wood products generates energy, including often electricity. In general, however, although paper mills often generate some electricity and sometimes heat that they sell to others, paper mills typically use more fossil fuel energy than they replace (Miller et al. 2015). Because of uncertainties regarding global energy use for sawmills, wood panel processing, and bioenergy uses overall, we have not attempted to include these additional energy costs or savings from wood waste.

Although our main analysis uses discounting, the results are surprisingly similar to the carbon effects of forestry on atmospheric carbon 40 years after harvest without any discounting at all (illustrated in Figure 15 and Appendix C by the 0 percent discount rate). For example, in our BAU "secondary forest harvest scenario," the gross change in carbon in the atmosphere after 40 years due to harvesting of wood is slightly lower without discounting at 3.9 $GtCO_2e$ per year versus almost 4.1 with discounting. (Including substitution benefits reduces those post-40-year undiscounted carbon costs to 2.9 $GtCO_2e$ versus 3.2).

The reason for this small difference is that the climate benefits and costs of harvesting wood are fairly dispersed over the first 40 years. Much of the carbon loss occurs in the first years after harvest as wood is burned, slash decomposes rapidly, and paper products are quickly consumed.

Figure 15 | We project 3.2-3.9 Gt annual carbon costs (2010–2050) 40 years after harvest without discounting with roughly 1 Gt substitution benefits for concrete and steel



Notes: BAU = business as usual. Positive values indicate emissions; negative values indicate avoided emissions.

Source: Carbon Harvest Model.

But much of the wood is also preserved in some other carbon pool in the first years as well, and the substitution benefits (from the replacement of concrete and steel) occur immediately, canceling out much of the costs.

If we were to focus on carbon effects much longer than 40 years after harvest—for example, 100 years—discounting would have a more significant but still not vast effect. The difference varies by scenario. In our secondary forest harvest scenario, the results are around 3 percent lower than the results we show for discounting over 40 years (Appendix Figure E-1). (In this 100-year discounting scenario, secondary forests are allowed to keep growing either if cut in the harvest scenario or not cut in the counterfactual, and existing plantations continue to be harvested according to their rotation length.) Discounting has a modestly greater effect because unharvested forest growth rates slow down more as they age, allowing newer forests a greater capacity to catch up. This statement is another way of saying that because of forest regrowth, the change in carbon in the air due to harvesting wood 100 years after the harvest is modestly less than it is after 40 years.

There is substantial uncertainty regarding many of the factors that go into this analysis. Uncertainties include rates of slash, including the damage to unharvested trees during harvesting, the relative energy use in making wood products for construction versus concrete and steel, and the shares of wood that go into different product uses. Reconciling FAO data from different categories of wood production and use is also challenging and requires some assumptions and adjustments. The growth rates of different forests are also important, particularly the relationship between forest growth in earlier decades after establishment versus later decades. There is also some uncertainty and debate regarding the quantity and carbon impacts of fuelwood harvests (Box 5). We rely primarily on growth rates estimated in Harris et al. (2021), but that paper did not need to differentiate growth rates from forests of different age classes older than 20 years, and some of its growth rates are implausibly low or high. We made some adjustments, but improvements in the data used for all of these parameters would contribute to an improved analysis.

BOX 5 | Fuelwood Harvests and Carbon

Wood harvested deliberately for fuel is roughly half of all wood harvested (in addition to the wood burned as a by-product of making other wood products), and the majority of those harvests occur in developing countries. Fuelwood is more than 50 percent of wood consumption in Latin America, more than 60 percent in Asia, and more than 90 percent in Africa.[a] The literature expresses different views about its effects on forests carbon.

For example, a report by the United Nations Environment Programme (UNEP) about fuelwood in Africa claims that "fuelwood is usually collected from trees and dead wood and its impacts on forest stocks and climate change may not be significant" while expressing somewhat more concern about charcoal.[b] In India, studies have estimated that trees on farms provide two-thirds of the fuelwood.[c]

Yet other studies have found that even in India, the harvest of remaining forests contributes significantly to degradation and to the net loss of carbon in forests.[d] In Africa, the majority of wood harvests come from forests or woodlands of some kind, and numerous studies have found resulting forest degradation in different countries.[e] One impressive study, which uses a combination of remote-sensing methods, found high forest degradation in African woodlands despite the fact that fuelwood composes more than 90 percent of wood consumption.[f] Using bookkeeping methods,[g] another paper estimated that firewood harvests were responsible for roughly one-third of the carbon losses in tropical forests due to forestry overall.

One reason for these competing viewpoints is the assumption—implicit, for example, in the UNEP report—that the only important problem is full deforestation (i.e., the complete loss of forest), rather than carbon losses through degradation. Another paper takes the approach of only counting emissions due to unsustainable wood harvesting, which means harvests in excess of local forest growth rates. This paper estimates fuelwood emissions at 1–1.2 gigatons of carbon dioxide equivalent per year.[h] As explained above, under our approach, as in Chidumayo's 2013 paper,[i] carbon losses include the forgone increases in forest carbon due to fuelwood harvests.

There are also important uncertainties regarding the land-use and carbon effects of traditional fuelwood harvests, including how much of this fuel harvest uses dead wood and what slash rates are created. Another question is how much fuelwood is provided by trees on farms; whether those trees enhance, coexist, or compete with food production; and whether they are planted to supply the wood or would exist anyway.

Our estimates rely on data from the Food and Agriculture Organization of the United Nations (FAO), which attempts to count roundwood harvests and assumes that the wood comes from live trees. It is possible that the FAO estimate may count some wood harvests that come from already dead wood or that are farm produced as being roundwood harvests. But there are also reasons the use of FAO data may underestimate the carbon effects of fuelwood. Using additional sources of data, including UN energy statistics, Bailis et al. (2015) estimated fuelwood harvests in Africa, Asia, and Latin America to be 37 percent larger than the FAO reported.[j]

Sources: a, b. UNEP 2019; c. Singh et al. 2021; d. Sharma 2017; e. Butz 2013; Sassen et al. 2015; Zidago and Wang 2016; f. McNicol et al. 2018; g. Pearson et al. 2017; h. Bailis et al. 2015; i. Chidumayo 2013; j. Bailis et al. 2015, Supplemental Table 2.

3.7 Summary of Projected Land-Use and Carbon Effects

Although there are many uncertainties in each of these projections, the overall global picture is one of intense global competition for land between 2010 and 2050. WRI's *Creating a Sustainable Food Future* report estimated agricultural land expansion of 600 Mha during that period, stemming from a 56 percent growth in food demand. The average estimate for urban expansion between 2010 and 2050 is roughly 80 Mha. Our forestry scenarios, which consider a projected 54 percent growth in wood demand, imply that if the world does not convert more land to forest plantations, the world must harvest more than 750 Mha of middle-aged secondary forests, or about 700 Mha of secondary forests when plantation productivity increases or fuelwood demand decreases. Land for new forest plantations could theoretically come out of agricultural land, but without concurrently reducing agricultural land demand, converting agricultural land to timber plantations would just lead to additional clearing of forests or savannas elsewhere to replace the forgone food production.

Annual projected carbon costs are also high. From agricultural expansion under BAU, they are expected to be around 6.0 $GtCO_2e$ per year, from urban expansion another 0.7 Gt, and from forestry using our method 3.5–4.2 Gt (and roughly 1.0 Gt less when factoring in substitution benefits for concrete and steel.) Total impacts are 10.0–11.0 $GtCO_2e$ per year.

4. Potential Implications of Policies That Increase Land-Use Demands

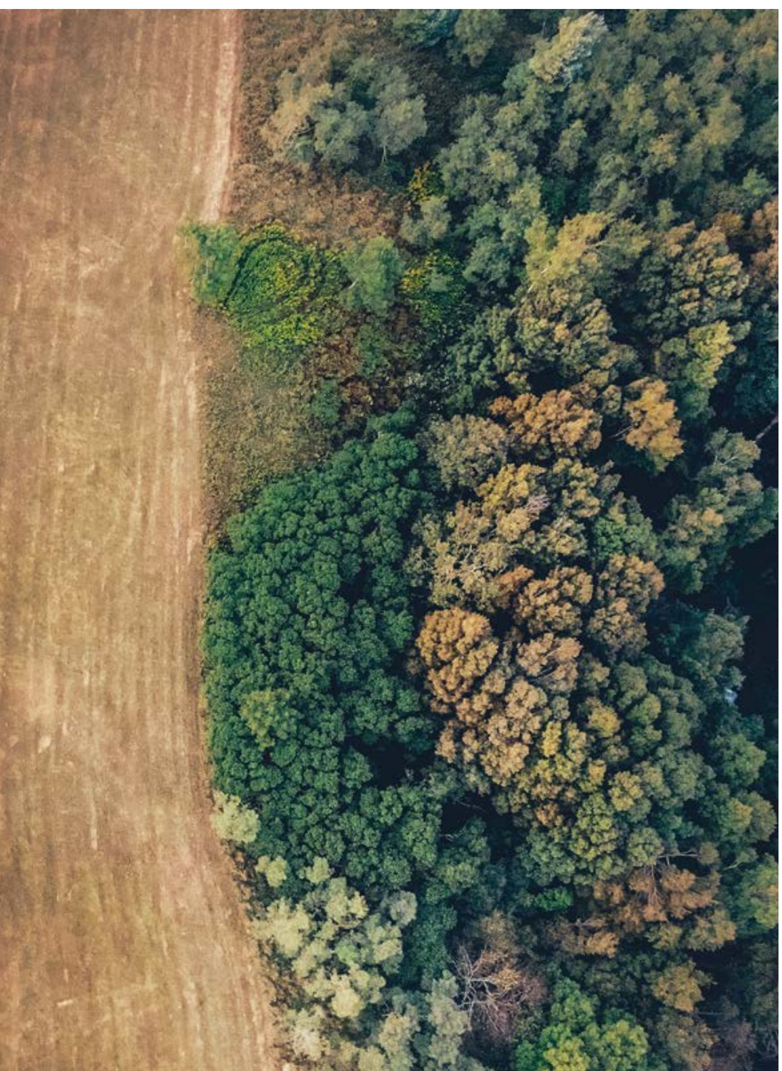
The analysis in Section 3 assumes no new policies to increase land use for human products beyond BAU, but some researchers and public officials are encouraging two strategies that increase human land uses in the name of reducing climate change.

One strategy is to expand bioenergy—energy from food crops, energy crops, or forest biomass—with the goal of replacing fossil fuels. The other is to increase the use of wood in construction as a substitute for concrete and steel. In this section, we examine the potential land-use and carbon implications of these potential additional land demands.

4.1 Bioenergy

WRI's *Creating a Sustainable Food Future* report presents a substantial analysis of bioenergy, both of the potential implications for land-use competition and its effect on the climate.

Bioenergy is any method that produces energy from burning biomass, which is any of the fruits of photosynthesis but typically means plants. Partly motivated by the view that bioenergy is carbon neutral, governments have been promoting bioenergy from sources that increase land-use competition in two ways. First, they have promoted the use of crops (e.g., maize, soybeans, and sugarcane) to make liquid fuels for transportation in the form of ethanol and biodiesel. Second, they have promoted the replacement of coal and natural gas in the production of energy or heat with wood, overwhelmingly from additional wood harvests. Researchers also have contemplated vast increases in biomass from the growth of energy crops, such as fast-growing grasses or small trees, as an important future solution to climate change. The potential volumes of biomass, and therefore land-use competition, contemplated are extremely large:



- Many countries have adopted goals to supply 10 percent or more of transportation fuel using liquid biofuels (instead of fossil fuels). If achieved at the global level by 2050, the biofuel would provide only about 2 percent of global energy production but would require a quantity of crops equal to 30 percent of the world's crop production in 2010, measured by their energy content.
- Many modeled pathways to a stable climate assume that biomass is carbon neutral and include between 200 and 250 exajoules of biomass energy (IPCC 2014), which would supply around 20 percent of likely total global energy needs by 2050 (Searchinger et al. 2019). Unfortunately, that goal would require a quantity of biomass roughly equivalent to all the biomass harvested on the planet: all the crops, all the crop residues, all the grasses and leaves eaten by livestock, and all the wood (Haberl et al. 2012). Put another way, to meet this 20 percent energy goal while still feeding people, total biomass harvests would need to roughly double.
- Meeting 5 percent of Europe's final energy demand, a plausible target of present renewable energy standards, would require a doubling of Europe's wood harvests, which equals roughly a 20 percent increase in global commercial wood harvests (Searchinger, Beringer, et al. 2018).
- Producing an additional 2 percent of global energy from wood today, beyond the wood presently burned and while still meeting other demands, would require roughly a doubling of global commercial wood harvests (Searchinger, Beringer, et al. 2018).

Some studies project less land-use competition by assuming that biomass will be supplied by energy crops and that these crops will achieve high yields. Today, biomass yields of energy crops in actual production, such as switchgrass and fast-growing coppice willows, tend to be less than 10 tons of dry matter per hectare per year (Nord-Larsen et al. 2014; Searle and Malins 2014). In some well-watered areas of the tropics, eucalyptus yields can achieve more than 20 tons, and the national average in Brazil appears to be around 16 tons of dry matter.[15] At this high yield of 20 tons of dry matter per hectare per year, and without factoring in what are often large losses during storage, supplying 230 exajoules of bioenergy (20 percent of likely biomass needed to supply total global energy needs by 2050) would still require 575 Mha (an area of well-watered lands that would be equivalent to three-quarters of the continental United States).

Searle and Malins (2014) also provide good reasons for skepticism that such high yields would be achieved on average. As that paper discussed, papers often project that energy crops will have the same rates of yield gains as grain crops in the past while ignoring the fact that the gains in cereal crops were often due to increasing the harvest index—the percentage of plant growth going into the edible seed—rather than total plant growth. If so, actual land demands for bioenergy would be higher.

Whether using food or energy crops or harvesting forests, these bioenergy feedstocks also involve the "dedicated use of land." This means that using them for energy requires diverting some or all of the productive capacity of a piece of land away from food, wood production, or carbon storage and toward energy use. There are some alternative waste sources of biomass, such as municipal waste, but large estimates of future bioenergy use, and most biofuel policies to date, either do not distinguish or still encourage use of some forms of biomass that make dedicated uses of land. And the basic lesson from these analyses is that producing even small quantities of energy from such dedicated uses of land implies large additional competition for land and biomass.

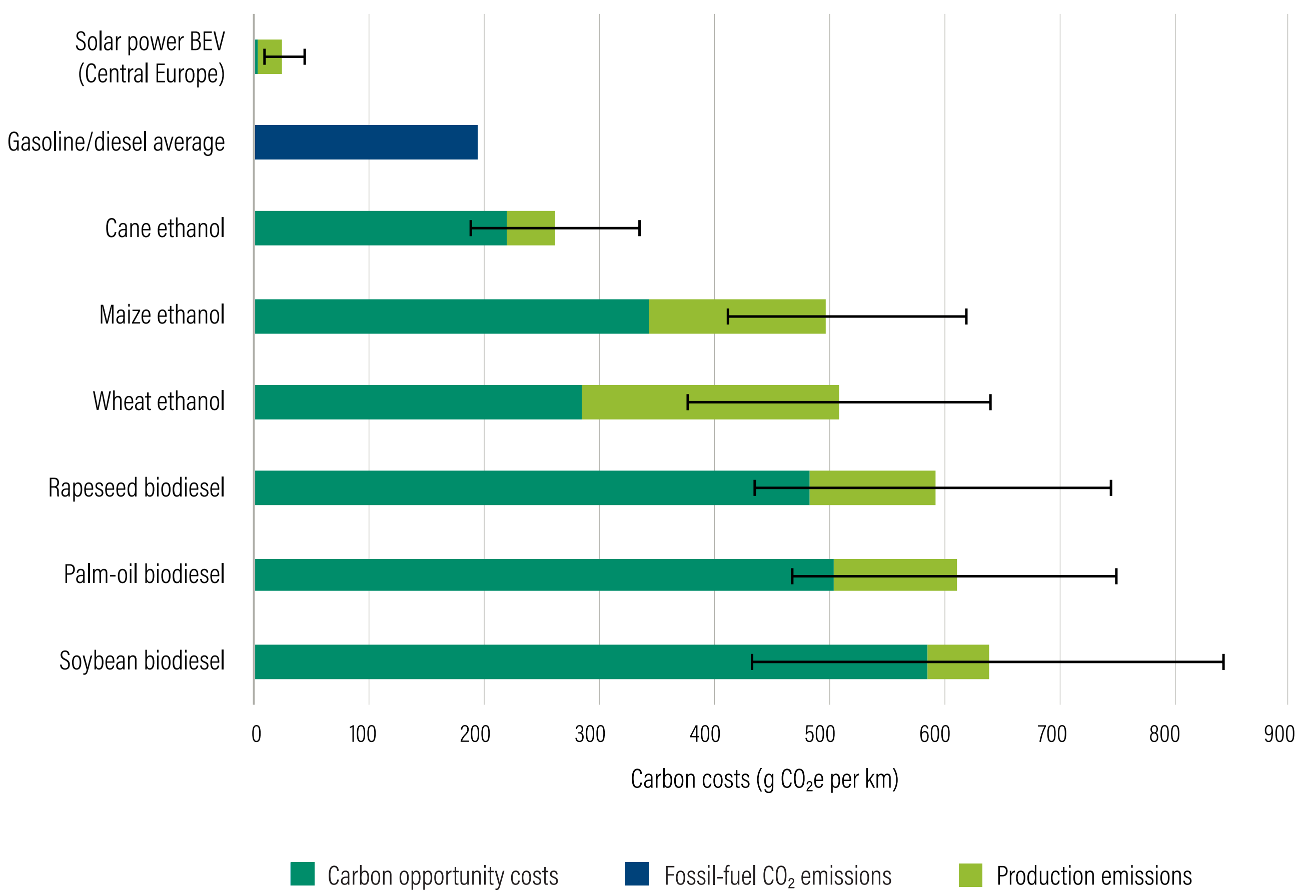
The biophysical reason for bioenergy's high need for land starts with the inherent inefficiencies of photosynthesis. Even under ideal conditions, for the sun hitting a growing leaf with access to all water and other nutrients needed, photosynthesis is likely to convert only a small percentage of the full energy in the sun's radiation into energy in biomass (Batista-Silva et al. 2020). Efficiencies are further reduced by numerous factors: sun that does not hit a leaf, limited water and nutrient availability, a limited portion of the year used to grow crops in most of the world because of cold weather or limited rainfall, and the large quantity of energy that the plant uses to maintain itself. There are then further energy losses in converting raw biomass into usable energy. As a result, even sugarcane ethanol generated in Brazil only converts around 0.2 percent of the energy in the sun's radiation into energy in ethanol (Searchinger et al. 2017).

This efficiency can be contrasted with various forms of solar power, such as photovoltaic cells or solar thermal energy. WRI calculated that on roughly three-quarters of the world's land, photovoltaic cells today would produce at least 100 times more usable energy than cellulosic ethanol is likely to do in the future. That advantage rises to more than 250 times when factoring in the added efficiency of electric drivetrains (Searchinger et al. 2017). There are even larger land-use efficiency gains from other forms of solar power, such as solar thermal (Searchinger et al. 2017). Just as importantly, unlike biomass, solar energy does not require use of well-watered, highly productive land but can use desert and rooftops. Biomass can be more easily stored than solar power, but it comes at a heavy land cost.

To determine the GHG consequences of bioenergy, the climate benefits of using land to avoid fossil emissions have to be combined with the climate costs of not using land to meet other needs. For years, and still today, many bioenergy calculations just assume that there is no land-use cost, which leads them to treat the biomass as being carbon neutral. The theory is that the carbon emitted by burning the biomass is offset by the carbon absorbed by growing that biomass. However, this approach fails to recognize that if the land were not used to produce bioenergy, it would still grow plants, which absorb carbon. Those plants could be used directly to store carbon or they could be used for food or timber, which allows other lands to store carbon while the world still meets the same food and timber needs. This carbon cost for using land for bioenergy is the same carbon cost that applies, and this paper has applied, to food and wood production as well.

Based on our review of the evidence, the best way to calculate liquid biofuels is to factor in the "carbon opportunity cost" of using land to produce crops used for biofuels. This approach, based on a paper published in *Nature* in 2018, measures the average global quantity of land-based carbon lost to produce the crops that are incorporated to produce a certain amount of energy from biofuels (Searchinger, Wirsenius, et al. 2018). Because biofuel crops can be produced for many years on the same land, this method also uses time discounting in the same way we analyze the climate consequences of forestry in this paper, which is roughly equivalent to evaluating the aggregate land-based emissions and fossil fuel savings over 30 years. By this method, per kilometer driven, emissions from using sugarcane ethanol are roughly 40 percent higher than the average emissions from using gasoline and diesel. Emissions from using maize and wheat are roughly two times higher, and emissions from using vegetable oil are roughly three times higher (Figure 16). (Using this method, emissions from palm oil are high but slightly less than those from soybean oil because the higher yields of palm oil roughly compensate for the fact that oil palm trees grow primarily in former carbon-rich, tropical rain forests. This method is also based

Figure 16 | Biofuel emissions greatly exceed emissions from gasoline/diesel or solar-based electric fuel when incorporating the carbon opportunity costs of using land



Notes: BEV = battery electric vehicle. Error bars reflect the range of literature estimates of vegetation and soil carbon stocks used in part to derive the carbon opportunity costs.

Source: Searchinger, Wirsenius, et al. 2018.

on average carbon losses for oil palm and therefore does not fully factor in the increased use of drained peatlands to produce oil palms in the last decade.)

For bioenergy from forest products, the opportunity cost is measured by the carbon that would be stored if the trees were not harvested. A vast number of studies have examined the net climate consequences under different scenarios: different types of forests, different harvest regimes, pelletizing or just chipping the wood, using the wood for electricity or heat, and using the wood to replace coal or natural gas (Appendix D). The consistent finding is that switching from fossil fuels to burning wood will increase carbon in the atmosphere for decades to centuries.

The reasons for this adverse climate impact from wood-based bioenergy result from certain basic biophysical factors (summarized in Searchinger, Beringer, et al. 2018). When wood is harvested, much is left behind (including roots and typically tops and branches), where it decomposes and gives up its carbon to the air. Much wood is lost in the drying process and in debarking, and even more wood is lost when wood is converted to wood pellets. These processes add carbon to the air without replacing fossil fuels. When burned, wood also generates more carbon per kilowatt-hour of energy. This is because its combustion releases more carbon than even coal per unit of energy, and much higher than natural gas, and wood burns at a lower temperature, which reduces the efficiency of converting its energy into electricity. Overall, in the year burned, the committed emissions of wood are at least two times—and often three times—higher than those of fossil fuels for the same amount of electricity or heat, creating what is known as a "carbon debt."

Assuming forests regrow, they can eventually recapture the carbon lost from the harvest and burning of wood for energy use and pay off the carbon debt. For at least a few years, the new regrowing forests would typically grow more slowly than an unharvested forest (because the seedlings are so small). After a few years, they will grow faster, which starts to pay off the carbon debt. But even when the trees harvested in the first year of bioenergy use have regrown enough to pay off their carbon debt, forests harvested in later years for bioenergy have still not regrown sufficiently to pay off their own debts, and it takes many more years for enough carbon debt to be paid off to just match the emissions from fossil fuels. Overall, the precise time period required to pay off the carbon debt varies with the type of forest and harvesting strategy used; whether wood is burned for electricity, heat, or both; and whether wood substitutes for coal or natural gas. Yet as numerous studies of different scenarios have shown, the time is always decades to centuries (See papers referenced in the supplement for Searchinger, Beringer et al. 2018). And even then, it takes many more years of forest regrowth to achieve substantial GHG reductions.

Although over long enough time periods, using wood for bioenergy can therefore reduce emissions relative to fossil fuels, it typically increases emissions for decades to centuries. These uses are therefore inconsistent with public policies seeking immediate reductions in emissions to slow warming.

4.2 Additional Wood in Construction

In addition to bioenergy, there is currently high interest in using additional wood in tall building construction as a mechanism for reducing construction-related GHG emissions, particularly from the use of concrete and steel. The production of both concrete and steel generates high emissions. Each requires abundant energy now supplied by fossil fuels, and the typical production of each releases additional carbon either from the rocks used to make cement or from the carbon used in turning iron into steel. With population and income growth, the world is likely to have a great construction boom in the coming decades, and the potential emissions from concrete and steel in the construction process are a major challenge for climate change (Davis et al. 2018; Steckel et al. 2013). Some policymakers and researchers believe that using more wood in construction would be a low-carbon alternative to concrete and steel. They seek to take advantage of new techniques that

generate thick wood panels of cross-laminated timber that can support taller buildings with far less steel and concrete.

The approach of making broad use of wood in construction is often referred to as "mass timber." In this section, we analyze its potential implications for global wood demand, forests, and land-use competition. In Section 5, we analyze the potential carbon implications, including the potential effects of using wood to replace concrete and steel.

Estimating the potential additional quantity of wood for so-called mass timber has uncertainties and requires estimates or assumptions of the percentage of the population that will become urban, how much additional construction will be built, and how much wood would be required to build each unit on average. We start with projections from a recent study by Churkina et al. (2020), which developed an estimate of the additional timber and wood fiber required per additional urban resident. As described in more detail in Appendix A,[16] we applied these estimates to a projected increased urban population using the SSP2 ("middle of the road scenario"; Dellink et al. 2017). (Some increased use of wood products is already factored into our baseline, and this analysis focuses on the implications of public policies to increase those uses further.)

In supplying this level of wood from industrial roundwood, we followed the assumption in Churkina et al. (2020) that two tons of harvested wood would be required to produce each ton of wood used for construction. When wood is harvested, only some of the wood is usable for construction. Some of the remainder is used for other products, such as paper or wood panels. In our analysis, such uses of wood replace other wood required to meet these needs. But much of the wood is a true waste burned for energy. Here, we are in effect assuming that of the quantity used for construction, an equal quantity will be burned and used to supply some of the energy needed to generate these wood products.

Table 5 shows our results for two scenarios of industrial wood use in which additional wood supplies either 10 percent or 50 percent of new urban construction between 2010 and 2050. Figure 17 shows these "additional timber demand" scenarios on top of the BAU scenario (Figure 12B). Under a BAU scenario without additional wood for new construction, industrial roundwood use rises by 88 percent from 883 million tons of dry matter in 2010 to 1,656 million tons in 2050. Because this increase in the annual use of industrial roundwood phases in over time, the cumulative wood use rises by 15,860 million tons of dry matter (44 percent) compared to a scenario in which global wood supply remains at the 2010 level (see the green triangle in Figure 17). But in this baseline, only 0.5 percent of new urban buildings (mid-rise residential and commercial buildings) are constructed with timber (Churkina et al. 2020).

In a scenario in which an additional 10 percent of urban construction comes from wood, the increase between 2010 and 2050 in the total annual industrial wood use rises by 11 percent more, for a total increase of 55 percent. Cumulative wood use rises another 4,107 million tons of dry matter. If 50 percent of additional urban construction uses wood, the cumulative increase in wood use rises by 20,537 million tons compared to BAU. That 20,537 million tons represents an increase of 57 percent above the BAU industrial wood harvest (44 percent). This leads to a cumulative increase of 101 percent compared to the scenario where the harvest remained otherwise at 2010 levels, or a cumulative increase of 39 percent above BAU levels. Overall, in that "50 percent of construction uses wood" scenario, annual industrial wood use in 2050 would be 201 percent more than in 2010, tripling annual consumption.

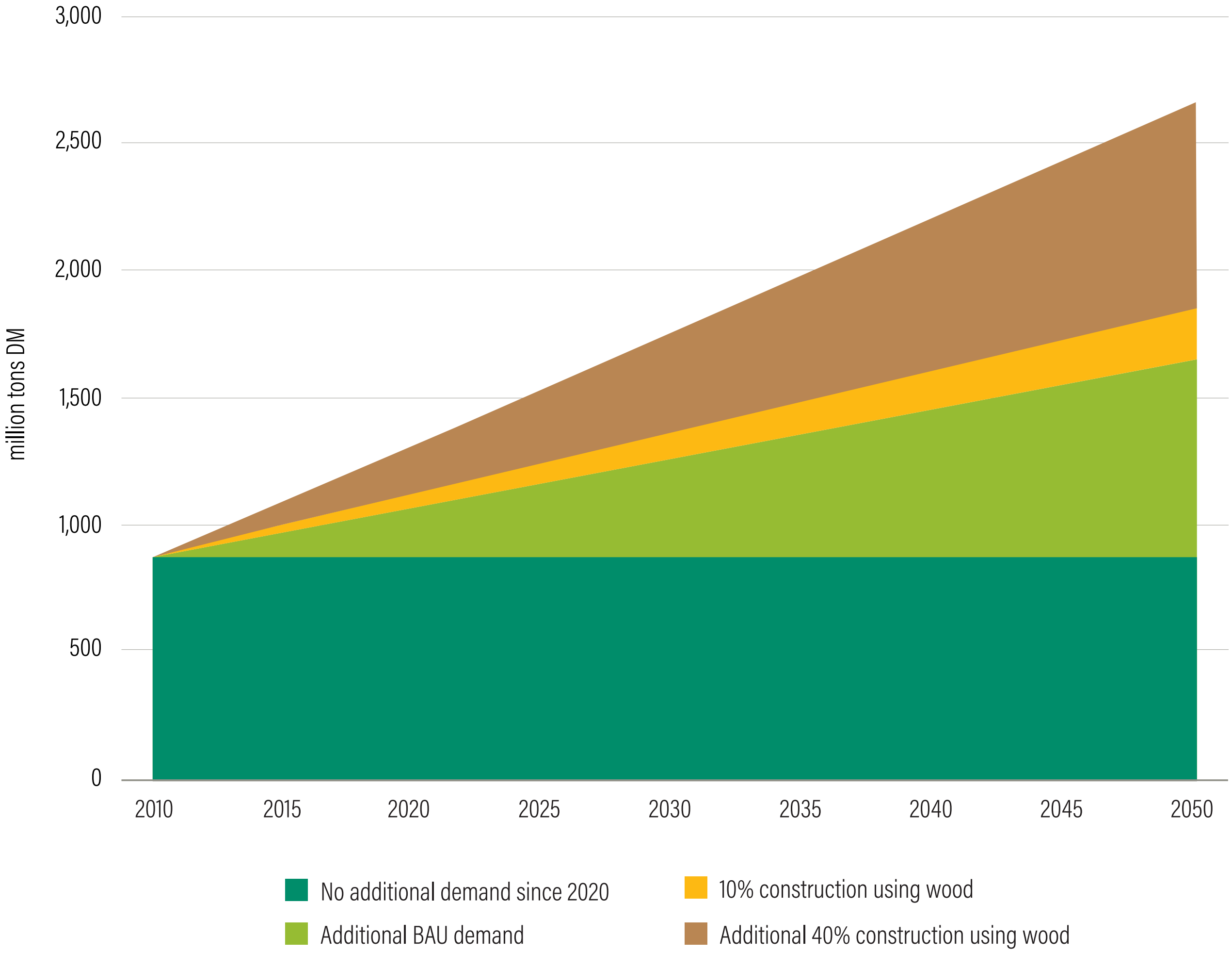
Table 5 | Changes in Annual and Cumulative Wood Demand under Scenarios of Additional Wood Demand for New Urban Construction, 2010–2050

<table>
<tr><th>INDUSTRIAL ROUNDWOOD (MILLION TONS DM)</th><th>2010 (ANNUAL)</th><th>2050 (ANNUAL)</th><th>CHANGE BETWEEN 2010 AND 2050 (ANNUAL, %)</th><th>TOTAL CUMULATIVE INDUSTRIAL ROUNDWOOD DEMAND (2010–50)</th><th>CUMULATIVE INCREASE RELATIVE TO MAINTAINING 2010 SUPPLY (%)</th><th>CUMULATIVE INCREASE RELATIVE TO 2050 BAU (%)</th></tr>
<tr><td>Maintain 2010 supply</td><td rowspan="4">883</td><td>883</td><td>–</td><td>36,184</td><td>–</td><td>–</td></tr>
<tr><td>BAU</td><td>1,656</td><td>88</td><td>52,044</td><td>–</td><td>–</td></tr>
<tr><td>BAU and 10% construction using wood</td><td>1,857</td><td>110</td><td>56,151</td><td>55</td><td>8</td></tr>
<tr><td>BAU and 50% construction using wood</td><td>2,658</td><td>201</td><td>72,581</td><td>101</td><td>39</td></tr>
</table>

Notes: BAU = business as usual; DM = dry matter.

Source: Authors, adapting additional wood demand scenarios from Churkina et al. 2020.

Figure 17 | Mass timber could greatly increase global timber demand



Notes: BAU = business as usual.

