CARBON SEQUESTRATION

Releasing global forests from human management: How much more carbon could be stored?

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Carbon storage in forests is a cornerstone of policy-making to prevent global warming from exceeding 1.5°C. However, the global impact of management (for example, harvesting) on the carbon budget of forests remains poorly quantified. We integrated global maps of forest biomass and management with machine learning to show that by removing human intervention, under current climatic conditions and carbon dioxide (CO_2) concentration, existing global forests could increase their aboveground biomass by up to 44.1 (error range: 21.0 to 63.0) petagrams of carbon. This is an increase of 15 to 16% over current levels, equating to about 4 years of current anthropogenic CO_2 emissions. Therefore, without strong reductions in emissions, this strategy holds low mitigation potential, and the forest sink should be preserved to offset residual carbon emissions rather than to compensate for present emissions levels.

Forests play a key role in the global carbon cycle (*1*) by capturing and storing carbon in tree biomass and enhancing soil organic matter. As such, they are a key component in global policy-making to mitigate climate change. Most of the main strategies aiming to keep global warming below a threshold of 1.5°C rely on forest-based mitigation plans as approaches to complement hard reductions in anthropogenic carbon emissions to reach carbon neutrality (*2*). In these scenarios, forests constitute one of the main carbon sinks that offset continuing emissions (*3*) from agriculture and other sectors that will require a longer time frame to decarbonize or are unlikely to reach effective net-zero emissions (*4*).

In past decades, intact forests have provided a strong carbon sink (*5*) thanks to the fertilization effect of the increasing CO_2 concentration on photosynthesis, which has spurred increased tree growth and carbon storage. However, the CO_2-fertilization effect, although still positive, is likely in decline because of the increasing importance of other limiting factors (*6*). Consequentially, the terrestrial carbon sink will likely stabilize (*3*). At the same time, climate change is increasingly pushing tree populations to the edge of their natural climate envelopes (*7*, *8*) and increasing the frequency and intensity of natural disturbances, leading to higher risks of tree mortality (*9*, *10*). This situation may change forests that are now see reliable carbon sinks into active net ca sources. These processes shift the perspective of forest-based climate change mitigation toward two strategies: adapting management practices in forests that are currently below their natural equilibrium biomass level (*11*) and expanding forest areas through afforestation and reforestation programs.

Both strategies present substantial complications in their implementation, as documented in the Intergovernmental Panel on Climate Change (IPCC) special report on land (*4*). Afforestation and reforestation potential is mainly limited by the strong competition for land (*12*). Adapting management practices in forests—for example, reducing wood harvesting—has the potential to increase the carbon stock (*11*, *13*–*15*). However, this potential is limited by the societal demand for wood and other forest-based products, which also provide climate benefits by substituting for energy and materials that would have contributed more severely to climate change, such as fossil fuels and concrete. Nevertheless, recent research shows that reducing harvesting intensity has strong climate mitigation benefits, especially at shorter timescales, even after accounting for such substitutions (*15*). However, on the long term and at a global scale, the total amount of carbon that could realistically be stored in forests remains poorly understood (*16*).

In this study, we focused on the natural limits to additional carbon accumulation in the biomass of existing forests, aiming to quantify how much more carbon could realistically be stored in the hypothetical scenario in which all current forests reach natural equilibrium. This hypothetical scenario defines the upper bound of carbon storage in

