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Response to Comments on "The global tree restoration potential"

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Our study quantified the global tree restoration potential and its associated carbon storage potential under existing climate conditions. We received multiple technical comments, both supporting and disputing our findings. We recognize that several issues raised in these comments are worthy of discussion. We therefore provide a detailed common answer where we show that our original estimations are accurate.

Our study exploring the global tree restoration potential (*1*) inspired many discussions within and beyond the scientific community. Here, we provide a point-by-point response to several technical comments that were raised (*2*–*4*). However, we first want to highlight a theme that pervades the technical comments, which stems from a lack of clarity in our original text. Given the potential to capture more than 200 gigatonnes of carbon (GtC) at full maturity, we suggested in the abstract that global tree restoration is our most effective climate change solution to date. In saying this, we intended to highlight that we are aware of no other viable climate change solution that is quantitatively as large in terms of carbon drawdown. We did not suggest that tree restoration should be considered as the unique solution to climate change. To avoid this confusion, we have corrected the abstract accordingly.

The real value of our analysis is to show that tree restoration may be a far more powerful carbon drawdown solution than previously expected. With the potential to capture 205 GtC at full maturity, tree restoration constitutes an important component in the fight against climate change. Restoring even 10% of the 900 Mha of available land could draw down a meaningful proportion of the ~300 GtC that was added to the atmosphere as a result of human activity (*5*). "Project Drawdown" lists the leading climate change solutions (*6*), which are ranked in terms of the quantity of carbon dioxide equivalent. Effective "refrigeration management" is highlighted as the leading solution, with the potential to save 89 $GtCO_2$ (i.e., ~24 GtC) by 2050. Until now, forest restoration has been broken down by region and listed below the top solutions. However, the maximum global potential (*1*) of regenerating forests is likely to be as high as any other solution in terms of carbon capture alone. Our study provides quantitative evidence to support this point and the claim by Lewis *et al.* (*7*) that "restoring natural forests is the best way to remove atmospheric carbon."

By revealing the potential of restoration as a carbon drawdown solution, our study does not preclude the urgent need to reduce greenhouse gas emissions from the combustion of fossil fuels, from deforestation and forest degradation. There is no compromise or trade-off between the two. This has notably been well understood by the European Commission that, following our study, has published a communication entitled "Stepping up EU Action to Protect and Restore the World's Forests" where conservation and restoration of forests are both proposed as concrete actions (*8*).

We also stress that restoration does not mean planting trees everywhere. As highlighted in our analysis, there are many regions where tree cover is not suitable. Restoration can be natural or assisted, but it means only allowing ecosystems to recover to a natural state, including ecosystems with 0% of tree cover.

Finally, before providing detailed responses to specific issues raised, we think it is critical to highlight that although there is still ongoing debate about the exact carbon drawdown potential of trees, the scientific community is not divided on the importance of responsible global resto-

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ration as an extremely valuable carbon drawdown solution that must be combined with emissions cuts in the fight against climate change.

The carbon drawdown potential of forest restoration compared to atmospheric stocks

Friedlingstein *et al.* (*3*) emphasize that restored trees cannot capture two-thirds of anthropogenic carbon emissions. They point out that a considerable proportion of anthropogenic emissions is absorbed each year by the land and ocean, and so only 45% of the emitted carbon remains in the atmosphere. This point is entirely correct, and we absolutely recognize the constant airborne fraction of 45%. However, our statement, "reaching this maximum restoration potential would reduce a considerable proportion of the global anthropogenic carbon burden (~300 GtC) to date," certainly does not contradict their point. We simply state that, if we could store an extra 205 GtC in newly formed ecosystems, this process would indeed reduce a considerable amount of the excess carbon that resides in the atmosphere following human activity. To provide an order of magnitude, we clarified that the total excess carbon remaining in the atmosphere is approximately 300 GtC, as highlighted in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (*9*).

