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Timing of carbon emissions from global forest clearance

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Land-use change, primarily from conventional agricultural expansion and deforestation, contributes to approximately 17% of global greenhouse-gas emissions[1]. The fate of cleared wood and subsequent carbon storage as wood products, however, has not been consistently estimated, and is largely ignored or oversimplified by most models estimating greenhouse-gas emissions from global land-use conversion[2,3]. Here, we estimate the fate of cleared wood and timing of atmospheric carbon emissions for 169 countries. We show that 30 years after forest clearance the percentage of carbon stored in wood products and landfills ranges from about 0% to 62% globally. For 90 countries, less than 5% of carbon remains after 30 years, whereas 34 countries have more than 25% in storage. Higher storage rates result primarily from a greater percentage of long-lived products such as wood panels and lumber, and tend to occur in countries with predominantly temperate forests. Alternatively, lower storage rates are associated with a greater fraction of non-merchantable wood and more wood used for energy and paper production, which tend to occur in countries with predominantly tropical forests. Hence, the country and fate of cleared wood can considerably affect the timing of greenhouse-gas emissions from forest clearance.

Rising demand for agricultural products such as food, feed and bioenergy is a primary driver of forest clearance globally. In 2000, an estimated 1,510–1,611 million hectares (Mha) of cropland and 2,500–3,410 Mha of pasture existed[4]. Largely owing to population growth, food-based cropland and pasture is expected to increase by 2.7–4.9 Mha yr^{-1} and 0–5 Mha yr^{-1}, respectively[4]. Furthermore, meeting present mandates for biofuels may require an additional 1.5–3.9 Mha yr^{-1} (ref. 4). During the 1980s and 1990s, satellite imagery suggests that tropical forests were the main source of new agricultural land[5]. Future bioenergy production may also lead to substantial forest clearance and resulting greenhouse-gas (GHG) emissions[6–9]. Previous studies estimate that increases in biofuel production in either the United States or Brazil may lead to significant forest clearance domestically and abroad[6–8,10–12]. Such studies suggest that clearing pasture and, in particular, forests for bioenergy crops can emit large quantities of GHGs, potentially reversing bioenergy's climate benefit over fossil fuels.

Past land-use change (LUC) studies, however, carry out little to no analysis on the fate of cleared wood and stored carbon following forest clearance. Yet, carbon storage in wood products and subsequent decay in landfills in North America, Europe and globally have been investigated in depth[13–20]. Here, we bridge the gap between LUC models and wood-product carbon models. Specifically, we use the Intergovernmental Panel on Climate Change production accounting approach to temporally describe how much above-ground biomass carbon will be released to the atmosphere or remains stored in forest products and landfills after clearing a hectare of forest for 169 countries. Although we model carbon storage over 100 years, 30-year results are emphasized as a policy-relevant time frame.

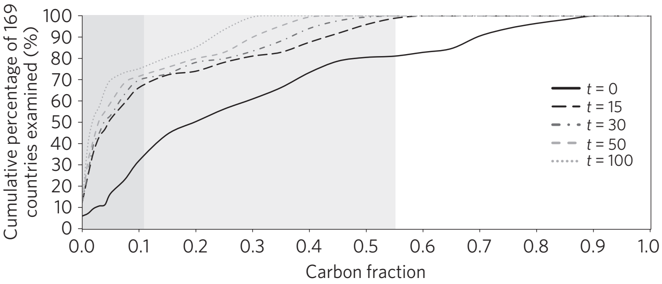

Figure 1 | Fraction of carbon remaining in wood products and landfills following land clearance for different time horizons. Darker shaded box represents countries with a high fraction of fuelwood, paper and/or non-merchantable wood at $t = 30$. Lighter shaded box represents countries with a high fraction of lumber, plywood and/or fibreboard at $t = 30$.

Immediately after forest clearance the amount of carbon remaining in wood products and landfills varies greatly among countries (see black line in Fig. 1). At time zero, this value depends on whether a tree is of commercial species and a minimum threshold for tree diameter that classifies it as growing stock. We estimate, for instance, that on average in the United States about 60% of above-ground live biomass is commercial growing stock. As another example, in Brazil we estimate that only 24% of wood is commercial growing stock (see Supplementary Information for entire list and detailed information, including definitions and method of calculation).

