Science

Forest restoration: Transformative trees

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Arid conditions limit the forest restoration potential of many regions of Australia.

LETTERS

Edited by **Jennifer Sills**

Forest restoration: Overlooked constraints

In their Report "The global tree restoration potential" (5 July, p. 76), J.-F. Bastin *et al.* use machine learning to derive the carbon storage potential of global tree restoration, which they identify as the most effective climate change mitigation option. However, the study likely overestimates the actual potential by identifying opportunities for increasing canopy cover in environments with obvious environmental or socioeconomic constraints.

In high-latitude regions of Russia, Scandinavia, and North America, permafrost and short growing seasons (*1*) impair tree growth. In large parts of Australia and other arid and hyperarid regions, salinity, sodicity, hardpans, and moisture limitations prevent tree establishment (*2*, *3*). In African grasslands, infertile soils, grazing animals, water constraints, and wildfires maintain patchy shrub–grass environments (*4*). In areas with severely degraded soils and biodiversity loss in the Americas and in Asia (*5*, *6*), prospects of restoring pre-degradation canopy cover are limited. In grazing lands and production forests, abandoning current uses implies staggering absolute opportunity costs. Finally, Bastin *et al.* excluded areas classified as urban, but the data set they used (*7*) fails to recognize some major

urban centers and many towns and villages in rural areas (*7*); more than 2.5 billion people live in areas that Bastin *et al.* considered eligible for restoration (*8*), including entire cities, such as Kinshasa, the capital of the Democratic Republic of Congo.

Bastin *et al.* introduced further overestimation by multiplying tree cover expansion potential by total ecosystem carbon. This operation lowers the baseline by assuming that carbon stock is proportionally related to canopy cover—i.e., that land with no trees contains no carbon. The use of biome-level carbon stock averages, without considering spatial variation, also adds considerable error, especially in alleged high-potential areas, where these averages (154.7 to 282.5 Mg ha^{-1}) are approximately 5 times greater than what has been reported in site-specific assessments (*9*, *10*).

We appreciate the need for benchmark estimates of carbon storage and restoration potentials, but realistic predictions require tapping expert knowledge to ensure relevant constraints are considered, as well as more rigorous quality control, such as mapping how model validation errors are spatially distributed. Overly hopeful figures produced by models without necessary supervision may misguide the development of climate policy (*11*, *12*).

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Forest restoration: Expanding agriculture

In their Report "The global tree restoration potential" (5 July, p. 76), J.-F. Bastin *et al.* determine the available potential forest restoration area by excluding areas with existing trees, urban settlement, and cropland. However, they overestimate the potential area because they do not account for projected agricultural land expansion or current use of pasture land.

There is evidence from satellite imagery that most of global agricultural land expansion in the previous three decades happened and is still happening on tropical forest land, especially in Brazil and Southeast Asia (*1–3*). Given that this trend is likely to continue, especially in the highly productive areas in Central and South America, agricultural land expansion must be taken into account when assessing future tree restoration potentials (*4–6*). Food and Agriculture Organization projections expect an increase of cropland by 7% until 2030 (*7*), and evidence suggests an increase in global cropland area between 11 and 26% until 2050 (*8*), the latter corresponding to 4 million km². Based on one approach (*4*), not using this area for crop production would reduce global crop production by 11% and increase crop prices by 23%.

Furthermore, Bastin *et al.* assume that grassland would be available for tree restoration. They choose to ignore the data showing that currently about 30 million km² of grassland areas are used for extensive livestock production (*9*). Not utilizing areas for cropland expansion and pasture land requires a higher intensification of agriculture, which in turn is associated with higher agricultural emissions (*10*) and loss of biodiversity (*4*).

Bastin *et al.* do not consider current and future trade-offs with food security and neglect socioeconomic aspects of increasing consumption that arise through population growth, income growth, and preference changes toward more livestock products in fast-growing economies (*11*). Excluding estimated expansion areas and grazing land reduces the calculated sequestration potential by 19 and 57%, respectively, when applying the carbon densities of the bookkeeping model BLUE (*12*).