On our estimation of potential carbon drawdown from global forest restoration

Friedlingstein *et al.*, Lewis *et al.*, and Veldman *et al.* (*2*–*4*) claim that our global estimate of total potential carbon in restoration areas is too high. The discrepancies between our estimate and their estimates arise from (i) misinterpretations or confusion between the definitions of forest cover and associated carbon pools, and (ii) a lack of sufficient detail in the original manuscript on how existing carbon in potential restoration areas was removed for estimating the global restoration potential. We clarify these points here.

Lewis *et al.* cite several studies (*7*, *10*, *11*) that appear to report lower forest carbon values than the ones we used. As such, once extrapolated to the 900 Mha that we report as canopy cover available for restoration, this leads to a considerably lower total carbon potential than our estimate (*1*). However, we emphasize that none of these studies contradicts our estimations. In fact, the differences arise because of some misconceptions in the interpretation of Lewis *et al.*, which we outline below:

1) Three of the four examples provided are based on a different definition of forest: namely forest area, rather than tree canopy cover. Global forest area (land containing at least 10% tree cover) across the globe is considerably larger than global tree canopy cover (cumulative tree cover). We estimated that there is 1657 Mha of forest area available [table S2 of (*1*)], which contains 900 Mha available as cumulative tree canopy cover. Because these papers (*7*, *10*, *11*) were addressing forest area, the carbon density estimates would need to be scaled to 1657 Mha instead of 900 Mha. Correcting for this consideration of forest area almost doubles the carbon estimates proposed by Lewis *et al.*

2) The numbers provided by Lewis *et al.* in their restoration study (*7*) concern only two of the five carbon pools for vegetation ecosystems (i.e., aboveground and belowground plant biomass). Restoring forest ecosystems would actually have an impact on all five pools of carbon, including soil, litter, and dead wood (*12*). In our analysis, we included all five, which drastically increases the amount of carbon expected to be stored in restored forests.

3) Lewis *et al.* state that sequestering 205 GtC by restoring natural forests across the globe is unrealistic because anthropogenic land-use change since 1750 has emitted only 200 GtC in total (*13*). We think this assumption is flawed. In many regions, substantial deforestation occurred before 1750 (*14*, *15*). But more important, as with all global historical estimates, the uncertainty in this IPCC estimate is considerable because of our limited knowledge of the changes in vegetation ecosystem carbon storage over such a long historical time period. This uncertainty only highlights the need for more quantitative analyses, such as the present study, that are needed to refine these early IPCC estimates. As new data and analytical approaches become available, they will be increasingly critical for refining our understanding of the global changes in land carbon storage.

All three technical comments raise the importance of removing the carbon content that currently exists in potential restoration areas in order to calculate the gain associated with tree restoration. Although it was not fully clear in our manuscript, we agree with this. To clarify, we provide a more detailed description of our approach and of related uncertainties. We show that our 205 GtC estimate is a conservative estimate of the additional carbon that could be stored by ecosystems supporting trees.

Calculation of the carbon potentially stored in areas available for restoration

To calculate the amount of carbon that could be potentially stored in areas available for forest restoration, we use the potential tree cover available for restoration in each pixel [figure 2B of (*1*)]. We then estimate the amount of carbon that could be stored in each pixel through a "tree cover – carbon equivalent" calculation. To consider uncertainties, we associate three different baselines of "tree cover – carbon equivalent" with the average carbon density observed in protected areas within the Boreal, Dry, Temperate, and Tropical biomes (*16*, *17*) (Table 1). We calculate the median, the 75th percentile, and the 95th percentile of tree cover in forests. This can then be used to scale the tree cover estimates to existing biome-level estimates of carbon storage (Table 1).

By upscaling this calculation to the global area available for restoration, we infer the total amount of carbon that could be stored in restored ecosystems:

- 349 GtC for the median tree cover – average carbon equivalent per biome;
- 239 GtC for the 75th percentile tree cover – average carbon equivalent per biome;
- 206 GtC for the 95th percentile tree cover – average carbon equivalent per biome.

Thus, we estimate that the total carbon that could be stored in areas available for restoration ranges between 206 and 349 GtC.

