One Earth

Gold Standard for the Global Goals
1 ton of CO_2 offset

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Commentary

Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits

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The built environment is hard to decarbonize but has a pivotal role in climate-change mitigation amid rapid urbanization. Substituting conventional building materials with bio-based materials that store carbon offers one possible solution. Here, we reflect on the capacity of global forests to deliver the floor area required by mid-century.

Buildings and construction account for ~40% of global final energy use and energy- and process-related emissions.[1] The efficiency of buildings while in operation has received great attention over the past four decades. Meanwhile, the embodied greenhouse gas emissions linked to material manufacture, transportation and construction, and end-of-life disposal only recently received global attention. These emissions are of great concern because (1) construction is a hard-to-decarbonize sector[2] and (2) global urbanization and population growth will add 230 billion m^2 of new buildings by 2060, the majority of which will be in the Global South.[1] A continued use of conventional building materials poses significant carbon-lock-in challenges because emissions linked to the manufacture of steel and cement are incurred now on carbon-intensive energy sources and then locked into buildings and their assemblies for their whole decades-long lifespan.

One of the most effective strategies for mitigating embodied emissions is through interventions at the material level.[3] These interventions can be clustered into material efficiency (using less of the same material) and material substitution (using alternative materials with lower embodied emissions). When conventional materials are substituted, a further opportunity exists if the choice falls on so-called bio-based materials that can store carbon. The transition to zero-carbon cities requires the use of carbon-storing materials because of both their storage potential and their reduced life-cycle emissions. A recent study estimated[4] that, with aggressive adoption of bio-based structural materials, the cumulative total carbon storage in primary building structures between 2020 and 2050 could range from approximately 7 to 60 Gt CO_2 depending on the floor area per capita. However, this is a theoretical limit that raises practical questions of feasibility and sustainability based on the timber potential offered by global forests and other carbon-storing materials.

Which Materials Can Store Carbon?

Carbon storage in construction materials can be classified into two categories based upon their carbon-uptake mechanism. Bio-based materials (e.g., timber and bamboo) convert CO_2 into biomass through photosynthesis during the growth of the plant before being processed and used as materials. Cementitious materials (e.g., concrete and mortar) instead absorb carbon through the carbonation of hydration products. A portion of the globally significant carbon emissions released during manufacturing (from the calcination of limestone) are reabsorbed as the concrete ages. This carbon-uptake process is slow and depends upon a variety of factors, such as the surface area exposed and the diffusion rate of CO_2 through the material. Although cementitious materials are ubiquitous in construction, the amount of carbon absorbed is a fraction of the carbon emissions required for manufacturing the concrete; thus, they are net carbon emitters.

Carbon-storing materials are most commonly used in building structures, envelopes (e.g., facades), and insulation. Timber has been used for centuries as a structural material and has become more prominent as a low-carbon solution for mid- and high-rise buildings as global urbanization drives buildings to be taller. Bamboo is a fast-growing bio-based structural material that can be grown around the world and has the potential both to meet the increasing demands of the Global South's building stock and to store carbon. In building envelopes, insulation materials such as blown cellulose, cork, and hempcrete reduce the energy needed to heat and cool a building while also providing carbon storage. Figure 1 compares the "cradle-to-gate," or manufacturing, emissions against the carbon uptake of various carbon-storing materials on a per-mass basis (kg CO_2e per kg material). This figure should not be used for making comparisons between materials because there is no functional equivalence between each material's usage.

The comparison between carbon uptake in a bio-based product and carbon emissions is not always one to one. The timing of emissions, harvest cycles, management practices, and end-of-life scenarios has an impact on the amount of carbon that is eventually stored in both the ecosystem and the bio-based product that is removed from it. As a result, we must take a more nuanced approach, such as using dynamic life-cycle inventories, when considering how to treat the uptake of carbon in the environmental accounting of buildings.