The trends in carbon retention differ between two groups of countries—countries with low relative production of long-lived solid wood products and countries with high relative production of longer-lived products. For countries that have a high fraction of non-merchantable wood and/or timber converted to fuelwood and paper either domestically or abroad, combustion fully releases carbon stored as fuelwood to the atmosphere shortly after forest clearance, and 95% of paper is assumed to be disposed of to a landfill within five years (after accounting for recycling). Thus, 30 years after forest clearance around 0–15% of carbon remains in storage for countries with a high fraction of fuelwood, paper and/or non-merchantable wood. Nearly 73% of countries fall within this category in year 30 (see $t = 30$ line in Fig. 1). For countries with a high fraction of merchantable timber and long-lived products such as lumber and wood panels (about 27% of countries), 15–55%

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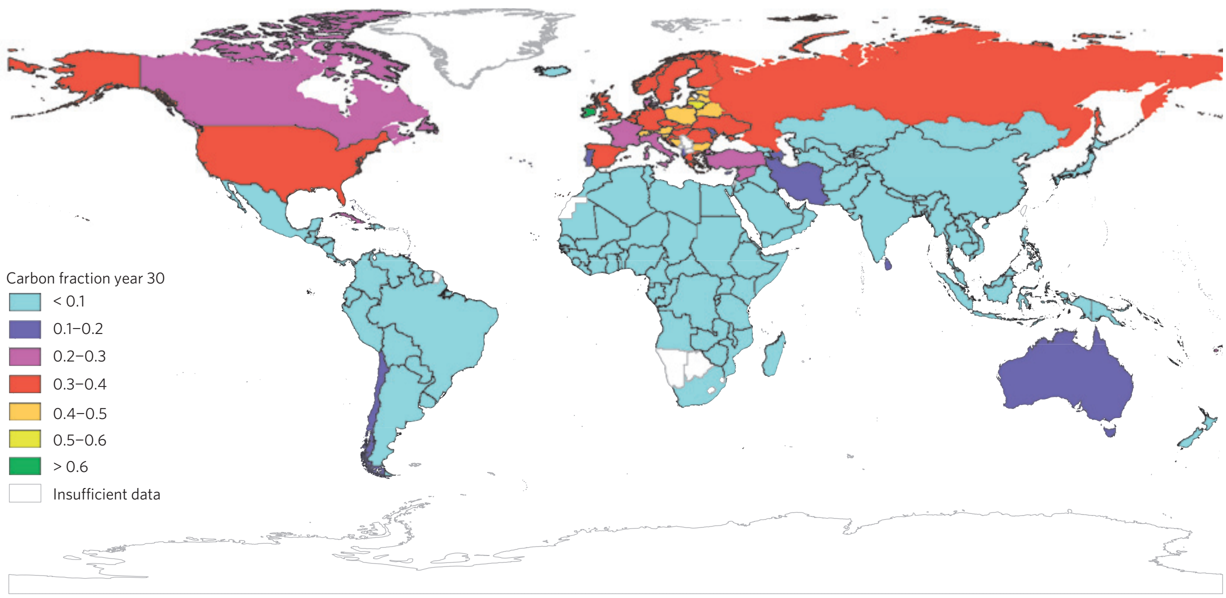

Figure 2 | Carbon remaining in storage 30 years after land clearance as a fraction of initial above-ground biomass.