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Expanding agricultural land and livestock production could conflict with forest restoration goals.

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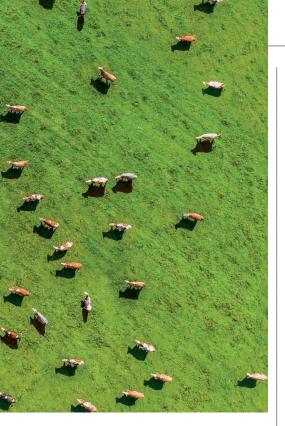
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Forest restoration: Transformative trees

We welcome the attention given to forest and trees by the Report "The global tree restoration potential" (5 July, p. 76), in which J.-F. Bastin *et al.* study the potential of tree cover to reduce climate change. However, we are concerned by their neglect of the water cycle. They consider how water influences tree cover but disregard how tree cover influences water. Bastin *et al.* recognize that their extrapolations are not "future projections of potential forest extent" but instead represent potential tree cover "under existing environmental conditions." However, given the influence of forests on their environment, the concept of potential tree cover under current conditions is problematic. Trees influence several of the variables Bastin *et al.* used to model tree cover, including precipitation quantity, variability, and seasonality, as well as soil moisture and atmospheric water transport (*1–4*).

While much remains uncertain (*2*), we know enough to foresee that afforestation and reforestation have potential for both negative and positive hydrological impacts. Negative impacts can result if plantings deplete groundwater and thus exacerbate local water scarcity. Changes can manifest quickly and are a recognized problem with fast-growing monoculture plantations (*5*). Positive impacts can result when tree cover improves soil and groundwater recharge and storage, such as through suitable species and tree densities (*6*). Forest cover can also promote rainfall recycling and thus bolster and stabilize regional and downwind rainfall (*1, 7, 8*). In suitable circumstances, increased forest cover may even return wetter climates to currently drier regions, expanding the land available for trees (*2*). These outcomes have profound implications given that reliable access to water is central to achieving the UN Sustainable Development Goals. Accounting for the potentially transformative power of trees for both water and carbon offers crucial constraints as well as vast benefits.

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TECHNICAL COMMENT ABSTRACTS

Comment on "The global tree restoration potential"

Pierre Friedlingstein, Myles Allen, Josep G. Canadell, Glen P. Peters, Sonia I. Seneviratne

Bastin *et al.* (Reports, 5 July 2019, p. 76) claim that global tree restoration is the most effective climate change solution to date, with a reported carbon storage potential of 205 gigatonnes of carbon. However, this estimate and its implications for climate mitigation are inconsistent with the dynamics of the global carbon cycle and its response to anthropogenic carbon dioxide emissions.

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Comment on "The global tree restoration potential"

Joseph W. Veldman, Julie C. Aleman, Swanni T. Alvarado, T. Michael Anderson, Sally Archibald, William J. Bond, Thomas W. Boutton, Nina Buchmann, Elise Buisson, Josep G. Canadell, Michele de Sá Dechoum, Milton H. Diaz-Toribio, Giselda Durigan, John J. Ewel, G. Wilson Fernandes, Alessandra Fidelis, Forrest Fleischman, Stephen P. Good, Daniel M. Griffith, Julia-Maria Hermann, William A. Hoffmann, Soizig Le Stradic, Caroline E. R. Lehmann, Gregory Mahy, Ashish N. Nerlekar, Jesse B. Nippert, Reed F. Noss, Colin P. Osborne, Gerhard E. Overbeck, Catherine L. Parr, Juli G. Pausas, R. Toby Pennington, Michael P. Perring, Francis E. Putz, Jayashree Ratnam, Mahesh Sankaran, Isabel B. Schmidt, Christine B. Schmitt,

Fernando A. O. Silveira, A. Carla Staver, Nicola Stevens, Christopher Still, Caroline A. E. Strömberg, Vicky M. Temperton, J. Morgan Varner, Nicholas P. Zaloumis

Bastin *et al.*'s estimate (Reports, 5 July 2019, p. 76) that tree planting for climate change mitigation could sequester 205 gigatonnes of carbon is approximately five times too large. Their analysis inflated soil organic carbon gains, failed to safeguard against warming from trees at high latitudes and elevations, and considered afforestation of savannas, grasslands, and shrublands to be restoration.