Of all bio-based materials, timber is the one that has received the most global

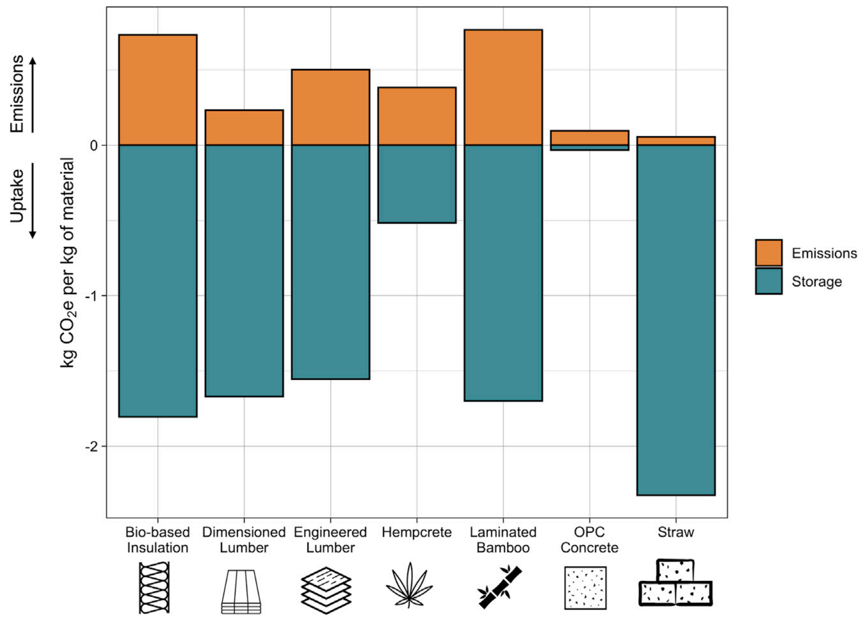

Figure 1. Net Carbon-Storage Potential of Building Materials
The carbon-storage potential (negative values) compared with the cradle-to-gate emissions (positive values) associated with manufacturing the material per kilogram of material.[5]

attention for its increasing potential to compete with steel and reinforced concrete in building structures.[4] We explore the global potential for timber buildings and related sustainability challenges and questions in the next sections.

Timber Buildings: Panacea or Threat to Ecosystems?

Three broad strategies can be used to meet the growing demand for timber in buildings while attempting to meet climate-change mitigation and sustainable development objectives. First, we can plant new areas of forestry, managed to maximize productivity. Such projects can only help us to meet demand for construction products in the long run (when trees are ready for harvest, usually well beyond 2050), by which time the benefits of substituting materials in a decarbonized economy will be lower anyway.

Second, we can extract more timber from existing forests and reforest as we go. This can be a reasonable option in some contexts, but it is risky in terms of the damage that might be done to ecosystems, from soil and groundwater to the forest canopy. Also, in and around regions prone to deforestation, increased extraction should of course be avoided because the rate of extraction already exceeds the growth rate. The scope for increased carbon storage in buildings referred to above[4] should be understood in the context of declining carbon storage in the forest. Even at current rates of consumption, carbon stored in the world's forests has reduced by 0.73 $GtCO_2$ per year since 1990,[6] a number that might increase if demand increases.

Third, we can use timber more wisely by diverting it from uses that offer little climate benefit to uses that capitalize on the advantages that timber products have over their counterparts. This would involve mobilizing the construction industry, globally, to understand and to act on how to use its share of the world's timber resources most effectively. Industry and governments can work together by eliminating incentives to burn wood while developing markets for products that can make good use of lower grades of timber and by-products: wood-fiber insulation is a case in point. With every year that passes, the carbon intensity of energy displaced by biomass combustion is reduced, and any argument for continuing to support its use is diminished.

One general approach to promoting the sustainability of forests in response to increased timber demand is to ensure that extraction in each region is exceeded by growth, and it has been suggested that annual removals should not exceed 70% of the annual growth increment.[7] But regional differences in forest area (Figure 2A) and timber demand imply varying capacity to meet increased demand sustainably. Even though more than a quarter of the world's forest area is valued primarily for production, only 3% is intensively managed plantation forest. Intensively managed plantation forestry, in suitable contexts, can easily generate sufficient timber to produce 4 $m^3 ha^{-1} year^{-1}$ (~2 t $ha^{-1} year^{-1}$) of sawnwood. However, if we aggregate across wider areas, we see much lower yields: the corresponding figure is around 0.35 t $ha^{-1} year^{-1}$ for the EU and 0.06 t $ha^{-1} year^{-1}$ for global forests. Many factors contribute to these regional differences. For instance, according to the 2020 Global Forest Resources Assessment of the UN Food and Agriculture Organization (FAO),[6] more than a quarter of global forest area is still primary forest, untouched by commercial activities. Additional areas are protected for other purposes.