Carbon to remove

Carbon currently existing in potential restoration areas must be subtracted from the above-mentioned values to estimate the global extra carbon storage potential. We estimated the amount of carbon currently held in vegetation using the IPCC global biomass map (*18*) and the carbon held in soil using the soilgrid layers (*19*). Summing these two layers gives us the total amount of carbon per pixel that currently exists in areas available for restoration. Globally, we infer a total of 5.7 GtC currently present in vegetation and 67.1 GtC present in soils.

Final calculation

After subtraction of the existing carbon content from the potential global carbon content that could be stored in areas available for restoration, the global carbon gain from tree restoration potential ranges between 133.2 and 276.2 GtC with a mid-range value of 204.7 GtC. This range reflects the uncertainty in calibrating the biome-specific carbon density values to a baseline percent tree cover (see Table 1).

On the potential effect of albedo and evapotranspiration

Friedlingstein *et al.* and Veldman *et al.* (*3*, *4*) raise the important point that forests have an impact on climate not only through changes in the carbon cycle, but also through changes in evapotranspiration and albedo.

We completely agree that changes in forest cover resulting from restoration would also affect the climate through a range of mechanisms including changes in surface albedo and evapotranspiration. Indeed, because of a mixture of biochemical and biophysical impacts, it is possible that forest restoration could have a warming impact in some areas, especially at higher latitudes. Although these are important avenues for future research, calculating the changes in albedo and evapotranspiration associated with restoration is beyond the scope of the present study. Our analysis only highlighted the potential for considerable carbon drawdown in restoring trees. But we hope that our analysis provides a stepping stone to future research efforts to evaluate how global tree restoration might affect the climate.

Should drylands be considered for tree restoration?

Veldman *et al.* (*4*) criticize our results in dryland biomes, stating that many of these areas simply should not be considered suitable for tree restoration. Generally, we must highlight that our analysis does not ever address whether any actions "should" or "should not" take place. Our analysis simply estimated the biophysical limits of global forest growth by highlighting where trees "can" exist. However, we disagree with the suggestion of Veldman *et al.* for a number of reasons:

1) Veldman *et al.* neglect that large areas of dryland that are classed as savannas have, since the 1970s, been designated by UNEP as suffering from various degrees of vegetation and soil degradation, called desertification (*20*). Indeed, in the latest reports of the IPCC (*21*), it is stated with "high confidence" that the range and intensity of desertification has increased over the past decades (*22*). Desertification hotspots extended to about 9.2% of drylands (±0.5%), affecting about 500 million (±120 million) people in 2015 (*21*). Research since 1990 has suggested that restoring tree cover that would naturally exist on these lands would help in soil restoration (*23*). Veldman *et al.* also neglect the current vegetation encroachment trend in dryland regions that are unaffected by desertification (*24*). Indeed, the current climate differs from the climate of past decades, leading to a natural increase in land available for tree cover in some regions.

2) Veldman *et al.* stress that our model had low predictive power across many of the open-canopy biomes, suggesting that it fails to account for natural fire and the presence of large mammals. Here, they have misinterpreted the uncertainty of our model. First, natural fires and large mammals exist in protected areas. They are therefore indirectly accounted for in our model. Second, as natural fire cannot be distinguished from human-made fire, it cannot be accounted for as a variable of the model to extrapolate the natural tree cover outside protected areas. Third, the high uncertainty in intermediate tree cover is due to the general low occurrence of intermediate tree cover.

3) The authors suggest that the restoration of savanna ecosystems "requires tree-cutting and prescribed fire." However, contrary to the recommendation of Veldman and colleagues, we would not say what "should" be done by humans, we only say what is most likely to happen naturally if we remove the human factor from the equation (*25*).

We agree with Veldman *et al.* that forests should not replace natural grasslands. Our model does not contradict this statement at all. Indeed, our model only estimates where trees could exist, from a purely biophysical perspective. And by estimating from 0 to 100% of potential tree cover, our model also estimates the distribution of natural grasslands, which must absolutely be protected and conserved.