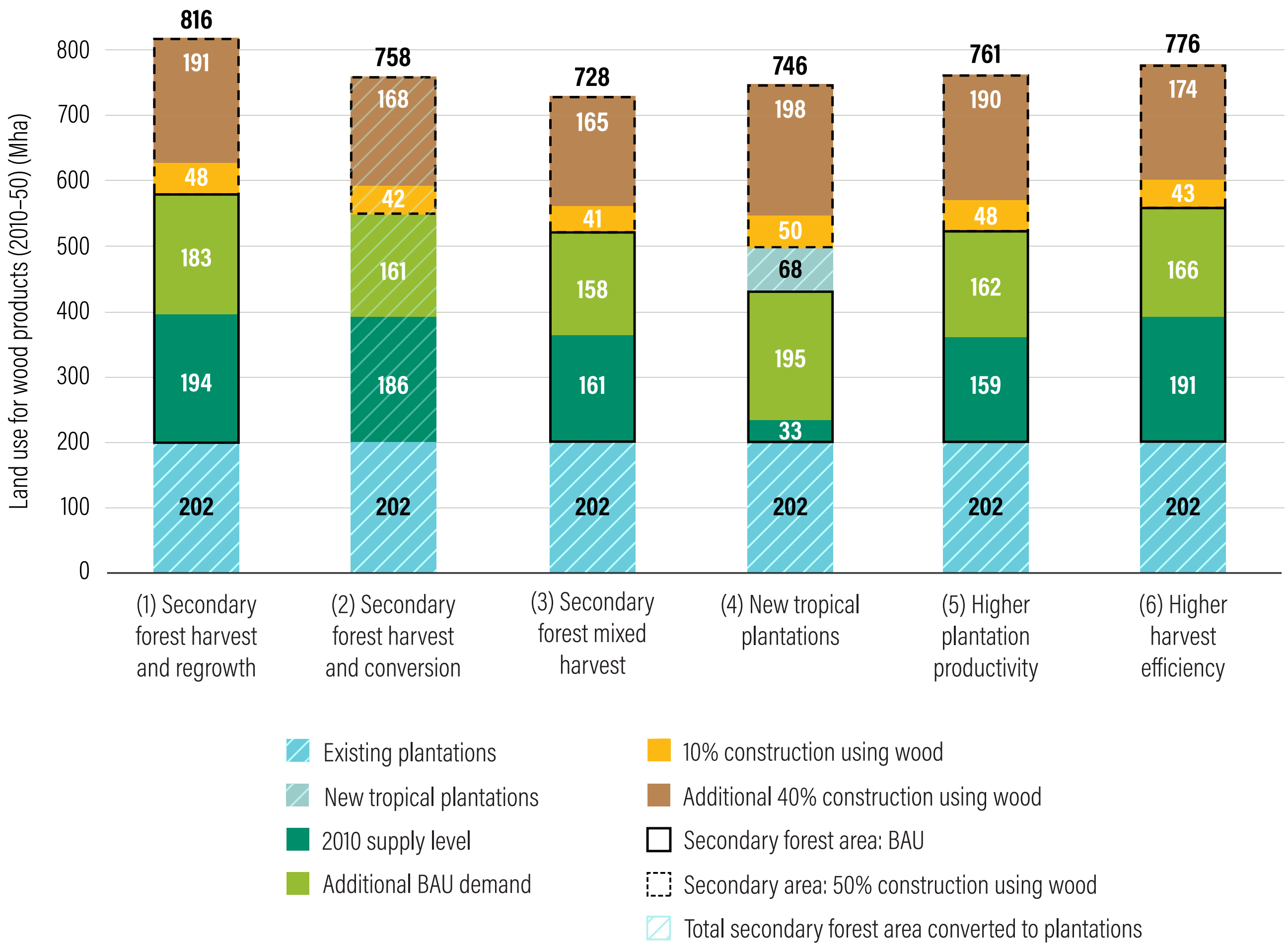
Source: Authors, adapting additional wood demand scenarios from Churkina et al. 2020.

Scaling up our prior global estimates of the BAU wood supply for industrial wood use implies large increases in global area of forest harvested for industrial wood use, as shown in Figure 18. Under the 50 percent construction using wood scenario, there would be around 200-250 Mha of additional secondary forest area required for the first six scenarios (sum of the yellow and brown bars in Figure 18). For the first three scenarios, instead of forest harvest areas (in addition to 2010 plantations) of 320-380 Mha in our BAU scenario (green solid bars), secondary forest harvest areas would range between 525 Mha (Scenario 3) to 615 Mha (Scenario 1).

A larger area harvested would also imply additional releases of carbon to the atmosphere. We did not estimate these carbon implications at this time because they would depend on the type of forest used and many other parameters that are uncertain at this time. We instead discuss below the carbon implications of a variety of different scenarios for supplying this wood.

Other studies have also estimated large additional land requirements under additional demand for wood for construction. One study projected a 170 percent growth in timber demand between 2020 and 2050 (van Romunde 2020) because of urbanization, a shift in preference from steel

Figure 18 | Use of wood to replace 50 percent of concrete and steel in construction would require roughly 200 Mha more wood harvest per year (clear-cut equivalent)



Notes: Projections assume that secondary forests are sources of additional construction wood. Solid bars indicate wood use under business as usual (BAU); hatched bars indicate wood use for construction. Assumes linear phasing in of additional wood demand from 2010 to 2050. Scenarios adapted from Churkina et al. 2020.

Source: Carbon Harvest Model.

and concrete to wood in buildings, and increased construction. It noted that this increased level of timber demand would be 23–57 percent higher than the estimated “sustainable timber supply” during that period (O’Brien and Bringezu 2017). A study by Chatham House found that if newly planted forests were to replace 25 percent of global concrete, the additional forest harvest area would need to expand 1.5 times the size of India (Lehne and Preston 2018). In addition, the preliminary findings from a joint United Nations Economic Commission for Europe and FAO study into future wood supply and demand scenarios showed that additional demand for wood for construction could drive up the prices in forest product markets (up to 47 percent relative to the year 2015) and result in the lowest projected forest sector carbon sequestration potential among various scenarios (Nepal and Prestemon 2019).

Churkina et al. (2020) claimed that such large increases in wood demand would be sustainable because they would not exceed the global growth in forests. Whether or not it is sustainable, this harvest of wood is not carbon neutral for the reasons we have explained elsewhere in this report.

5. GHG Consequences of Using Wood for Construction

Modern efforts to increase the use of wood in construction, known as mass timber, rely on new wood construction techniques for wood to support taller buildings. They involve ways of gluing together multiple layers of smaller boards under high pressure, typically in alternating directions, to create thick panels known as cross-laminated timber (CLT) or beams known as glued-laminated timber. (We hereafter refer to both as CLT.)

The core purpose, as reflected in the Churkina et al. (2020) analysis, journalism, and many nongovernmental organization or industry papers, is to reduce GHG emissions by replacing concrete and steel with wood products in construction (EESI 2018; Robbins 2020; Roberts 2020). But there are also competing papers that find increased use of wood for construction will actually increase emissions (see Appendix B), a view articulated by more than 200 scientists in a letter to the U.S. Congress in 2020 (Moomaw et al. 2020). We ask the following question: Under what conditions, if any, does the use of wood in construction yield a net-benefit effect on the climate?

To analyze the GHG consequences of using wood for construction, we first examined the formal literature to identify the key differences between analyses. Most differences depend on whether the harvest of wood is viewed as carbon neutral, meaning that carbon emitted by the burning or decomposition of wood is not counted as an emission. The accounting question of whether "sustainably" harvested wood should be viewed as carbon neutral is the same as that presented by different analyses of the consequences of using wood for bioenergy (although the details of the proper carbon calculations will differ between construction wood and bioenergy). As discussed above, a complete analysis should factor in all carbon pools, including forest carbon pools; we then use CHARM to explore the GHG consequences of wood use in construction under different possible scenarios and with different assumptions.

5.1 Lessons from the Literature

To understand the different estimates of the GHG consequences of using wood for construction, we performed a careful review of more than 60 papers addressing this topic. We group these into several categories, as set forth in a comprehensive table in Appendix B, and we explain them and our assessment of their accounting approaches in this section.

5.1.1 Papers finding benefits for construction that treat harvesting wood as carbon neutral

Of the papers reviewed, 59 find net climate benefits from wood construction using analysis that treats wood as carbon neutral. This assumption means that although they do factor in emissions from fossil fuel used in the production of wood, they do not factor in the carbon lost to the air due to decomposing or burned wood. That loss of carbon is counted neither at the point where it occurs nor as the loss of carbon storage in the forest, either of which can be a legitimate way of factoring in these carbon losses. Papers treating wood as carbon neutral in this way fall into one or more of the following categories:

- **Wood is carbon neutral if forestry is sustainable or if forest carbon stocks are maintained overall.** Of these papers treating wood as carbon neutral, nearly all do so based on the assumption that wood is inherently carbon neutral so long as forests are managed sustainably. Often the term *sustainable* is left undefined, but for some papers *sustainable forest management* means that carbon losses from forest harvests in a given year are at most equal to gains in carbon elsewhere within a defined "forest management area" (e.g., see Lippke et al. 2011). According to certain papers, this forest management area can include a whole state or even a whole country (Ganguly et al. 2020).
    - Of these papers, all factor in a substitution benefit for replacing concrete and steel. This is based on calculations that the fossil fuel requirements to produce the wood for constructing a building are less than those for making the steel and concrete the wood replaces.
    - Within this group, 46 papers go even further: they not only count these substitution benefits and ignore the loss of carbon in the forest, but they also count the wood incorporated into buildings or other LLPs as a carbon storage gain. In effect, just transferring the same wood and the same carbon from the forest to a building is considered to be a carbon gain—even though that carbon transfer does not remove more carbon dioxide from the atmosphere. To illustrate the implications of such an approach using an extreme example, a forest harvest could take 100 tC out of the forest, incorporate just 1 ton of carbon into buildings, add 99 tC to the air by burning the wood or allowing it to decompose, and this approach would count the overall

process as an increase of 1 ton of carbon storage and therefore a removal of 1 ton of carbon from the air.

- As we discuss above, sustainable forest management does not make wood carbon neutral, even if that means just harvesting the "incremental growth" of wood so that the overall carbon stock in a country's forests (or a smaller forest management unit) is not reduced. If that growth were not harvested, more carbon would be stored in the forest; thus, the net effect of the harvest is to reduce that forest carbon. If forest management increases the growth of wood, that increased growth must be factored into the analysis (and scenarios that include such growth are included in our CHARM modeling). But the mere fact that forests are growing in some broader area, country, region, or the world does not make harvests carbon neutral.

- To justify the carbon neutrality approach, a few of the reviewed papers offer a brief economic argument although without actual economic analysis. This argument is usually a variation of the contention that forests grow to meet the demand for wood rather than simply existing on their own, so increasing wood demand will result in more forests. (Although none of these papers provides an economic analysis, a couple use economic analysis to address other questions, such as the possible effects on the prices of different harvests [Xu et al. 2018].)

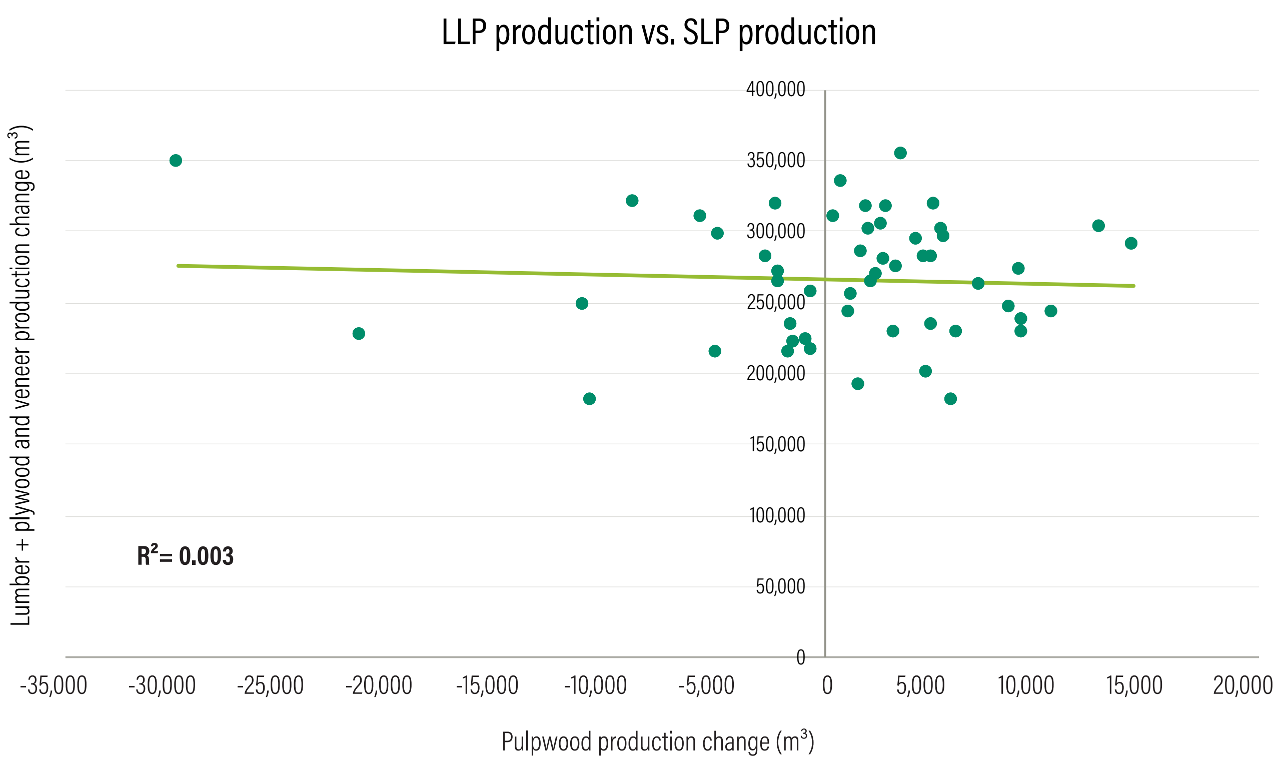
As we discuss in Box 6, the vast majority of forests exist because the areas they occupy are not economically usable for agriculture either because of biophysical conditions that make the benefit-cost ratio of their agricultural use poor or because of a lack of local infrastructure. Whether changes in forest product demand results in a global increase in areas planted for forests at the margin, or triggers more intensive management (with a variety of consequences), is a challenging econometric question, whose implications for policy we address in Box 6.

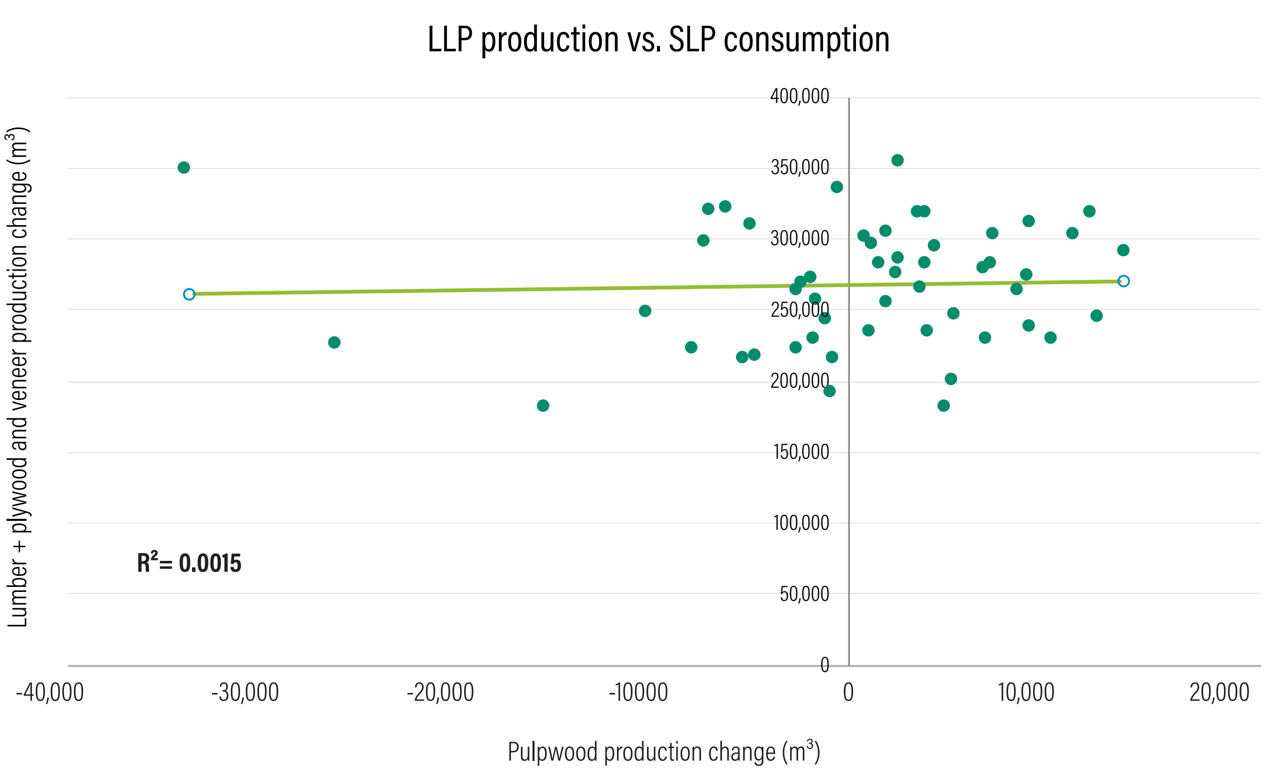
- **Wood for construction is carbon neutral so long as wood is diverted from pulp and paper products.** A few papers do not assume that forest biomass is carbon neutral in general, or even just because forests are "sustainably" managed, but examine scenarios in which they assume that the additional wood used for construction would otherwise be used for pulp and paper. As a result, increasing wood for construction causes no additional wood harvesting. For example, Smyth et al. (2020) and Xu et al. (2018) analyzed such scenarios, and, not surprisingly, they result in climate benefits. In this scenario, wood that would otherwise decompose quickly after being used as paper is instead stored longer in buildings, effectively delaying the emissions associated with the wood products. Showing the importance of this assumption, Smyth et al. (2020) also included an analysis that involved additional harvests in the northern lake states of the United States, and in that scenario, there was an increase in GHG emissions.

For the use of wood in construction to divert wood from pulp and paper, it is not enough for pulp and paper product use to decline over time (which may or may not occur for other reasons); instead, the additional use of wood for construction must actually cause a decline in pulp and paper. None of the papers reviewed offers any evidence of such a causal relationship. To do this kind of analysis rigorously requires challenging economics, but it is possible to gain insights just by examining whether there is any correlation between LLP consumption or production and production and consumption of pulp and paper. Using data from the United States (Howard and Liang 2019), which is the world's largest producer of pulp and paper, we found no correlation as shown in Figure 19 (R^2 of .003 and .0015).[17]

In addition, even if there were a relationship, this type of analysis would not show that increasing demand for timber would be better than using other tools to reduce demand for paper. To the contrary, if leaving wood unharvested is better than harvesting that wood for timber, it logically follows that the better carbon result is to reduce demand for paper and use that reduction to harvest less wood.

Figure 19 | There has been no correlation between production of LLPs and paper production or consumption in the United States





Notes: LLP = long-lived product; SLP = short-lived product. Each point represents a separate year.

Source: Howard and Liang 2019.

- **Harvesting wood is not only carbon neutral but is also credited with all forest wood growth.** Some papers not only assume that harvested wood is carbon neutral but they also give wood products a credit for all the carbon in forests used to supply the wood. Implicitly, these papers assume that, without the demand for wood for construction, the land in effect would be barren. Under these assumptions, use of wood for construction results in no costs but three benefits: more wood stored in products (buildings), substitution benefits for concrete and steel, and more carbon stored in wood on forestland. One such paper (Lippke et al. 2004) is an official publication of the Consortium for Research on Renewable Industrial Materials. In this paper, the wood growth was responsible for more than 80 percent of the claimed climate benefit of constructing a wood-framed house (with the remainder coming from less fossil energy use).

  In effect, this approach assumes that forests that supply wood for construction exist because of the construction wood demand. The implicit assumption—or logical conclusion—of such analytical approaches is that all forests in the world exist because of wood demand. We consider this approach untenable both because vast areas of forests that are harvested cannot possibly exist only because of those harvests and because large areas of forest exist that are not harvested at all. In addition, devoting any land to providing human products, including wood, has carbon costs relative to devoting land just to storing carbon or to meeting other human needs (Box 6).

  Wood demand does lead to economic effects. At the margin, these economic effects may alter forest areas or management and may lead to rebound effects on agricultural land and even uses of steel and concrete elsewhere, and those consequences can affect carbon balances. Nevertheless, merely incorporating economics into the analysis does not justify treating wood as carbon neutral, let alone claiming that harvesting wood is what causes all forests to store carbon in the first place. Instead, such an analysis must examine and not merely assume the economic effects, and it must incorporate those economic effects on carbon storage into the analysis.

  Economic analysis must also occur in a balanced way. For example, if a paper examines whether increased use of wood for construction would reduce uses of wood for other purposes, it should also examine whether reduced steel and concrete for construction would increase their uses in other ways as well. Both would be caused by the price effects of changing wood or steel consumption. As we explain in Box 6, any such analysis should only contribute to policy recommendations after first analyzing, through biophysical models, what physical changes in land use and management are most desirable.

  Potential biodiversity effects provide an additional reason to separate biophysical from economic analyses. For example, if additional demand for wood were to result in increased forest plantings, a likely source would be plantations or other highly managed forests established on agricultural lands with very low productivity. In Europe, an estimated 10–20 percent of agricultural land consists of diverse grassland and woodland complexes with extremely low grazing use that are categorized as "high nature value" farmland (Paracchini et al. 2008; Strohbach et al. 2015). The conversion of such lands to forest plantations is broadly recognized as a major threat to European biodiversity (Strohbach et al. 2015). This example highlights that no land is "free" from either a carbon or biodiversity perspective. A first analysis (such as in this report) therefore should be to determine which land-use alterations are environmentally desirable from a biophysical standpoint; only after doing so should it examine how different policies, including their economic feedbacks, can help achieve those results.

BOX 6 | Economic Feedbacks and Relevance for Treating Wood as "Carbon Neutral"

Some papers, such as Lippke et al. (2004), implicitly assume that forests only exist to supply wood and, as a result, all carbon stored in forests or in construction material represents additional carbon storage caused by the use of wood. We consider this argument untenable.

Vast areas of forests predated any wood harvest. Few people would argue, for example, that the Amazon or Congo rain forests, or vast boreal forests, exist because of the demand for wood. There is also a rich literature that finds forest regrowth occurring in countries for a range of reasons separate from forest demand. These reasons include the declining need for agricultural land; the declining agricultural competitiveness of some lands; and the reduced harvesting of forests for bioenergy, which occurred as countries shifted to fossil fuels.[a] In general, the vast bulk of forests exists in places where agriculture is too marginal to be competitive, whether because of cold, intermittent rainfall, poor soils, or lack of sufficient human infrastructure. Most of these forests are still regularly or at least occasionally logged, including nearly all forests in Europe and the United States. For this large quantity of forests, there can be no serious claim that forests exist because of the demand for wood.

In addition, if people only allowed forests to exist to supply wood, there would be no reason for forests to grow in excess of the growth in forest product demand. People would only grow forests enough to meet expected demand. But forests are growing both globally and regionally, which creates what is known as the "forest carbon sink."[b] In addition to forest area expansion in many developed countries as agricultural land declined, large increases in forest growth are caused by climate change itself.[c] These facts do not mean that wood product demand cannot encourage some more forest area at the margin, but they do mean that forest product demand cannot explain the overall pattern of net forest growth even after accounting for rising harvests.

A legitimate economic question is whether increasing the demand for wood can induce additional forest plantings and expansion of forest area to offset some or all of the carbon losses from harvesting wood. Economic effects might also lead to more intensive management of existing forest areas, for example, by planting monocultures of fast-growing trees such as loblolly pine or eucalyptus or by thinning forests more. These can be thought of as economic feedback effects. We do examine biophysically the possible carbon consequences of supplying more wood from plantations in this report, but we do not examine these economic feedback effects in part because those effects address a secondary question. They address the question of how to achieve certain global land-use or management changes and what role is played by increased demand. This report addresses the question of what actual changes in land use are advisable from a global environmental perspective in the first place.

Put another way, the model used in this report, like other biophysical models, assumes aggregate levels of demand and specific yields for food or wood on different lands. It is possible that changes in consumption by one person affect the consumption by others and the types of supply through changes in prices. The model we use evaluates the effects of aggregate demand and supply regardless of what forces shape them. What this type of model can therefore answer is what the carbon and land-use consequences are of changes in these aggregate levels.

The economic effects of increasing or decreasing demand for oil provides a useful analogy. Technology road maps for climate change mitigation commonly seek to identify possible future paths for reducing overall energy consumption and replacing oil with various low-carbon alternatives. Yet if any one individual or country reduces oil consumption, the price of oil will decline. Absent any other policy measures, lower prices will lead to increased oil consumption by others, which reduces some of the climate benefits.[d] That is an important effect to understand in crafting policies to achieve desired energy transitions. But it is not necessary to estimate what the efficient and desirable energy transitions should be.

If policies induce increased demand for construction timber, there will be effects on prices, which could lead to a range of changes with advantages and disadvantages for climate change. Beneficial changes might include increased forest plantings. More intensive management might also lead to faster wood growth, generating more usable wood on the same land. But negative effects are also likely. Increased plantings in one location on agricultural land would tend to result in expansion

BOX 6 | Economic Feedbacks and Relevance for Treating Wood as "Carbon Neutral" (cont.)

of agricultural land elsewhere to replace the forgone food production. If the yields in the new land are lower than in the land planted as forest, the effect could be a loss of forest globally. More intensively managed forests, although producing faster growth, also commonly store less carbon because they are harvested at a younger age. Although using more wood in construction might reduce the use of concrete and steel for construction in some buildings, that reduction would also marginally reduce the prices of concrete and steel and likely result in some offsetting uses of concrete and steel by others.

Estimating any, let alone all, of these effects is enormously challenging. The limited availability of different demand and supply elasticities that are estimated using rigorous econometrics raises doubts about whether such estimates can be meaningful. Gaps include almost no data on cross-price elasticities (how changes in demand or supply of one product influence demand or supply of another). Other major gaps include few if any long-term elasticities. Both such types of effects must be known with reasonable confidence to make such estimates meaningful.

Fortunately, as in the oil consumption analogy, these effects are not necessary to estimate the extent of future land competition or potential and desirable paths for resolving these conflicts. The world has a fixed quantity of land. To the extent that wood demand leads to more forest plantings, they do not create more land beyond the world's fixed land base but rather take land away from some other use, typically agriculture. More land dedicated to wood production means less land available to produce food. More intensive management can lead to less carbon storage on site but spare more natural forests and other habitats.

Biophysical models, such as GlobAgri-WRR and the Carbon Harvest Model, can be used to estimate what combination of production or consumption changes for food and wood would be most desirable from a carbon and biodiversity perspective. They can answer such questions as what consumption or production changes are needed to free up more land for plantation or natural forests. They can also answer questions such as whether it would be better to restore forests and leave them alone or to plant forests and harvest them for wood products if more agricultural land were available for forests.

In short, biophysical accounting models are a way of assessing what combinations of production systems and consumption patterns would be necessary to minimize land-use change emissions and maximize land-based carbon storage while still meeting all human demands for land-based products. To do that analysis, uses of land to supply one source of demand, such as wood, cannot expand without consequences for meeting demand supplied by another use, such as food. And if one land-use pattern is conditioned on reduced consumption, such as reduced food consumption, this type of analysis can identify if such a change is feasible or even desirable. The land-use requirements for each demand must be assessed, and then the scenarios must be analyzed that can assess the consequences and methods of meeting overall use land demands (and not merely shift one use of land to another).

Using biophysical models to determine what are the most desirable outcomes does not mean that economic effects are unimportant or that economic analysis has no role to play. Economic analysis, if rigorously done, can help people understand how economic effects amplify or buffer policy effects. Economic analysis can also help guide the most effective use of economic incentives. The first step, however, should be to determine what biophysical changes are most desirable—and that is the focus of this report.

Sources: a. Birdsey et al. 2006; Krausmann et al. 2015; Meyfroidt and Lambin 2011; b. Friedlingstein et al. 2019; Harris et al. 2021; Pan et al. 2011; c. Ciais, Schelhaas, et al. 2008; d. Gillingham et al. 2016.

5.1.2 Papers applying an all-carbon-pools accounting approach

A substantial but smaller group of papers analyzes the consequences of additional wood harvests using some variation of the "all-carbon-pools" modeling approach used by CHARM to calculate the carbon effects of global wood harvests. This approach uses a biophysical model to compare the benefits of harvesting wood over time to the benefits of leaving wood unharvested.

In this approach, the scenario may start with a middle-aged forest, which initially stores carbon in live vegetation, dead standing trees, and detritus (wood decomposing on the forest floor). If unharvested, these pools of carbon keep growing as the forest ages, although the growth rate will decline over time. For the harvested scenario, the live wood is immediately diminished, but some of the wood is left in the forest in a pool of dead tops, branches, and roots, which then declines over several years. Of the wood removed from the forest, some is used for timber products, creating different timber product carbon pools. These pools can include wood used in construction, which lasts longer, and wood used in furniture, which does not last as long. Another pool includes wood used for paper products, which are quickly used and then recycled or thrown away. And much of the wood is burned as a by-product in the process of making timber and paper products. As wood products are thrown away, they build and then decay in landfills. Each of these pools has its own decay rate, and the loss of carbon from all these pools adds carbon to the air. Forests are also allowed to regrow, so the pool of live carbon in the forest increases in the years after harvest. Models of this type track the change in all these pools of carbon over time.

These models can also track the effects on another carbon pool, which is the pool of carbon stored underground in fossil fuels. Fossil energy used in the process of harvesting and making wood products reduces that pool (i.e., increases carbon in the air), but the use of wood products can save fossil and related emissions used to produce steel, concrete, or other products; in that way, it increases the quantity of carbon that remains stored underground. Waste wood burned in the process of making timber and paper products can also save fossil fuels, although it is usually less than the fossil fuels used to make wood products. The net fossil fuel consequences of using wood rather than alternatives are usually expressed as a "substitution value" for replacing standard construction materials such as concrete and steel with wood.

Applying this approach generates a net GHG emissions result in each future year, and this approach is typically then used to estimate a net effect on the climate at a specific time. Because this approach accounts for the reduction of carbon in the forest due to wood harvesting, the results are less favorable to the use of wood than treating the wood as carbon neutral (assuming the same substitution values). The papers applying this approach can still differ from each other based on the assumptions used for key parameters.

One general finding of these papers, when applied to specific stands of forest, is that when the harvests and uses of wood occur as they have typically occurred in the past—with wood going to its average mix of uses—the harvest of additional forest stands to supply construction increases carbon in the atmosphere for at least decades. That was one of the conclusions of the original Schlamadinger and Marland (1996) model, discussed above, which originated this all-carbon-pools approach. Analyzing U.S. forests, it found that "it takes over 100 years for the conventional forestry scenario . . . to achieve the same net C benefit as the forest protection scenario." The paper also found that a scenario with "highly efficient conventional forestry," such as plantation forestry, resulted in increased emissions initially and required 40 years to match the consequence of leaving a forest unharvested. This result means that forest harvests lead to more carbon in the air for 40 years; at 40 years, the carbon is the same, but by 100 years, there would be significant GHG reductions relative to leaving the forest unharvested.

Following a similar all-carbon-pools approach, Keith et al. (2014) found that wood harvests in Australia, using two major forest types as examples, would increase emissions even after 100 years compared to leaving the trees unharvested. Ingerson (2009) analyzed wood harvests in the United States and generally found large increases in carbon emissions for decades.

Studies of wood harvests have come to the same conclusion when analyzing a whole region's or country's forest harvests as they have occurred or do occur. For example, Hudiburg et al. (2019) used an all-carbon-pools approach to analyze the net effect of forest harvests after 1900 in the western United States (California, Oregon, and Washington) based on the best available data from actual wood uses. That paper found that forestry had resulted in large net increases in carbon in the atmosphere, even more than 100 years after the start of harvests analyzed. Essentially the same research team, using data based on forestry practices in Oregon, also projected that forest harvests would increase emissions relative to reduced forest harvest through at least 2100 (Law et al. 2018).

Xu et al. (2018) produced similar results studying options for changing Canadian forest management, finding that harvesting less had better climate results, even though one result of harvesting less would be less wood in LLPs.[18] Kalliokoski et al. (2020) applied the same approach in Finland for carbon and found that harvesting wood in typical ways (15 percent for process energy and the rest divided between LLPs and SLPs) resulted in higher emissions than leaving the same wood unharvested for many years.[19] Skytt et al. (2021) found the same for Swedish forests, finding increased emissions from harvesting versus not harvesting for at least 50 years in each of four different forest areas. Even two alternative papers analyzing Swedish forest harvests still found increases in atmospheric carbon from increased rather than decreased harvesting for at least several decades; however, one paper found the potential for immediate benefits if, contrary to present practice, very high levels of residues and tree stumps were removed and used for bioenergy (Gustavsson et al. 2017, 2021).