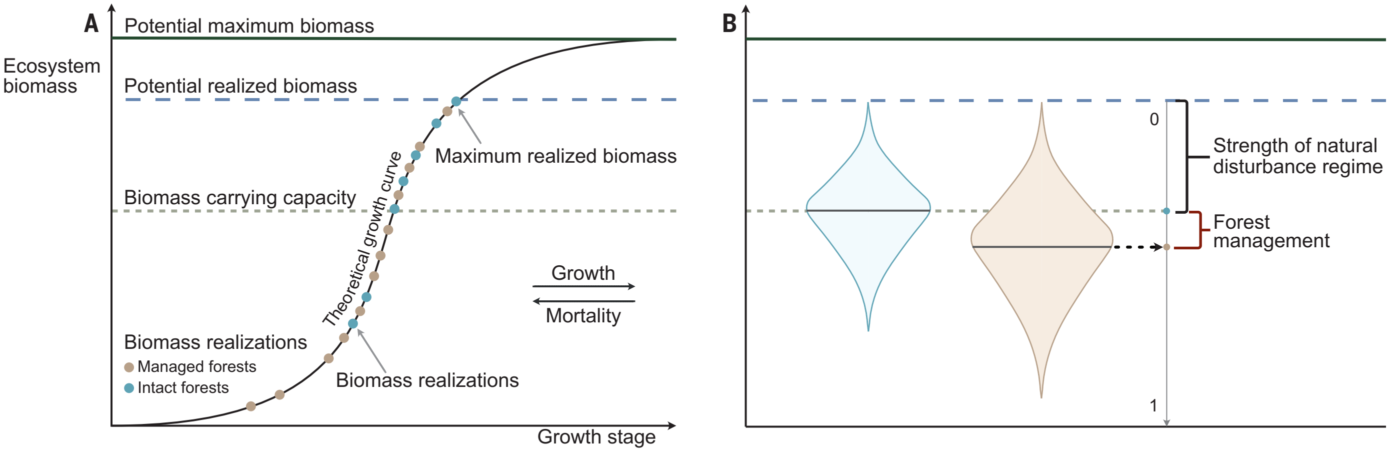

Fig. 1. Graphical representation of both the natural and human-altered forest biomass budget and the impact of natural and anthropogenic disturbance regimes. (**A**) Idealized temporal dynamics of biomass in an undisturbed system (curved black line) that translates across the landscape in a series of realized forest patches (blue and brown dots) at various biomass levels as a result of natural and anthropogenic disturbances. (**B**) When aggregated at a regional scale, biomass levels in forest patches can be described with frequency distributions (violin plots) that will differ between managed and intact forests because of direct human management (brown bracket). This biomass gap is finally interpreted as the potential for additional carbon storage of forests if human intervention were to be suspended.

existing forests and implies the removal of all direct human management from forests (meaning any human-caused physical changes in forest structure, carbon storage, or species composition that are due to harvesting, fire suppression, plantation, or other factors). Throughout this text, we refer to forests that have been altered by direct human action simply as "managed forests" as opposed to "intact forests." Some human interventions, such as active fire suppression, could in practice enhance carbon stored in forests, but from a global perspective, managed forests contain substantially less carbon than their intact counterparts (*11, 16*). We focused on existing forests because other studies suggest that they hold most of the additional carbon storage potential of forests, considering management as well as afforestation and reforestation when accounting for competition with other land uses (*16*).

Defining additional carbon storage potential

The additional carbon storage potential of forests has been studied indirectly as part of estimating carbon storage potential on land, including afforestation and reforestation as well as removal of all human management from forests (*11*, *16*, *17*). However, previous studies did not strictly account for and separate the effect of natural disturbances and human interventions on potential carbon storage in forests. They instead targeted potential maximum biomass in the absence of both natural disturbances and management (*16*), thus creating an upper bound estimate, which likely overestimates the realistic residual carbon storage potential of forests (*17*).

We approached the realistic potential additional carbon storage in forests as the difference between the existing carbon stock and the current carbon carrying capacity. Carbon carrying capacity is defined as the carbon "stored in a forest ecosystem under prevailing environmental conditions and natural disturbance regimes, but excluding anthropogenic disturbance" (*18*) (Fig. 1), in which anthropogenic disturbances can be understood as any direct human management in forests. Carbon carrying capacity is an inherent trait of a climate state and thus excludes any future changes in forest growth potential, likelihood of natural disturbances, and enhanced growth due to higher atmospheric CO_2 concentrations. In the context of biomass, we refer to it as "biomass carrying capacity," and it is directly translatable with the general rule of thumb that biomass contains 50% carbon.