Can Timber Supply Match Demand Sustainably?

This potential increase in demand for timber for building materials threatens to intensify deforestation and illegal logging,[11,12] which must be eradicated. Some studies suggest that global forest area is actually increasing,[13] whereas others report an increase in harvested forest area of 49% and an increase in biomass loss of 69% between 2011–2015 and 2016–2018.[14] The World Bank[8] reports close to 40 million km^2 of global forests (2016 data), whose breakdown at the country level as a percentage of land area in each country is shown in Figure 2A. Studies on global urbanization[9] have investigated where the hotspots of population growth and urbanization are likely to be; related estimates of the demand for new floor area by 2050 are shown in Figure 2B. Combining these figures with recent estimates[10] of material intensity for timber-based construction, we develop simplified supply-demand estimates through mid-century.

According to these estimates, global demand in 2020–2050 would exceed supply by ~3,900 Mt with current figures for forest area, and total timber supply represents only ~36% of what would be

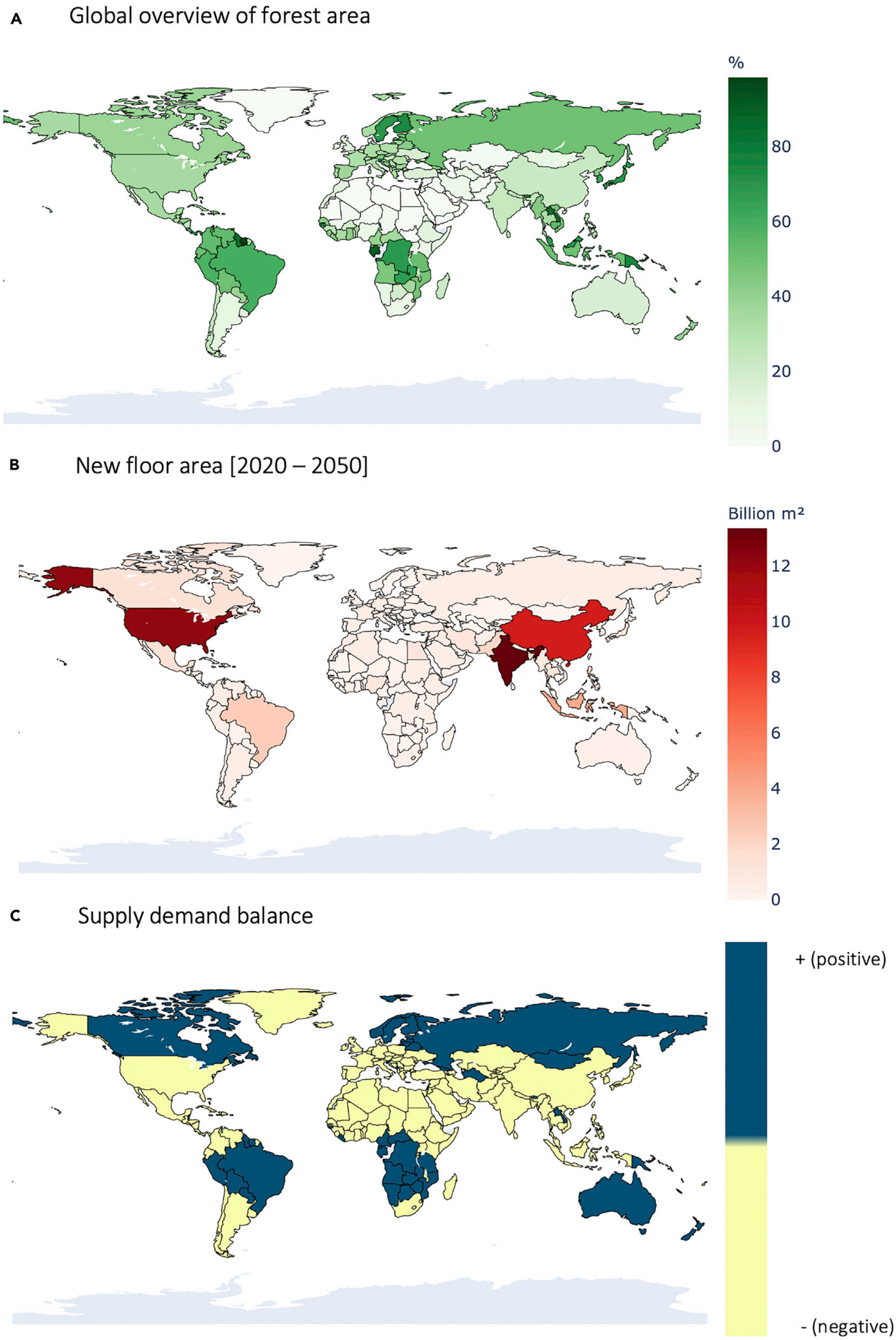

Figure 2. Simplified Supply-Demand Model for Timber-Based Floor Area Globally by 2050
(A) Global overview of 2016 forest area as a percentage of land area according to data from the World Bank[8] (n = 264 countries).
(B) New floor area required for 199 countries in the world[9] between 2020 and 2050.

(legend continued on next page)

required for building all projected new floor area out of timber. This is significantly different from recent work[4] that estimated the possibility of a timber-only world delivered within the current forest capacity. However, our estimates are all based on national-level supply-demand balances and do not directly consider global timber trade. Our simplified national-level estimates of supply-demand balance are a preliminary effort to demonstrate the need for more robust supply-side scenario analyses to address concerns about trans-national deforestation pressures, embodied emissions, and related ecosystem impacts that could result from increased timber demand.

The analysis shown in Figure 2C is intended as a simplified preliminary estimate, and as such it assumes no increase in each country's forest area between now and 2050. We assume that the area cleared annually for construction timber is sustainably managed and replanted with similar species that will come to fruition in future decades. This is a simplified global model with limitations. From Figures 2B and 2C, it is evident that there are countries with limited demand for new floor area and an apparently abundant supply potential for construction timber. Globally, though, the supply-demand balance is unfavorable such that more timber is needed than