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Comment on "The global tree restoration potential"

Simon L. Lewis, Edward T. A. Mitchard, Colin Prentice, Mark Maslin, Ben Poulter

Bastin *et al.* (Reports, 5 July 2019, p. 76) state that the restoration potential of new forests globally is 205 gigatonnes of carbon, conclude that "global tree restoration [is] our most effective climate change solution to date," and state that climate change will drive the loss of 450 million hectares of existing tropical forest by 2050. Here we show that these three statements are incorrect.

Full text: dx.doi.org/10.1126/science.aaz0388

Response to Comments on "The global tree restoration potential"

Jean-Francois Bastin, Yelena Finegold, Claude Garcia, Nick Gellie, Andrew Lowe, Danilo Mollicone, Marcelo Rezende, Devin Routh, Moctar Sacande, Ben Sparrow, Constantin M. Zohner, Thomas W. Crowther

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.

Full text: dx.doi.org/10.1126/science.aay8108

Comment on "The global tree restoration potential"

Alan Grainger, Louis R. Iverson, Gregg H. Marland, Anantha Prasad

Bastin *et al.* (Reports, 5 July 2019, p. 76) neglect considerable research into forest-based climate change mitigation during the 1980s and 1990s. This research supports some of their findings on the area of land technically suitable for expanding tree cover and can be used to extend their analysis to include the area of actually available land and operational feasibility.

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Comment on "The global tree restoration potential"

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Bastin *et al.* (Reports, 5 July 2019, p. 76) claim that global tree restoration is the most effective climate change solution to date, with a reported carbon storage potential of 205 gigatonnes of carbon. However, this estimate and its implications for climate mitigation are inconsistent with the dynamics of the global carbon cycle and its response to anthropogenic carbon dioxide emissions.

In their recent report, Bastin *et al.* (*1*) claimed that their study "highlights global tree restoration as our most effective climate change solution to date." The authors estimate that one could restore about 0.9 billion ha of canopy cover, which could store 205 GtC (gigatonnes of carbon) in areas that would naturally support woodlands and forests. The authors claim that "reaching this maximum restoration potential would reduce a considerable proportion of the global anthropogenic carbon burden (~300 GtC) to date. This places ecosystem restoration as the most effective solution at our disposal to mitigate climate change." We believe this conclusion is wrong because of the authors' misunderstanding of both carbon storage potential and the global carbon cycle response to anthropogenic emissions.

First, Bastin *et al.* compared their estimate of 205 GtC with "the global anthropogenic carbon burden" of about 300 GtC to date. The 300 GtC figure seems to refer to the historical increase in atmospheric CO_2 (expressed in their paper in units of mass, GtC, as opposed to the usual units of concentration, ppm), which is only about half of the historical anthropogenic emissions of about 600 GtC (*2*). Only about 45% of these emissions remain in the atmosphere; the rest has been absorbed by the ocean and land ecosystems. The ratio of atmospheric CO_2 increase to anthropogenic CO_2 emissions, called the airborne fraction, is relatively constant over the historical record and was described more than 40 years ago (*3*). Assuming that fossil fuel emissions continue at some level for the duration of a forest restoration program as suggested by Bastin *et al.*, net anthropogenic emissions over this period will be the difference between the fossil fuel emissions and the net biospheric uptake due to forest restoration. The balance between future emissions and future uptake will be subject to the same airborne fraction of around 45% (*4*, *5*). The authors should have estimated the atmospheric carbon removal from forest restoration as the

potential carbon storage multiplied by the airborne fraction, reducing by about 45% the reported impact of this forest restoration option on the atmospheric CO_2 growth rate. Alternatively, the potential carbon removal from forest restoration could be directly compared to cumulative anthropogenic emissions to date (about 600 GtC), but not the fraction remaining in the atmosphere.