We propose a modeling framework that calculates the biomass carrying capacity and expected biomass occurring under local conditions—including both natural disturbances and direct human management (which we refer to as "expected biomass")—in two steps [Fig. 1 and (*19*)]. First, potential maximum biomass for each pixel is modeled from biomass observations [GlobBiomass, which reproduces country-aggregated field observations with a coefficient of determination (R^2) of 0.96 (*20*)]. Second, disturbance regimes are calculated as the average ratio between current biomass and the potential biomass [1 – (biomass/potential biomass)]. Forests persisting close to the potential are thus attributed a low disturbance-regime value and vice versa. This is done twice: The natural disturbance regime is derived from the ratio found in intact forests, whereas the total (natural disturbance regime and management) uses the ratio found in all forests (intact and managed). Multiplying the potential maximum biomass by the natural disturbance–regime ratio yields the biomass carrying capacity, whereas multiplying by the total disturbance regime results in the expected biomass. Furthermore, the difference between biomass carrying capacity and expected biomass is interpreted as the net effect of all direct human management, a measure of the

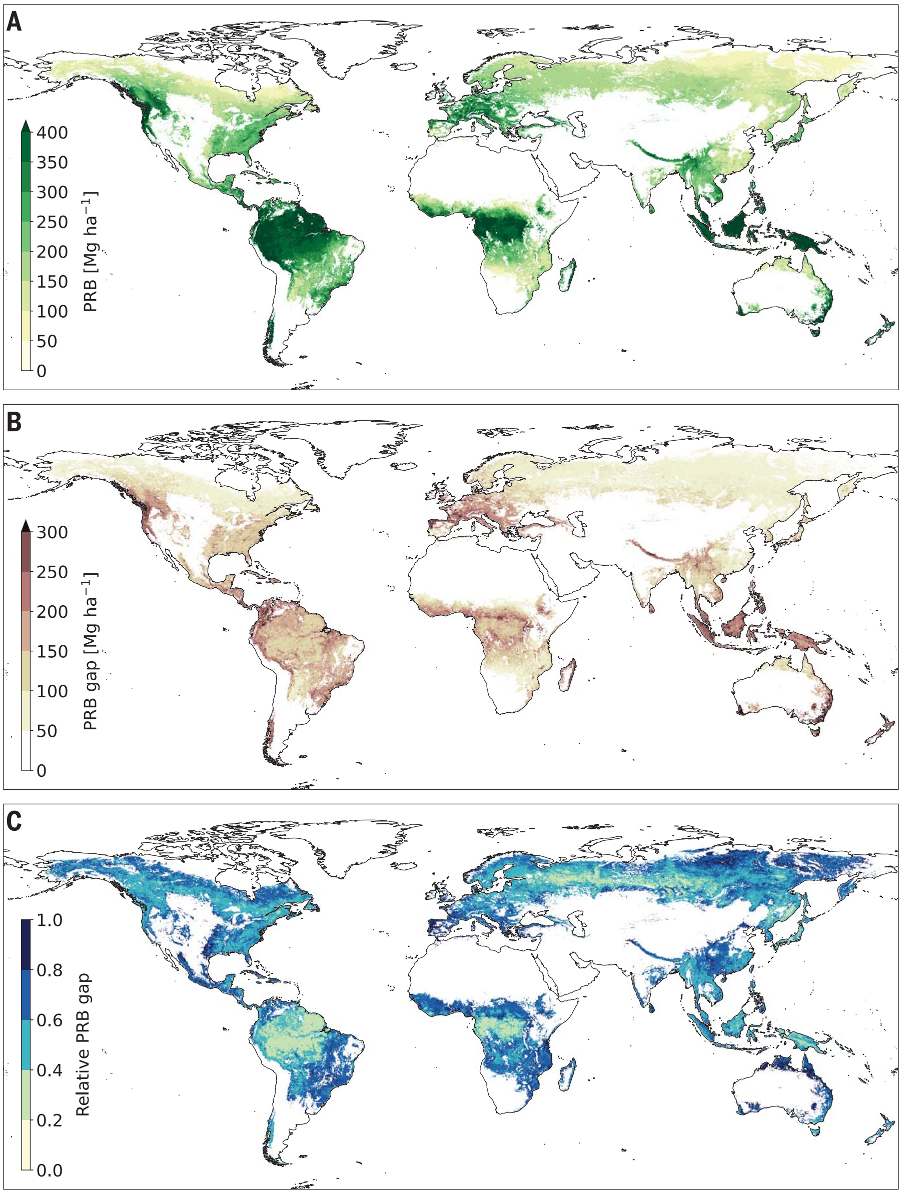

Fig. 2. Global representation of the potential realized biomass and its comparison with observed biomass values. Maps of (**A**) the absolute values of potential realized biomass (PRB), the maximum aboveground biomass that could occur without natural disturbances, (**B**) the absolute difference between PRB and the currently observed biomass, and (**C**) the relative difference between biomass observations and PRB [1 – (observed biomass/potential realized biomass)].