These estimates of the multiple uses of wood as they typically occur do not by themselves prove that harvesting of more wood just for construction generates adverse effects. A few papers apply this accounting framework and find net terrestrial carbon gains compared to nonharvesting under three conditions. First, forests are efficiently harvested, meaning little wood is left behind.

Second, the great majority of the additional wood harvested is used to replace concrete and steel. Third, doing so has a large substitution benefit in the form of reduced overall fossil and other production emissions in construction. For example, Oliver et al. (2014) found that if some forests were very efficiently harvested and used primarily to provide structural beams that replaced steel in construction, the net climate effects were immediately positive.

Chen et al. (2018) illustrates the importance of key parameters in estimating the years to "parity" for wood use and harvests from Canadian forests. (Until parity is reached, wood harvests increase emissions.) Like the results in the western U.S. studies, Chen et al. (2018) found that if wood is harvested and used with the average mix of construction, pulp and paper, and other uses, these harvests increase carbon in the atmosphere for 84 years.[20] However, when Chen et al. (2018) analyzed alternative scenarios, they showed quick benefits in some scenarios and under some assumptions. For example, they found immediate benefits if 73 percent of harvested wood were used for structural construction panels (i.e., CLT) and if they assumed large substitution benefits in replacing concrete and steel in construction (i.e., lower uses of fossil fuels). Yet the parity period still varied greatly depending on the substitution value. Using what the paper described as a "low" substitution value (0.68 tC saved per ton of carbon in wood), even structural panels required 75 years to reach parity with alternatives. Using what it called a "midrange" substitution value (2.43 tC/tC in wood), structural panels generated immediate carbon savings, and using "high-end" substitution values (4.20 tC/tC in wood), all LLPs generated immediate climate benefits.

One general finding . . . is that when the harvests and uses of wood occur as they have typically occurred in the past . . . the harvest of additional forest stands to supply construction increases carbon in the atmosphere for at least decades.

The analysis by Chen et al. (2018) shows that the assumed biophysical parameters matter (and many such parameters have important subparameters). That study highlighted two categories of parameters: those that determine the percentage of wood harvested that is incorporated into products used in construction to replace steel and concrete and those that determine the quantity of production emissions saved by each ton of wood used in this way (i.e., the substitution value). These parameters have a multiplicative effect because the more wood used for construction, the more emissions can be saved by reducing production of concrete and steel.

Yet the best-case scenario in Chen et al. (2018) is far from present practice and may not be achievable. As the paper itself notes, its percentage of wood incorporated into any LLP is far more than double the use for wood in construction that is currently typical in Canada. A 2020 publication by the U.S. Forest Business Network, based on consultation with the major CLT suppliers, estimated that, on average, only 50 percent of raw wood originally dedicated to CLT ends up in the product (Anderson et al. 2020, 12, Table 1.2). The percentage of the total wood removed from the forest turned into CLT is likely lower because some of the logs will not be of a quality to be brought to a CLT plant. Moreover, the substitution value required by Chen et al. for quick GHG reductions from the best product (structural panels) is more than four times higher than the estimate in Smyth et al. (2017), another Canadian researcher with the same institute.[21] We include this scenario because it was included in this other paper, but we doubt that it can be commonly achieved.

5.3 Percentage Change in Emissions Compared to Concrete and Steel

Another reason substitution parameters matter is that they are important for estimating a critical question that is almost ignored in the literature. Even in cases where using wood reduces emissions, what is the percentage reduction in overall GHG emissions from the use of wood in construction to replace concrete and steel?

This is a standard question for most GHG analyses but is surprisingly left uncalculated, or at least not presented, by nearly all papers addressing the climate benefits of mass timber. The standard method in these papers is to report the kilograms of GHG emissions reductions per kilogram of wood, but that is a different issue. If the goal of substituting concrete and steel in construction with wood is to reduce GHG emissions, then a key question is what percentage of the GHG emissions from construction are reduced when wood is substituted. Put another way, for every square meter of building constructed, what percentage change in emissions occurs? If that percentage reduction could be high under common and likely harvest and use scenarios (e.g., close to 100 percent), then substituting wood in construction could be a valuable practice, justifying large effort and incentives. But if that percentage reduction is low even in optimistic scenarios, then other strategies would be necessary to meet climate targets and less effort would be justified in developing mass timber as a climate solution.

The percentage reduction fits into policies in other ways as well:

- If the percentage reduction is large only under limited scenarios—particularly if it increases emissions under others—then the potential benefit may not justify the risk that wood use will result in adverse scenarios.
- If the percentage reduction is medium (e.g., 50 percent), then it could entirely disappear if emissions from concrete and steel could be reduced by 50 percent. In addition, if the mass timber development strategy relies on use of badly managed land, that suggests the badly managed land could be improved to provide climate benefits in other ways. An example might be producing more wood for existing uses, allowing other forests to remain unharvested. The combination of reducing emissions from concrete and steel plus using forestland in other ways (e.g., to store even more carbon) could therefore produce two sources of GHG mitigation versus the single source of using the land to reduce construction emissions.
- If the percentage reduction today is low, any justifiable incentive payment would be low, and benefits might not justify adverse effects on biodiversity.

One interesting question is what the percentage reduction in emissions from using wood instead of concrete and steel would be even assuming the carbon neutrality of wood. Few studies provide sufficient information because the final substitution value per ton of carbon in wood is not enough.[22] Using data provided in Churkina et al. (2020), which has a substitution value of 0.45 tC/tC in wood used for construction, the net reductions estimated from uses of construction material were 36 percent for residential housing and 65 percent for commercial housing.[23] These seem like meaningful reductions, but in the range of what might be achievable with new techniques for concrete and steel as well. Extrapolating some of the numbers in Churkina et al. (2020) to the higher substitution value of 1.2 in Leskinen et al. (2018)—and still keeping the authors' carbon neutrality assumption—the percentage reduction from using wood becomes 83 percent, which gets close to the elimination of emissions.

These calculations, however, treat wood as carbon neutral, meaning they do not factor in the loss and emission to the air of any carbon in wood itself, so they are incomplete. What these calculations do suggest, though, is that the substitution value is an important parameter in determining the percentage reduction, and it is also likely to vary by building technique and wood material.

Percentage reductions are also likely to decline over time because techniques are also available to reduce emissions from concrete and steel and will be a priority regardless of the use of wood in construction because of other uses of these materials. Possible techniques for reducing emissions from steel or concrete include capturing the carbon emitted from their production and putting it underground, a variety of alternative manufacturing techniques using various forms of renewable energy in their production, new chemical forms of concrete, new smelting processes for steel, and adjusting building designs to require less concrete and steel (Lehne and Preston 2018).

Because the percentage change is a critical policy question, the nearly universal failure of literature to calculate and discuss it is a major limitation in the analysis of mass timber. A proper analysis needs to calculate the percentage reduction in emissions by using wood for construction but also to do so using an all-carbon-pools approach to the effects of wood harvest.

We therefore built into CHARM an analysis of percentage changes using an all-carbon-pools approach. Factoring in this approach means that the change in emissions from harvesting wood, including its effect on construction emissions, factors in not only the change in production emissions (e.g., the fossil fuel emissions used to produce construction material) but also the change in carbon stored in some pool (such as forest vegetation and wood products).

5.4 Analyses of Carbon Implications of Harvesting Wood for Construction Using CHARM

To further explore the GHG consequences of harvesting additional wood in which some goes for construction and some goes to other uses, we applied CHARM to a range of possible forests and harvest scenarios. As described above, the model follows the all-carbon-pools approach originally developed by Schlamadinger and Marland (1996) and used in many other papers.

We also show the results using two approaches to time: one is just the net effect on GHGs in the atmosphere 40 years after each harvest. The other is a time-discounting approach using a 4 percent discount rate. In the results discussed in this section, we apply this discount rate to carbon flows over 40 years. (In Appendix E we discuss the effect of applying the 4 percent discount rate to carbon flows over 100 years, which has little effect except in a few scenarios. We do not make 100 years our central scenario because it is difficult to predict future conditions accurately, such as future substitution values.)

We apply CHARM to several different forest types: typical western U.S. forests, southeastern U.S. hardwood forests, southeastern U.S. intensive loblolly pine, and various scenarios in forests in Germany, Brazil, and Indonesia. For each of these scenarios, we show a variety of options and assumptions. We mainly show results with substitution values, using 1.2 tC avoided per ton of carbon in wood used, the midrange value in Leskinen et al. (2018). We also show results with different percentages of harvested wood used for construction material to replace concrete and steel. The graphic for each scenario identifies the parameters used and shows how different carbon pools change over time. Our goal is both to explore some likely results and to explore the importance of key parameters listed in Table 6, which represent real biophysical differences.

The general counterfactual to harvesting is to let a natural forest continue to grow. This assumption does not require that the specific stand of forest used for wood for construction would otherwise remain unharvested. In many situations, a particular stand of wood would be harvested and used for another purpose if not used for construction (just as a particular liter of gasoline if not used by one person would almost certainly be used by another). But more wood use requires more harvesting overall. As when evaluating gasoline, our assumption is that a similar stand somewhere, which would otherwise continue to grow, is harvested because of the increased overall demand for wood.

For plantation forests, our assumption is a little different. The assumption that any plantation forest would be left to grow unharvested generally makes little sense because they were planted specifically to be harvested. For plantation forests, we therefore use the counterfactual assumption that a natural forest would have otherwise been allowed to start growing at the time the plantation forest was established. As a result, the higher growth rates that derive from plantations are fully “credited” to the wood products. For harvests of secondary forests, we also assume 40-year-old forests.

Table 6 | Main biophysical and wood usage parameters for CHARM wood harvest analysis

	U.S. PACIFIC NORTHWEST HEMLOCK-SITKA SPRUCE	U.S. PACIFIC NORTHWEST DOUGLAS FIR	U.S. SOUTHEAST OAK-HICKORY	U.S. SOUTHEAST LOBLOLLY-SHORTLEAF PINE	BRAZIL	INDONESIA	GERMANY
Time period (year)	41	41	41	41	41	41	41
Rotation length (year)	50	50	25	25	7	7	60
First harvest age of secondary forest (year)	74	89	60	58	40	40	74
Young plantation growth rate (tC/ha/year)	2.8	2.7	3.6	3.6	8.2	7.2	1.7
Old plantation growth rate (tC/ha/year)	3.6	3.3	2.2	2.2	8.2	7.2	1.7
Young secondary forest growth rate (tC/ha/year)	2.7	2.3	2.0	2.1	3.7	4.3	1.7
Middle-aged secondary forest growth rate (tC/ha/year)	2.2	2.2	0.8	0.5	1.1	1.2	1.3
Plantation slash share (%)	13	13	9	9	13	29	25
Secondary forest slash share (%)	23	23	23	23	55	71	23
Existing wood usage							
LLP share (%)	33	33	33	33	31	60	54
SLP share (%)	29	29	29	29	31	2	8
VSLP share (%)	38	38	38	38	38	38	38
% of LLP used for construction	45	45	45	45	42	42	30
% of LLP that displaces concrete and steel	64	64	64	64	64	64	64

	40% CLT	70% CLT
LLP share (%)	50	70
SLP share (%)	25	15
VSLP share (%)	25	15
% of LLP used for construction	100	100
% of LLP that displaces concrete and steel	80	100

Notes: adj = adjusted; GDP = gross domestic product; proj = projection; RSE = residual standard error.

Source: Carbon Harvest Model.

Table 7 presents results for all the example scenarios, which we discuss below using figures that illustrate the changes in carbon pools over time. In these figures, the dotted green line shows the carbon stored without wood harvesting and the solid black line shows the total carbon stored as a result of wood harvests (including additional fossil carbon that remains underground). If the point on the black line in any year is below the dotted green line, it means the harvest increases carbon in the air, and if above the dotted green line, it means GHG savings. The position of these lines after 40 years shows the net effect at that time. Other lines show the different components of carbon storage caused by wood harvests, which sum to the solid black line. Each chart also shows the present discount value (PDV) of the wood harvest, and the percentage change in the GHG emissions by switching from concrete and steel to wood for construction.

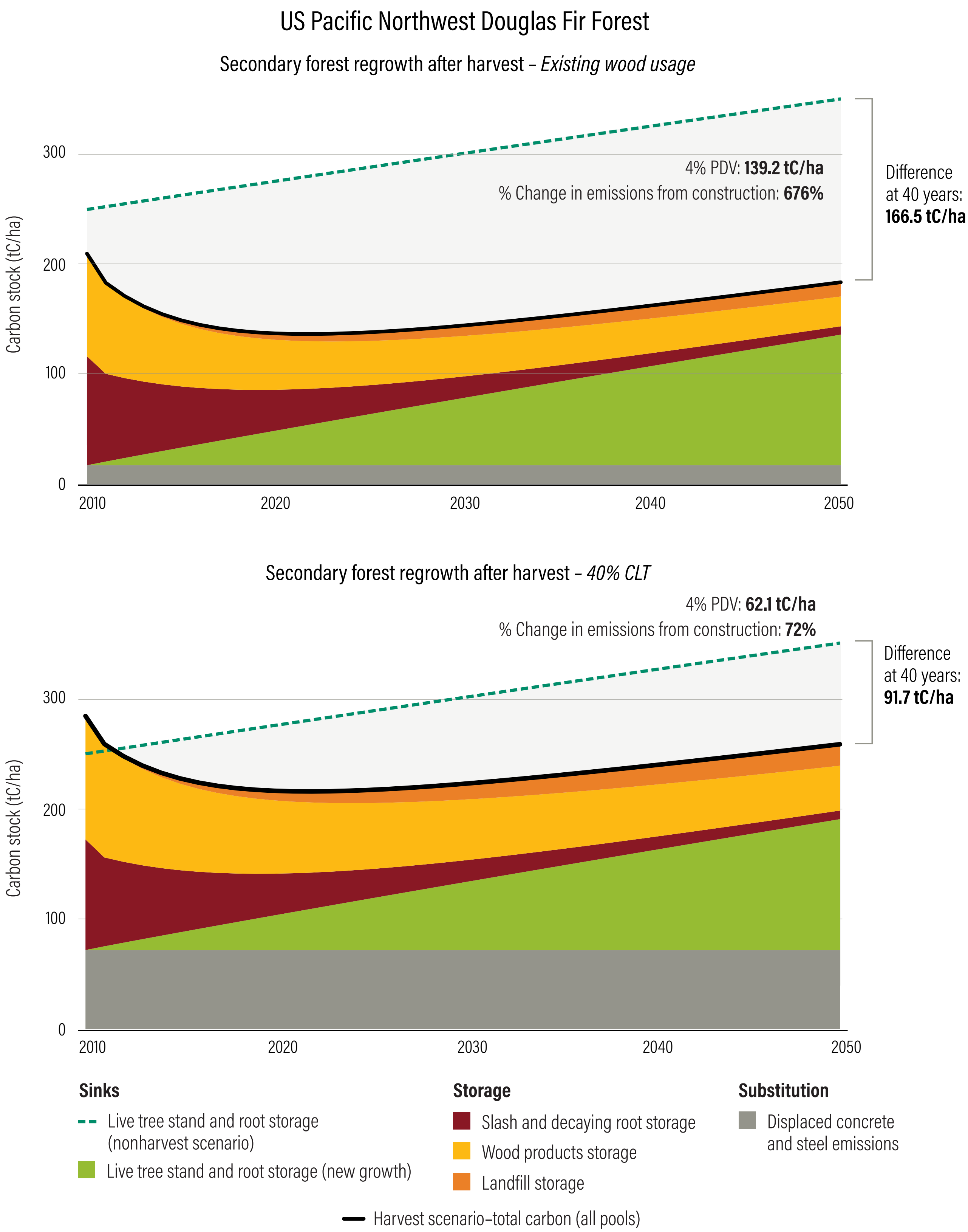
5.4.1 U.S. Pacific Northwest

Our first two examples involve harvests of two major forest types in the western (wetter) portions of the U.S. Pacific Northwest, including Hemlock-Sitka spruce forests and Douglas fir on highly productive sites. When directing wood according to existing patterns of wood use, any harvest is highly negative (Figure 20).

We did alternative scenarios under assumptions that 40 percent of the wood would be turned into construction timber that replaces steel and concrete, the "40 percent CLT scenario." As shown in Table 7, under these scenarios, the additional harvest of wood would also be adverse for the climate in all variations.

If, however, 70 percent of wood could be used to replace concrete and steel, which we call the "70 percent CLT scenario," there could be GHG savings. For Hemlock-Sitka spruce forests (Table 7), the savings would be 18 percent if the forest is allowed to regrow naturally and 26 percent if converted to a plantation. For Douglas fir, the GHG reductions for such variations would be 11 percent and 20 percent, respectively. We consider these reductions to be informative because we doubt that such a percentage of wood could replace concrete and steel. However, because even doing so would fail to achieve a 50 percent GHG reduction, the result suggests limited potential for this kind of strategy for these types of forests.

Figure 20 | Carbon Cost of Harvesting the U.S. Pacific Northwest Douglas Fir



Note: PDV = present discount value. Positive carbon numbers mean increases in emissions while negative numbers mean decline in emissions.

Source: Carbon Harvest Model.

5.4.2 Southeastern United States

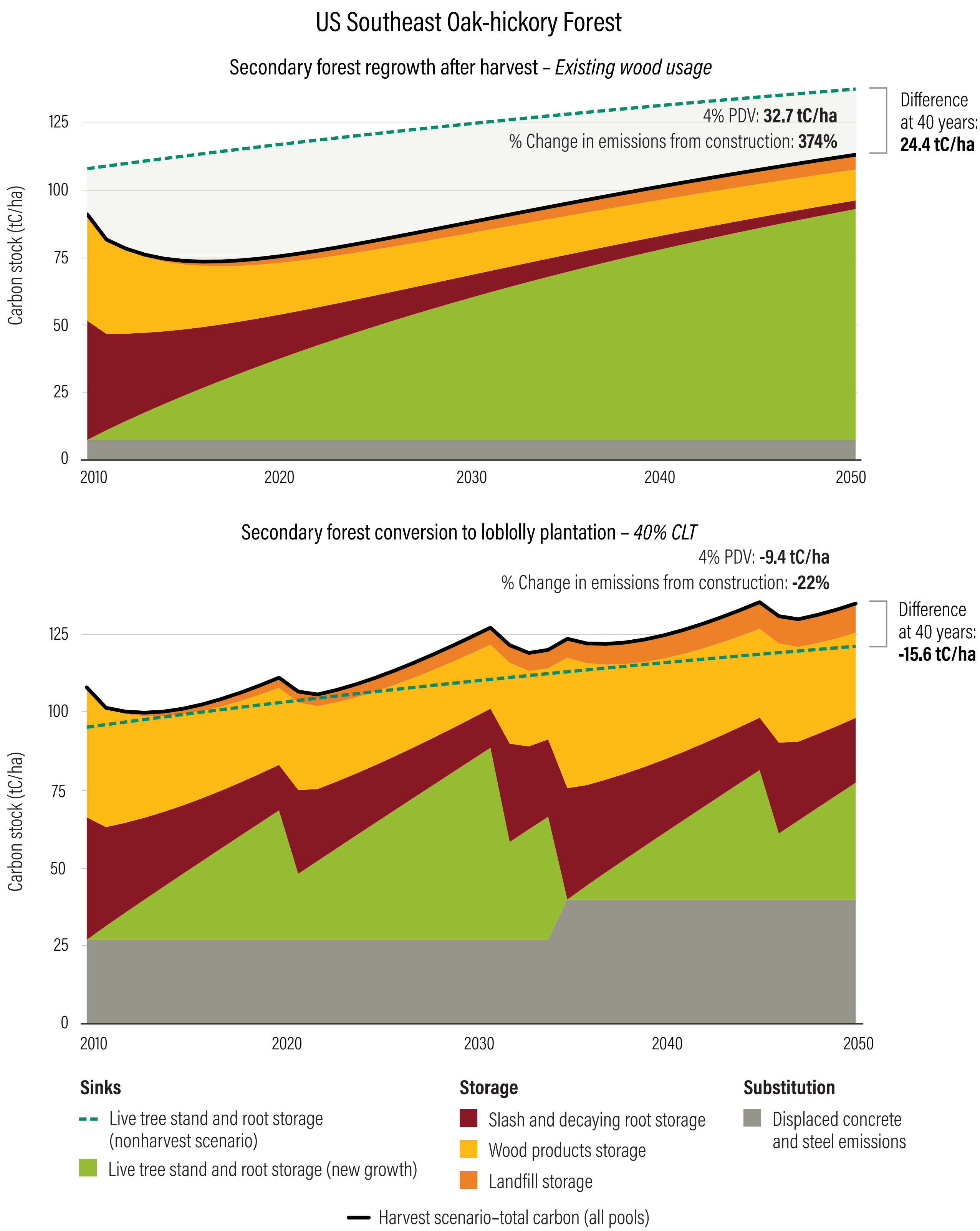
We also looked at scenarios that focused on the southeastern United States, which has become the major "wood basket" of the United States and where the vast majority of wood comes from privately owned forests. We first looked at scenarios for harvesting hardwood forests, in particular an oak-hickory forest. In our current wood-uses scenario, although a third of the wood is used for solid wood products, only 10 percent ultimately replaces concrete or steel in construction. The net effect is multifold increases in GHG emissions if wood replaces concrete and steel in construction, and that is true even if secondary forests are converted to plantations (Figure 21).

In our 40 percent CLT scenario, there is no benefit to harvesting wood in this type of forest and allowing a secondary forest to regrow and a small reduction (22 percent) if converting that forest to a loblolly pine plantation. As in our Pacific Northwest forest examples, however, there would be gain even with secondary forest regrowth of 52 percent if 70 percent of the wood could be devoted to CLT.

We also evaluated the use of intensively managed loblolly pine plantations in the southeastern United States. There is a large disparity in growth rates between average planted loblolly stands and those that are highly managed, but here we used the average growth rates between the artifical regenerated loblolly without disturbance (from U.S. Forest Service inventory data for WRI) and the regional high productivity loblolly stands (Hoover et al. 2021). We analyzed an existing loblolly plantation using the assumption that if that plantation had not been planted, a secondary forest would have been allowed to grow instead. (This rationale reflected the fact that any plantation is intended to be harvested, but the opportunity cost was allowing a secondary forest to grow.) In this scenario, emissions increase roughly threefold.

In our 40 percent CLT scenario (Figure 22), however, the emissions reductions are roughly 29 percent for harvesting an existing plantation. In our 70 percent CLT scenario (Table 7), the emissions reductions rise to roughly 70 percent.

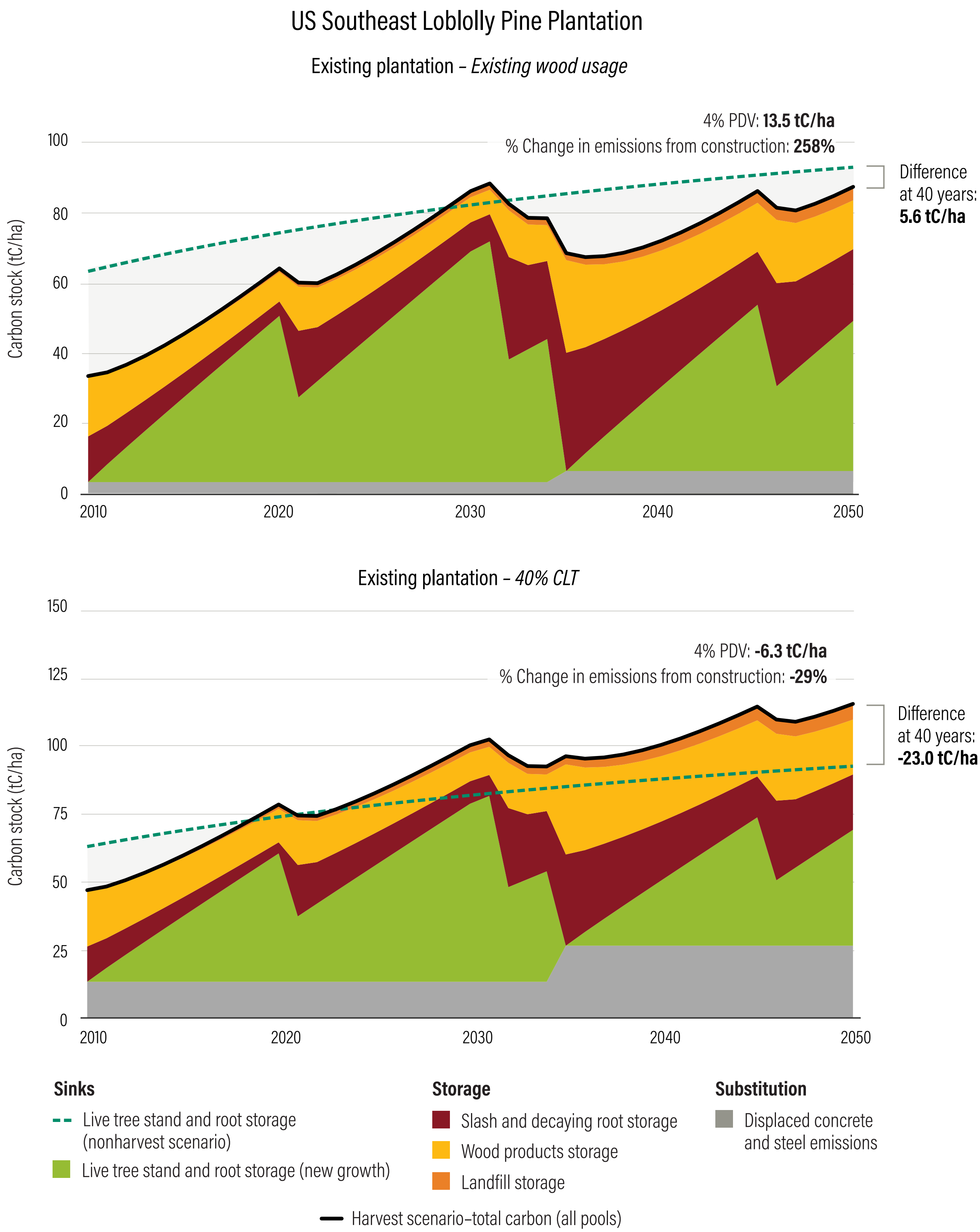
Figure 21 | Carbon Cost of Harvesting the U.S. Southeast Oak-hickory



Note: PDV = present discount value. Positive carbon numbers mean increases in emissions while negative numbers mean decline in emissions.

Source: Carbon Harvest Model.

Figure 22 | Carbon Cost of Harvesting the U.S. Southeast Loblolly Pine



Note: PDV = present discount value. Positive carbon numbers mean increases in emissions while negative numbers mean decline in emissions.

Source: Carbon Harvest Model.

5.4.3 Germany

Our analysis of forests in Germany provides similar results to our analysis of secondary forests in the United States (Figure 23). For these analyses, we are using both secondary forest and plantation forest growth rates from Harris et al. (2021). Both growth rates are relatively modest. In these scenarios, given these growth rates, harvesting secondary forests and allowing them to regrow, harvesting secondary forests and converting them to plantations, and harvesting established plantations all result in large (several hundred percent) increases in emissions for construction material.

Even in our 70 percent CLT displacement scenarios, harvesting wood for CLT produces small emissions reductions. In all variations of this highly optimistic scenario (involving secondary forests and regrowth, conversion to plantations, and harvest of existing plantations), the net GHG effect is within 25 percent range as using concrete and steel. These limited results for plantations are partly due to the data finding that plantations in Germany generally do not grow significantly faster than more natural forests. That may be due to the fact that even forests considered more natural are heavily managed in Germany.

5.4.4 Brazil

We analyzed scenarios for forests in Brazil using both natural forests and plantations (Figure 24). At this time, CLT does not use hardwoods, which means it would not use normal tropical forests. In addition, CLT cannot presently use eucalyptus, which is the primary plantation type in Brazil. Nevertheless, we analyze Brazilian scenarios for several reasons. First, even if CLT is not used, sawn wood could also be used for additional construction in general. Our analysis is applicable to sawn wood although the results are likely to be less favorable since it is likely to be less effective in replacing concrete and steel. Second, it is possible that manufacturing CLT may determine a way to use both eucalyptus and hardwoods (Liao et al. 2017). Third, tropical forests of one kind or another could become the indirect sources of wood if temperate forests are used more for construction, and our analysis implicitly addresses such a scenario.

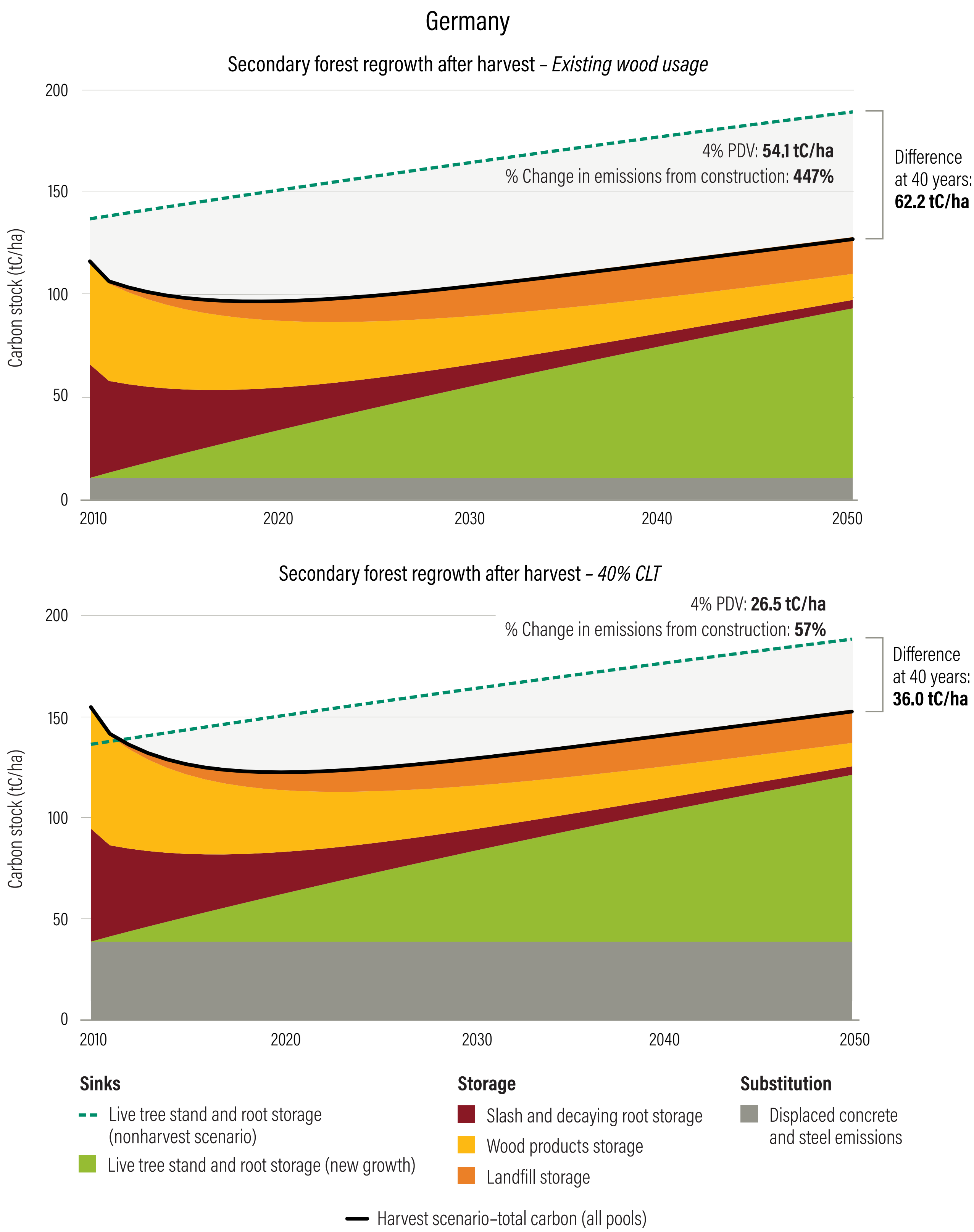
Our first group of scenarios allocates wood based on Brazil's present overall uses of wood in which only 10 percent of wood harvested both gets into construction and is used to replace concrete and steel. In these scenarios, all harvests of secondary forests have adverse carbon impacts compared to leaving forests alone, even if converting secondary forests to plantations. Even harvesting plantations has adverse consequences.

In our 40 percent CLT scenario, however, there is a 75 percent reduction in emissions from construction material when converting existing forests to plantations (Figure 24B) and an 113 percent reduction when using existing plantations (Table 7). In the 70 percent theoretical CLT scenario, these reductions rise to 95 percent and 117 percent, respectively. In this 70 percent CLT scenario, even harvesting secondary forests would reduce emissions from construction materials by 33 percent.