actual forests can produce. Much future construction will be in areas that have the kind of timber that we should preserve, and as such ensuring viable routes for timber construction is paramount to succeeding in its intended use as a sustainability catalyst for the built environment. Several countries in blue have problems with the sustainability of their timber supply. Deforestation issues in the Amazon basin and in Siberia, for instance, are well known. Even Scandinavian countries have been harvesting timber faster than it grows in recent years because demand has increased: even if deforestation per se might not be the issue here, this raises the question about "net carbon sink or displaced carbon storage" that we address in the following section.

Net Carbon Sink or Displaced Carbon Storage?

Growing and felling trees, clearing up the land, sawing, milling, drying, transporting, and constructing all require energy and incur emissions. Far into the future, the carbon stored in timber will, however, return to the environment. One might ask, is it still worth it? The answer is, as usual, it depends. Competition for land is high across sectors of the global economy—there is rising demand for pulp and paper and from agriculture—and it is a fine balance to meet immediate needs while guaranteeing Earth's capacity to regenerate resources and provide goods and services in the future.[15] If trees are felled and not replaced, then timber-based construction is simply an inefficient form of displacing carbon from forests in one region to cities in another region with the certainty that a mature living tree will continue, no matter how slowly, to sequester carbon, whereas a timber beam surely will not. Combined with well-designed timber supply-side policies, a rigorous approach to sustainably managing forest resources could actually increase the global amount of stored carbon by maintaining (or, better yet, increasing) carbon sequestered by forests while increasing carbon stored in buildings. Our simplified global model challenges timber as a "one-size-fits-all" solution.[4] For most countries in the world, a timber-only solution is neither possible nor desirable. Faster-growing bio-based materials (e.g., bamboo and grasses) that have greater yields can be explored as alternatives that might be able to partially satisfy the demand for bio-based building materials. This requires an interdisciplinary approach to understanding how to supply and build the floor area that the world needs in the next three decades in such a way that maximizes the carbon-storage potential and minimizes the tradeoffs for the sustainable management of global forest ecosystems.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further information and requests for resources should be directed to the corresponding author, Francesco Pomponi (f.pomponi@napier.ac.uk).