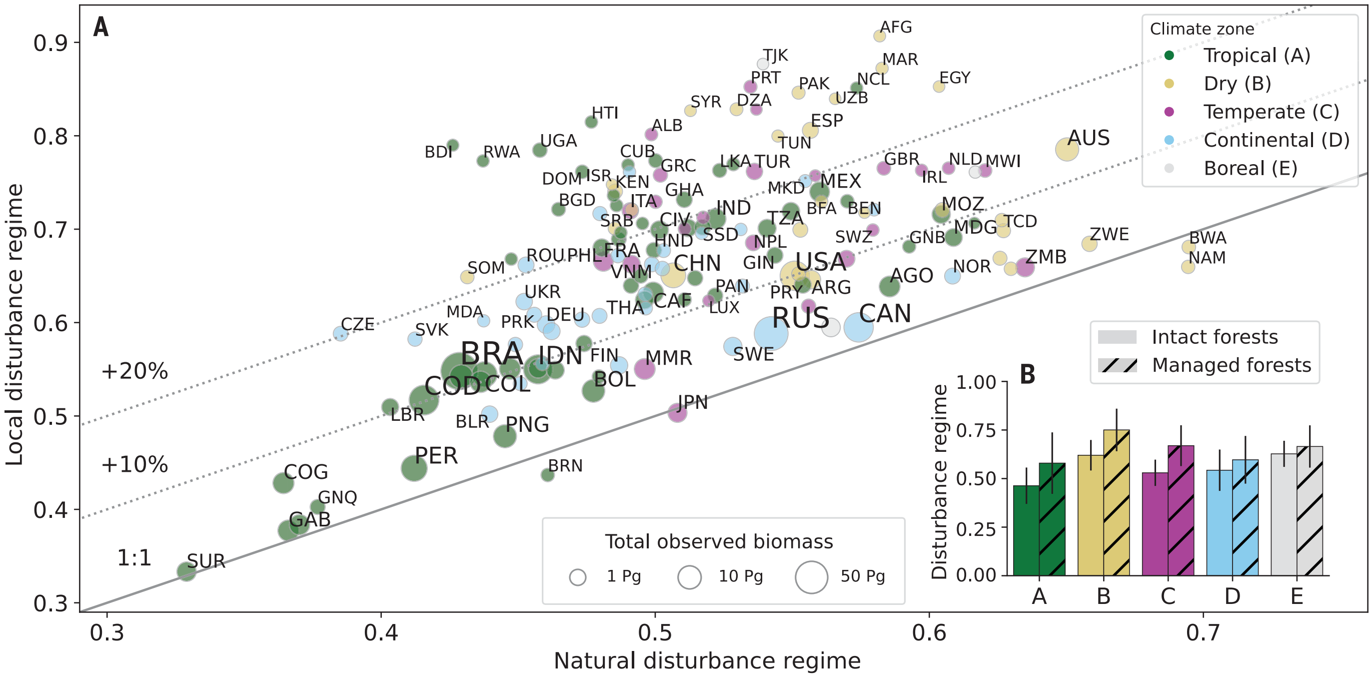

Fig. 3. Difference between natural and total disturbance regimes. (**A**) Countries are shown with their natural and total (natural plus direct human management) dsturbance regimes. Most countries display a substantial increase in the disturbance regime when current disturbance regimes are compared with those expected in equivalent intact forests. Within-country variability is large, with the highest increases in the impact of disturbance regimes almost tripling. Country abbreviations are defined at https://www.iso.org/obp/ui/#search/code/. (**B**) The same results noted in (A) are shown per the Köppen-Geiger climate zones. All climate zones see a substantial increase in disturbance regime when accounting for human interventions. Disturbance regimes are reported as fractions of potential realized biomass (Fig. 1).

additional carbon storage potential from theoretically removing all human management.