5.4.5 Indonesia

The Indonesia examples (Table 7) have some similarities to Brazil but also some distinctions, which are probably due to our higher estimates of secondary forest growth rates and our higher estimates of wood used for construction under existing conditions. Harvesting secondary forests and regrowth is disadvantageous, and even in the 70 percent CLT scenario, it generates no savings. Using existing plantations is beneficial in all wood-use scenarios, but only reaches 68 percent reduction in emissions compared to concrete and steel in the 40 percent CLT scenario. Only in the 70 percent CLT scenario do even existing plantations reach very high levels, in this case 91 percent. Perhaps most significantly, in the conversion scenario, the harvest is adverse with existing usage patterns, reaches only a very small level (24 percent) at the 40 percent CLT level, and only reaches 65 percent in the 70 percent CLT scenario (Table 7).

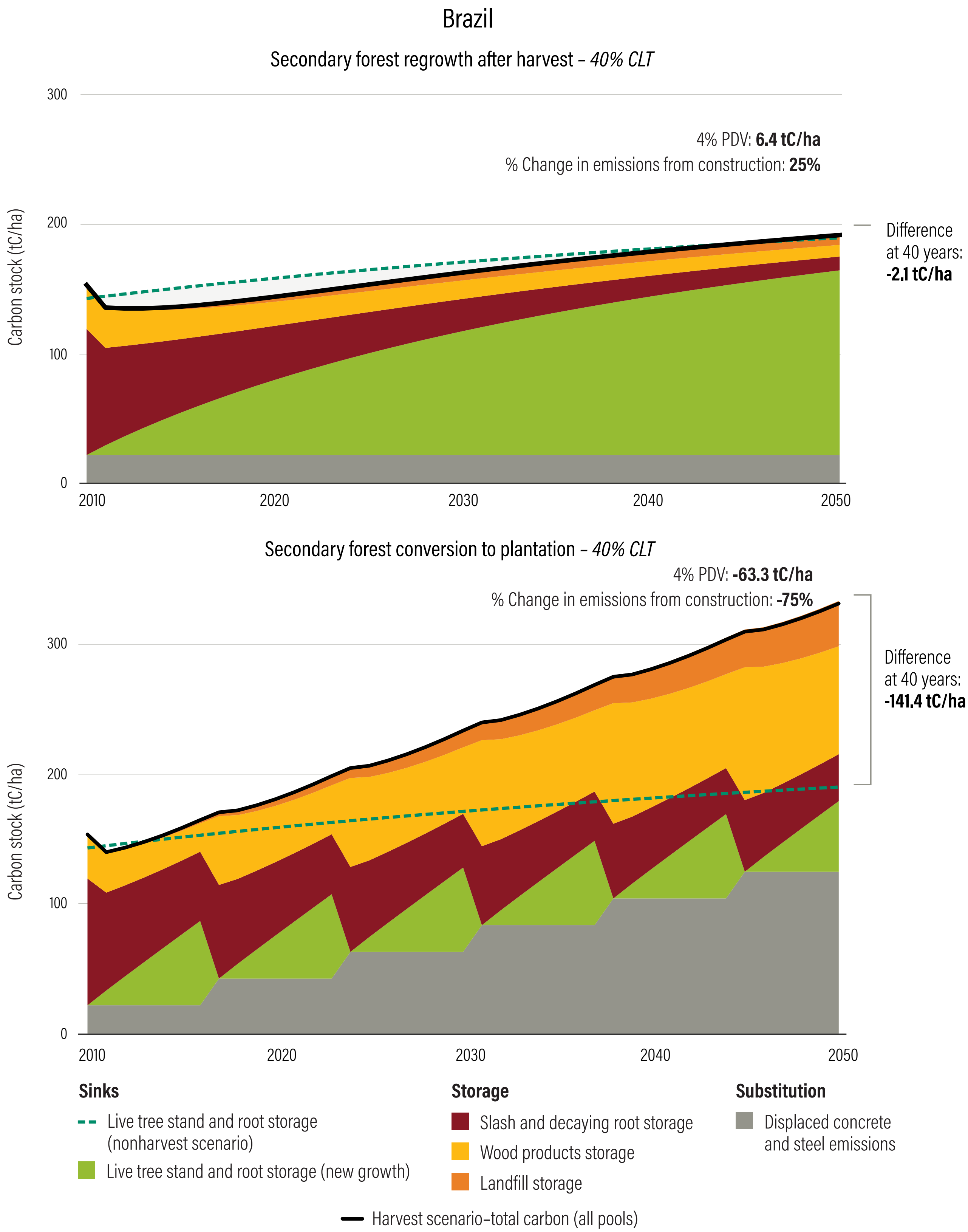
Figure 23 | Carbon Cost of Harvesting Forests in Germany



Note: PDV = present discount value. Positive carbon numbers mean increases in emissions while negative numbers mean decline in emissions.

Source: Carbon Harvest Model.

Figure 24 | Carbon Cost of Harvesting Forests in Brazil



Note: PDV = present discount value. Positive carbon numbers mean increases in emissions while negative numbers mean decline in emissions.

Source: Carbon Harvest Model.

Table 7 | Climate effects of harvesting wood for construction under different scenarios

SCENARIO	EXISTING WOOD USAGE			40% CLT			70% CLT			EXISTING WOOD USAGE			40% CLT			70% CLT		
SUBSTITUTION FACTOR	0.44 tC/tC									1.2 tC/tC								
DISCOUNT RATE	Carbon impact (tC/ha)		% change emissions	Carbon impact (tC/ha)		% change emissions	Carbon impact (tC/ha)		% change emissions	CCarbon impact (tC/ha)		% change emissions	Carbon impact (tC/ha)		% change emissions	Carbon impact (tC/ha)		% change emissions
	4%	No discount		4%	No discount		4%	No discount		4%	No discount		4%	No discount		4%	No discount	
U.S. Pacific Northwest Hemlock-Sitka spruce																		
Secondary forest and regrowth	125.4	140.7	+1,419	86.8	104.2	+235	46.5	65.1	+73	115.6	131.0	+622	46.1	63.5	+59	-24.3	-5.7	-18
Secondary forest and conversion to plantation	114.7	109.4	+1,299	76.2	72.9	+207	35.9	33.8	+56	105.0	99.7	+565	35.5	32.2	+46	-34.9	-37.0	-26
Existing plantation	78.9	66.0	+1,121	47.9	36.5	+162	15.2	4.7	+29	71.1	58.2	+480	15.2	3.8	+24	-42.0	-52.5	-39
U.S. Pacific Northwest Douglas Fir																		
Secondary forest and regrowth	150.0	177.3	+1,532	107.3	136.9	+263	62.6	93.6	+88	139.2	166.5	+676	62.1	91.7	+72	-15.9	15.1	-11
Secondary forest and conversion to plantation	135.7	142.1	+1,386	93.0	101.7	+228	48.3	58.4	+68	124.9	131.3	+606	47.8	56.6	+56	-30.2	-20.1	-20
Existing plantation	72.3	65.7	+1,101	43.4	38.2	+157	12.9	8.5	+27	65.0	58.4	+471	12.9	7.7	+22	-40.5	-44.9	-40
U.S. Southeast Oak-hickory																		
Secondary forest and regrowth	37.3	29.0	+898	19.2	11.8	+111	0.2	-6.5	+1	32.7	24.4	+374	0.0	-7.3	0	-33.0	-39.8	-52
Secondary forest and conversion to plantation	34.8	39.1	+709	13.3	12.8	+65	-9.3	-15.5	-26	29.4	32.3	+285	-9.4	-15.6	-22	-48.7	-65.0	-65
U.S. Southeast Loblolly-shortleaf pine																		
Existing plantation	16.2	9.6	+653	5.2	-6.2	+50	-6.4	-23.3	-35	13.5	5.6	+258	-6.3	-23.0	-29	-26.6	-52.6	-69
Brazil																		
Secondary forest and regrowth	34.0	23.9	+1,203	20.1	11.6	+162	8.2	0.7	+40	30.8	20.8	+519	6.4	-2.1	+25	-14.3	-21.8	-33
Secondary forest and conversion to plantation	26.1	15.4	+303	-19.0	−62.9	-47	-61.6	-139.6	-89	16.6	-1.2	+92	-63.3	-141.4	-75	-137.7	-275.6	-95
Existing plantation	-6.4	-9.6	-77	-50.5	−87.6	−128	-93.9	-165.5	-136	-15.5	-25.8	-89	-94.1	-165.4	-113	-107.2	-301.7	-117

Table 7 | Climate effects of harvesting wood for construction under different scenarios (cont.)

SCENARIO	EXISTING WOOD USAGE			40% CLT			70% CLT			EXISTING WOOD USAGE			40% CLT			70% CLT		
SUBSTITUTION FACTOR	0.44 tC/tC									1.2 tC/tC								
DISCOUNT RATE	Carbon impact (tC/ha)		% change emissions	Carbon impact (tC/ha)		% change emissions	Carbon impact (tC/ha)		% change emissions	Carbon impact (tC/ha)		% change emissions	Carbon impact (tC/ha)		% change emissions	Carbon impact (tC/ha)		% change emissions
	4%	No discount		4%	No discount		4%	No discount		4%	No discount		4%	No discount		4%	No discount	
Indonesia																		
Secondary forest and regrowth	25.3	16.2	+609	24.5	16.7	+269	16.1	9.2	+110	-20.7	-11.6	+237	14.4	6.6	+75	0.0	-6.9	0
Secondary forest and conversion to plantation	22.1	3.1	+182	17.6	-1.0	+61	-12.7	-55.6	-26	-8.7	20.2	+34	-14.3	-57.4	-24	-67.1	-152.8	-65
Existing plantation	-3.8	-18.7	-33	-9.0	-24.2	-32	-40.0	-79.9	-81	16.3	41.1	-68	-40.1	-79.8	−68	−94.6	−177.2	−91
Germany																		
Secondary forest and regrowth	60.5	68.6	+1,050	50.8	60.3	+231	27.6	39.0	+72	54.1	62.2	+447	26.5	36.0	+57	-14.7	-3.3	-18
Secondary forest and conversion to plantation	57.9	60.7	+1,005	48.2	52.5	+219	25.1	31.2	+65	51.6	54.4	+425	23.9	28.2	+51	-17.3	-11.1	-21
Existing plantation	61.0	58.1	+1,696	54.9	52.8	+395	40.1	39.2	+165	57.1	54.2	+754	39.6	37.5	+135	13.3	12.4	+26

Notes: Positive numbers show increases in emissions while negative numbers show reductions. Pink cells show results that are adverse for the climate while green cells show results that are beneficial for the climate.

Source: Carbon Harvest Model.

5.5 Sensitivity of Results to Different CLT Percentages and Substitution Factors

We analyzed additional scenarios to explore the significance of different substitution factors for concrete and steel. Analyses shown above use a substitution factor of 1.2 tC avoided per ton of carbon in wood based on a global meta-analysis of substitution coefficients (Leskinen et al. 2018). We then reanalyzed the results using an alternative substitution factor of 0.44 derived from data in Churkina et al. (2020), which is similar to estimates by Smyth et al. (2017).

The results are complex, but the basic lessons are as follows. In scenarios with existing wood uses, in which little wood goes to CLT, the substitution factor has only a small effect. In 40 percent and 70 percent CLT scenarios, however, the different substitution effects can be meaningful. For example, when converting a secondary forest to a loblolly pine plantation in the 40 percent CLT scenario, the different substitution effects change an 65 percent increase of emissions into a small reduction at 22 percent. And in the 70 percent CLT scenario, a reduction of 26 percent rises to 65 percent. This effect makes sense because the substitution value is of little importance if only a small percentage of wood is replacing concrete and steel, but it can have a bigger effect if a large percentage of wood is replacing concrete and steel.

5.6 Converting Agricultural Land to Plantations

One other option for supplying wood might come from converting agricultural land to wood plantations. Assuming land can be available for reforestation, we used CHARM to compare the climate benefits of establishing plantations and harvesting them for wood versus allowing secondary forests to regrow without harvests. Where we estimate that plantation growth rates are not significantly different from secondary forest growth rates, which are in the western United States and Germany, the better climate result is to support secondary growth. Where plantation growth rates are much higher, such as in the U.S. loblolly pine, Brazil, and Indonesia examples, the net effect of harvests is more beneficial than secondary forest regrowth. The reduction of emission with existing uses of wood is the largest in the U.S. loblolly pine example, and our 70 percent CLT examples have higher emissions reduction in Brazil and Indonesia (Table 8).

The critical additional question for these scenarios is under what conditions such a strategy would be beneficial. Unless agricultural land is declining globally—in contrast to the current situation in which agricultural land continues to expand—such strategies have a high risk of just shifting deforestation around, so that plantation development in one location leads to deforestation (and carbon costs) elsewhere.

Table 8 | Effects of establishing plantations on agricultural land relative to allowing secondary forests to regrow

SCENARIO	EXISTING WOOD USAGE			40% CLT			70% CLT			EXISTING WOOD USAGE			40% CLT			70% CLT		
SUBSTITUTION FACTOR	0.44 tC/tC									1.2 tC/tC								
	Carbon cost (tC/ha)		% change emissions	Carbon cost (tC/ha)		% change emissions	Carbon cost (tC/ha)		% change emissions	Carbon cost (tC/ha)		% change emissions	Carbon cost (tC/ha)		% change emissions	Carbon cost (tC/ha)		% change emissions
DISCOUNT RATE	4%	No discount		4%	No discount		4%	No discount		4%	No discount		4%	No discount		4%	No discount	
Agricultural land conversion to plantation																		
U.S. Southeast Loblolly-shortleaf pine	-1.3	4.2	-192	-4.4	-4.1	-153	-7.6	-13.0	-153	-2.0	2.2	-144	-7.5	-12.4	-125	-13.1	-27.7	-125
Brazil	-7.9	-8.4	-136	-39.1	-74.5	-141	-69.8	-140.4	-144	-14.3	-21.9	-117	-69.7	-139.3	-119	-123.4	-253.8	-121
Indonesia	-3.2	-13.1	-40	-6.9	-17.7	-35	-28.8	-64.8	-83	-12.0	-31.8	-71	-28.8	-64.0	-69	-67.2	-145.9	-92

Notes: Positive numbers show increases in emissions while negative numbers show reductions. Pink cells show results that are adverse for the climate while green cells show results that are beneficial for the climate.

Source: Carbon Harvest Model (assumptions set forth in Appendix A).

5.7 Summary and Lessons from This Analysis

Our analysis yields a few summary observations and related conclusions:

- **Similarity to other analyses:** In general, our analysis matches those of other researchers using the all-carbon-pools approach with net GHG costs.
- **Secondary forests and regrowth:** When harvesting secondary forests and allowing them to regrow, we find significant net increases in emissions when harvesting wood for construction if wood is used in typical proportions. That is also true if 40 percent of harvested wood can be used to replace concrete and steel. We only find small GHG savings in many forest types if 70 percent of harvested wood could be used to replace steel, and with a 1.2 substitution factor.
- **Slow plantations:** If plantation growth rates are not much faster than secondary forest growth rates, as in our Germany scenarios, harvesting additional wood even from plantations is either adverse or only achieves small percentage savings in our high-use (70 percent CLT) scenario.
- **Conversion to plantations; high plantation growth rates:** In scenarios that involve converting secondary forests to fast-growing plantations (typically in warm regions), we also find small percentage reductions. The exception is Brazil, where the reduction reaches 75 percent.
- **High savings percentage:** Our only scenarios that achieve high percentage savings for construction material, more than 60 percent, require three conditions: the 70 percent utilization rate, either use existing plantations or conversion to plantations, and high plantation growth rates, which only exist in warmer areas.
- **New plantations from agricultural land:** Where plantations are established on prior agricultural land, doing so would not generate savings unless the plantation growth rates are fast-growing and much higher than secondary forest growth.

Overall, our findings are consistent with those of the European Joint Research Centre for Europe. It reviewed the literature and concluded that at least for decades, increases in wood harvest to provide construction and other timber materials would cost more in lost carbon from forests than gained from material substitution (Grassi et al. 2021).

Our findings about fast-growing plantations in the tropics suggest that if and when the world is able to free up land currently used for agriculture, plantations for construction could become beneficial. At this time, however, there is no surplus of agricultural land to use for plantations. If land becomes surplus, the first need for plantations will likely be just to meet growing demand for wood for other purposes. There will also be other competing uses, including plantations for bioenergy with carbon capture and storage. In addition, there is a good chance that emissions from concrete and steel will decline over time due to the many opportunities for reducing their emissions. That would make the use of wood for construction less beneficial. If and when net agricultural land declines, careful analysis will be required of the competing benefits of alternative land uses based on the information that becomes available at such a fortunate future time.

6. Potential Solutions for the Global Competition for Land: Produce, Protect, Reduce, and Restore

Our review indicates a massive and growing demand for land to produce food and wood products and to accommodate growing urban areas. The potential land conversion between 2010 and 2050 numbers in the hundreds of millions of hectares even with robust agricultural yield growth, plus hundreds of millions of hectares to be harvested for forest products.

Our estimates of forest carbon loss by 2050 under BAU suggest around 10 $GtCO_2e$ per year. These carbon losses include at least 3 Gt from the annualized cost of forestry over a period of 40 years after harvest. Due to various accounting protocols, these carbon losses from forestry are typically not counted in global analyses, mostly because they represent avoided carbon sequestration; nonetheless, they are real costs of human activity.

At the same time, modeled pathways to keep climate change below 1.5°C nearly all call for eliminating emissions from land-use change, along with large-scale ecosystem restoration. Avoiding large-scale species extinctions requires restoring native habitats instead of clearing more. Balancing these conflicting land demands is essential to achieving several of the Sustainable Development Goals in tandem, including goals around hunger, human health, energy, forests and terrestrial ecosystems, and the climate.

6.1 What Are the Solutions?

In *Creating a Sustainable Food Future*, we explored these issues extensively while focusing on the challenge of feeding 10 billion people by 2050. Our analysis suggests that the solutions to managing the global competition for land for agriculture fall into four categories, which also apply to other drivers of land-use change (e.g., wood demand growth and urban expansion). These categories can be summarized as "produce, protect, reduce, and restore."

- **Produce** means to produce more land-based goods and services on the same land, including boosting agricultural productivity, increasing urban density, and producing more forest products per hectare affected while at the same time reducing GHG emissions and other environmental impacts.
- **Protect** means using these land-use efficiency gains to protect remaining forests and other native habitats.
- **Reduce** means reducing the demand for land and land-based products, such as reducing food loss and waste, shifting to plant-rich diets, and recycling paper.
- **Restore** means both improving damaged forests and habitats so that they provide the maximum benefits for climate and biodiversity and reforesting those agricultural lands that provide little food and have little improvement potential but that could be restored to healthy forests or other habitats. Over time, if agricultural land demand can be reduced even as the global population grows, larger restoration efforts become appropriate.

6.2 Produce and Reduce Strategies

Managing the global land squeeze requires reducing the pressure to convert more native habitats to human uses. That occurs partially by doing more to meet those human demands on existing land and partially by reducing the demand for products that require land, particularly those that require a great deal of land relative to their benefits. We refer to these types of solutions as produce and reduce. We discuss these solutions first for food and other agricultural products, from which we can borrow from *Creating a Sustainable Food Future*, and then address the growing demand for urban land and for forest products.

6.2.1 Food and agricultural products

In *Creating a Sustainable Food Future*, we developed a menu of different strategies (Figure 25) to implement produce, protect, reduce, and restore globally. Solutions to accelerate agricultural productivity growth beyond historical rates, further reducing agricultural land demand, include the following:

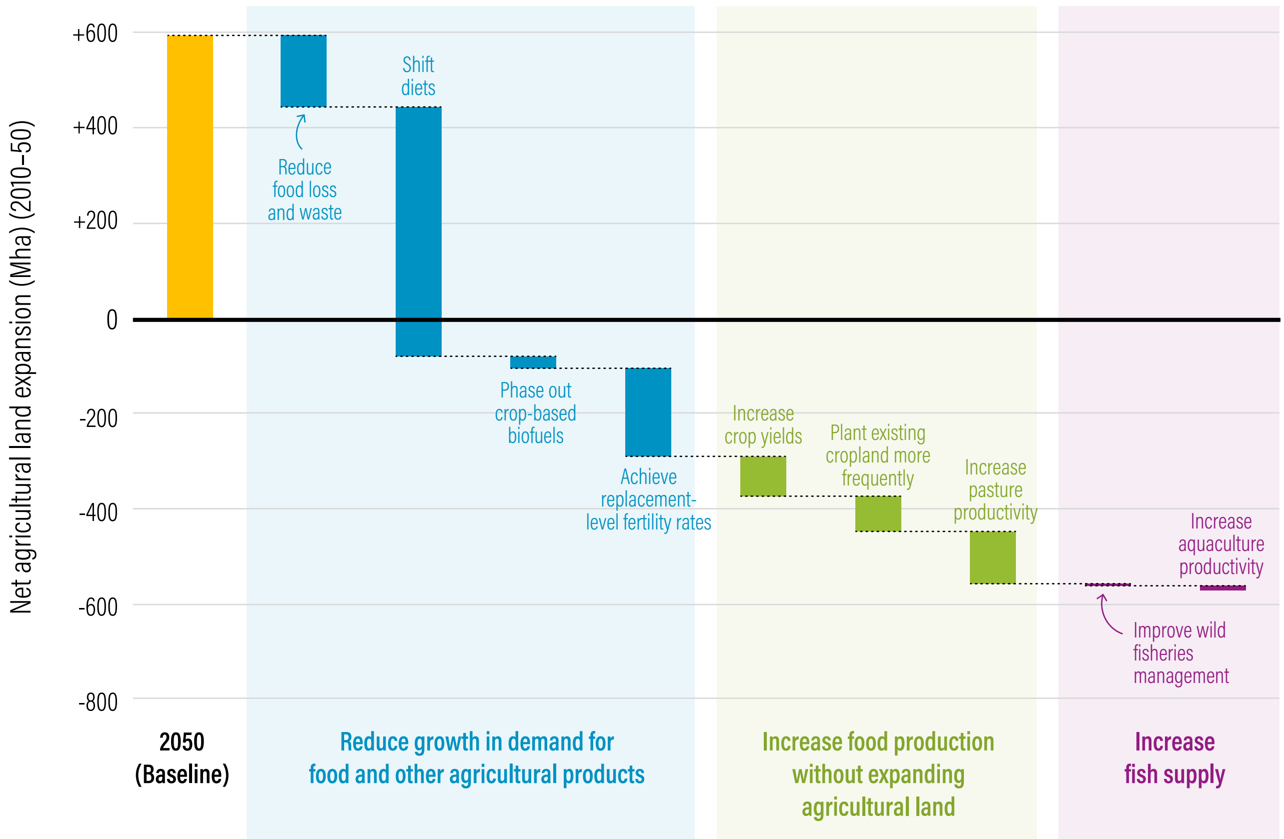
- **Increase livestock and pasture productivity.** Land-use requirements per kilogram of beef produced vary by a factor of 100 across all countries. That means there is great potential to improve performance of low-productivity systems, particularly across the tropics. Improved feeds (including pasture grasses), animal breeds, veterinary care, and grazing practices can all increase pasture productivity, helping to meet growing meat and milk demand while reducing pressure on forests.
- **Improve crop breeding to boost yields.** Crop breeding is responsible for roughly half of all historical yield gains. New technologies create new opportunities to accelerate yield gains while also adapting crop varieties to a changing climate.

- **Improve soil and water management.** Agroforestry, silvopasture, and rainwater harvesting can help revitalize degraded soils and boost yields in some areas, such as the African Sahel. Collectively, we estimate that accelerating crop yield gains through breeding and improved soil and water management could reduce agricultural land demand by 200 Mha.
- **Plant existing cropland more frequently.** More than 400 Mha of cropland go unharvested each year, whereas 150 Mha of cropland is planted twice or more each year (FAO 2020a). Increasing double cropping and decreasing fallow times can help reduce agricultural land demand. However, water constraints can limit such opportunities. Increasing cropping intensity by 5 percent beyond BAU could reduce agricultural land demand by around 70 Mha.
- **Sustainably increase fish supply.** Fish demand is projected to increase by nearly 60 percent between 2010 and 2050, but the global wild fish catch peaked during the 1990s. Improving wild fisheries management and raising the productivity and environmental performance of aquaculture can help meet growing fish demand while protecting marine fish stocks and reducing the land needed to grow crop-based aquaculture feeds by 14 Mha.

Several major strategies exist to reduce demand for agricultural land:

- **Reduce food loss and waste.** Roughly one-third of all food produced is lost or wasted between the farm and the fork (Gustavsson et al. 2011). Reducing food losses in developing countries would primarily occur through improvements to harvesting equipment, low-cost cooling and storage technologies, and improved infrastructure between farm and market. Reducing food waste in developed countries results primarily through "nudges" to consumer and corporate behavior, such as cafeterias without trays, and clearer distinctions between sell-by and use-by dates. Cutting overall food loss and waste by 50 percent could reduce land demand by more than 200 Mha.

Figure 25 | An extremely ambitious menu of food and agriculture solutions could theoretically reduce land demand by 800 Mha while feeding 10 billion people



Source: GlobAgri-WRR model in Searchinger et al. 2019.

- **Shift to healthier, more sustainable diets.** Per gram of edible protein, beef production uses 20 times the land as plant proteins such as beans. In countries with high meat consumption, shifting to more plant-rich diets can reduce per capita diet-related land use and "open up" planetary space for the world's poorer consumers to moderately increase their consumption of animal-based foods. Limiting consumption of beef and other ruminant meats to no more than 1.5 burgers per person per week in all regions could reduce land demand by around 500 Mha relative to BAU.

- **Phase out crop-based biofuels.** As discussed in Section 4, dedicating land to bioenergy production is an inefficient way to produce energy and increases the food production challenge and overall GHG emissions. Instead of increasing biofuel mandates and targets, governments should instead phase them out and only source bioenergy from wastes and residues. Doing so would reduce agricultural land demand by 24 Mha and, perhaps even more importantly, avoid any additional land demands from further expansion of biofuel policies.

Some advocates for bioenergy claim that increased demand for land is permissible because people can turn to "marginal land." However, although some of these lands might be called “marginal,” their improvement already is built into these “produce” strategies and, as discussed in Box 7, cannot justify deliberately increasing the global demand for land for bioenergy or other products.

- **Achieve replacement-level fertility rates.** Expected population growth of nearly 3 billion people between 2010 and 2050 drives the majority of the projected food demand increase (and is a key driver of increases in wood demand and urban expansion as well). If all world regions reached replacement-level fertility by 2050 (i.e., 2.1 children born per woman), the population would only grow to 9.3 billion by midcentury. Experience from all world regions shows that a combination of strategies (increasing educational opportunities for girls, increasing access to reproductive health services, and reducing infant and child mortality) has led to voluntary reductions in fertility rates. Rapid reductions in fertility also can play a major role in helping developing countries start a period of sustained economic growth because a much larger share of the population is of working age. A cobenefit of these important health and education measures is a reduction in agricultural land demand of 180 Mha relative to BAU.

BOX 7 | Can "Marginal" Land Justify Policies That Increase Demand for Land?

It has become common for papers to claim that desired additional land uses, such as for bioenergy, forest products, meat consumption, or lower-yield agriculture, are possible because they can just use "marginal" land or, if they use agricultural land, agriculture can just expand into marginal land. In its report *Creating a Sustainable Food Future* (Chapters 7, 17, and 19), the World Resources Institute reviewed these claims and found, in effect, that large areas of potentially productive, essentially unused land do not exist and, in any event, that all potentially productive land has a high opportunity cost and is not free to use to meet policy-induced increases in demand.[a]

As reviewed in that report, there are certainly lands that are underperforming, including some with soils that have become physically degraded in one way or another. But these lands are nearly all still in some use. Some are agricultural lands that are or will become abandoned and revert to forests, sequestering carbon. Others will remain in agricultural use, but their improvement is one of the core means of meeting rising human demands for food and fiber without clearing more native habitats. They are therefore not "free" to meet additional human demands beyond what is already expected under business as usual.

As discussed in *Creating a Sustainable Food Future*, several categories of land have frequently been referred to as marginal or degraded. Sometimes, the term is applied to broad estimates by experts of the percentage of agricultural lands that they consider to be suffering from some level of soil degradation.[b] Often the term is applied to large portions of the world's grazing lands—if they are viewed as marginal for cropping—but it ignores their use to meet human demands for ruminant meat and milk. Sometimes the term is applied to abandoned agricultural land, ignoring the fact that the reforestation of abandoned cropland plays a critical role in holding down net deforestation.[c] Sometimes maps of marginal land are created by overlaying maps that seek to estimate lands with good and bad cropping potential over maps of agricultural land. Unfortunately, there are likely to be large errors in each of these maps, so when one is overlaid with another, some good agricultural lands will appear to be in fact marginal. The result can be maps that declare vast areas of agricultural land as marginal, including some of the better agricultural land in the United States.[d]

Other papers try to define marginal lands based on economic returns, treating land as marginal for one use if it could be more profitable in another use. (Khanna et al. [2021] summarizes these papers and one approach). This approach ignores the cost in lost carbon of replacing any forgone food production. Land can have relatively low financial value if its food can be replaced relatively cheaply somewhere else. One reason for that is because it is relatively cheap to replace the food by converting forest or other land to agriculture; thus, using this land may be cheap financially, but not from a carbon perspective.

There have also been suggestions that land that comes in and out of farm production should be deemed marginal. But much of this type of land is in rotation and is typically farmed that way for reasons such as the need to fallow it at times to replenish nutrients or water. Unless this type of land would be replaced by land not in rotation, using it for a new purpose will not lead to more efficient land use. Some of this land is also the farmland that tends to be farmed when prices are high but not when prices are low. In the future, prices will almost certainly continue to fluctuate because of weather patterns or other vagaries. Using this land for additional purposes will just require that additional land be brought into production in occasional years. Moreover, finding ways to farm land more frequently, increasing its so-called cropping intensity, is already an important strategy to meet rising food needs without expanding agricultural land, so using only occasionally farmed land for purposes other than meeting rising food demands reduces the potential to achieve this goal.

Another common pattern is to identify low-yielding tropical grazing land as marginal, and there is strong evidence that much grazing land in Latin America could be greatly improved and support much higher yields.[e] But as discussed elsewhere in this report, vast increases in yields on these lands are already required to meet rising demands for ruminant meat and milk. Some are likely also sufficiently degraded, or unimprovable, that their best use is to be restored as natural habitat, and maybe even some could be appropriately used as forest plantations to help meet rising wood supply. And if some combination of yield gains and demand reductions could reduce the need for such pastures in the future, these are the lands whose reforestation is most typically identified in papers about "nature-based solutions" to climate change.[f]

The key point is that even being degraded or marginal in these ways does not make these lands "free" in the sense of lacking an opportunity cost. These lands are already needed to meet rising demands for food, for wood to use to sequester carbon, and to restore biodiversity in native landscapes. They are not free to use to meet additional demands created by policymakers, such as for bioenergy, except at the cost of not being available to help meet all these other rising demands.

Sources: a. Searchinger et al. 2019; b. Gibbs and Salmon 2015; c. Smeets 2008; d. Cai et al. 2011; e. Strassburg et al. 2014; f. Griscom et al. 2017.

6.2.2 Urban expansion

The world's urban areas are growing not merely because of population growth but also because their density is declining. Rates of urban land expansion are exceeding rates of population growth in every region. Between 1990 and 2015, one study found that urban densities in developed countries were declining at a 1.5 percent annual rate and by 2.1 percent in less developed countries (Mahendra and Seto 2019). Another paper found that in Europe, China, India, and North America, declining population densities caused 12.5 Mha of additional land to be converted to urban uses between 1970 and 2010 (Güneralp et al. 2020).

Even so, both the overall density of cities and growth patterns vary widely, and the cities that use the most land per inhabitant are in the wealthiest regions. Asian cities average between 10,000 and 20,000 people per square kilometer. Latin American cities use twice as much space per person, European cities use 3 times as much space, and U.S. cities use 10 times as much. An extensive literature has found that expanding housing in this way is gratuitously expensive and often results in large areas without adequate services and lengthy commutes that are expensive in personal time and social interactions. One report estimated that promoting denser growth patterns by 2050 could save $17 trillion (Global Commission on the Economy and Climate 2018).

Several WRI reports explore the challenge of promoting denser, more livable cities (e.g., Mason 2017). As emphasized in "Upward and Outward Growth: Managing Urban Expansion for More Equitable Cities in the Global South" (Mahendra and Seto 2019), the solutions involve not merely encouraging density but doing so in equitable ways with adequate services and other amenities. The literature on urban sprawl identifies several areas for reform. There are four core tools: infrastructure funding, land-use regulations, taxes and other financial incentives, and property rights. Recommendations include the following:

- Reform distorted land markets that encourage inefficient speculation by regularizing informal land titles and reforming a variety of policies that otherwise allow displacement of poor, peri-urban communities and inefficient expansion.
- Use land-use regulations, financial incentives, and infrastructure development to encourage compact development with adequate services, integrating where people live and eat with where they work.
- Create public-private partnerships for development in targeted areas.