Materials Availability

This commentary did not generate new unique materials.

Data and Code Availability

See Mendeley Data: https://www.doi.org/10.17632/rtfmgzp357.1.

Simplified Supply-Demand Analysis

This commentary presents a supply-demand analysis based on a model that combines published and publicly available data to produce a simplified verification of the feasibility limits of timber buildings. For timber supply, we use data on forest area from the World Bank,[8] data on forest stocks, increment, and felling from the European Environment Agency,[7] and sawnwood yields from the FAOSTAT database of the FAO.[16,17]

The World Bank provides forest data at the country level for 264 countries.[8] Data are available both as a percentage of forest area over total land area in a country and as square kilometers of forest area in each country. The former is shown in Figure 2A; for the latter, we transform the value to hectares (ha) and label it f_{h_i}, where $i = 1\ldots247$ is an index that represents each country in turn.

As discussed in the main text, the European Environment Agency[7] recommends that commercial forests be around 30% of a country's total forest area to ensure sustainable growth and management. In our simplified analysis, we utilize an average global figure for the yield of sawnwood from forest area. This datum comes from the FAO.[16,17] Specifically, within data for "Forestry Production and Trade," we select "World Total" from "Regions," select "Production Quantity" from "Elements," select "Sawnwood Total" from "Items Aggregated," and select "2018" from "Years"; this shows a total value of 492,543,333 m^3 ($\approx$492 million m^3). From the same source,[4] we look at "Forest Land" data: we select "World Total" from "Regions," select "Area" from "Elements," select "Forest land" from "Items," and select "2018" from "Years"; this shows a value of 4,068,908,476.4 ha ($\approx$4,068 million ha). The division between these two numbers yields an average of 0.1210 $\approx$ 0.12 m^3/ha. We transform the value of 0.12 m^3/ha into 0.06 t/ha by assuming a density of ~0.5 t/m^3. This is lower than the overall mean calculated from analyzing 2,456 tree species,[18] thus representing a conservative hypothesis in our analysis. We label this average global yield for wood as $\overline{\eta}_{G_w}$.

These data allow us to calculate the annual available timber supply at the country level as $T_{S,a_i} = 0.3 \cdot f_{h_i} \cdot \overline{\eta}_{G_w}$, where $i = 1\ldots247$ represents the index for each country, which we extend from 2020 to 2050 as $T_{S_i} = 30 \cdot T_{S,a_i}$.

The floor-area projections that we use come from recent academic work at the global scale.[9] Güneralp et al.[9] offer a projected increase in floor area from 2010 to 2050 at the global scale and break this down into world regions. Given the time horizon of our analysis, we focus on the additional floor area reported from 2020 to 2050 in the S50 scenario from Güneralp et al.[9]—which represents the median estimate. In total, they cover 199 countries. However, data are aggregated at the regional rather than the country level. For instance, the projected increase in floor area is

(C) Global overview (n = 199 countries) of the supply-demand balance for the construction of timber according to a recent analysis of material intensities in buildings.[10] Countries in blue (n = 42) have commercial forest area remaining when all new projected floor area in the country is built out of timber, whereas countries in yellow (n = 157) do not have sufficient commercial forest area to meet the demand driven by the increase in floor area.
Calculations for obtaining the data shown in this figure are described in the Experimental Procedures.

given for the North American (NAM) region, which includes the US, Canada, the US Virgin Islands, Guam, and Puerto Rico. To break down the regional value to a value for each country within that region, we use population as a proxy because the correlation between the number of inhabitants in and the floor area of a country is a natural one. We label the gross floor area (GFA) projection for each country as p_{GFA_j}, where $j = 1 \ldots 199$. We show this in Figure 2B.