Global variation in potential realized biomass

The first step in the framework is to model potential maximum biomass. Because the values are derived from biomass observations and because the true potential will not always be present in the data, we refer to our model estimates as "potential realized biomass" (Fig. 1) (*21*–*23*). We chose a quantile machine-learning method [quantile random forest (*24*); see (*19*) and figs. S1 and S2] to model potential realized biomass because of its ability to deal with high-dimensional and nonlinear relationships (*24*). We modeled forest biomass (from GlobBiomass) as a function of the environmental characteristics (climate features, physical soil characteristics, and soil water availability; table S1), with the assumption that forests in similar conditions have similar potential realized biomass. A comparable approach was used by Walker *et al.* (*16*), with the difference being that we used a quantile regression approach (calculating the maxima rather than the mean) to focus strictly on potentials.

We found the highest values of potential realized biomass, around 600 Mg biomass/ha, to be in both the humid tropics and humid temperate zones, whereas boreal forests may contain up to 150 Mg biomass/ha (Fig. 2A). Tropical forests persist close to their maximum potential biomass (Figs. 2B and 2C), although a minimum difference of 10 to 15% between potential realized biomass and observed biomass is still to be expected in most of the tropics because of natural age dynamics and a relatively low frequency of natural disturbances (*25*). The biomass of temperate forests can also reach very large values yet experience stronger natural disturbance regimes, with forest fires, windthrows, and insect outbreaks being an integral part of the ecosystem dynamics (*26*). This difference is reflected in greater spatial variation in the original biomass data, which translates to larger differences between potential and observed forest biomass. Europe in particular shows a large difference between potential and realized biomass levels as a result of the long history of land management.

Effects of disturbance on biomass

The second step in the modeling framework is to calculate the disturbance regimes. The natural disturbance regimes were modeled similarly to potential realized biomass, as a function of environmental variables, assuming that how close an intact forest is on average to the potential realized biomass is again driven by the environmental context of the forest. In contrast to the potential realized biomass model, we used a standard (mean) random forest regression model, trained on forests that fall within intact forest landscapes (*27*). The total disturbance regimes (natural plus direct human management) were calculated by means of a similar random forest machine-learning model but with geographical coordinates for predictions instead of climate gradients. A comparison between the natural and the total, human-affected disturbance regimes (Fig. 3) shows that in most countries, the effective total disturbance regime has at least a 10% greater impact on biomass than what would be expected from natural disturbances alone. In the 10 countries with the highest total potential realized biomass, an increase of 20% is observed as compared with the natural level. Locally, the direct impacts of human interventions are greater, such as in some areas of Eastern South America, Western Africa, Europe, and China, where we show more than double the disturbance impacts in managed forests when compared with the equivalent intact forests.

Biomass carrying capacity of intact forests

By multiplying the previously obtained natural disturbance–regime ratio (fig. S8) by the potential realized biomass, we calculated the biomass carrying capacity—that is, the biomass that can realistically be expected to be obtained in intact forests given the natural disturbance regime [Eq. 2 in (*19*)] (fig. S9). In