6.2.3 Wood demand

In part because of the flawed accounting regarding forest carbon in previous studies (as described in Sections 3–4), we are aware of no thorough analysis of a global strategy for reducing likely future impacts on forests and their carbon. As a whole, the evidence supports a "produce and reduce" strategy for addressing growing demand for forest products.

Reducing wood demand has value even if increased demand for wood causes forest owners to manage forests more intensively or to establish more plantations because those land uses still compete with other land uses. More intensive management sacrifices biodiversity. Increased plantation forests come at the expense of using land for food production, natural forests, or other biodiversity needs. Although improved management may be one way to meet wood demand with fewer environmental effects, that does not mean that more forest harvesting is better than less harvesting.

Several strategies exist to reduce the demand to harvest more wood while still meeting human needs, and we address these "reduce" strategies first.

Increase the efficiency of wood processing. Although the percentages vary, we estimate from FAO data that roughly 40 percent of industrial roundwood intended for sawn wood, wood-based panels, and paper and paperboard is burned as some kind of waste without getting into one of those products. This estimate is uncertain because some FAO data are inconsistent. But the estimate is consistent with general technological estimates that around half of wood used for wood pulp is burned as a waste and half of wood sent to sawmills is not used, although much of that sawmill waste can be used for wood-based panels or wood pulp (FAO et al. 2020). Over the last several decades, improvements have been made that allow more of the wood harvest to be used for timber products. There is undoubtedly some continuing potential to increase efficiencies in wood use, and these more efficient uses should be encouraged.

Recycle and reuse wood. The effort to reduce demand for forest products is reflected in global paper recycling. Advanced through government policies, recycling rates for used paper have grown greatly. According to a company that closely tracks the global forest industry, recycling rates reached 47 percent in 2012. In Europe, paper recycling increased from 40 percent in 1981 to 72 percent in 2019 (Recovery Worldwide 2019). Recycling rates are roughly 70 percent in the United States and 80 percent in Japan (EPA 2017).

Paper recycling has disproportionate benefits beyond the percentage recycled. It takes less carbon from recycled paper to produce one ton of pulp than raw wood (because the lignin in raw wood cannot be used). And because most recycled fiber can then be used again, the net savings can continue. Overall, paper fibers are used on average 3.6 times in Europe and 5–7 times in the United States, and the global average is 2.4 times (EPA 2016; Recovery Worldwide 2019).

Recycling rates in developed countries cannot grow endlessly. Fibers cannot be endlessly reused, and most paper products require some virgin fiber; likewise, some paper (such as tissues) cannot be safely recycled. Globally, however, there remains significant room to increase both recycling overall and the percentage of that recycled paper used for paper. Even in countries such as the United States, much of the paper is not reused for paper production but for other products.

In addition to recycling, the potential also exists to reuse more solid wood. For example, Höglmeier et al. (2013) found that in southeastern Germany, one-third of the wood from old buildings could be recycled into high-value products, but only a small amount was being used in this way. There are also creative ideas to turn wood waste into composite that can replace some cement (Berger et al. 2020).

Use wood products more efficiently. When wood consumption is replaced by a nonwood product, the net results are complex, as our analysis of construction timber suggests. But one way to reduce wood consumption is merely to reduce the quantity of wood used for a given purpose. The switch to computers has substantially reduced the demand for true paper, including newsprint. But printing and writing paper, which is still 30 percent of pulp and paper consumption, contains on average only 8 percent recycled paper content (Martin and Haggith 2018). Reductions in its use are therefore disproportionately valuable.

In part because of flawed [carbon] accounting … we are aware of no thorough analysis of a global strategy for reducing likely future impacts [of wood demand] on forests and their carbon. As a whole, the evidence supports a "produce and reduce" strategy for addressing growing demand for forest products as well.

Packaging is now 60 percent of all global paper and paperboard use (FAO 2020a), and there are numerous examples of companies reducing the quantity used for each package. The Environmental Paper Network (Martin and Haggith 2018) gives the example of Hewlett Packard, which redesigned its printer packaging to reduce the volume of material by 90 percent.

Reduce the use of fuelwood. As discussed earlier, the additional harvest of wood to burn for energy increases emissions for decades even when it replaces coal in industrial power plants and heating facilities. A goal should be to burn wood products only as a last resort in the use of processing wastes and not to harvest wood intentionally for direct energy use. In the developed world, the increased use of wood is being driven by climate-motivated laws that treat biomass as being carbon neutral (Searchinger, Beringer, et al. 2018). Critical reforms are needed to properly account for the carbon from harvesting wood (as discussed in Section 4 of this report) and to develop additional simple rules, such as prohibiting incentives for the use of stem wood.

Even today, most fuelwood is used for traditional stoves and charcoal production in developing countries. This traditional use is particularly inefficient because open wood burning only directs a portion of its energy into heating food and because charcoal production is inherently inefficient. There have been a large number of initiatives to replace open fires with cookstoves, in large part because of health benefits, which have had mixed success (Sedighi and Salarian 2017; Suresh et al. 2016).

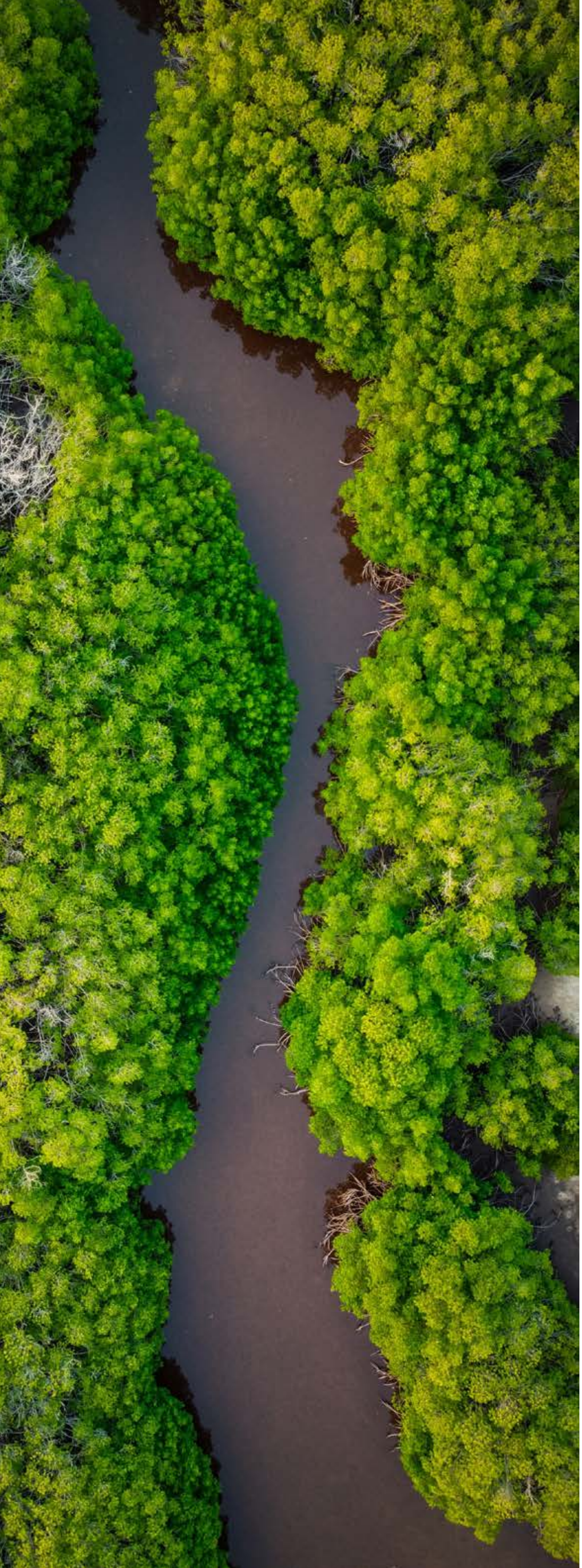
Overall, the degree of reliance on wood in developing countries appears to be closely correlated with the affordability and access to alternative energy sources. One important variable is the alternatives to biomass in rural areas of Africa that are not served by central electricity. A primary alternative involves a combination of solar cells and batteries. Electricity, of course, has additional benefits beyond cooking. Showing both the opportunity and limitations, one study estimated that roughly one-third of rural residents in Africa could afford electricity and would find solar cells and battery options cheaper than diesel generators (Szabó et al. 2021). That level of penetration would be significant, but another study finds even greater potential if batteries continue their declining costs (Batchelor et al. 2018). In general, efforts to promote decentralized rural electricity appear to have significant promise for reducing wood demand in the next several decades.

Beyond these strategies to reduce growth in wood demand, the principal alternatives involve more efficient production. These "produce" strategies are listed below. The options fall into two major categories: more efficient harvest or more efficient growth.

Harvest wood more efficiently. As wood is harvested, much is left behind as slash. Some of that slash is from the tops and branches of trees, and it generally constitutes around 30 percent of natural wood harvests. Other slash consists of small trees and other vegetation that is killed in the process of harvesting the wood. Harvesting is particularly inefficient in the tropics. A number of studies have estimated losses in the tropics, and a recent review in Ellis et al. (2019) estimated that, on average, for every 1.0 tC removed from the forest, 5.7 tC in wood are felled and left to decompose. The paper estimated that reducing that ratio of lost wood to 2.3-to-1.0 would reflect best practices and reduce 366 million tCO_2 per year. (These are gross emissions reductions and are not counted in our time-discounting way.)

In temperate forests, clear-cuts (either large or small) are a more significant mechanism for forest harvest, and slash rates are lower in clear-cuts. There are also benefits to some level of slash; for example, leaving slash behind in a forest helps provide habitat benefits. In addition, slash is generally left because it is not economical to remove it. Whether greater removal of slash is advisable requires closer analysis of these different costs and benefits.

Grow more trees on farms to supply fuelwood. One question is whether increased growing of trees on farms can become a larger source of fuelwood without reducing agricultural production. In India, some studies have estimated that trees on farms provide two-thirds of the fuelwood (Singh et al. 2021). In general, the



idea is that growing trees on field borders or in degraded or nonproductive parts of farms can provide additional benefits without sacrificing food production. Although that is not always the case (Ivezić et al. 2021), some forest buffers can enhance yields by blocking wind (Osorio et al. 2019), shading livestock in hot countries, or increasing nitrogen-uptake in the case of nitrogen-fixing trees as discussed in *Creating a Sustainable Food Future*. A variety of options exist for farmer-assisted natural regeneration, such as excluding cattle from certain areas. Just planting more trees in farms is not an automatic solution, as it can displace food production, but it should be pursued where it can be done in ways that preserve or enhance food production.

Rely more on plantations with more intensive management. The other major option is to shift more and more wood production to plantations. This shift is already a major global trend (McEwan et al. 2020). The basic reason is that plantations can deliver more wood per hectare per year. Plantations produce straight trees that can be harvested more efficiently. They can use new varieties of trees that are bred to grow faster. And they can use fundamentally fast-growing trees, such as species of eucalyptus, acacia, and bamboo, and plant them in place of slower-growing trees.

The advantage of plantations has also been growing. The most intensively managed eucalyptus plantations in Brazil can generate three to four times the aboveground biomass growth rate even of regenerating tropical forests. Brazil's plantation growth rate is 6.1 tons of carbon (tC) per hectare per year, and its secondary forest growth rate ranges from 1.2 tC/ha/year for mature forests to 3.7 tC/ha/yr for young forests (Harris et al. 2021). In the southeastern United States, the growth rates for intensively managed loblolly pine trees have been consistently increasing (Ince 2000).

Although plantations come with this advantage, they have other high costs, as discussed elsewhere in this report. Biodiversity is much lower in plantations than in natural forests. More intensive management nearly always means even shorter rotations, less wood in any form other than the intended trees, and ever lower biodiversity. Plantations can use so much water that they draw out streams and other water supplies (Hoogar et al. 2019; Trabucco et al. 2008). Plantation forests are also a prime driver of peatland drainage, occupying an estimated 12 Mha—roughly one-third of drained peatlands globally (Biancalani and Avagyan 2014). This use suggests that plantations located in drained peatlands are responsible for more than 300 million tons of ongoing carbon dioxide emissions per year based on global estimates of peatland loss rates (Biancalani and Avagyan 2014; Searchinger et al. 2019).

From a carbon standpoint, our analysis shows that shifting to plantations would reduce carbon costs in many areas. This is particularly true if the shift would be to highly managed, intensive plantations. The prevailing view is that shifting to intensive plantations would also have large biodiversity benefits if doing so resulted in leaving natural forests alone (Burivalova et al. 2014), particularly intact forests (Betts et al. 2017). However, we are unaware of any rigorous analyses to support that view, which suggests an important direction for future research.

The benefits of shifting to plantations obviously depend on several factors, including where the plantations are located. The spread of acacia plantations in peatlands in Southeast Asia is an example of the extreme damage to both climate and biodiversity that forest plantations can create, so improving siting of new plantations is critical. Even when plantations are established on prior agricultural land, as the experience in China illustrates, these plantations can be part of an overall global dynamic in which food production shifts and leads to the clearing of natural forests elsewhere. And any biodiversity benefits are only realized if greater plantation use means leaving other forests undisturbed.

From a purely biophysical standpoint, the potential benefits of using intensive forest plantations to replace natural tropical wood harvests are likely to be high. One reason is that typical tropical forestry operations now kill around 4.5 times as much aboveground wood as they harvest (Ellis et al. 2019), whereas plantation harvests are much more efficient and result in much lower damage to trees. Perhaps even more importantly, the indirect effects of road building and forest clearing in tropical forests on both carbon and biodiversity are vast, with carbon impacts sometimes estimated at 6 times that of direct effects (Maxwell et al. 2019).

We estimate that industrial wood harvesting that occurs over time in hundreds of millions of hectares of tropical secondary and primary forests produces only around 14 percent of the global wood harvest. From the standpoint of sheer volumes of wood, that 14 percent could be replaced by only 6.1 Mha of additional tropical plantations (author calculations using CHARM). Yet harvests of tropical forests focus on quantity as well as quality, seeking valuable hardwoods. It seems likely that plantations can help save natural forests from being harvested, but getting good governance in place is likely to be important as well.

Most environmental public policy related to tropical forests has been based on the concept of sustainable forest harvesting with reduced-impact logging. Changing forest protection strategies by shifting away from trying to make harvests of natural tropical forests sustainable in favor of relying on plantations would be a significant policy shift. One key issue would be compensating local people the potential income from logging in primary and secondary forests, which could be a good use of funding intended to compensate for forest protection in low-income countries. Another key issue is establishing the enforcement mechanisms to protect forests, which is complicated by the failure by most governments to fully recognize customary property rights of those who live in forests (Notess et al. 2018). A third issue, more related to wood supply, is to replace these natural tropical hardwoods by a combination of technologies to make quality furniture from other woods, and through tropical hardwood plantations, such as teak. A full-scale analysis of realistic, comprehensive strategies to reduce the carbon and biodiversity costs of meeting wood product demand remains to be performed.

Avoid creating new wood demands. This challenge of meeting rising wood demand under BAU creates the challenging context of adding demand for mass timber for construction. For the reasons articulated in our discussions of mass timber, our results are generally skeptical about the potential climate benefits of mass timber for three reasons. First, the conditions for significant climate benefits are limited and nearly all require more wood plantations. Second, the potential GHG emissions reductions from replacing concrete and steel with wood can be greatly reduced if progress is made in reducing emissions from concrete and steel. And finally, given growing demands for wood and land-based products overall, the first use of additional plantations should be to meet rising demands for wood.

6.3 Protect and Restore Strategies

Uses of land are driven not only by the demand for land but also by its "supply." The demand for land is based on the demand for food and agricultural products, forest products, and urban uses. The supply of land refers to the overall cost of using land for these purposes, which reflects such factors as legal restrictions and physical infrastructure such as roads. If governments make it easy to clear more forests, for example by building roads, the incentives to produce more food on the same land will decrease, undermining efforts to increase yields.

Efforts by themselves both to increase production on the same land and to reduce demand also can have rebound effects. If increased yields reduce the cost of producing a food—which depends on the causes of that yield increase—prices will decline, and people may consume more. If so, cropland area may not decline as much as without the price effect. In *Creating a Sustainable Food Future*, we explained why this price effect should generally not be a concern. This is partially because food consumption is inelastic and responds in a limited way to price, so increasing efficiency and reducing prices will generally have a limited effect on food consumption. And it is also true because achieving global food security requires providing adequate food for even the poorest consumers, who are the most responsive to food prices. But evidence shows that beef consumption is more responsive to price effects, probably involving trade-offs and substitution with other livestock products. Without efforts to limit land expansion, it is therefore possible that many of the land-use reductions expected from more land-efficient beef production could be erased by higher beef consumption.

Disproportionate increases in agricultural yields in regions that have abundant forests and productive savannas could also encourage global shifts in locations of agricultural land. For example, once Brazil and Argentina developed ways of growing soybeans with yields similar to those in the United States, they became more competitive globally and could sell more soybeans to China and Europe. That phenomenon led to an expansion of soybean area in Latin America. This shifting in agricultural land location increases the land that can be reforested in wealthier countries but at a disproportionate cost in both carbon and biodiversity through new land clearing in the tropics.

6.3.1 Protecting native habitats

Because of these challenges, efforts to boost yields must be closely linked to efforts to protect native landscapes. Linking "produce and protect" can mean specific conditions, such as those enacted previously in Brazil that restrict agricultural credit to farmers or municipalities that comply with forest protection legislation. Wealthier countries can also increase their agricultural assistance, or provide favorable trade rules, to those countries that protect forests. International food companies should not only avoid purchasing food produced on recently deforested land but also actively work with their supplying farmers to boost yields enough to avoid contributing to global land expansion.

6.3.2 Regulating forestry

Protect strategies also apply to forest products. As in the case of food, just reducing demand alone is unlikely to fully protect forests, and strategies to protect them are also necessary. Protection strategies (when coupled with demand strategies) can make it harder to harvest wood, pushing for strategies to better harvest and use other wood resources. Protection strategies can also help avoid the most harmful and wasteful forms of harvesting.

International efforts for decades have focused on governance, prohibiting illegal wood harvests. Doing so is important both to enable any governance strategies to succeed and because illegal wood harvests are the most likely to be done in harmful and wasteful ways (Barber and Canby 2018). Another important strategy is securing community land rights, which is not only critical to be fair to indigenous communities and other rural people but can lead to greater forest protection (Veit 2019). As WRI has discussed elsewhere, governments have mechanisms for recognizing such rights but have been far too limited in doing so.

6.3.3 Restoring forests, peatlands, and other high-priority habitats

Efforts to restore forests and other habitats are also important. These efforts fall into two categories: those that should occur immediately, and those that can only occur if success in "produce and protect" strategies reduce the demand for agricultural land.

Forests in urban areas, which have modest overall benefits for the climate but provide a variety of other health and social benefits, have some potential for improvement. Opportunities exist to restore trees on farm boundaries and within agricultural fields in silvopastoral and other agroforestry systems that not only do not reduce food production but can sometimes enhance it (Montagnini et al. 2013). Some studies have also claimed a significant potential to restore forests on lands that are neither forests nor agricultural lands (Fargione et al. 2018). Such studies typically rely on overlaying different remote-sensed maps and would benefit from actual surveys of field conditions to determine present uses.

Degraded habitats in protected areas, such as parks and wildlife areas, need to be better protected and restored. These are areas intended to serve natural purposes, but there is abundant evidence that many are degraded and invaded (Dasgupta 2017; Laurance et al. 2012).

Some agricultural areas are not only marginal for food production but also face strong limits to their improvement, such as the low-productivity pastures located on high slopes in parts of Brazil dominated by the Atlantic Forest. The likely carbon sequestration benefits of reforestation in the area exceed the carbon costs of any reduced food production (Searchinger, Wirsenius, et al. 2018).

Larger-scale restoration is an important climate change strategy, but doing so can only occur if the world is able to free up agricultural land by the methods we describe above (e.g., boosting productivity, reducing food demand growth). Several papers claim vast restoration potential without addressing the challenge of reducing agricultural land demand. Bastin et al. (2019), for example, prominently estimated a large potential to mitigate climate change by restoring forests, but they did so mainly by identifying pasture that was historically forested—even though the paper claims to have excluded all "agricultural land." Such an analysis implicitly treats vast parts of the world's agricultural land as though it is not producing food that would otherwise need to be produced elsewhere. Griscom et al. (2017) also relied primarily on reforesting such lands and made only brief citations to papers that claim some potential to increase pasture output and reduce demand for beef. Overall, the world's ability to protect its remaining natural ecosystems and restore ecosystems at the scale needed to keep warming below 1.5°C is closely linked to and dependent on its ability to implement "produce" and "reduce" strategies at unprecedented (though theoretically possible) scales.

7. Conclusion and Key Takeaways

The world is facing a land squeeze as the global population grows to 10 billion people by 2050, incomes rise, and people move to cities. BAU projections involve massive increases in land-use demands and associated losses of carbon that would put the global goal of limiting temperature rise to 1.5°C out of reach.

Many climate strategies that involve land ignore this global land-use competition and focus only on localized analyses that ignore system-wide effects of new uses of land-based products. Even analyses that use global models often hide adverse effects in their results, such as reductions in food consumption by the poor to compensate for additional uses of land by the rich (e.g., bioenergy). Some assume that yield gains can compensate for increased demand for land for other nonfood uses, even though those same yield gains are already required to meet rising food and wood product demands without further deforestation.

There is potential to improve the use of many lands, but no land use is "free." All land capable of growing plants well has a high carbon opportunity cost (the carbon potentially stored in native vegetation), which should be factored into analyses of carbon benefits and costs of alternative land uses. For example, planting tropical forest plantations on existing grazing land might be a carbon-efficient way of using that land, but that land is not currently free for the taking, especially in a world with a growing population and food demands. Large increases in meat output per hectare and major dietary shifts are probably needed to free up such lands.

Our analysis casts serious doubt about any potential policy that would spur additional land demands above and beyond BAU demands for food, wood, and urban areas. Strategies focused on increased bioenergy and wood use for construction have nearly always been justified by climate analyses that treat biomass as "carbon neutral," meaning that they neither count the loss of carbon in forests and other terrestrial vegetation nor count the release of carbon when this biomass is burned or decomposes. The potential for such policies to intensify land-use competition is also vast. Strategies for supplying 20 percent of the world's energy from bioenergy would require doubling the harvest of plant material on top of all the additional uses of plants and land discussed in this report. Producing 50 percent of new urban construction with wood would likely require more than a 50 percent increase in uses of industrial roundwood. These levels of competition, along with the vast competition already inherent just from rising incomes and population, pose enormous challenges for both the climate and biodiversity.

Our analysis also shows that "sustainable forest management," as conventionally understood, does not mean that wood use is carbon neutral or that using wood in construction in place of concrete and steel necessarily provides a net climate benefit. Harvesting wood comes with a time-discounted cost in lost carbon in the forest. The climate benefits of harvesting wood include the storage of some of that forest carbon elsewhere and avoided emissions from other carbon-intensive products such as concrete and steel. But the climate costs are reduced storage of carbon in the forest.

According to our analysis, large net climate benefits from wood harvesting probably require that a high percentage of this wood is used to replace concrete and steel in construction—perhaps at levels not realistic—and that the wood come from or be associated with the establishment of fast-growing forest plantations. If these plantations come at the expense of natural forests, they would have high biodiversity costs. In the future, plantations to produce wood for construction might be established on agricultural land that is no longer necessary for food, but those uses should be evaluated against other demands for land, including ecosystem restoration, bioenergy, or using the same plantations to meet other rising demands for wood products.

There are possible technical strategies to feed and house 10 billion people by 2050 while halting deforestation and making land available for forest restoration or other uses. Scenarios that achieve these goals are highly ambitious and their success uncertain, requiring unprecedented growth in agricultural productivity and changes in food consumption patterns. In general, our analysis suggests that it is not appropriate to enact policies to spur increased demand for land-based products (e.g., wood for construction) until strategies to meet BAU food and wood demands without further land clearing have been proved successful.

APPENDIX A: CHARM: DESCRIPTION AND METHODS

CHARM is a biophysical accounting model developed for this report that provides two outputs: the estimated land area requirements to meet wood demands and the estimated GHG implications of meeting those demands, both of which can vary according to different methods of growing, harvesting, and using wood. The model can be used at the forest-stand level to analyze the GHG consequences over time of different forest growth patterns, harvests, wood use, and forest regrowth. The model can also be used to estimate national and global land-use and GHG consequences of meeting different levels and types of different wood product supply and demand scenarios in the future. The model is designed to be transparent, so that it is easy to evaluate alternative scenarios and the effect of different parameters and assumptions. The principal version of the model runs in Python using input files from Excel.

Land requirements are defined as the area of plantation and of nonplantation forests harvested over a given time period of focus, which initially is between 2010 and 2050. We chose 2010 as our base year to be compatible with the agricultural modeling results of the World Resources Report *Creating a Sustainable Food Future*. The present version of the model uses an optimistic assumption that all forests harvested will be from secondary forests rather than primary forests, which are typically more carbon dense. To estimate land-use requirements to meet wood product demand, the model starts by segregating wood product demand into three broad categories: LLPs, which are essentially wood for construction and furniture; SLPs, which are paper and paperboard products; and VSLPs, which are various forms of bioenergy. The model starts with existing wood sources and demands as of 2010. Demands for different wood products are aggregated into total wood demands by country (using factors that translate each ton of a wood product into a ton of industrial roundwood harvested that accounts for processing losses.) Wood supply each year is met based on the average wood supply available per hectare in that year. In the scenarios analyzed to date, the model separates wood supplied by existing plantation forests and wood supplied by secondary forests, each based on their harvest efficiencies and growth rates.

To estimate land-use requirements, the model assumes that all harvesting is achieved through at least small clear-cuts. (The model also allows for thinning of forests, but that is done on the same lands as those ultimately harvested and therefore does not increase harvest area counted.) The clear-cut assumption increases the wood harvest per hectare and therefore reduces the area affected by harvest. In the tropics, in particular, most nonplantation forest harvests occur selectively. However, there are problems of definition between selective harvests and miniature clear-cuts as well as uncertainties about the quantities of wood removed by different logging techniques. These uncertainties make it challenging to provide a precise estimate of area affected. The area of land use calculated by CHARM should therefore be viewed as hectares of clear-cut equivalent (i.e., the hectares that must be harvested assuming all hectares affected are clear-cut). One hectare counted by the model might, in reality, be several hectares selectively harvested.

The model also estimates the GHG consequences of meeting wood demands, and it does so both at the stand level and by analyzing the effects of harvests to meet future demands at the national and global levels. To estimate the effects on GHGs, the model tracks the flow of carbon between pools, following a basic approach employed by models developed during the 1990s, most prominently by Schlamadinger and Marland (1996). At the stand level, the model can be used to analyze any type of forest for any type of purpose with readily changeable parameters. At the national and global level, the model uses information about each country's forests and assumes that wood demand will first be met by plantations to the extent available and that secondary forests will be harvested for the remainder. The model tracks the carbon consequences of harvesting these forests under allocation and regrowth management rules specified by the scenario. When estimating future production, the model assumes that existing global trade patterns remain the same. For example, if timber-importing countries increase their demand, the model assumes that imports will grow proportionately and that exporting countries will proportionately increase their exports to meet this increasing demand.

A.1 Basic Model Structure

A.1.1 Establishing the 2010 reference for wood demand and use

CHARM starts with 2010 numbers by country for consumption and production of different wood products and harvest levels using data from FAOSTAT (FAO 2021). Based on the relationship between wood harvests and different wood uses, the model can estimate how harvest quantities in each country must change in response to changes in consumption of different categories of wood products. As demand changes over time, the version of CHARM used in this report keeps trade balances constant. For example, if a country imports 20 percent of its wood in 2010, the model assumes it will do so in 2050, and exporting countries will change their exports in response to meet import demands in proportion to their share of global exports.

Figure 10 re-creates the flow of wood harvests to wood products. Global roundwood harvests in FAOSTAT are divided into two major categories: industrial roundwood (FAOSTAT item code 1865) and wood fuel (1864). Industrial roundwood itself falls into three categories: generally larger logs that are sawn into timber or peeled to provide veneer, typically called "sawlogs and veneer logs" (1868); generally smaller logs harvested for paper, particleboard, and paperboard (e.g., cardboard), called "pulpwood" (1870 and 2038); and "other industrial roundwood" (1871) that is used for poles, piling, posts, fencing, wood wool, tanning, distillation and match blocks, and so forth. FAOSTAT always reports the production quantities for the above categories, but not all of them have import/export quantities reported. Most of the time, only the two major categories, industrial roundwood and wood fuel, have both production and trade flow records.

The wood harvests provide the raw materials for manufactured forest products. Sawlogs and veneer logs are processed in sawmills and are then turned into sawn wood (1872) and plywood (1640). The production of sawlogs generates wood chips and particles and wood residues (1619), some of which are used for particleboard (1697), OSB (1606) and fiberboard (1874), and some are used for pulp production or are burned for energy. Pulpwood is primarily used for wood pulp (1875), and some of it is also used for particleboard and fiberboard. Wood pulp comes from pulpwood and wood residues from sawlogs, and it is used for about 40 percent of the raw materials for paper and paperboard (1876), where the remaining 60 percent is from recovered paper (1669) and other pulp (1668). In other words, both sawlogs and pulpwood can be used for particleboard, OSB, fiberboard, and wood pulp. Wood-based panels (1873), a commonly used aggregated primary forest product, are the sum of particleboard, OSB, fiberboard, and plywood. Wood chips and particles and wood residues (1619) exclude the chips in the production of pulp, particleboard, fiberboard, as well as chips counted as pulpwood, wood fuel, and other industrial roundwood.

In summary, sawlogs, veneer logs, and pulpwood are turned into sawn wood (SNW), wood-based panels (WBP), and wood pulp (WPL). We define these as main industrial roundwood (IND-M) products. Industrial roundwood (IND) is the sum of main industrial roundwood and other industrial roundwood (IND-O). Table A1 lists the main FAOSTAT items we use to calculate wood demand (consumption). In country *N (N = 1 ... 176)* at year *T*, we first calculated net exports by subtracting imports from exports. If exports or imports is missing from the data for a country, then net exports is set to "missing" and is not counted. We then calculated consumption by subtracting the net exports from production. If both production and net exports are missing, consumption is set to "missing" and is not counted. If either production or net exports is missing, consumption is set to "production" or "net imports" (– net exports), assuming the missing element is a gap filled by zero.

Closing the material balance using FAOSTAT requires significant effort. We first convert the units when the items are not in cubic meter solid volume. The unit of wood pulp or paper is converted from metric tons (10 percent moisture content) to cubic meters using a conversion factor (= 1.87 m^3/ton):

$$CF = \frac{1 - MC_w}{\rho_b}$$

MC_W is the 10 percent moisture content and is the global average wood basic density 0.48 tons/m^3 derived from the FAO forestry products conversion guideline. Second, we identify whether there is missing data in other industrial roundwood, then we calculate other industrial roundwood using industrial roundwood minus the sum of sawlogs and veneer logs and pulpwood. If other industrial roundwood and either sawlogs and veneer logs or pulpwood are missing, then other industrial roundwood is set to zero. Third, we implement two tests of data quality for industrial roundwood at the country level. If a country in a given year does not pass either of the following criteria, we set the records as missing for all industrial roundwood products in this country: industrial roundwood supply and the consumption of wood products (sawn wood, wood-based panels, wood pulp) should be positive and/or total sawlogs domestic use (production minus net exports) should be greater than sawn wood production. Last, we set the quantity elements (production, consumption, net exports) for paper and paperboard or wood fuel as missing if its consumption is negative.

Wood products require much more roundwood than the actual quantity of the products. The production of industrial roundwood such as pulping and sawing, generates wood waste. Determining the amount of industrial waste is important for estimating the immediate carbon emissions for burning. We first checked reported

Table A1 | FAOSTAT items and elements

COUNTRY *N* IN YEAR *T*	INDUSTRIAL ROUNDWOOD (IND)	SAWNWOOD (SNW)	WOOD-BASED PANELS (WBP)	WOOD PULP (WPL)	OTHER INDUSTRIAL ROUNDWOOD (IND-O)	WOOD FUEL (WFL)
Production	Y	Y	Y	Y	Y	C
Net exports	Y	Y	Y	Y	-	-
Consumption	C	C	C	C	C	-

Notes: The data directly from FAOSTAT are labeled "Y," the statistics derived or calculated are labeled "C," and the unavailable or not required ones are labeled "-."

Source: Description of data sources used in Carbon Harvest Model.

conversion factors, such as the input-to-output ratio and the yield. The pulp yield is fairly stable. Based on the FAO forestry products conversion guideline, the global average input-to-output ratio for pulp is 3.58 m^3/ton, and the pulp weight to solid volume conversion factor is 1.87 m^3/ton (see above). The pulp waste in solid volume per ton of wood pulp becomes 3.58 – 1.87 = 1.71 m^3/ton, so the waste to roundwood percentage is 1.71/3.58 = 48 percent. In other words, around half of roundwood devoted to wood pulp is burned for energy use as waste. Similarly, the global average input-to-output ratio of other industrial roundwood is 1.4 m^3/m^3, which means about 29 percent of the other industrial roundwood is wasted.