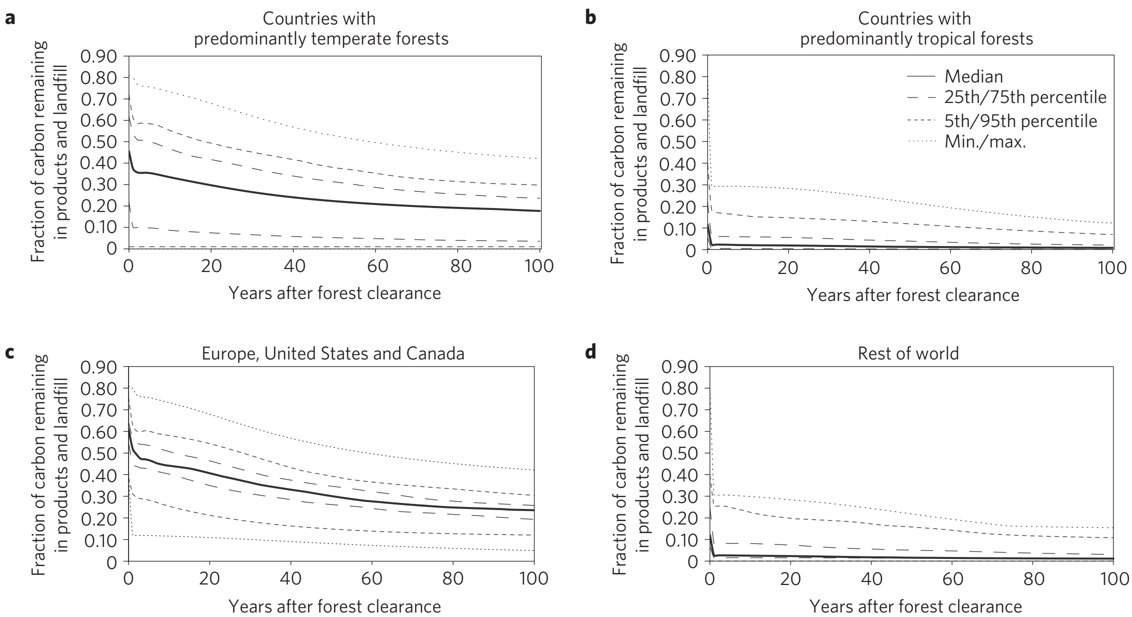

Figure 3 | Carbon storage following land clearance as a fraction of initial above-ground biomass. Top row aggregates carbon storage by predominant forest type defined as **a**, >75% area under temperate forest ($n = 64$) or **b**, tropical forest ($n = 99$) with mixed forest ($n = 6$) not shown. Bottom row aggregates carbon storage by region as **c**, Europe, United States and Canada ($n = 36$) and **d**, rest of world ($n = 133$).

of carbon is still stored in year 30. In these countries the fraction of carbon stored decreases to 10–35% by year 100. Figure 2 summarizes the fraction of carbon remaining in year 30 across all countries examined.

To identify differences in storage among countries we select two different types of country groupings (Fig. 3). Countries were first grouped by their predominant forest type: temperate and tropical. Countries with predominantly temperate forests show much greater variation relative to the median in carbon storage than those with predominantly tropical forests. Storage tends to be much higher where temperate forests are dominant. More than 75% of countries dominated by tropical forest have 5% or less carbon remaining in storage by year 30. During the same time frame, 50% of countries dominated by temperate forest have more than 25% carbon remaining in storage.

We next grouped countries into two regions: Europe/United States/Canada and rest of world. We find that more than 95% of countries outside Europe, the United States and Canada have 19% or less carbon remaining in storage after 30 years. For Europe, the United States and Canada 95% of countries have more than 18% carbon remaining after 30 years. The median carbon stored after 30 years is 2% for rest of world and 36% for Europe, the United States and Canada. Moreover, the variation relative to the median in the Rest of World category is substantially lower than that of Europe, the United States and Canada. Forest clearance in South American, Asian and African countries tends to transfer most forest carbon to the atmosphere in less than 30 years. European countries, the United States and Canada, however, may store substantially more carbon after forest clearance—delaying the release of some carbon to the atmosphere.

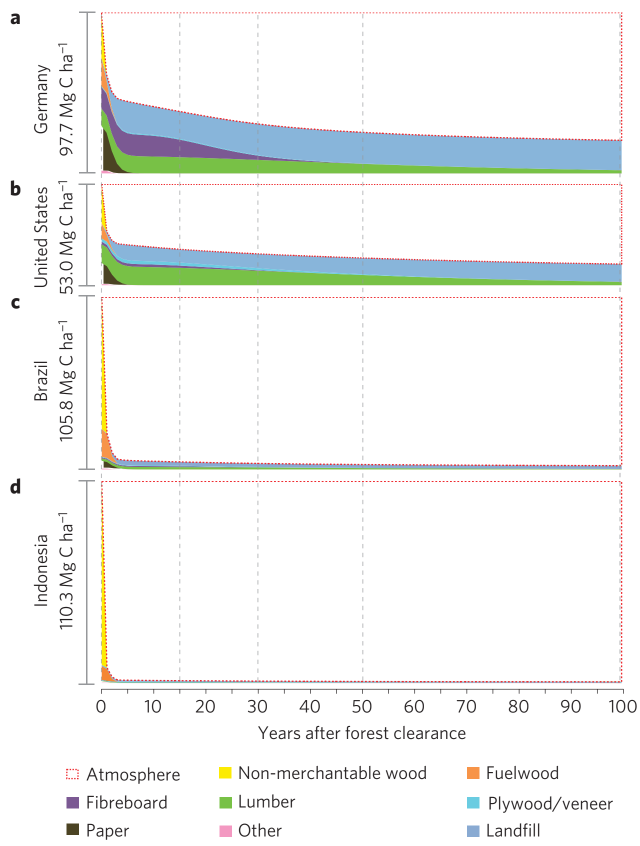

Figure 4 | Fate of carbon following forest clearance for four countries. **a**, Germany; **b**, United States; **c**, Brazil and **d**, Indonesia.