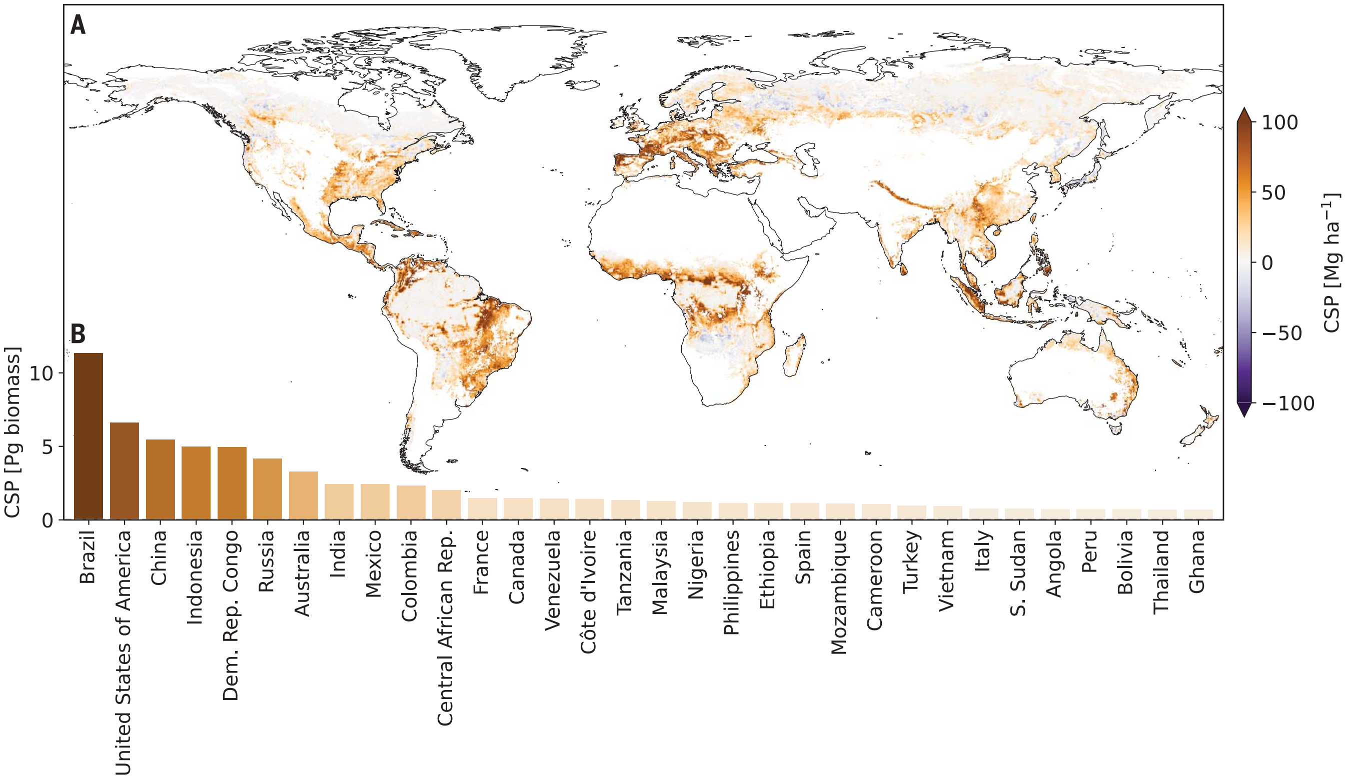

Fig. 4. Additional carbon storage potential. (**A**) Additional carbon storage potential (CSP) in the hypothetical scenario in which all forests would resettle in their natural equilibrium if all direct human management was removed from them. The CSP is calculated from the difference between biomass carrying capacity and the expected biomass (the biomass that would occur under local conditions with the given natural disturbance regime and average intensity of human intervention). (**B**) National statistics of additional CSP for countries where absolute values exceed 0.7 Pg biomass.

comparison with the average biomass per ecosystem type used in other studies (*5*, *17*), our average biomass carrying capacity values are slightly smaller—for example, the average in natural tropical rainforests is approximately 8% less at 260 Mg biomass/ha (*5*), although some areas surpass 390 Mg biomass/ha. This difference is likely due to the careful accounting of the impact of climate-driven natural disturbances on the forest biomass budget that can be achieved with our methodology and to a lower bias resulting from a more representative sample of forests per ecosystem type.

Additional carbon storage potential

Additional carbon storage potential, which is the direct opposite of the net effect of direct human management in forests, was calculated as the difference between the biomass carrying capacity and expected biomass. Almost all world regions show additional carbon storage potential (Fig. 4), with the largest potentials concentrated in the regions on the edges of tropical rainforests in South America and Africa, corresponding to areas that have experienced high rates of deforestation and forest degradation (*28*). Intact ecosystems (fig. S10), identified from remote sensing data as regions with no sign of human intervention (*27*), show close-to-zero differences between the natural and total disturbance regimes (globally average deviation biomass carrying capacity and observed biomass is 0.3 Mg biomass/ha).