For sawn waste, there is not enough reliable information to use that data directly from another source. We therefore developed a material balance approach to estimate the global and national industrial waste from pulping and sawing. Although FAOSTAT does not provide the data directly, we can derive them because the industrial roundwood domestic use (production plus imports minus exports) should be balanced by the sum of the production of sawn wood, wood-based panels, wood pulp, other industrial roundwood, the pulp waste that is estimated above, and sawn waste (Figure 10).

We calculate the actual pulp and sawn (PS) waste ratio in each country:

$$\textit{PS waste ratio} = \frac{C_{IND} - P_{IND\text{-}O} - P_{SNW} - P_{WBP} - P_{WPL}}{C_{IND} - P_{IND\text{-}O}} = 1 - \frac{\textit{IND-M}}{\textit{IND-PS}}$$

where C_{IND} is the domestic use of industrial roundwood (production plus imports minus exports); $P_{IND\text{-}O}$ is the production of other industrial roundwood; $C_{IND} - P_{IND\text{-}O}$ is defined as industrial roundwood used for pulping and sawing *IND-PS*; P_{SNW} , P_{WBP} and P_{WPL} are the production of sawn wood, wood-based panels, and wood pulp; and the sum of the three is defined as the main industrial roundwood product *IND-M*. We gather all the records during the baseline period from 176 countries that have valid records and then derive the distribution of the PS waste ratio. We observed an average at about 48 percent between 2006 and 2014, and a standard deviation at about 22 percent. This estimate allows us to define hard boundaries for the waste percentage in each country.

We set a waste ratio minimum (10 percent) and maximum (70 percent) to determine whether a country has an excessive surplus or excessive deficit of industrial roundwood supply, which is likely the result of inaccurate wood accounting. If the PS waste ratio is negative (such as in China and Japan), the country does not have enough industrial roundwood supply. If the PS waste ratio is less than 10 percent, the efficiency is too high to be true. If the PS waste ratio is greater than 70 percent, the country may have excessive industrial roundwood supply, as the efficiency is too low. To adjust these unrealistic country-level imbalances, we cap the PS waste ratio to between 0.1 and 0.7. Therefore, we can invert the required quantity of IND-PS′:

$$\textit{IND-PS} = \begin{cases} \frac{\textit{IND-M}}{1-0.7}, & \text{PS waste ratio} > 0.1 \\ C_{IND} - P_{IND\text{-}O}, & 0.1 \le \text{PS waste ratio} \le 0.7, \\ \frac{\textit{IND-M}}{1-0.1}, & \text{PS waste ratio} < 0.1 \end{cases}$$

When the PS waste ratio is less than 0.1, IND-PS′ – IND-PS is defined as the additional consumption (additional production or imports) required for the country. When the PS waste ratio is greater than 0.7, IND-PS′ – IND-PS is defined as the reduced consumption (additional exports) for the country to supply the need from the countries without deficits. There are three groups of countries regarding their waste ratios: Group 1 has reasonable waste (no adjustment needed, IND-PS′ – IND-PS = 0), Group 2 has too much waste (IND-PS′ – IND-PS < 0), and Group 3 does not have enough waste (IND-PS′ – IND-PS > 0).

The first step is to adjust the net exports of the "net importer" countries (net exports < 0). For countries (e.g., China, Japan) that do not have enough waste (IND-PS′ – IND-PS > 0), net exports will increase by the additional waste (IND-PS′ – IND-PS). For countries (e.g., India) that have too much waste (IND-PS′ – IND-PS < 0), we remove the extra waste from the net exports (IND-PS′ – IND-PS < 0). After the first step, we calculate the world total industrial roundwood net exports, which need to be balanced by the exports from the "net exporter" countries. We then update the national net exports and redefine the net importer and net exporter countries.

The second step is to adjust the net exporter countries (net exports > 0). The goal is to meet the world total industrial roundwood net exports by adjusting the net exports in the three groups of countries and to adjust the PS waste ratio in Groups 2 and 3 by adjusting the (production – net exports). We assume that Group 3's net exports should not increase because they already have a wood deficit. Therefore, to adjust the PS waste ratio, we only change their production. Group 1's PS waste ratio should not change; therefore, Group 1's net exports and production will increase at the same quantity. (Production – net exports) of Group 2 will be reduced, so net exports must increase, and production may change or may not change. We calculate the total net exports in Groups 1 and 2 and then calculate the net export share among these countries. The shares of net exporter countries are used to increase their net exports and meet the world total industrial roundwood net exports. After that, we adjust the production of the three groups so that their PS waste ratios range from 0.1 to 0.7.

The above procedures create an adjusted FAOSTAT database for the nine-year period of 2006–14 that has reasonable national PS waste ratios and consistent production and consumption numbers. CHARM determines emissions based on the half-lives of wood products. Therefore, we define three major categories: LLPs, which are uses of wood for construction and furniture and other long-term uses; SLPs, which are various paper products; and VSLPs, which are essentially uses of wood for energy (Table 2). The LLP category includes solid wood products such as sawn wood, wood-based panels, and other industrial roundwood uses (IND-O, about 71 percent of other industrial roundwood). The SLP category consists only of wood pulp, which is directly related to pulpwood or sawlog wood harvests. The VSLP category includes two subcategories: wood fuel (VSLP-WFL) and industrial waste (VSLP-IND). Industrial waste (VSLP-IND) also includes two groups: pulp and sawn waste and other industrial roundwood waste (VSLP-IND-O, about 29 percent of other industrial roundwood). For our 2010 reference, we calculate the national averages for LLPs, SLPs, and VSLPs in cubic meters. Each one has production, net exports, and consumption. They can be converted to dry matter tons by multiplying the global average wood basic density 0.48 tons/m^3.

A.1.2 Projecting Future Demand

Future wood harvests are based on projections of future world wood demand. Wood harvesting has been rising, driven by increased consumption. Wood consumption is highly driven by income and population growth.

For our projection of wood products consumption, we selected sawn wood (SNW), wood-based panels (WBP), paper and paperboard (PPB), and wood fuel (WFL). This is because their consumptions are directly driven by socioeconomic factors and have statistics that can be tracked through trade. (Items such as wood pulp, other industrial roundwood, and industrial waste do not have trade statistics.)

The historical socioeconomic statistics include GDP and population from the World Bank for 1961–2020 (World Bank n.d.a). We use projected growth percentages between 2010 and 2050 for GDP per capita and population. GDP per capita growth is derived from three sources. The first is the ENV-Growth model SSP2 ("middle of the road") by the Organisation for Economic Co-operation and Development (OECD; Dellink et al. 2017); the second is the International Institute for Applied Systems Analysis (IIASA) model SSP2 (Cuaresma et al. 2017); and the last one is based on recent historical (between 1991 and 2010) trend line linear extrapolation, hereafter called LINE. The projections from OECD and IIASA are in constant 2005$ and can be converted to match the World Bank unit in constant 2010$ with an inflation rate of 1.12.[24] Population is based on the UN projection under the medium-fertility variant scenario. All the future projections are divided by their own 2010 estimates (not the same as the World Bank 2010 reference) to obtain the growth percentages.

A preliminary regression analysis shows that industrial roundwood consumption generally has significant positive relationships with GDP per capita. However, wood consumption varies with socioeconomic factors (e.g., demographics, income levels, technology) and also varies significantly between countries, apparently influenced by the availability of wood. For example, countries such as Sweden and the United States, which have abundant forests, use far more wood than Spain and Romania, which have few forests. We therefore used a fixed effects (FE) model (Wooldridge 2001) and reported the projections of wood demand for each country, each product category, and each scenario from 2015 to 2050. Trend lines of wood consumption implicitly factor in relationships between demand and supply because all of those demand and supply interactions were occurring in the past. The FE model applies the same relationship of wood consumption to each country's per capita income growth but starts with each country's initial wood consumption. The FE model helps represent the persistent differences that are caused by the specific properties in the countries and are not related to the GDP per capita, such as the total area of natural forest. Extrapolating the trend lines to the future has the disadvantage of assuming the future will be the same as the past and ignoring lots of other factors that might change demand for any one type of product. However, this is the best guess because the past relationships (parameters) between wood demand and its drivers are not clearly known, and even if they were, these relationships can also change in the future.

Although wood consumption has a generally positive relationship with GDP per capita, some high-income countries, such as Australia, Canada, Japan, and the United States, saw decreases in their historical per capita consumption of sawn wood, wood-based panels, and paper and paperboard consumption as their GDP per capita grew beyond certain levels. We therefore separated the countries into developed and developing countries to avoid overestimating future wood consumption in high-income countries. We used a threshold of US$40,000 for sawnwood and wood-based panels, and a threshold of US$12,000 for paper, paperboard, and fuelwood. We choose $12,000 for paper and paperboard and wood fuel because the threshold for high-income countries is $12,615 by the UN definition. For sawn wood and wood-based panels, we found that $40,000 is a better threshold for model fitting to group the responses of wood consumption to GDP and population.

In each FE regression model, we have dependent variable wood consumption and multiple predictor variables. We use two types of formulas: one only depending on the GDP and population, and the other one including the effect of development and policy change after 2000. We select the year 2000 because the transitions of wood consumption growth in many countries occur around 2000, when the internet usage boom started and modified paper needs. The wood consumption is log transformed (natural), and two predictor variables, GDP per capita and population, are log transformed.

$$\log(W_{it}) = \alpha_i + \beta_1 \log(G_{it}) + \beta_2 \log(P_{it})$$

$$\log(W_{it}) = \alpha_i + \beta_1 \log(G_{it}) + \beta_2 \log(P_{it}) + \beta_3 Y_t^n + \beta_4 Y_t^s$$

W is the wood consumption per capita of each product type (tons per capita), and G is GDP per capita (US$ per capita). The index i refers to the country, and t refers to a data point in time, meaning year = 1961, ..., 2017 in this study. The expression α_i, $i = 1, ..., n$, can be understood as the unobserved time-invariant heterogeneities across the countries $i=1, ..., n$. These individual specific intercepts are considered the fixed effects of countries. Y_t^n is the number of years since 1961, and Y_t^s is the number of years after a shifting technology takes place. Holding the variables related to time trends constant, the ratio of wood consumption between two countries (W_1/W_2) equals the ratio of GDP per capita (G_1/G_2) to the power of

β_1, multiplying the ratio of population *(P_1/P_2)* to the power of β_2. It tells us that if the ratios of GDP per capita and population remain the same, the ratio of wood consumption stays the same too. Otherwise, the combined effects of GDP per capita and population on wood consumption are no longer linear. The variables related to years are not log transformed because they have zero values. We can say that for a one-year increase in the number of years since 1961, it is expected to see ($\exp(\beta_3)-1$) increase in wood consumption.

In summary, we establish 12 relationships ("models") based on three different types of wood products, two different trend lines in developed and developing countries, and two different regression formulas. The FE model parameters β_1, β_2, β_3, and β_4 and goodness of fit are estimated by the ordinary least squares regression model with *n - 1* dummy regressors using the R packages "lm" and "lfe." We obtained an output of a global slope for each model and individual α_i for each country i. All the models have high R^2 full (> 0.88) and significant P values (< 0.05) and have a residual standard error (RSE) between 0.32 and 0.84 (Table A2). R^2 full is the typical R^2 between all pairs of FE-predicted values and original values. For the FE model, another goodness of fit R^2 projection is also considered, which means how much of the variation in the dependent variable for each country is captured by the model. R^2 projection is expected to be small. Paper and paperboard per capita has the highest R^2 projection, and wood fuel per capita has the lowest R^2 projection, which means the time trend cannot explain the variations of wood fuel very well. The FE models have good predicting power in developed countries for sawn wood, wood-based panels, and paper and paperboard and in developing countries for wood fuel (RSE < 0.4).

Table A2 | FE Model Statistics

MODEL	COUNTRY GROUP	COUNTRY NUMBER	R^2 FULL	R^2 FULL ADJ	R^2 PROJ	R^2 PROJ ADJ	RSE
log(SNW_WBP) ~ log(GDP_pcap) + log(POP) + NYEAR + NYEARS	GDP per cap > $40,000	29	0.98	0.98	0.33	0.31	0.32
	GDP per cap < $40,000	166	0.88	0.88	0.28	0.26	0.83
log(PPB) ~ log(GDP_pcap) + log(POP) + NYEAR + NYEARS	GDP per cap > $12,000	67	0.98	0.98	0.65	0.64	0.39
	GDP per cap < $12,000	121	0.92	0.92	0.57	0.56	0.82
log(WFL) ~ log(GDP_pcap) + log(POP) + NYEAR + NYEARS	GDP per cap > $12,000	64	0.95	0.95	0.10	0.08	0.65
	GDP per cap < $12,000	119	0.98	0.98	0.19	0.17	0.40
log(SNW_WBP) ~ log(GDP_pcap) + log(POP)	GDP per cap > $40,000	29	0.98	0.98	0.28	0.26	0.33
	GDP per cap < $40,000	166	0.88	0.88	0.27	0.25	0.84
log(PPB) ~ log(GDP_pcap) + log(POP)	GDP per cap > $12,000	67	0.98	0.98	0.63	0.62	0.40
	GDP per cap < $12,000	121	0.92	0.92	0.57	0.56	0.83
log(WFL) ~ log(GDP_pcap) + log(POP)	GDP per cap > $12,000	64	0.95	0.94	0.04	0.02	0.68
	GDP per cap < $12,000	119	0.98	0.98	0.18	0.17	0.40

Notes: adj = adjusted; GDP = gross domestic product; proj = projection; RSE = residual standard error.

Source: Authors' calculations.

We interpreted these as indicative relationships. In theory, the quantity of wood use could drive GDP growth rather than the other way around, but because wood consumption is a small part of overall GDP growth, that is unlikely. And even if both wood use and per capita income were driven by a third, unknown factor related to both, per capita income growth could still be a good predictor of future wood use.

Based on the coefficients for the models with the time effect, we can derive the wood consumption in the 2010 reference year and the 2050 projected year as follows:

$$\log (W_{i,t=2010}) = \alpha_i + \beta_1 \log (G_{i,t=2010}) + \beta_2 \log (P_{i,t=2010}) + \beta_3 (2010-1961) + \beta_4 (2010-2000)$$

$$\log (W_{i,t=2050}) = \alpha_i + \beta_1 \log (G_{i,t=2050}) + \beta_2 \log (P_{i,t=2050}) + \beta_3 (2050-1961) + \beta_4 (2050-2000)$$

Subtracting wood consumption in 2010 from 2050 leads to

$$\log \left(\frac{W_{i,t=2050}}{W_{i,t=2010}}\right) = \quad \beta_1 \log \left(\frac{G_{i,t=2050}}{G_{i,t=2010}}\right) = \quad \beta_2 \log \left(\frac{P_{i,t=2050}}{P_{i,t=2010}}\right) \quad + (\beta_3 + \beta_4)(2010-2000)$$

$W_{i,t=2010}$ is the 2010 reference wood consumption, which is the 2006–2014 average of the annual wood consumption. $\frac{G_{i,t=2050}}{G_{i,t=2010}}$ is the ratio of GDP per capita between 2050 and 2010, and $\frac{P_{i,t=2050}}{P_{i,t=2010}}$ is the ratio of population between 2050 and 2010 from the United Nations. The 2050 wood consumption in each country is derived from the above formula for three GDP per capita projection models (OECD, IIASA, and LINE) and for two regions (developed and developing). Similarly, the 2050 wood consumption for the models excluding time effect can be derived as this simplified formula:

$$\log\left(\frac{W_{i,t=2050}}{W_{i,t=2010}}\right) = \beta_1 \log\left(\frac{G_{i,t=2050}}{G_{i,t=2010}}\right) + \beta_2 \log\left(\frac{P_{i,t=2050}}{P_{i,t=2010}}\right) = \log \left(\left(\frac{G_{i,t=2050}}{G_{i,t=2010}}\right)^{\beta_1} \left(\frac{P_{i,t=2050}}{P_{i,t=2010}}\right)^{\beta_2} \right)$$

GDP per capita from the complex model projections are dramatically high in developing countries, and the GDP per capita from the simple linear model may be too low in developed countries. To avoid the unrealistic overestimation of future wood consumption, we first apply a cap to the developing countries' wood consumption per capita using the 75th percentile of the developed countries' wood consumption per capita in 2050. After capping the developing countries, we further filter the unlikely high wood consumption per capita that has more than a 10-fold increase between 2010 and 2050. Then we obtain the intermediate prediction by applying equal weights to the results based on complex models (OECD/IIASA) and recent linear extrapolation (LINE). In other words, the weights for OECD, IIASA, and LINE are 0.25, 0.25, and 0.5, respectively.

Considering the combination of matching FAOSTAT recent trends and higher R^2, for sawn wood and wood-based panels, we selected the regression formula with the time effect for developed regions and without the time effect for developing regions; for paper and paperboard, we selected the regression formula with the time effect for both regions. For wood fuel, we calculate the average between the two formulas in developing countries. In developed countries, we use the formula excluding time effect for wood fuel because the recent increasing trend in wood fuel is related to short-term policy and should not be built into the model for long-term projection. Finally, we obtain the average national growth percentages from 2010 to 2050 for the three wood products.

A.1.3 Estimating Future Production

We apply the growth percentages of sawn wood and wood-based panels, paper and paperboard, and wood fuel to consumption of LLPs-M (main), SLPs (wood pulp), and VSLPs-WFL. We keep the LLPs-O (other) unchanged between 2010 and 2050 because there are no available trade statistics for other industrial roundwood and we cannot assume LLPs-O grow at the same rate as LLPs-M. Note that this can underestimate the real wood demand. We keep wood pulp growing at the similar rate as paper and paperboard, assuming that the ration of wood pulp to paper remains unchanged between 2010 and 2050.

The results of this FE model are the consumption of each wood product category in 2050. However, the inputs for CHARM are the amount of wood production. To predict the production in 2050 for CHARM inputs, we assume the trade balances in 2050 are the same as the 2010 reference. We first split the countries in 2010 into net importers (net imports < 0) and net exporters (net exports > 0). For net importers, we calculate the import percentages (net imports/consumption) and apply these percentages to the 2050 consumption to get 2050 net exports. For example, if a country imports 20 percent of its wood in 2010, the model assumes it will do so in 2050. After that, we calculate the 2050 world total net exports (= sum of world total net imports). For net exporters, we calculate the 2010 export shares of global exports (net exports/world total net exports) for each country. We adjust the 2050 net exports of these countries in response to match the 2050 world total net exports in proportion to their share of global exports. Finally, we derive the 2050 production using 2050 consumption and 2050 net exports for both net importers and net exporters.

For other industrial roundwood, LLP-O and VSLP-IND-O 2050 production remains the same as 2010 production. To estimate industrial wood waste (VSLP-IND-M) production in 2050, we calculate the ratio of VSLP-IND-M to IND-M. Then we calculate the difference of IND-M 2050 and IND-M 2010, and then apply the ratio to this difference and get the additional waste (VSLP-IND-M 2050 – VSLP-IND-M 2010). At the end, we get the total VSLP-IND 2050 production by adding up VSLP-IND-M 2050 and VSLP-IND-O 2050. We then sort the country-level results by 2010 production from greatest to least and use the top 20 percent of countries across the three product categories. This gives us a list of 30 countries that accounted for 80 percent of global wood production in 2010.

A.1.4 Conceptual explanation of land-use calculation

The land area requirements for the model are calculated at the national and global levels. Demand for different types of wood products per year is provided as an input, converted into roundwood equivalents, and then used to estimate wood harvest. Wood is supplied from one of two sources, plantation forests and secondary forests, each with its own efficiencies of wood harvested. Wood supply from plantation forests is used first, with remaining forest supplied by secondary forests.

To estimate wood supplied by secondary forests, the forest types in each country are characterized by their aboveground growth rates, areas, and some other characteristics, and a composite national-level forest type is created by the weighted average of the secondary forests. (The result is mathematically equivalent to allocating wood harvests to each separate forest type based on its percentage area.) Wood supply from each hectare is provided by this national-average forest based on the percentage of aboveground wood harvested that makes it into a product pool while the remainder is left as slash. Although slash rates can be altered in the model, in our scenarios presently used, slash rates for developed countries are based on U.S. calculations of average slash rates for nonplantation forests, and for tropical countries, slash rates are based on estimated average slash rates by Ellis et al. (2019).

Natural forest carbon stocks at time of harvest can be varied. For our present scenarios, we assume that only secondary forests will be harvested, and they are harvested at least after 40 years or 20 years growth after reaching the national average aboveground carbon stock.

For plantation forests, initial wood supply in 2010 is based on the area of planted forest estimated by the FAO divided by the estimated average rotation length. For example, if the rotation length is 10 years, then a 10th of the plantation forest is estimated to be available in 2010 and in subsequent years. Plantation slash rates are established separately. Plantation forests can also be thinned, with some of the wood harvested in this way available for SLPs or VSLPs.

Different scenarios allow plantation areas to evolve over time according to different rules. For example, in one scenario, new plantations come from agricultural land. In another, secondary forests are converted to plantation forests as secondary forests are harvested. Because plantation forests need to grow before they can supply wood, the supply from plantation forests can be constrained. The model estimates the potential supply of wood from plantation forests each year between 2010 and 2050 and allocates the remainder of the supply to secondary forests. Model results for each country include the total area of plantation forests that will be established in 2050 and the total hectares of harvests of secondary forests that must occur between 2010 and 2050 to meet wood product demands.

Wood demand and supply is estimated for the world's top 30 wood-producing countries because of the higher quality of data available for those countries. Together, these countries made up around 80 percent of the world's wood production in 2010. For the global calculations, the full 100 percent wood demand is allocated to these 30 countries. Supply is met from within the country based on its share of demand produced internally, and imports are met proportionately by exporting countries. We divide the areas by 0.8 to generate global estimates, which assumes that the remaining 20 percent would be met with a harvest efficiency equal to the average of the other 80 percent.

A.1.5 Mathematical description of land area calculation

For each scenario, we calculate the total number of hectares required for harvesting every year from 2010 to 2050. To do this, we first calculate the total amount of each product required every year in each product pool (LLP, SLP, VSLP) using the formula below:

For each product pool *j* in year *i*,

$$T_{i,j} = T_{i,j-1} + r$$

where *i* is the year in the range of 2011–50, *T* is the tons of dry matter of a product type *j* produced in year *i* (the dry matter in product pool j in the year 2010 is calculated based on the ratio of LLP:SLP:VSLP in the 2010 baseline), and *r* is the annual proportion of increased demand calculated as

$$r = \frac{T_{2050} - T_{2010}}{2050 - 2010}$$

We then convert the total tons of dry matter in all product pools into tons of carbon based on the assumption that dry matter is 50 percent carbon.

We assume that there is a maximum number of plantation hectares that may be harvested such that all hectares are harvested over the course of a single rotation period. For example, if a country has an average rotation period of 10 years, every hectare may be harvested four times over 40 years, and no more than 10 percent of managed forests may be harvested each year.

For countries where there is a large area of plantation forest, and supply for a given year is less than the maximum production capacity from plantation hectares, the number of hectares harvested is scaled down accordingly to eliminate any surplus. For example, if a country with a rotation period of 10 years can harvest up to 100 ha every year with a capacity of 1,000 tC in products per year, but the supply needed in a certain year is only 900 tC, then the model would only simulate the harvest of 90 ha. If the supply needed is 1,100 tC, then 100 ha of plantation would be harvested, and the rest of the wood would come from secondary forests.

After calculating the amount of wood supplied from plantation forests in a given year, we determine the number of secondary forest hectares required if all supply is not met from the first or subsequent harvest of plantations:

$$area = \frac{T_c}{\text{AGB}}$$

where *AGB* is the amount of aboveground biomass that makes it into a product pool in units of tons of carbon per hectare of secondary forest, and T_C is the remaining amount of carbon required that is not supplied by plantation forests.

The sum of the area required every year from 2010 to 2050 is the total area harvested in the period of analysis.

A.1.6 Conceptual description of carbon calculation

The carbon implications of forest harvests are based on a comparison of two scenarios: a "harvest" scenario, which measures the total carbon stocks in various carbon pools, and a "nonharvest" scenario, which measures the carbon stocks in the unharvested forest, also known as a counterfactual. For unharvested forests, the carbon stock includes all live vegetation carbon, which varies by age. If a secondary forest is not harvested, it will continue to grow up to a maximum carbon density. If a forest is harvested, the carbon that was live is allocated each year to different pools, such as residues and roots left in the forest and wood used for the three product types (LLP, SLP, and VSLP). Carbon in most pools declines over time, some decaying directly into the air, some being burned for energy, and some being put into landfills, from which further decay occurs either as carbon dioxide or as methane. The allocation of wood to different pools and decay rates are established as model inputs and can vary by forest type. For the live vegetation pool, because clear-cuts are assumed, the pool is eliminated in the first year of harvest. But this pool regrows over time according to growth rates specified for that forest type in each country. Table A3 describes the pools.

Our model assumes that all VSLPs are burned as they "decay," all SLPs are burned after use, and LLPs go to landfills as they decay. Burned biomass is counted as an immediate emission. Meanwhile, the landfill pool can be interpreted as temporary storage because the carbon in the wood products is not immediately released into the atmosphere. However, some percentage of the carbon emitted from the landfill is converted to methane, which has a much higher global warming potential (GWP). Thus, when we calculate the total carbon "benefit" of a harvest in any given year based on the amount of carbon stored across all of the pools, we subtract the additional climate impact of methane converted into CO_2e using a GWP of 34.

Table A3 | Description of Carbon Pools in CHARM

POOL	HALF-LIFE (YEARS)	DESCRIPTION
Stand	N/A	Live aboveground and belowground biomass in the forest
Slash	18[a]	Dead biomass that is left following a harvest
Dead roots	5.2[b]	Decaying roots from trees that have been harvested
VSLP	N/A	Very short-lived products (biomass burned for energy immediately)
SLP	2.5[c]	Short-lived products (paper products)
LLP	13–47[d]	Long-lived products (timber used for furniture or construction). LLPs are subdivided into wood used for furniture and wood used for construction because of their different storage lives
Landfill	29[e]	Temporary storage of LLPs that are disposed of at the end of life
Fossil carbon		Changes in fossil carbon due to the use of wood as a substitute for alternative products

Note: N/A = not applicable.

Sources: a. Russell et al. 2014; b. Brunner and Godbold 2007; Zhang and Wang 2015; c, d. Pingoud et al. 2006; e. Skog 2008.

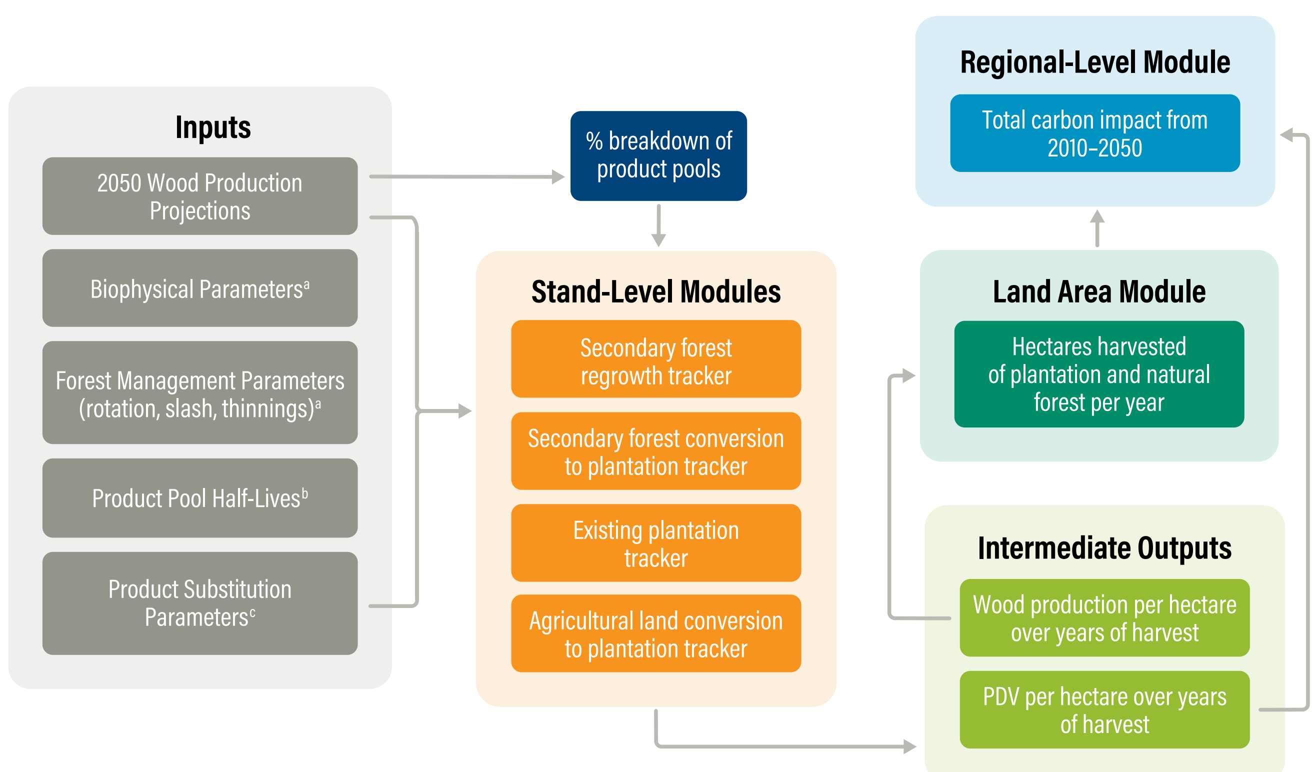
One pool that can be implicitly counted by the model is a pool of underground carbon stored in fossil fuels that is affected by the harvest. Fossil fuels are used in growing, harvesting, and processing wood products. Although these are real emissions, the model does not count them by themselves. However, the model can be run with a "substitution value," which estimates the amount of carbon emissions avoided from the use of wood to replace conventional construction products, such as concrete and steel. When run with substitution values, the model implicitly counts both the production emissions from the wood product and the production emissions of the LLPs.

The use of VSLPs also potentially saves fossil emissions, but the production of both VSLPs and SLPs generates emissions. The model is set up to calculate the net effects on fossil emissions use. Because of numerous data uncertainties about how much wood is ultimately burned for energy used outside of the wood products industry, how much is used for wood products, and how much fossil energy is used in generating pulp and paper products, the present model runs consider these effects to cancel each other out. These runs therefore do not count bioenergy savings but also do not count fossil emissions used to produce any product other than LLPs and the materials for which they substitute.

Substitution values do not mean that the forest harvest produces fewer emissions. Those forestry-related emissions are still real. But the model can calculate a net effect of forest harvests for LLPs compared to the use of conventional construction materials. Users must input the percentage of LLPs that make it into construction and the percentage of that quantity that displaces the conventional construction materials.

One feature of the model is that it calculates a present discount value of the changes in carbon each year. The present discount value is calculated to the year of harvest, whenever that occurs. The choice of a discount rate is a policy decision, which can represent two benefits of earlier mitigation. One of these benefits is in service of the goals of avoiding immediate and permanent damages from rising temperature (e.g., the effects of ice sheet melting or biodiversity loss) and reducing the risk of crossing a variety of climate thresholds. Earlier mitigation in effect increases the time people can improve technology and organize the political will and resources to combat climate change (Daniel et al. 2019). The other benefit of earlier mitigation results from the time value of money. Our approach follows the discounting employed in Searchinger, Wirsenius, et al. (2018) and is designed to be a rigorous way of reflecting current global policies that seek to reduce emissions greatly or even to net zero by 2050. The precise discounting formula is described in Section A.1.8. CHARM's structure is summarized in Figure A1.

Figure A1 | CHARM Structure



Note: PDV = present discount value.

Sources: a. Harris et al. 2021; b. various sources; c. Leskinen et al. 2018.

A.1.7 Description of the counterfactual

For each wood supply scenario, we estimate the required land area and carbon costs (PDV per hectare) for the plantation and the secondary forest area harvested. The carbon costs are determined by the planting/harvesting action (harvest scenario) and the alternative action (nonharvest scenario). Table A4 shows the main harvest scenarios and corresponding nonharvest scenarios:

- Allowing for a secondary forest regrowth after an initial harvest
- Converting a secondary forest into a plantation
- Harvesting an existing plantation
- Converting agricultural land into a plantation

For Scenarios 2–4, the land is growing as a plantation and being harvested after each rotation cycle. In Scenario 3, we assume that the nonharvest scenario is a secondary forest that is the same age as the plantation's rotation period because that focuses the alternative at the time of the last harvest.

A plantation forest either can grow at a young growth rate for the first 20 years and at an old growth rate after 20 years or at one plantation growth rate throughout the rotation period.
A secondary forest typically grows at a Monod function of forest age (McMahon et al. 2010):

$$C\,(Age) = \frac{AGB_{max} * Age}{Age + Age_{50\%}}$$

The parameters AGB_{max} and $AGB_{50\%}$ are derived from Harris et al. (2021) and Bernal et al. (2018). The initial carbon stock for forests being harvested depends on the age of harvest. The harvesting age is at least 40 years, or 20 years growth after the average aboveground carbon stock from the Harris et al. (2021) data set.