To understand the fate of cleared forests in more detail, we analyse the product-level fate of carbon in 169 countries. Four representative countries are illustrated in Fig. 4. Germany, for example, has an average of 97.7 Mg C ha^{-1} above-ground live biomass. When an average hectare of land is cleared, nearly 28% (27.4 Mg C ha^{-1}) of this biomass is assumed to be burned immediately as non-merchantable wood. More than 17% (17.2 Mg C ha^{-1}) is burned shortly after clearance as fuelwood (which includes charcoal and residues burned at mills). Another 28% (27.3 Mg C ha^{-1}) is used to produce paper, which enters the landfill either directly after its first use or after recycling, and is eventually released as CO_2 or CH_4 to the atmosphere. Lumber and fibreboard comprise 11% (10.6 Mg C ha^{-1}) and 13% (13.1 Mg C ha^{-1}) of carbon removals in Germany, respectively. These two products, along with plywood and veneer panels, largely drive long-term storage potential for a given country. Aside from its lower average above-ground live biomass, stored carbon in the United States follows a similar fate to that of Germany (see Supplementary Information for regional sensitivity analysis in the United States). Hence, Germany and the United States represent countries in which carbon stored in wood products may substantially reduce the GHG effects of forest clearance—especially under shorter time horizons (that is, 15–50 years).

Brazil and Indonesia's carbon disposition after forest clearance represent the Rest of World category, which differs greatly from that of Germany and the USA. Both countries have high initial above-ground live biomass stocks owing to their mostly dense tropical forests (Brazil = 105.8 Mg C ha^{-1}; Indonesia = 110.3 Mg C ha^{-1}). Land clearance rapidly releases this carbon to the atmosphere as most of the wood is either non-merchantable or used as fuelwood. Forest products capable of longer-term storage represent a very small fraction of the total above-ground live biomass carbon of these countries. Consequently, the GHG effects owing to forest clearance in countries such as Indonesia and Brazil will be dampened little by long-term storage of biomass in wood products.

The proportion of forest carbon consumed as wood products domestically versus abroad varies by country (Supplementary Fig. S6 and Table S12). About 4% of cleared wood in Indonesia is consumed abroad and 4% domestically, whereas 92% is non-merchantable. The United States consumes 50% domestically and exports 7%, whereas 43% of above-ground live biomass is non-merchantable. Thus, trade can play an important role in determining the location of carbon release with respect to wood products. However, in countries that have predominantly non-merchantable growing stock, such as Indonesia, carbon is more likely to be emitted at the site of forest clearance, making trade of secondary importance.

We assume that a somewhat uncertain fraction of fuelwood comes from growing stock (either commercial or non-commercial species) and the remaining fraction from non-growing stock. To examine the significance of this assumption we investigate a scenario in which fuelwood comes exclusively from non-growing stock. The fraction of carbon remaining after 30 years is greater than the case where some fuelwood originates from growing stock. In countries with predominantly tropical forests the fraction of initial above-ground carbon cleared that remains in storage for the upper 75th percentile shifts from 0.05 to 0.11. In countries with predominantly temperate forests the upper 75th percentile shifts less significantly from 0.38 to 0.42. Despite such shifts, there is still a substantial difference in carbon storage between countries with predominantly tropical and temperate forests (see Supplementary Figs S6 and S7).