On the future projection being uncertain

Lewis *et al.* (*2*) caution against our interpretation of the risk of change in potential tree cover due to high uncertainty in future effects of climate change on natural ecosystems. Here we must agree that the uncertainty in our estimates is important, but this is already fully recognized in our paper (*1*). Our risk assessment is an extrapolation, not an interpolation, and there are considerable uncertainties in our model and in future climate projections. But it is important to note that this is not a projection of changes in tree cover. It is the expectation of differences in potential tree cover. That is, we are not estimating where trees will be lost and gained. Rather, we highlight where the potential for new forests might be altered under a different climate. As this "potential" is not subject to the same biological feedbacks that limit the changes in existing ecosystems, the future shifts are likely to be considerably more striking.

It is widely expected that a greening of the planet will happen, as increases in temperature and atmospheric CO_2 lead to increased tree cover in high-latitude areas (*26*). Our model predicts this same phenomenon. However, our model provides new insights into this trend, suggesting that conditions are simultaneously becoming harsher in tropical regions. Indeed, hotter temperatures and severe droughts are very likely to have a negative impact on tropical forests (*27*). This has previously been demonstrated by studies showing that climate change is happening too fast to allow for renewal or replacement of tropical tree species [e.g., (*28*)].

Of course, when considering future changes in vegetation, it is important to recognize the importance of feedbacks. We stress in the paper that "it is possible that elevated CO_2 concentrations under future climate scenarios might enhance the growth of those existing trees." A clear limitation is that we could not represent such CO_2 fertilization effects in our model. Such feedbacks must be considered using process-based biogeochemical models to fully represent the mechanisms underpinning the future changes in vegetation. However, the uncertainty in these Earth System Model (ESM) projections of land carbon storage is exceptionally high (*29*), highlighting the need for independent data-driven approaches to evaluate such expectations. With high accuracy to predict potential forest cover, our model can serve as a useful independent approach.

Conclusion

We show that our global estimate of potential tree cover and carbon storage in restored ecosystems is accurate, supports the pre-2000 scientific literature (*30*), and does not contradict previous studies (*7*). This underscores the fact that restoration of natural tree cover should be considered as the most viable solution to remove atmospheric carbon. As a scientific contribution, we do not state what "should" be done at any location around the world, but instead highlight what is possible. We recognize that most issues raised in the comments by our colleagues are relevant and worthy of consideration. The differences in approaches and related estimates illustrate the uncertainty that remains and justify the need for more quantitative and data-driven approaches. Until now, most of our understanding of restoration potential stemmed from ESMs with high uncertainties (*29*) or from "expert opinion" pieces (*7*), which cannot reflect the full global potential for carbon capture. We consider that quantitative global approaches based on observations are needed to understand and promote restoration as one of the most promising tools at our disposal in the fight against climate change and biodiversity loss.

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Table 1. Tree cover statistics summary observed within the ~78,000 photo-interpreted points.

Biome	Canopy cover (Mha)	Median tree cover (%)	75th percentile tree cover (%)	95th percentile tree cover (%)	Carbon density (tC ha^{-1})
Boreal forests/taiga	178	90	100	100	239.2
Desert and xeric shrublands	77.6	20	65	100***	202.4
Flooded grasslands and savannas	9	55	100	100	202.4
Mangroves	2.6	100	100	100	282.5
Mediterranean forests, woodlands, and scrub	18.8	55	90	100***	202.4
Montane grasslands and shrublands	19.3	90	100	100	202.4
Temperate broadleaf and mixed forests	109	100***	100	100	154.7
Temperate conifer forests	35.9	100	100	100	154.7
Temperate grasslands, savannas, and shrublands	72.5	80	100	100	154.7
Tropical and subtropical coniferous forests	7.1	100	100	100	282.5
Tropical and subtropical dry broadleaf forests	32.8	100	100	100	282.5
Tropical and subtropical grasslands, savannas, and shrublands	189.5	45	90	100	282.5
Tropical and subtropical moist broadleaf forests	97.1	100	100	100	282.5
Tundra	50.6	80	100	100	239.2

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Response to Comments on "The global tree restoration potential"

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