Table A4 | Estimating carbon costs under four different scenarios

	SCENARIO	INITIAL CONDITION	GROWTH FUNCTION
(1) Allowing a secondary forest regrowth after harvest	Harvest scenario	Monod function at the age of harvest	Harvested once and grows at Monod function
	Nonharvest scenario	Monod function at the age of harvest	Continue growing at Monod function
(2) Converting a secondary forest into a plantation	Harvest scenario	Monod function at the age of harvest	Harvested after each rotation cycle and grows at plantation growth rate
	Nonharvest scenario	Monod function at the age of harvest	Continue growing at Monod function
(3) Harvesting an existing plantation	Harvest scenario	Plantation carbon stock after one rotation cycle	Harvested after each rotation cycle and grows at plantation growth rate
	Nonharvest scenario	Monod function at the age of one plantation rotation cycle	Continue growing at Monod function
(4) Converting agricultural land into a plantation	Harvest scenario	Zero carbon stock	Harvested after each rotation cycle and grows at plantation growth rate
	Nonharvest scenario	Zero carbon stock	Grows at Monod function

Source: Carbon Harvest Model.

A.1.8 Mathematical description of the carbon calculation

The model calculates a PDV for the harvest of single hectares of secondary and plantation forests (separately) over the period of 40 years from the year of harvest at a discounted rate of 4 percent. To calculate the PDV, we start by calculating the annual carbon "benefit," which is the sum of all carbon stored in all pools, the regrowth on the stand minus any emissions of methane that occur in the landfill. For calculations with substitution values, we include the changes in both fossil fuels and other production emissions from using wood for construction or traditional bioenergy rather than using concrete and steel or propane gas for traditional bioenergy.

Next, for each year, we calculate the difference between the total annual benefit and the carbon "cost," which is the counterfactual stand carbon density in that year. We then calculate the difference in this value relative to the previous year. This value, shown below as ΔC_{change}, is what we discount. The PDV for the harvest of a single hectare in the year 2010 is therefore calculated as

$$PDV = \sum_{i=0}^{t} \frac{\Delta C_{change,i}}{(1+r)^{i}}$$

where *i* is the number of years since 2010, *r* is the discount rate (4 percent), and *t* is 40 years.

This is done separately for both plantations and secondary forests. For national and global results, we then multiply each PDV by the number of hectares required of each forest type in the year harvested.

The total PDV is the sum across all years of the PDV for secondary and plantation forests in each year multiplied by the area of each forest type harvested in that same year:

$$PDV_{total} = \sum_{h=2010}^{K} PDV_{secondary,h} \times a_{secondary,h} + \sum_{h=2010}^{K} PDV_{secondary,h} \times a_{secondary,h}$$

where *h* represents the year of harvest that starts from 2010, *K* represents the number of years for harvests (for example, 40 years), *a* represents the new area of one forest type harvested in year *h*. The next subsection describes the calculation of area required for each forest type.

A.1.9 Brief comparison with alternative accounting approaches

The carbon accounting approach used in this model follows the approach originated by Schlamadinger and Marland (1996) and used by numerous models since then, including those in Chen et al. (2018) and Smyth et al. (2020) as well as in papers specifically analyzing forest-based bioenergy (Bernier and Paré 2013; Booth 2018; Holtsmark 2012, 2013; Hudiburg et al. 2011; Laganière et al. 2017; Manomet Center for Conservation Sciences 2010; McKechnie et al. 2011; Mitchell et al. 2012; Stephenson and MacKay 2014; Zanchi et al. 2012). Accounting for the GHG costs of forestry is presently done using a wide variety of approaches, which are typically presented with little discussion (Ter-Mikaelian et al. 2015).

Some alternative approaches treat wood harvest as "carbon neutral" so long as forests are harvested "sustainably," which means reductions of carbon in the forest are not incorporated into the carbon accounting. In its strongest formulation, sustainable management in this context is used to mean that the harvest of forests does not exceed the annual growth of the forest, so that overall existing carbon stocks are maintained. However, as explained in numerous papers, if forests would gain carbon if not harvested, then the harvest by definition reduces the carbon (EASAC 2018; Haberl et al. 2012; Searchinger et al. 2009; Ter-Mikaelian et al. 2015). Put another way, the effect of a harvest in one area is not altered by changes in forests anywhere else that would occur anyway. Among other effects, this carbon neutrality approach treats the elimination of the forest carbon sink (due to increased carbon dioxide) through wood harvesting as having no climate consequence even though that sink is critical to restraining climate change (Schimel et al. 2015; Searchinger, Wirsenius, et al. 2018).

In our biophysical model, CHARM, the offsetting benefits of forest harvesting result from storage of carbon in forest products and the forest regrowth that occurs after a harvest; they can also include substitution benefits with alternative products. Unharvested forests also continue to grow, but their growth in carbon eventually slows down. As a result, regrowth will eventually have higher growth and therefore carbon sequestration rates, and the net increase in growth rates provides benefits. The net changes in all carbon pools each year, including carbon in regrowing forests, are then valued based on their present discount value dated to the year of harvest in order to compare the flows of carbon from different harvest or nonharvest scenarios and to reflect the general public policy goal of seeking rapid reductions in emissions between today and 2050.

There is a debate about whether increasing wood demand, through market signals, results in changes in land-use behavior that should be incorporated into modeling. For example, increased market demand driven by policy for additional wood for construction could cause some landowners to intensify their forest management, such as shifting from secondary forests to plantations. Alternatives might include converting some agricultural land to forest or diverting wood harvests from SLPs to LLPs. These are potential uses affected by increases in wood prices. Such analyses are econometrically challenging, and if they are going to reflect economic responses, they must also include such other possible responses to changing prices as the expansion of agriculture into forests in other areas to maintain agricultural production, the reduction in other uses of wood for LLPs, and offsetting increases in steel and concrete production for other uses.

By itself, CHARM is agnostic about whether increased demand for wood causes cascading changes in supply. Instead, CHARM analyzes the carbon consequences of aggregate specified levels of supply and demand. For example, if a policy is expected to drive more conversion of secondary forest to plantations, or to establish plantations on existing agricultural land on a net basis, CHARM can analyze the carbon implications of such changes. Some of our scenarios evaluate changes in wood supply sources that, in theory, could result from economic feedback effects or other policy changes.

A.2 Model Inputs

A.2.1 Biophysical forest inputs

Colleagues at WRI developed a model that generates regional biophysical forest data described in Harris et al. (2021). The resulting data set provides many parameters, some of which are integral to our analysis. For any given country and ecozone (tropical, temperate, etc.), the model provides the forest type (primary, young secondary, old secondary, or plantation), area, aboveground carbon stock across the entire area, aboveground carbon density per hectare, and annual growth rate per hectare.

Our model requires separate biophysical inputs for secondary forests and managed forests (plantations). For both forest types, we create an "average forest," which includes the growth rate as an average across all ecozones weighted by area. We used the weighted average of "wood fiber" type for plantation and used the average growth rate.

For secondary forest growth rates, Harris et al. (2021) provides two growth rates: less than 20 years of age (GR1) and greater than 20 years of age (GR2). We used the estimates and adjusted them based on the following rules. If the ratio of GR2 to GR1 is large, above 85 percent, or even if GR2 is larger than GR1, we utilized another data set's GR2 and GR1 ratio and calculated the average GR2/GR1 between the two data sets (Bernal et al. 2018; see Table A8).

We used the Monod function to simulate the higher growth rates in the younger forests and lower growth rates in the older forests (McMahon et al. 2010; Poorter et al. 2016). Because we are discounting growth by time, higher growth rates for younger forests (versus older forests) matter to our calculations. For growth rates beyond 20 years, the data set includes very old secondary forests with slow growth rates because this categorization served the purposes of the study by Harris et al. (2021).

Although most biophysical forest inputs come from Harris et al. (2021), we consulted external sources for a select few countries for plantations whose parameters had a great impact on the overall results and for which there was conflicting evidence about average growth rates. Particularly, we sought alternative plantation growth rates for Brazil, China, Mexico, Indonesia, and the United States.

Plantation Growth Rates in the United States

For U.S. plantation growth rates, Harris et al. (2021) used an analysis prepared by Richard Birdsey based on growth rates for artificial regeneration without disturbance plantations using national forestry inventory data compiled by the U.S. Forest Service. These data sources resulted in an estimate of 3.85 tC ha-1 yr-1 of above-ground carbon gains as a weighted average of different plantation types. However, these growth rates were substantially higher for key plantation types presented from the same data source for all loblolly and other plantation types in the southeastern United States in the 2017 Forest Resources Assessment (Oswalt et al. 2019). The Southeast is the region that supplies the great majority of plantation wood in the United States. The area of plantations in that publication generally matched the data for plantations used from FAO. The difference in growth rates from the same data sources likely represents a difference in quality of plantation analyzed. Because the model uses a larger plantation area definition, a modified plantation growth rate was needed to accurately represent average growth rates.

They were also substantially higher than the carbon accumulation rates of high productivity stands of the four most widespread plantation types in a U.S. Forest Service Publication (Hoover et al. 2021). For the three most prevalent planted forest types, which comprise 82% of the total U.S. planted forest area as estimated by Harris et al. (2021), we found a 42% difference between estimates from the Birdsey analysis and those for high productivity sites in Hoover et al. (2021). We chose to average the results and accordingly reduced the Harris et al. (2021) estimated growth rate for all plantations by 21%, yielding an average plantation growth rate of 3.05 tC/ha/yr in above-ground carbon.

Plantation growth rates in Brazil

As in the United States, literature values for plantation growth rates vary and tend to emphasize higher values. IBA, the association of the Brazilian Tree Industry, provides annual reports with information on planted forest area by type and consumption of wood by facilities that harvest this wood. Our estimate of growth rates per hectare uses 2012 information on planted forest area, separately provided for eucalyptus, pine and other, and 2016 information on quantities of wood consumed. Planted area in 2012 is provided in the 2014 report, and quantities consumed is provided in the 2022 report. We used this lag to recognize that because Brazil's area of planted forest is growing, some of the planted forests in 2012 would be newly planted and would not be generating harvests in 2012. Because the wood consumed is only the wood harvested, we also used a biomass expansion factor (BEF) to estimate total above ground carbon. In Brazil, the great majority of plantation forest wood is used for pulp or charcoal, allowing highly efficient uses of above-ground carbon reported at 88% by Greenwood Resources, a major owner and operator of Brazilian forest plantations, which gives an inverted BEF of 1.14, which we applied both to eucalyptus and pine, while using a higher BEF of 1.35 for other. The final calculation results in an estimate of 8.22 tC/ha/yr above-ground forest gains.

Plantation growth rates in China

For growth rates in China, we collected statistics from the literature based on the National Forest Inventories. We gathered the annual volume increment (m^3 ha^{-1} yr^1; Liu et al. 2019), area (ha; State Forestry and Grassland Administration 2022), biomass expansion factor, and wood basic density (t m^{-3}; Zeng 2017) for different species and then aggregated them to the average national growth rate of 1.27 tC/ha/yr of existing plantation.

Plantation growth rates in Mexico

Similarly, for growth rates in Mexico, we used the annual volume increment, wood density, and area from the report of the Mexican National Forestry Commission (CONAFOR 2012). We aggregated the growth rate for major plantation species to the national average plantation growth rate at 3.60 tC/ha/yr.

Summary of biophysical forest parameters

The data set from Harris et al. (2021) also included the areas of plantation forests. However, we found some inconsistencies. For example, some countries had no reported hectares of plantation forest. To overcome this issue and maintain consistency, we instead used the area of managed forest provided by FAO Global Forest Resources Assessment (FRA) for the relevant countries. Table A5 lists the growth rates and plantation area for the 30 countries.

A.2.2 Harvest inputs

The model also requires information on management decisions and harvest efficiency. The model requires the proportion of wood from a harvest or thinning that makes it into each product pool, how much AGB is left as slash after a harvest, and the proportion

Table A5 | Biophysical Parameters and Area Used for the Global Analysis

COUNTRY	YOUNG SECONDARY GR1 (tC HA^{-1} YR^{-1})	MIDDLE-AGED SECONDARY GR2 (tC HA^{-1} YR^{-1})	AVERAGE SECONDARY CARBON STOCK (MgC/ha)	EXISTING PLANTATION GR (tC HA^{-1} YR^{-1})	FAO PLANTATION AREA (ha)
Australia	1.53	1.4	59.55	4.64	1,903,000
Austria	1.74	1.23	66.28	1.53	1,696,000
Bangladesh	3.43	1.14	88.61	2.74	237,000
Brazil	3.68	1.07	52.38	8.22	6,973,000
Canada	0.92	0.76	31.43	0.84	13,975,000
Chile	3.06	1.91	57.35	5.48	2,384,000
China	2.25	0.73	62.22	1.27	73,066,500
D. R. Congo	4.42	1.65	57.97	7.97	58,779
Ethiopia	2.75	0.79	61.97	5.82	511,000
Finland	0.89	0.61	27.77	0.86	6,775,401
France	1.83	1.3	79.99	1.73	2,086,000
Germany	1.68	1.26	81.32	1.73	5,290,000
Ghana	5.04	1.56	60.66	5.04	260,000
India	2.78	1.89	97.4	1.73	11,139,000
Indonesia	4.33	1.16	86.99	7.21	4,803,000
Japan	1.51	1.31	78.86	1.75	10,292,000
Kenya	3.37	0.75	54.79	3.37	193,000
Mexico	3.24	1.39	49.52	3.6	59,000
Myanmar	3.1	2.53	104.16	2.74	988,000

Table A5 | Biophysical Parameters and Area Used for the Global Analysis (cont.)

COUNTRY	YOUNG SECONDARY GR1 (tC HA^{-1} YR^{-1})	MIDDLE-AGED SECONDARY GR2 (tC HA^{-1} YR^{-1})	AVERAGE SECONDARY CARBON STOCK (MgC/ha)	EXISTING PLANTATION GR (tC HA^{-1} YR^{-1})	FAO PLANTATION AREA (ha)
Nigeria	5.2	1.36	59.72	5.2	328,000
Pakistan	1.3	0.39	81.45	2.74	340,000
Poland	1.8	1.3	54.46	1.81	8,877,000
Russia	1.04	0.72	37.8	0.88	19,612,900
South Africa	1.74	0.81	59.97	3.59	1,763,000
Sweden	1.2	0.84	31.04	1.18	12,564,000
Thailand	3.96	2.04	93.75	3.7	3,986,000
Uganda	3.4	1.35	40.82	3.4	55,000
Tanzania	3.14	1.49	58.52	3.14	240,000
USA	2.11	1.09	61.46	3.05	25,564,000
Vietnam	3.38	2.62	82.34	6.74	3,823,000

Note: GR = growth rate.

Source: Authors' calculations based on FAO (2020) and Harris et al. (2021).

of AGB that is removed during the thinning. For plantation, the slash proportion is the wood that are not for industrial usage. In order to be consistent with our plantation growth rate, we used BEF to estimate the branches and leaves, which results in a slash rate at (BEF – 1)/BEF (see Table A6). For the secondary forest slash rate, the model uses a default value of 20 percent for the VSLP share. For the LLP and SLP share, the model uses a 25 percent for EU and North American countries and a 30 percent for the remaining nontropical countries. In tropical countries, the slash rate is far higher (Ellis et al. 2019). At present, we apply country-specific secondary forest slash rates to 16 tropical forests based on Ellis et al. (2019) and Pearson et al. (2017; see Table A6).

Another key parameter relevant to management is the rotation period for both the harvests and the thinnings. At present, we apply parameters for thinnings to some stand-level analyses but do not apply thinnings to the global scenarios; however, the effects of thinning are implicitly incorporated into estimated growth rates and harvest volumes.

The rotation period is a highly variable parameter that depends on the specific management regime for a given plantation. For a stand-level scenario, users can input a specific rotation period. However, we consulted the literature to find the best estimate for each country for our global analysis (e.g., European Parliament 1997; Natural Resources Institute Finland 2012; Torres-Rojo et al. 2016; UNDP 2013; Directorate General of the State Forests 2017; Hertog et al. 2019; FSIV 2009; Hoover et al. 2021; World Bank 2019.). When the rotation information was not readily available for some countries, we made educated guesses based on the plantation growth rates and the known rotation periods of other countries.

We also apply decay rates for each carbon pool according to Table 12.2 of the 2006 IPCC *Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) described in Table A3. However, these values can be modified for more specific scenarios. Annual emissions are calculated by tracking the decay that occurs in each pool from one year to the next, including methane due to landfilled LLPs, as previously described.

A.2.3 Construction and substitution inputs

CHARM calculates the benefits due to avoided emissions from concrete and steel in construction by estimating the percentage of LLPs in a country that are used for construction and then estimating the quantity of construction material that actually displaces concrete and steel. This value is highly uncertain because the quantity of wood that replaces a given amount of concrete and/or steel varies widely by region and building type. Smyth et al. (2017), for example, compare the emissions of construction materials required for a less-wood-intensive building relative to a similar more-wood-intensive building in Canada in order to estimate the substitution coefficient. Chen et al. (2018) estimate that 64 percent of LLPs used in construction displaces concrete and steel in Canada.

Table A6 | Secondary Forest Slash Rates for Tropical Countries

COUNTRY	SECONDARY FOREST SR (%)	SOURCE	PLANTATION SR (%)	SOURCE
Australia	30	This study	17	BEF = 1.2
Austria	25	This study	13	BEF = 1.15
Bangladesh	79	Ellis et al., Pearson et al.	33	BEF = 1.5
Brazil	65	Ellis et al., Pearson et al.	13	BEF = 1.15[a]
Canada	25	This study	25	Use natural slash rate at high efficiency
Chile	79	Ellis et al., Pearson et al.	22	BEF 1.2 for Pine and 1.5 for Eucalyptus[b]
China	30	This study	19	BEF = 1.15-1.5[b]
D.R. Congo	82	Ellis et al., Pearson et al.	33	BEF = 1.5
Ethiopia	64	Ellis et al., Pearson et al.	33	BEF = 1.5
Finland	25	This study	25	Use natural slash rate at high efficiency
France	25	This study	13	BEF = 1.15
Germany	25	This study	25	Use natural slash rate at high efficiency
Ghana	64	Ellis et al., Pearson et al.	25	Use natural slash rate at high efficiency
India	79	Ellis et al., Pearson et al.	33	BEF = 1.5
Indonesia	79	Ellis et al., Pearson et al.	29	BEF 1.33 for Acacia and 1.5 for Eucalyptus[b]
Japan	30	This study	13	BEF = 1.15
Kenya	64	Ellis et al., Pearson et al.	25	Use natural slash rate at high efficiency
Mexico	71	Ellis et al., Pearson et al.	24	BEF = 1.05-1.5[b]
Myanmar	79	Ellis et al., Pearson et al.	33	BEF = 1.5
Nigeria	64	Ellis et al., Pearson et al.	25	Use natural slash rate at high efficiency
Pakistan	30	This study	33	BEF = 1.5
Poland	25	This study	25	Use natural slash rate at high efficiency
Russia	30	This study	25	Use natural slash rate at high efficiency
South Africa	30	This study	25	Use natural slash rate at high efficiency
Sweden	25	This study	25	Use natural slash rate at high efficiency
Thailand	79	Ellis et al., Pearson et al.	33	BEF = 1.5
Uganda	64	Ellis et al., Pearson et al.	25	Use natural slash rate at high efficiency
Tanzania	64	Ellis et al., Pearson et al.	25	Use natural slash rate at high efficiency
United States	25	This study	10	BEF=1.1-1.15[b]
Vietnam	79	Ellis et al., Pearson et al.	33	BEF = 1.5

Note: SR = slash rate. a. see our discussion on Brazil plantation growth rate; b. the slash rate is a weighted average of main species based on area share

Source: Authors' calculations.

Table A7 | LLP percentage in construction

COUNTRY	% LLP USED IN CONSTRUCTION
United States	45
Japan	67
United Kingdom	14
France	32
Germany	30
China	59
Russia	17
Finland	56
Sweden	50
Canada	51
All other LLP-producing countries	42

Note: LLP = long-lived product.

Source: Authors' calculations.

Zhang et al. (2020) developed a new method for estimating the percentage of LLPs that are used in construction by mapping FAOSTAT production data to the Eora Global Supply Chain Database's consumption data. They estimated the quantity of wood used in construction for the top 10 hardwood-product-producing countries (all of which are included in our analysis). For all other countries that produce hardwood products, they provided a single ratio. The ratios for the top 10 countries and the remainder are presented in Table A7.

This parameter impacts the average half-life assigned to LLPs because the half-life varies depending on whether a product is used for construction or other uses. Zhang et al. (2020) provide half-lives derived from a meta-analysis for several different countries, many of which are relevant to our model. Where this information is not available, Zhang et al. defer to the IPCC (Pingoud et al. 2006), stating that LLPs in construction have a half-life of 40 years, whereas all other LLPs have a half-life of 23 years. Table A8 shows the half-lives for construction material and other LLPs for each country.

Table A8 | Half-lives for LLP in construction and other use

COUNTRY/REGION	HALF-LIFE FOR LLPS IN CONSTRUCTION (YEARS)	HALF-LIFE FOR OTHER LLPS (YEARS)
Canada	66	29
United States	65	30
Germany	35	17
Ireland	67	30
Finland	21	23 (default)
France	17	11
Czech Republic	45	23 (default)
Portugal	21	14
Switzerland	55	35
Spain	17	12
European Union (other)	43	27
Japan	33	20
All other countries	40	23

Note: LLP = long-lived product.

Source: Authors' calculations.

We use these half-lives to calculate a weighted average half-life based on the percent of LLPs in construction in Table A7. The calculation is as follows: (% LLP in construction x half-life for LLP in construction) + ([1 – % LLP in construction] x half-life for other LLP). The resulting half-lives for LLPs are between 12 and 47 for the 30 countries.

Table A9 | Parameters used to generate substitution factor

AVOIDED TONS CONCRETE/TON WOOD USED	AVOIDED TONS STEEL/ TON WOOD USED	EMISSIONS FACTOR FOR CONCRETE	EMISSIONS FACTOR FOR STEEL	EMISSIONS FACTOR FOR WOOD
2.91	0.39	0.15	2.11	0.44

Source: Churkina et al. (2020).

We currently use a default substitution factor of 1.2 tC avoided per ton of carbon in wood (Leskinen et al. 2018). However, the substitution factor is compiled from several subfactors, which include the production emissions for the wood product, the production emissions for construction products (concrete and steel), and the quantity of concrete and steel replaced by each ton of wood. This information is not provided in the Leskinen et al. (2018) meta-analysis or in most of the papers that served as inputs to that analysis.

We designed our model to include each of these factors and then adjusted the parameters to generate a substitution value for wood used in construction to replace concrete and steel. Table A9 shows the results. In the stand-level analysis, we also tested a different set of substitution parameters from a recent study (Churkina et al. 2020).

The substitution factor (SF) can be calculated as

$$SF = (AC \times EFC + AS \times EFS - EFW) / CF_1 / CF_2$$

AC: Avoided tons of concrete per dry ton of wood (t concrete/t wood)

AS: Avoided tons of steel per dry ton of wood (t steel/t wood)

EFC: Emissions factor for concrete (tCO_2e/t concrete)

EFS: Emissions factor for steel (tCO_2e/t steel)

EFW: Emissions factor for wood (tCO_2e/t wood)

CF1: Conversion factor from CO_2e to carbon = 3.67 CO_2e/C

CF2: Conversion factor from dry wood tons to carbon tons = 0.5 tC/t dry matter

We used a substitution factor of 0.44, derived from the above parameters, to compare with the 1.2 average.

Our current scenarios effectively use our best estimate for these ratios. We have run the model assuming that 50 percent of LLPs produced are used for construction and 75 percent of that construction material actually displaces fossil fuels related to concrete and steel production.

A.3 Future Wood Supply Scenarios Descriptions

We analyze seven different scenarios. For each scenario, we calculate the carbon impacts and land-use requirement with two supply levels. In the first supply level, timber supply remains constant at 2010 levels, and "BAU" means that timber supply changes according to a business-as-usual projection.

Scenarios 1 and 2 explore the effects of changes in timber production and the difference between allowing a natural forest to regenerate after harvesting rather than converting it to a plantation. This serves as a bounding exercise because, in reality, a mix of natural regeneration and conversion to plantation occurs at the margin. Scenario 3 is the same as Scenario 1, except that the wood supply from the secondary forest is sourcing from mature forests as well.

- **Scenario 1 (secondary forest harvest and regrowth)** assumes that the existing plantations are supplying wood at our best estimate of their present growth rates. Additional wood demand is met by the harvest of wood from middle-aged secondary forests (stands aged 20–80 years) and the forests are allowed to regrow for 40 years. This scenario also assumes that all wood is supplied by at least small clear-cuts, and it measures the area of such clear-cuts.
- **Scenario 2 (secondary forest harvest and conversion)** assumes that the existing plantations are supplying wood at present growth rates and that after secondary forest areas are harvested as Scenario 1, they are reestablished as plantations (assume at productive locations with at least the present growth rates of secondary forests) to maximize the amount of future wood supplied by plantations. Plantations have substantially higher output of wood per hectare per year and are typically harvested more efficiently than natural forests, which means

that more of the wood felled is utilized for wood instead of being left as deadwood in the forest. This scenario is designed to analyze the effects of a high level of intensification in forest management.

Although we assume that the same lands are replanted as plantations, something similar to this scenario could also occur if natural forests continue to be cleared in some areas while plantations are regrown in others. In China, for example, as discussed above, the large-scale conversion of less productive agriculture lands to plantations is associated with a heavier reliance on imported foods associated with a large quantity of offsetting deforestation (Pendrill, Persson, Godar, Kastner, et al. 2019). On a global basis, growth of plantations on abandoned agricultural land can therefore indirectly achieve a conversion of natural forests to plantations.

- **Scenario 3 (secondary forest mixed harvest)** is similar to Scenario 1 except that 50 percent of wood demand is provided by middle-aged secondary forests (20–80 years) and 50 percent is provided by mature secondary forests (80–140 years). Both secondary forests are harvested at the same slash rates.
- **Scenario 4 (new tropical plantations)** assumes that 68 Mha of tropical agricultural lands become available for establishing highly productive plantations in the tropics and are harvested evenly between 2020 and 2050 (2 Mha per year since the first harvest occurs after 7 years). All new plantations are located in existing agricultural lands in the tropics and neotropics, where yields are higher. The secondary forests are harvested less due to the wood supply from the new tropical plantations. This scenario assumes that these lands have been spared from agriculture, so the carbon costs of using these lands for plantations is the loss of carbon sequestration that would otherwise occur in regrowing secondary forests.
- **Scenario 5 (higher plantation productivity)** is identical to Scenario 1 but assumes that existing plantation forest growth rates increase by 25 percent between 2010 and 2050.
- **Scenario 6 (higher harvest efficiency)** is identical to Scenario 1 but assumes that existing tropical secondary forest harvest efficiency increases so that the slash rate reduces to the level of best practices as described by Ellis et al. (2019).
- **Scenario 7 (50 percent less 2050 fuelwood demand)** is a variant of Scenario 1 in which fuelwood demand in 2050 reduces by half compared to the demand under the BAU projection in Scenario 1.

APPENDIX B: LITERATURE REVIEW OF PUBLISHED FORESTRY AND CLIMATE STUDIES

Table B1 characterizes the literature we reviewed regarding the climate consequences of harvesting wood, including its use in construction material and other LLPs. (This list does not include papers primarily focused on bioenergy although bioenergy factors into many of the papers below.)

The first group of papers in the table factors in changes in all carbon pools, which we consider the appropriate form of accounting. These papers in turn are divided into two categories (although some papers belong in both): the first category (fifth column) analyzes specific scenarios in which a high majority of the wood is used for construction material and results in net GHG benefits either immediately or within the first 30 years at least if combined with a substantial substitution value (reduction in fossil emissions in construction material); the second category (sixth column) focuses on the typical end uses of wood, which do not find benefits in these periods.

The second group of papers assumes that harvested wood is carbon neutral. These papers do not factor in emissions of carbon to the air from the reduction of carbon in the forest, which is usually justified by the claim that wood is carbon neutral if sustainably managed. We explain in the main text our disagreement with this assumption. These papers all compare the fossil emissions from producing and using wood products with the fossil emissions (and process emissions from making concrete and steel) of construction materials or other products replaced by wood. This is the potential "substitution benefit." These papers typically find climate benefits from harvests at least for replacing many construction materials.

We add some additional categories for description. All papers in this carbon neutral category count the substitution benefits. Those with a check box in the third column also factor in carbon benefits from stored wood products. In other words, if wood is harvested and turned into furniture or a building, the carbon stored in those products is counted as a reduction in carbon in the air although the carbon reduction in the forest is not counted. The fourth column signifies papers that generally do not assume that all sustainably managed wood is carbon neutral; they analyze scenarios that assume all additional wood used for construction is diverted from uses of wood for pulp or other short-lived purposes, and those uses are not replaced. For several of these papers, such as Smyth et al. (2020) or Xu et al. (2018), that is simply an assumption in a potential scenario, and these papers do not assert that such wood product diversion will happen or is likely.

The carbon consequences in all of these papers are purely biophysical. None of these papers incorporates any economic analysis to claim that additional wood demand will lead to additional carbon storage due to changes in economic price effects. (Some papers use economic analysis for other purposes, such as to estimate prices.)

Table B1 | Forestry and Climate Studies Reviewed

PAPER	CARBON-NEUTRAL ASSUMPTION	CARBON-NEUTRAL ASSUMPTION PLUS WOOD PRODUCT STORAGE	ASSUMES SHIFT FROM PAPER PRODUCTS OR IGNORES PRODUCT DISPLACEMENT	FACTORS IN ALL CARBON POOLS AND FINDS SHORT-TERM BENEFITS USING SPECIFIC OPTIMISTIC SCENARIOS	FACTORS IN ALL CARBON POOLS AND FINDS AT LEAST NET COSTS FOR AT LEAST SEVERAL DECADES BASED ON PRESENT OR COMMON WOOD USAGE
Counts all Carbon Pools					
Chen et al. (2018)				Y	Y
Gustavsson et al. (2017)					Y
Gustavsson et al. (2021)				Y	Y
Ingerson (2009)					Y
Kalliokoski et al. (2020)					Y
Keith et al. (2015)					Y
Law et al. (2018)					Y
Oliver et al. (2014)				Y	Y
Peñaloza et al. (2016)				Y	
Schlamadinger and Marland (1999)					Y
Skytt et al. (2021)					Y
Smyth et al. (2020, also listed below)					Y
Assumes Wood Is Carbon Neutral					
Achachlouei and Moberg (2015)	Y				
Ayikoe Tettey et al. (2019)	Y	Y			
Bergman et al. (2014)	Y	Y			
Bolin and Smith (2011)	Y				
Brunet-Navarro et al. (2017)	Y		Y		
Buchanan and Levine (1999)	Y	Y			
Churkina et al. (2020)		Y	Y		
Dodoo et al. (2009)	Y				
Durlinger et al. (2013)	Y	Y			
Betser and McCulloch (2019)	Y?	Y?			
Eriksson (2004)	Y				
Eriksson et al. (2012)	Y	Y	Y		

Table B1 | Forestry and Climate Studies Reviewed (cont.)

PAPER	CARBON-NEUTRAL ASSUMPTION	CARBON-NEUTRAL ASSUMPTION PLUS WOOD PRODUCT STORAGE	ASSUMES SHIFT FROM PAPER PRODUCTS OR IGNORES PRODUCT DISPLACEMENT	FACTORS IN ALL CARBON POOLS AND FINDS SHORT-TERM BENEFITS USING SPECIFIC OPTIMISTIC SCENARIOS	FACTORS IN ALL CARBON POOLS AND FINDS AT LEAST NET COSTS FOR AT LEAST SEVERAL DECADES BASED ON PRESENT OR COMMON WOOD USAGE
Geng et al. (2017)	Y	Y			
Grann (2013)	Y	Y, plus regrowth			
Guest et al. (2013)		Y			
Guo et al. (2017)	Y	Y			
Gustavsson et al. (2006)	Y	Y, plus regrowth			
John et al. (2009)	Y	Y			
Jönsson et al. (1997)	Y				
Kayo and Noda (2018)		Y, plus regrowth			
Kayo et al. (2011)	Y	Y			
Kayo et al. (2015)	Y	Y			
Knight et al. (2005)	Y				
Lan et al. (2020)		Y, plus regrowth			
Li and Altan (2011)	Y	Y	Y		
Lippke et al. (2004)	Y	Y			
Lippke et al. (2011)		Y			
Liu et al. (2016)	Y	Y			
Lu, El Hanandeh, Gilbert, and Bailleres (2017)	Y	Y			
Lu and El Hanandeh (2017)	Y	Y			
Lu, El Hanandeh, and Gilbert (2017)	Y	Y			
Noda et al. (2014)	Y	Y			
Noda et al. (2016)	Y	Y			
Padilla-Rivera et al. (2018)	Y				
Perez-Garcia et al. (2004)		Y			
Petersen and Solberg (2002)	Y	Y			
Petersen and Solberg (2004)	Y	Y			
Pierobon et al. (2019)	Y	Y			

Table B1 | Forestry and Climate Studies Reviewed (cont.)