The fraction of above-ground biomass relative to growing stock is also uncertain and can vary widely within a country[21]. To examine the significance of such uncertainty, we adjust fractions derived from the Food and Agricultural Organization 2010 Forest Resource Assessment[23] (FRA) by +50% and −50% with a minimum possible value of one meaning that above-ground biomass equals growing stock. In countries with predominantly temperate forests, the median fraction of carbon in storage after 30 years changes from 0.26 to 0.19 and 0.38 for the +50% and −50% scenarios, respectively. Countries with predominantly tropical forests experience a change in the median value from 0.02 to 0.01 and no change for the same scenarios (Supplementary Figs S7 and S8). Thus, even after such adjustments a substantial difference in carbon storage exists between countries with predominantly tropical and temperate forests. Notably, global above-ground biomass estimates vary considerably across previous studies[21]. Although adjusting above-ground biomass and growing stock proportionally will not affect the fraction of carbon stored, it will alter the quantity of carbon remaining after forest clearance, which should be considered when applying the fractions presented here in other studies. As documented in the Supplementary Information, the sensitivity of carbon storage to seven other parameters was tested and found to be of less significance than our assumption about the fraction of fuelwood from growing stock and relative fraction of above-ground biomass to growing stock.

Future work should examine several factors that are not included here. For instance, we consider only the flow of carbon stored in products. We do not consider the chemical species, CO_2 or CH_4 emitted from wood in use or wood in landfills. Applying a metric such as global warming potential[22] may be useful to include the additional effect of emitting CH_4 from landfills versus CO_2. Another limitation here is that we do not consider the spatial distribution of forest-product industries relative to land clearance. If spatially resolved data on forest-product facilities were available by country, further resolution may be achieved with respect to identifying the likelihood of storage versus on-site combustion. Similarly, the use of country-wide averages is a limitation that could be improved with spatially resolved data on forest clearance and wood removals. Finally, it is important to note that the carbon-storage factors do not include woody understorey, roots and dead wood. These compartments must be accounted for separately in carbon accounting associated with forest clearance.

Barring such limitations, our analysis supports the conclusion that the country and fate of cleared wood can have a considerable effect on the timing of GHG emissions from LUC. Indeed, given the importance of above-ground biomass GHG emissions in total LUC GHG emission estimates, land-use models should account for global variation in stored carbon after forest clearance. Carbon stored in forests outside Europe, the United States and Canada, for example in tropical climates such as Brazil and Indonesia, will be almost entirely lost shortly after clearance. At the same time, in Europe, along with the United States and Canada, carbon storage after forest clearance tends to be of increasing importance as the time horizon of analysis shortens. Along with these generalized findings, our research provides a global set of dynamic carbon-storage factors that can be used to improve LUC models and help develop carbon-mitigating bioenergy policies.

Methods

Here, we temporally describe how much above-ground biomass carbon will be released to the atmosphere or remains stored in forest products after clearing a hectare of forest for 169 countries in the world. We begin with country-specific growing stock data (in terms of $m^3\ ha^{-1}$) collected for the FRA[23]. The fraction of merchantable versus non-merchantable wood is then determined using 2010 FRA data on per cent commercial tree species and biomass expansion factors. Of the merchantable fraction, we estimate the proportion of growing stock that ends up in eight end-products: fuelwood, charcoal, mill-fuel residues, pulp/paper, fibreboard, plywood/veneer, lumber and other uses. The ForeStat database of the Food and Agriculture Organization of the United Nations provides production and trade data by country that can be used to estimate the relative quantities and location of production/consumption for each end-product. To link the growing stock data and the production data, we use manufacturing coefficients estimated for the US Forest Products Model[24] that describe the amount of wood input required per unit of end-product output (for example cubic metre of growing stock per cubic metre of plywood). By combining these data sets we end up with an average volumetric estimate of the fate of wood following the clearance of a hectare of land for 169 countries.

In the second stage of this research, we convert these volumetric estimates into tons of carbon per hectare cleared and track their fate over time. To do this, we characterize the use stage for each product using a gamma distribution as put forward by Marland and colleagues[25]. A very small fraction of lumber, for instance, will begin to exit use after year one. The amount of lumber exiting the product pool peaks at 35 years with 95% removed after 150 years. Each product has unique parameters defining its use curve, which are listed in the Supplementary Information. As a product exits use, it is either recycled, landfilled or incinerated. Landfill decomposition rates are modelled based on country-specific climatic and landfill conditions, using an exponential decay curve as described in ref. 22. The final result is a global set of dynamic carbon-storage factors that can easily be applied to LUC modelling to more precisely represent carbon storage following forest clearance.

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Author contributions

J.M.E. and S.Y. identified research questions and conceptualized the study. J.M.E. constructed the model and carried out the analysis. J.M.E, S.Y. and K.E.S. analysed the results and revised/improved the study approach.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.M.E.