The boreal regions show limited potential, with some areas even displaying negative carbon storage potential. These negative values might be explained by several hypotheses: (i) In these regions, intact forests are not fully comparable to the managed forests because of the preferred selection of the most fertile sites for forest management. (ii) Management increased the maximum potential realized biomass (for example, through the introduction of highly productive monospecific stands) or deliberately decreased the natural disturbance regime (for example, active and passive suppression of forest fires). (iii) Small differences appeared, with a relatively large effect on biomass potentials, in environmental conditions that are not resolved in the input data.

Our analysis estimates a total additional carbon storage potential in current forests of 88.1 Pg [error range: 42.0 to 125.9 Pg biomass; for error range definition, see (*19*)] of aboveground biomass (AGB) (15.2 to 16.1% more than the biomass reported in current forests, with large differences between countries) following the hypothetical scenario of no human intervention, which is roughly equivalent to 44.1 Pg of carbon (PgC) (error range: 21.0 to 63.0 PgC). About 37% of the carbon storage potential is located in five countries: Brazil, United States, China, Democratic Republic of the Congo, and Indonesia. This figure is less than half of the values found in previous work [for example, Walker *et al.*: 111.6 PgC AGB (*16*)], likely as a result of our strict accounting of naturally occurring disturbances. By comparison, recent work found that carbon storage potential of afforestation and reforestation is around 15.6 PgC of AGB when accounting for land-related constraints (*16*).

Conclusions

The modeling results were validated with a series of uncertainty analyses (*19*) (figs. S3 to S6), and estimates of the biomass carrying capacity were compared with the biomass observations of the intact forests (R^2 = 0.99; fig. S7A). We found that relative uncertainties of the biomass carrying capacity are approximately equal to the original biomass data (fig. S3). The largest uncertainties are found in the temperate regions, where few intact forests are available for the extrapolation of the disturbance regime. The effect of these uncertainties on the global values of additional carbon storage potential is relatively minor [(*19*), uncertainty analysis 5]. The results allow us to draw some highly relevant conclusions on the overall potential magnitude of forest-based mitigation options on the basis of the increase of carbon stocks.

First, carbon that can additionally be stored in the global aboveground forest biomass corresponds to about four times the amount of total human emissions released in 2019 (around 10 PgC). Although this is a substantial amount and an underestimation of the full potential because we only considered AGB, it corresponds to the emissions within a shorter period than the time that has elapsed since the Paris Agreement of 2015 and would require the full cessation of forest management. Second, all forests together now contain about four times as much carbon as could additionally be stored in their AGB (GlobBiomass values). This carbon is already at risk of being partially released into the atmosphere by forest degradation (*27*, *29*, *30*) and increased natural disturbances (*7*, *8*, *10*). Third, obtaining the equivalent of the potential increase of carbon in currently managed forests through reforestation and afforestation would require a land area of about 7.1 million km^2 (an area almost as large as Australia) (using an average biomass carrying capacity of 123 Mg biomass/ha). To dedicate enough land to achieve this number would be a massive undertaking, and furthermore, this carbon stock would require decades to fully develop.

These observations lead to the conclusion that current forests have only a limited additional carbon storage potential to substantially mitigate the increase in atmospheric CO$_2$ without major reductions to fossil emissions. For this reason, forest-based climate mitigation should not be mistaken as a trade-off for present carbon emissions levels. On the contrary, efforts to reverse trends in deforestation and increase carbon stocks should be seen as precious and effective strategies to offset future residual emissions from the agricultural sector and from essential industries that are unlikely to reach net-zero emissions.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S10
Table S1
References (*39*–*41*)
MDAR Reproducibility Checklist

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Releasing global forests from human management: How much more carbon could be stored?

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Editor's summary

Harnessing the carbon-capturing potential of forests is a key component of plans to mitigate global climate change. Planting new forests is a common strategy, but this approach can have negative social and ecological impacts and substantial costs. Roebroek *et al*. instead investigated how ceasing management (e.g., wood harvesting or fire suppression) of forests would change their global carbon sequestration capacity. The authors assessed the differences between the biomass of similar forests with and without human activities and used machine learning to predict the additional biomass gain from removing human activities from global forests. Even if all management ceased (an extremely unlikely scenario), global forest carbon would only increase by about 15%. This work provides further evidence that changing forest management is not an alternative to cutting carbon emissions. —Bianca Lopez

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