In order to estimate how much timber is required for building the projected floor area, we use novel findings from academic research on the material intensity of building structures[10] based on a large number (n = 31,380) of different structural frame designs. For cross-laminated timber (CLT), we use the material-intensity value of m_{CLT} = 80 kg/m^2. This value allows us to work out the total timber demand from 2020 to 2050 for each of the 199 countries as $T_{D_j} = p_{GFA_j} \cdot m_{CLT}$. The comparison between T_{S_i} and T_{D_j} (which of course can be done only for the 199 countries covered in Güneralp et al.;[9] these are a subset of the 264 countries covered in the World Bank data[8]) enables us to estimate which countries will have sufficient timber to meet the demand caused by the projected growth in floor area and which will not. This is shown in Figure 2C.

REFERENCES

1. International Energy Agency and the United Nations Environment Programme (2018). 2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector. https://www.unenvironment.org/resources/report/global-status-report-2018.
2. Committee on Climate Change (2018). Biomass in a low-carbon economy. https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy/.
3. Pomponi, F., De Wolf, C., and Moncaster, A. (2018). Embodied Carbon in Buildings: Measurement, Management, and Mitigation (Springer).
4. Churkina, G., Organschi, A., Reyer, C.P.O., Ruff, A., Vinke, K., Liu, Z., Reck, B.K., Graedel, T.E., and Schellnhuber, H.J. (2020). Buildings as a global carbon sink. Nat. Sustain. *3*, 269–276.
5. Arehart, J., Pomponi, F., D'Amico, B., and Srubar, W.V., III (2020). How much carbon can construction materials store?, Poster from AScUS (un)Conference 2020. https://ascus.metabolismofcities.org/presentations/18283/.
6. Food and Agriculture Organization (2020). Global Forest Resources Assessment 2020 – key findings. 10.4060/ca8753en.
7. European Environment Agency (2017). Forest: growing stock, increment and fellings. https://www.eea.europa.eu/data-and-maps/indicators/forest-growing-stock-increment-and-fellings-3/assessment.
8. The World Bank. Forest area (% of land area). https://data.worldbank.org/indicator/AG.LND.FRST.ZS.
9. Güneralp, B., Zhou, Y., Ürge-Vorsatz, D., Gupta, M., Yu, S., Patel, P.L., Fragkias, M., Li, X., and Seto, K.C. (2017). Global scenarios of urban density and its impacts on building energy use through 2050. Proc. Natl. Acad. Sci. USA *114*, 8945–8950.
10. D'Amico, B., and Pomponi, F. (2020). On mass quantities of gravity frames in building structures. J. Build. Eng. *31*, 101426.
11. Carrasco, L.R., Nghiem, T.P.L., Chen, Z., and Barbier, E.B. (2017). Unsustainable development pathways caused by tropical deforestation. Sci. Adv. *3*, e1602602.
12. Brancalion, P.H.S., de Almeida, D.R.A., Vidal, E., Molin, P.G., Sontag, V.E., Souza, S.E.X.F., and Schulze, M.D. (2018). Fake legal logging in the Brazilian Amazon. Sci. Adv. *4*, eaat1192.
13. Song, X.-P., Hansen, M.C., Stehman, S.V., Potapov, P.V., Tyukavina, A., Vermote, E.F., and Townshend, J.R. (2018). Global land change from 1982 to 2016. Nature *560*, 639–643.
14. Ceccherini, G., Duveiller, G., Grassi, G., Lemoine, G., Avitabile, V., Pilli, R., and Cescatti, A. (2020). Abrupt increase in harvested forest area over Europe after 2015. Nature *583*, 72–77.
15. Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., et al. (2005). Global consequences of land use. Science *309*, 570–574.
16. Food and Agriculture Organization (2018). FAOSTAT: forestry production and trade, data from 2018. http://www.fao.org/faostat/en/#data/FO.
17. Food and Agriculture Organization (2018). FAOSTAT: forest land, data from 2018. http://www.fao.org/faostat/en/#data/GF.
18. Chave, J., Muller-Landau, H.C., Baker, T.R., Easdale, T.A., ter Steege, H., and Webb, C.O. (2006). Regional and phylogenetic variation of wood density across 2456 Neotropical tree species. Ecol. Appl. *16*, 2356–2367.