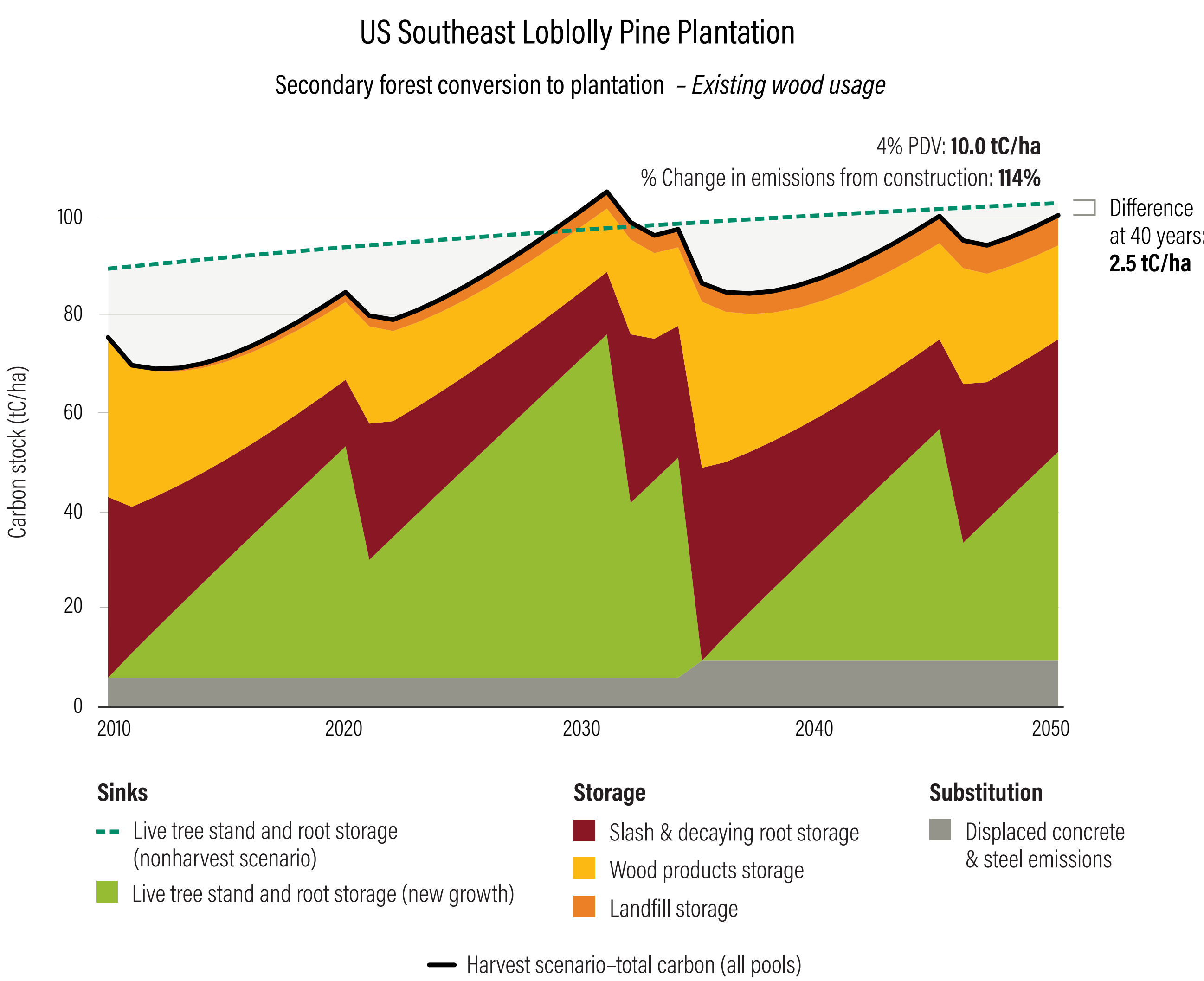
PAPER	CARBON-NEUTRAL ASSUMPTION	CARBON-NEUTRAL ASSUMPTION PLUS WOOD PRODUCT STORAGE	ASSUMES SHIFT FROM PAPER PRODUCTS OR IGNORES PRODUCT DISPLACEMENT	FACTORS IN ALL CARBON POOLS AND FINDS SHORT-TERM BENEFITS USING SPECIFIC OPTIMISTIC SCENARIOS	FACTORS IN ALL CARBON POOLS AND FINDS AT LEAST NET COSTS FOR AT LEAST SEVERAL DECADES BASED ON PRESENT OR COMMON WOOD USAGE
Pingoud et al. (2012)	Question carbon neutral hypothesis				
Robertson et al. (2012)	Y	Y			
Rüter et al. (2016)	Y	Y			
Salazar and Meil (2009)	Y	Y			
Sandanayake et al. (2018)	Not specified				
Sandin et al. (2014)	Y				
Santi (2015)	Y	Y			
Sathre and O'Connor (2010)	Y	Y			
Sedjo (2002)	Y	Y	Y		
Simone Souza et al. (2017)	Y				
Skullestad et al. (2016)		Y			
Smyth et al. (2014)		Y	Y		
Smyth et al. (2017)		Y			
Sommerhuber et al. (2017)	Y	Y			
Suter et al. (2017)	Y	Y			
Werner et al. (2005)	Y	Y			
Werner et al. (2010)	Y	Y	Y		
Xu et al. (2018)	Y	Y	Y		
Zeitz et al. (2019)	Y				

Source: Authors.

APPENDIX C: GRAPHICAL EXPLANATION OF TIME DISCOUNTING AND RESULTS AFTER 40 YEARS AT DIFFERENT DISCOUNT RATES

Discounting applies a different value to the change in carbon emissions (or removals) as a result of the harvest based on its changing value over time. In Figure C1, we use the loblolly pine conversion to plantation scenario to illustrate the change in carbon pools. In the first year of harvest, there is a net increase in carbon emissions (represented by the vertical difference between the dotted green line and the solid black line). These emissions are valued at 100 percent. In the second year, there are additional emissions, which can be seen by an expanding distance between the two lines. The expansion represents additional emissions, but they are valued at a 4 percent lower cost because they occur one year later. The last years are net gains, illustrated by the closing distance between the two lines. These emissions are also valued, but again they are valued in present discount value terms at a 4 percent discount rate. Table C1 shows the calculation, including the absolute change after 40 years, with the last column showing the calculation in PDV terms.

Figure C1 | Loblolly Pine Secondary Forest Conversion to Plantation



Notes: PDV = present discount value. tC/ha = tons of carbon per hectare.

Source: Carbon Harvest Model.

Table C1 | Example Time Discounting (4 Percent) Carbon Changes over 40 Years for Loblolly Pine Conversion to Plantation Scenario

YEAR	HARVEST	NONHARVEST	HARVEST - NONHARVEST	ABSOLUTE CHANGE IN EMISSIONS (+) OR REMOVALS (-)	DISCOUNT PERCENTAGE	VALUE WHEN DISCOUNTED TO YEAR 1 (tC/ha)
2010	75.6	89.6	14.0	14.0	100	14.0
2011	69.9	90.1	20.2	6.2	96	6.0
2012	69.2	90.6	21.4	1.2	92	1.1
2013	69.4	91.1	21.7	0.3	89	0.3
2014	70.3	91.5	21.2	-0.5	85	-0.4
2015	71.8	92.0	20.2	-1.1	82	-0.9
2016	73.8	92.4	18.6	-1.5	79	-1.2
2017	76.1	92.8	16.7	-1.9	76	-1.5
2018	78.8	93.2	14.4	-2.3	73	-1.6
2019	81.7	93.6	11.9	-2.5	70	-1.8
2020	84.8	94.0	9.2	-2.7	68	-1.8
2021	80.0	94.4	14.4	5.2	65	3.4
2022	79.2	94.8	15.6	1.2	62	0.7
2023	81.1	95.2	14.1	-1.5	60	-0.9
2024	83.4	95.5	12.2	-1.9	58	-1.1
2025	85.9	95.9	10.0	-2.2	56	-1.2
2026	88.8	96.3	7.5	-2.5	53	-1.3
2027	91.8	96.6	4.8	-2.7	51	-1.4
2028	95.0	96.9	1.9	-2.9	49	-1.4
2029	98.3	97.3	-1.1	-3.0	47	-1.4
2030	101.8	97.6	-4.2	-3.1	46	-1.4
2031	105.4	97.9	-7.4	-3.2	44	-1.4
2032	99.1	98.2	-0.9	6.6	42	2.8
2033	96.4	98.5	2.1	3.0	41	1.2
2034	97.7	98.8	1.1	-1.0	39	-0.4
2035	86.7	99.1	12.5	11.3	38	4.3
2036	84.8	99.4	14.6	2.1	36	0.8
2037	84.6	99.7	15.1	0.5	35	0.2

Table C1 | Example Time Discounting (4 Percent) Carbon Changes over 40 Years for Loblolly Pine Conversion to Plantation Scenario (cont.)

YEAR	HARVEST	NONHARVEST	HARVEST - NONHARVEST	ABSOLUTE CHANGE IN EMISSIONS (+) OR REMOVALS (-)	DISCOUNT PERCENTAGE	VALUE WHEN DISCOUNTED TO YEAR 1 (tC/ha)
2038	85.1	100.0	14.9	-0.2	33	-0.1
2039	86.2	100.3	14.1	-0.8	32	-0.3
2040	87.7	100.6	12.8	-1.3	31	-0.4
2041	89.7	100.8	11.1	-1.7	30	-0.5
2042	92.0	101.1	9.1	-2.0	29	-0.6
2043	94.6	101.3	6.7	-2.3	27	-0.6
2044	97.4	101.6	4.2	-2.5	26	-0.7
2045	100.4	101.8	1.5	-2.7	25	-0.7
2046	95.4	102.1	6.7	5.2	24	1.3
2047	94.4	102.3	7.9	1.2	23	0.3
2048	96.1	102.6	6.5	-1.5	23	-0.3
2049	98.2	102.8	4.6	-1.8	22	-0.4
2050	100.5	103.0	2.5	-2.1	21	-0.4
			Difference at 40 years	2.5	4% PDV	10.0

Notes: PDV = present discount value. In the example, the U.S. Southeast site is converted to loblolly pine plantation based on existing wood usage and with substitution effect. The absolute carbon change over 40 years (summing the column) is 2.5 tons of carbon emissions per hectare (tC/ha) and the present discount value is 10 tC/ha.

Source: Carbon Harvest Model.

Table C2 shows the global results with different discount rates. For example, in the secondary growth scenario, the gross emissions vary between 4.1 $GtCO_2e$/year with either a 4 percent or 6 percent discount rate and 3.9 $GtCO_2e$/year with a 0 percent discount rate. The 0 percent discount rate scenario also shows the absolute results after 40 years (annualized by dividing by the number of years).

Table C2 | Annual Average Time-Discounted Carbon Costs of Global Forestry at Different Discount Rates for Seven Scenarios over 40 Years

		DISCOUNTED VALUE TO YEAR OF HARVEST ($GTCO_2E$)						
		(1) SECONDARY FOREST HARVEST AND REGROWTH	(2) SECONDARY FOREST HARVEST AND CONVERSION	(3) SECONDARY FOREST MIXED HARVEST	(4) NEW TROPICAL PLANTATIONS	(5) HIGHER PLANTATION PRODUCTIVITY	(6) HIGHER HARVEST EFFICIENCY	(7) 50% LESS 2050 FUELWOOD DEMAND
0% (no discount)	Gross emissions	3.9	3.6	3.9	3.5	3.2	3.7	3.4
	Net emissions with substitution savings	2.9	2.5	2.9	2.6	2.2	2.7	2.5
2%	Gross emissions	4	3.7	4.1	3.6	3.4	3.8	3.6
	Net emissions with substitution savingss	3.1	2.7	3.1	2.7	2.5	2.9	2.7
4% (default)	Gross emissions	4.1	3.7	4.2	3.6	3.5	3.9	3.6
	Net emissions with substitution savings	3.2	2.7	3.2	2.8	2.6	3	2.8
6%	Gross emissions	4.1	3.7	4.2	3.6	3.6	4	3.6
	Net emissions with substitution savings	3.2	2.8	3.3	2.8	2.7	3.1	2.8

Note: $GtCO_2e$ = Gigatons of CO_2 equivalent.

Source: Authors' calculations.

APPENDIX D: PAPERS ASSESSING THE BIOPHYSICAL EFFECTS OF HARVESTING WOOD FOR BIOENERGY

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APPENDIX E: THE EFFECTS OF DISCOUNTING OVER 100 YEARS

To further examine the effect of discounting, we applied a 4 percent discount rate over 100 years as well as 40 years to our secondary regrowth scenario. Discounting is applied to each secondary stand harvested (including the carbon pools of various wood products) over a period of 40 years or alternatively 100 years after the harvest.

In general, with one exception, the only meaningful differences are in scenarios that involve existing plantations and 70 percent CLT. In this context, very high growth rates for plantations and high utilization rates for construction material mean that over time, there are increasing benefits to using the area to grow wood for construction. That is true even when the value of these benefits is discounted to the original year of harvest.

The significance differences are for existing plantations with the exception of conversion of secondary forest to plantation in Brazil. There are also significant additional benefits when converting secondary forests to plantation in Brazil.

Even though 100 years of discounting has a meaningful effect compared to 40 years of discounting in these plantation scenarios, the 70 percent CLT rate will be very hard to achieve.

Table E1 | Differences in Carbon Effects with Costs of Harvesting Wood for Construction, Discounting 100 versus 40 Years

SCENARIO	EXISTING WOOD USAGE			40% WOOD FOR MASS TIMBER			70% WOOD FOR MASS TIMBER			EXISTING WOOD USAGE			40% WOOD FOR MASS TIMBER			70% WOOD FOR MASS TIMBER		
SUBSTITUTION FACTOR	0.44 tC/tC									1.2 tC/tC								
	100	40	Diff	100	40	Diff	100	40	Diff	100	40	Diff	100	40	Diff	100	40	Diff
U.S. Pacific Northwest Hemlock-Sitka spruce																		
Secondary forest and regrowth	124	125	1	87	87	0	47	47	-1	115	116	1	46	46	0	-24	-24	-1
Secondary forest and conversion to plantation	127	115	-12	83	76	-7	37	36	-1	116	105	-11	36	35	0	-45	-35	11
Existing plantation	76	79	3	30	48	18	-18	15	33	64	71	7	-19	15	34	-103	-42	61
U.S. Pacific Northwest Douglas Fir																		
Secondary forest and regrowth	151	150	-1	109	107	-1	65	63	-2	140	139	-1	64	62	-1	-13	-16	-2
Secondary forest and conversion to plantation	150	136	-14	102	93	-9	52	48	-4	137	125	-13	51	48	-3	-37	-30	7
Existing plantation	71	72	1	29	43	14	-15	13	28	61	65	4	-16	13	29	-95	-41	54
U.S. Southeast Oak-hickory																		
Secondary forest and regrowth	36	37	2	18	19	1	-1	0	1	31	33	2	-1	0	1	-34	-33	1
Secondary forest and conversion to loblolly plantation	36	35	-1	13	13	1	-11	-9	2	30	29	0	-12	-9	3	-54	-49	5
U.S. Southeast Loblolly-shortleaf pine																		
Existing plantation	16	16	0	4	5	2	-9	-6	3	13	13	1	-10	-6	3	-33	-27	6
Brazil																		
Secondary forest and regrowth	33	34	1	19	20	1	7	8	1	30	31	1	5	6	1	-15	-14	1
Secondary forest and conversion to plantation	25	26	1	-28	-19	9	-78	-62	16	14	17	3	-82	-63	18	-171	-138	33
Existing plantation	-6	-6	0	-58	-50	8	-109	-94	15	-17	-15	2	-111	-94	17	-202	-170	32

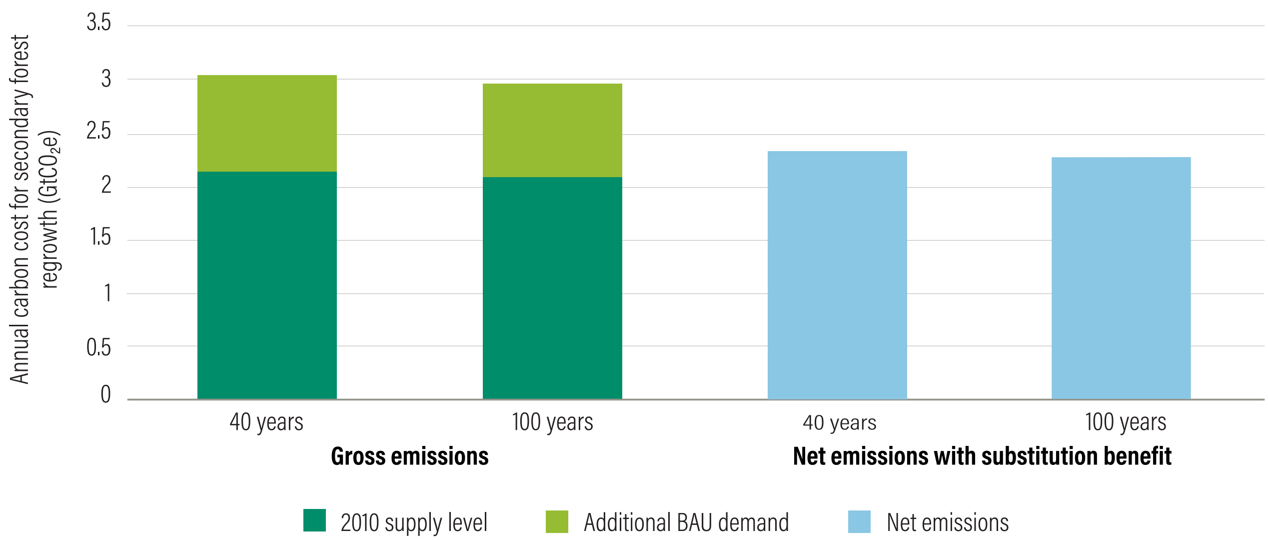
Table E1 | Differences in Carbon Effects with Costs of Harvesting Wood for Construction, Discounting 100 versus 40 Years (cont.)

SCENARIO	EXISTING WOOD USAGE			40% WOOD FOR MASS TIMBER			70% WOOD FOR MASS TIMBER			EXISTING WOOD USAGE			40% WOOD FOR MASS TIMBER			70% WOOD FOR MASS TIMBER		
SUBSTITUTION FACTOR	0.44 tC/tC									1.2 tC/tC								
	100	40	Diff	100	40	Diff	100	40	Diff	100	40	Diff	100	40	Diff	100	40	Diff
Indonesia																		
Secondary forest and regrowth	24	25	1	23	24	1	15	16	1	-20	-21	-1	13	14	1	-1	0	1
Secondary forest and conversion to plantation	19	22	3	13	18	5	-23	-13	10	-2	-9	-6	-26	-14	12	-89	-67	22
Existing plantation	-6	-4	3	-13	-9	4	-49	-40	9	22	16	-5	-51	-40	11	-116	-95	21
Germany																		
Secondary forest and regrowth	60	61	0	50	51	0	28	28	0	54	54	0	26	26	0	-14	-15	0
Secondary forest and conversion to plantation	62	58	-4	51	48	-3	27	25	-1	55	52	-3	25	24	-1	-20	-17	2
Existing plantation	46	61	15	36	55	19	12	40	28	39	57	18	10	40	29	-33	13	46

Notes: Analysis shows present discount t value in tons of carbon per hectare of harvest using 4 percent discount rate. Positive means increased emissions; negative means carbon savings. Green cells show results of 100 years that are less adverse than those of 40 years for the climate while pink cells show results of 100 years that are more adverse than those of 40 years for the climate. The zero values can represent either negative small values (red cells) or positive small values (green cells) due to rounding.

Source: Carbon Harvest Model.

Figure E1 | Difference between 40-Year and 100-Year Discounting for Secondary Forest Regrowth Scenario (Scenario 1) with 4 Percent Discounting



Note: BAU = business as usual. $GtCO_2e$ = Gigatons of CO_2 equivalent.

Source: Carbon Harvest Model.

ABBREVIATIONS

AGB	aboveground biomass
BAU	Business as usual
BEF	Biomass expansion factor
BGB	Belowground biomass
Bha	billon hectares
C&S	concrete and steel
CHARM	Carbon Harvest Model
CLT	cross-laminated timber
CO_2e	carbon dioxide equivalent
DM	dry matter
FAO	Food and Agriculture Organization of the United Nations
FE	fixed effects
FLUS	Future Land Use Simulation
GHG	greenhouse gas
GR1	growth rate of less than 20 years of age
GR2	growth rate of greater than 20 years of age
GRUMP	Global Rural-Urban Mapping Project
GtC	gigaton of carbon
$GtCO_2e$	gigaton of carbon dioxide equivalent
GWP	global warming potential
IIASA	International Institute for Applied Systems Analysis
IND	industrial roundwood
IND-M	main industrial roundwood
IND-O	other industrial roundwood
IND-PS	industrial roundwood used for pulping and sawing
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle assessment
LINE	linear extrapolation
LLP	long-lived product
LLP-M	main long-lived product
LLP-O	other long-lived product
LPG	liquefied petroleum gas
MgC	megagram of carbon
Mha	million hectares
NPP0	net primary productivity of native vegetation
OECD	Organisation for Economic Co-operation and Development
OSB	oriented strand board
PDV	present discount value
PPB	paper and paperboard
PS	pulp and sawn
RSE	residual standard error
SF	substitution factor
SLP	short-lived product
SNW	sawn wood
SR	Slash rate
SSP	Shared Socioeconomic Pathway
tC	tons of carbon
UNEP	United Nations Environment Programme
VSLP-IND	very-short-lived product, industrial waste
VSLP-IND-O	very-short-lived product, other industrial roundwood waste
VSLP-WFL	very-short-lived product, wood fuel
WBP	wood-based panels
WPL	wood pulp

ENDNOTES

1. Houghton and Nassikas (2017) estimated total carbon losses of around 150 Gt. Agricultural land use was found to result in a cumulative loss of 133 GtC in the upper two meters of soil, a difference between potential (3,144 GtC) and 2010 soil organic carbon stocks (3,011 GtC; Sanderman et al. 2017), or a cumulative loss of 98 GtC in croplands for 1850–2015 (Houghton and Nassikas 2017). Carbon losses from wood harvesting (including the oxidation of woody debris and wood products) between 1850 and 2015 were 135 GtC, but these losses were offset by 109 GtC from the forest regrowth after harvest, leading to net losses from wood harvesting of only 25. GtC, 17 percent of the land-use-induced historical cumulative emissions.

2. See MAPA n.d.

3. Beef imports to China increased by 1.2 million metric tons of beef during this period (Wiedower 2019). At even an optimistic yield of 100 kilograms of beef per hectare per year, substantially more than typically generated in Brazil's Cerrado (Cardoso et al. 2016), that implies 12 Mha producing beef for China.

4. In theory, losses due to forestry on land adjacent to actual forest clearings could be captured by bookkeeping methods. But this paper also summarized evidence that clearings in tropical forests also led to substantial carbon loss due to various physical forms of forest degradation, such as temperature effects and loss of seed dispersal due to effects on wildlife. Another major factor is the failure to count the loss of carbon sequestration in intact forests.

5. See Meinshausen et al. 2009; Figueres et al. 2017. For example, Meinshausen et al. estimated a need to hold emissions to 1,000 Gt between 2000 and 2050 to provide a 75 percent chance of holding warming to 2°C. As carbon dioxide emissions were roughly 600 Gt between 2000 and 2020, that leaves only a 400 Gt gap by 2020.

6. See World Bank n.d.a. The World Bank calculated the poverty head count ratio at $1.90 a day (2011 purchasing power parity).

7. Our estimate relies on dietary projections published by FAO in 2012 (Alexandratos and Bruinsma 2012), which assumed that people in India continue to consume few animal products because of cultural choices and that people in Africa consume even fewer because of poverty. Nearly all other estimates are higher (Valin et al. 2014), and our estimates assume that global growth in the future does not match estimates based entirely on relationships in the past to income and projected income trends (Tilman and Clark 2014).

8. Even the global areas of pasture have estimates that vary by more than 1 Bha (Fetzel et al. 2017), which is partly due to definitions and to poor data. Output per hectare depends on the quantity and quality of grass produced and the different animal characteristics, and the data on these is even worse. A large quantity of feed for cattle in Africa and Asia comes from "cut-and-carry" forages, which are grasses or leaves cut by people and fed to cattle in stalls, but the area and yields of land devoted to producing such forages are basically unknown. Modelers generally use highly stylized estimates of feed, feed production, and productivities to project future estimates.

9. Table Notes-1 lists urban area estimates from different sources based on different definitions.

Table Notes-1 | Historical Global Urban Extent (Mha)

Dataset	Definition	Resolution	Global urban area
GLC2000[a]	Artificial surfaces and associated areas	~1km	30.8 Mha (0.23%)
GlobCover[b]	Artificial surfaces and associated areas (>50% of a pixel)	~0.3km	31.3 Mha (0.24%)
GRUMP[c]	Not specified; nightlight data	~1km	350.7 Mha (2.64%)
GAEZ[d]	GLC2000 land cover plus population density relationship	5′ (~9km)	152.0 Mha (1.14%)
HYDE v3.1[e]	Built-up area and artificial surfaces and associated areas	5′ (~9km)	53.8 Mha (0.40%)
MODIS v5[f]	Dominated by built-up area (>50% of a pixel)	~0.5km	65.9 Mha (0.50%)

Notes: a. Bartholomé and Belward 2005; b. Bontemps et al. 2011; c. CIESIN et al. 2011; d. Fischer et al. 2012; e. Klein Goldewijk et al. 2010; f. Friedl et al. 2010.

10. To estimate this, we simply scaled our global estimate of carbon losses due to agricultural expansion of 593 Mha, which was 197.5 $GtCO_2e$ over 40 years, to the estimated urban expansion of 80 Mha (197.5 * 80/593 = 26.6).

11. For all models, P values were less than 0.05. If an individual country's fixed effects are included, we found good statistical fits with "full model" R^2 values varying from 0.88 to 0.98 across 12 models. If looking at how much of the country's variation in wood consumption is captured by the model, namely, the country's fixed effects are not included, the "projected model," R^2 values vary from 0.08 to 0.65. Overall, relationships are strong between per capita income and consumption of various

forms of industrial roundwood, but the relationships between income and consumption of fuelwood are much less strong.

12. Wood consumption at the country level was based on the reported production, export, and import of forestry products from FAOSTAT (FAO 2020a). Historical GDP data come from the World Bank (World Bank n.d.a) and future GDP data from the ENV-Growth model SSP2 of the Organisation for Economic Co-operation and Development (OECD). Future population projections, as in Searchinger et al. (2019), came from the United Nations Department of Economic and Social Affairs (UNDESA 2019a). All of the future projections are calibrated to match historical statistics for the reference year of 2010 using an average of 2008–12 to avoid overreliance on the results of year 2010. Future GDP data were obtained from the OECD ENV-Growth model SSP2 (middle of the road) and converted from constant 2005$ to match the World Bank unit in constant 2010$ with an inflation rate of 1.12 (see U.S. Inflation Calculator, https://www.usinflationcalculator.com/).

13. European forest area increased from roughly 25 percent of total land in 1900 to roughly 33 percent today, according to a reconstruction of European land use provided by Richard Fuchs, which is summarized in a number of published papers (including Fuchs et al. 2015 and Fuchs et al. 2013). The role played by the decline of draft animals is summarized by a large decline in forage used for draft animals as reconstructed in Malanima (2020b), used in support of Malanima (2020a).

14. Following personal correspondence with Dr. Rob Bailis at the Stockholm Environment Institute, we developed a substitution factor for the use of VSLPs for energy in wood cookstoves versus propane stoves. According to Dr. Bailis, one must burn only 90 grams (g) of liquefied petroleum gas (LPG) to obtain the same "useful energy" as 1 kilogram (kg) of air-dry wood or charcoal. Assuming perfect combustion, burning 1 kg of wood yields approximately 1.6 $kgCO_2$. The 90 g of LPG, which is 85 percent carbon, yields 0.26 $kgCO_2$. This gives a ratio of 1 $kgCO_2$ avoided from fossil fuels per 5.7 $kgCO_2$ from wood combustion. We incorporate this avoided emissions benefit into our calculation.

15. Indústria Brasileira de Árvores reports an average eucalyptus yield of 35 m^3/ha/year, which is roughly 16 dry tons (IBÁ 2020).

16. Churkina et al. (2020) provides a way of calculating the construction wood demand for newly built urban areas. This wood demand between 2010 and 2050 is the product of additional urban population, wood mass per capita, carbon-to-wood ratio, and the timber replacement pace ratio:

$$M_{2010}^{2050} = (P_{urban}^{2050} - P_{urban}^{2010}) * M_{timber}^{cap} * CW * PR$$

P_{urban}^{2010} = urban population in 2010 for each country
P_{urban}^{2050} = urban population in 2050 for each country
CW = carbon to wood ratio; all calculations are made with a carbon-to-wood ratio of 0.5, which is the global average of 0.476± 0.049 corrected to the first decimal place.
PR = timber replacement pace ratio, which is 0.1, 0.5, and 0.9 for 10 percent to timber, 50 percent to timber, and 90 percent to timber scenarios, respectively; the 10 percent timber scenario refers to countries with the capacity to manufacture mass timber products for the construction of new urban buildings; the 50 percent timber scenario refers to the countries with a high potential to construct new urban buildings with timber; the 90 percent timber scenario refers to the countries with low industrialization levels that will make the transition to timber through the evolution
M_{timber}^{cap} = mass of timber/wood fiber per capita estimated for primary structure and enclosure (Table Notes-2).

Table Notes-2 | Mass of Timber/Wood Fiber per Capita

	Primary structural system	Enclosure system timber	Enclosure system wood fiber
Timber/wood (kg/capita)	5942.50	1104.53	391.98

Source: Churkina et al. 2020, Supplementary Table 3-4.

Additional new urban construction wood demand. Using the SSP2 population and urban population share of 2010 and 2050, we determine that the global urban population increase for this period is 2,760,704,246. We then calculate the global additional construction wood needs for the 10 percent and 50 percent timber scenarios using the above equation based on Churkina et al. (2020), which are 2,053,690,649 and 10,268,453,247 tons of dry matter wood, respectively.

How much change is that? The industrial roundwood (LLP and SLP) demand for the reference year 2010 is 748 million tons of dry matter. Our BAU projection for industrial roundwood in 2050 is 1,332 million tons of dry matter. Figure 17 shows the BAU projection between 2010 and 2050. Assuming a linear increase from 2010 to 2050, BAU wood demand has a 78 percent increase relative to 2010, and the additional wood demand during the 41 years is 11,975 million tons of dry matter (light green triangle in Figure 17). Adding the 10,268,453,247 tons (yellow and brown triangles in Figure 17) to the BAU scenario, the percentage change of timber demand from 2050 to 2010 increases from 88 percent (BAU) to 201 percent (BAU and 50 percent timber scenario).

17. We used the U.S. production and consumption of timber products for 1965–2017 in Howard and Liang (2019, Table 5b). We aggregated the "lumber" and "plywood and veneer" to LLPs and used "pulpwood-based products" for SLPs. We then applied a regression analysis upon LLP production and SLP

production or consumption. We found that LLP production does not respond with SLP production (R^2 = 0.003) and consumption (R^2 = 0.002).

18. The paper also studied some obviously beneficial options that involve shifting the uses of wood, such as shifting paper production into LLPs. Those benefits, which are independent of harvesting less, would depend on reduced paper consumption and result from that reduced consumption.

19. This paper interestingly found the same general result when also factoring in changes in albedo.

20. This result reflects the paper's midrange estimate for substitution values.

21. That is the estimated savings for wood used in multistory housing in Smyth et al. (2017), which is the type of housing likely to use structural panels.

22. The comparison requires knowledge of how much wood substitutes for how much concrete and steel and the information attributed to each product.

23. Churkina et al. (2020) do not actually provide the substitution value, but their supplement provides all the information necessary to calculate the substitution value. According to the inputs provided, using wood to replace "composite" steel and concrete buildings saves 0.51 tC/tC in wood for residential housing and 0.44 tC/tC in wood for commercial buildings. The percentage reductions are our calculations that follow from the numbers provided in the Churkina et al. (2020) supplement of production emissions intensities for each product (ignoring changes in forest carbon) and the quantities used in different forms of construction. The example given is for composite systems of steel and concrete, the most likely alternative construction forms (and they are similar to replacing wholly concrete or wholly steel construction systems provided by the paper).

24. See U.S. Inflation Calculator, https://www.usinflationcalculator.com/.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

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