Second, the 205 GtC figure is obtained from the potential canopy cover spatial distribution (as shown in their figure 2, B and C) and the carbon densities across the major biomes of the world (table S2, with distribution shown in figure S2). From table S2, it appears that the authors simply multiplied the potential canopy cover (in Mha) by the carbon densities (in tC/ha) of the biome currently in these regions to estimate potential carbon storage. By doing so, they would, in effect, ignore the carbon that is currently stored in those regions. The right approach is to estimate the carbon storage potential as the difference between carbon potentially stored by a forest and the carbon currently stored by the existing ecosystem—for example, forest versus tundra (assuming that a forest could be sustained in the Arctic climate of the tundra biome). From the carbon densities given in table S2 for each biome, it is clear that the potential carbon storage would be substantially lower than reported. Boreal forests can only store about 15% more carbon than tundra; temperate (tropical) forests are given the same carbon density as temperate (tropical) grasslands, implying no clear carbon gain from forest restoration.

Moreover, forests affect climate through biophysical feedbacks, such as changes in albedo or evapotranspiration (*6*), which can counteract the cooling effect from CO_2 uptake. It is well established, for instance, that afforestation in snow-covered regions may lead to weak local cooling, or even to warming, as the positive radiative forcing induced by decreases in albedo can offset the negative radiative forc-

ing from carbon sequestration [e.g., (*7*, *8*)]. These biophysical feedbacks were not discussed in the article and could substantially reduce the potential of forest reforestation in some of the considered regions.

Third, regardless of the exact amount of carbon that could be stored via forest restoration, this solution can only temporarily delay future warming. The 205 GtC proposed by the authors is equal to about 20 years of global anthropogenic CO_2 emissions at the current emission rate of about 10 GtC/year (*2*). Without radical reductions in fossil carbon emissions, forest restoration can only offset a share of future emissions and has limited potential. The only long-term and sustainable way to stabilize the climate at any temperature target is to reduce anthropogenic CO_2 emissions to zero (over the coming 30 to 50 years to meet the temperature targets of the Paris Climate Agreement) (*9*).

Finally, the paper does not provide any evidence that ecosystem restoration is "the most effective solution at our disposal to mitigate climate change." Analyses showing the carbon mitigation potential of planting trees have been available for the past two decades [e.g., (*10*)], yet there has been very limited adoption of such a strategy because of concerns about unintended consequences (e.g., water availability) and complex land rights. In contrast, energy efficiency and deployment of nonfossil energy sources have helped reduce emissions in the past (*11*) and are key characteristics of deep mitigation pathways even when large-scale CO_2 removal is deployed (*12*). The literature indicates that a multitude of mitigation measures are needed [e.g., (*9*, *13*)], and it is unlikely that any measure would be the "most effective."

Bastin *et al.* strongly overestimate the potential of forest restoration to mitigate climate change. The claim that global tree restoration is our most effective climate change solution is simply incorrect scientifically and dangerously misleading.

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Comment on "The global tree restoration potential"

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Science

Comment on "The global tree restoration potential"

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Bastin *et al.*'s estimate (Reports, 5 July 2019, p. 76) that tree planting for climate change mitigation could sequester 205 gigatonnes of carbon is approximately five times too large. Their analysis inflated soil organic carbon gains, failed to safeguard against warming from trees at high latitudes and elevations, and considered afforestation of savannas, grasslands, and shrublands to be restoration.

Bastin *et al.* (*1*) used remote sensing and machine learning to estimate that global "tree restoration" could sequester 205 gigatonnes of carbon (GtC). If accurate and achievable, this would constitute an astounding accomplishment, equal to 20 times the current annual fossil fuel emissions (10 GtC/year) (*2*) and about one-third of total historical anthro-

pogenic emissions (660 GtC) (2). Unfortunately, key assumptions and data underlying Bastin *et al.*'s analyses are incorrect, resulting in a factor of 5 overestimate of the potential for new trees to capture carbon and mitigate climate change. We show that Bastin *et al.* (i) overestimated soil carbon gains from increased tree cover by a factor of 2; (ii) modeled new tree cover in regions where trees reduce albedo and increase climate warming (3, 4); and (iii) relied heavily on afforestation of grasslands and savannas—biodiverse ecosystems where fires and large herbivores have maintained low tree cover for millions of years (5, 6).

Bastin *et al.*'s inflation of soil carbon gains resulted in a ~98 GtC overestimate of potential carbon sequestration (Table 1). They mistakenly assumed that treeless areas have no soil organic carbon (SOC) and that SOC increases in direct (1:1) proportion to tree cover. The contribution of SOC to total carbon stocks is substantial in most terrestrial ecosystems. In humid tropical savannas, for example, 86% of all carbon is in soils (174 tonnes of SOC per hectare) (7). In boreal forests, 64% of carbon occurs in soils (8). North American grasslands can store as much carbon in soil (9) as tropical forests store as biomass (8). In Table 1, we display SOC-corrected carbon sequestration estimates that use more realistic (literature-derived) values for the changes in SOC that occur with afforestation and reforestation.

In addition to the SOC overestimate, Bastin *et al.* did not account for the warming effect of trees due to decreased albedo (3, 4). Trees, particularly evergreen conifers, are less reflective than snow, bare ground, or grasses, and thus absorb more solar energy, which is ultimately emitted as heat. At high latitudes and elevations, the warming effect of trees is greater than their cooling effect via carbon sequestration (3, 4). Similarly, trees planted in low-latitude, semi-arid regions can produce net warming for decades before carbon sequestration benefits are realized (10). Because, at a minimum, carbon from trees planted in boreal forests, tundra, or montane grasslands and shrublands should not be counted as climate change mitigation (Bastin *et al.* counted a SOC-corrected 17 GtC), in Table 1 we provide a corrected estimate that excludes these biomes.

The carbon sequestration estimate of Bastin *et al.* is also dependent on the false assumption that natural grasslands and savannas with fewer trees than predicted by their statistical model are "degraded" and in need of restoration (11). Ecological restoration of savannas and grasslands rarely involves planting trees, and more often requires tree-cutting and prescribed fire to promote biodiversity and ecosystem services (12). Yet after correcting for SOC, 46% of the carbon sequestration estimate of Bastin *et al.* comes from increased tree cover in grasslands, savannas, and shrublands (Table 1). Among all biomes, tropical grasslands are the largest contributor to Bastin *et al.*'s estimate of potential carbon sequestration (SOC-corrected 40 GtC or 37% of the global potential; Table 1).

Although Bastin *et al.*'s model, developed with climate and soil data in protected areas, may be reasonable in some of the driest and wettest places on Earth, any statistical approach to predict tree cover at intermediate precipitation (500 to 2500 mm annually) must include the effects of fire and, where they still exist, large grazing and browsing animals (13). Because Bastin *et al.* failed to account for fire, their model had low predictive power across many of the open-canopy biomes they analyzed, as shown by their own uncertainty analysis. Although we commend their intent to respect the "natural ecosystem type" by training their machine-learning algorithm on protected areas, they map many of these same areas—particularly those with grassland-forest mosaics (e.g., Yellowstone National Park, USA)—as opportunities for tree planting. Of additional concern, their method of interpolation between protected areas misrepresents some enormous savanna regions (e.g., western Los Llanos in Colombia is targeted for 75 to 100% tree cover), presumably because the protected areas are located in adjacent tropical forests, not savannas.

Bastin *et al.*'s model suggesting grasslands and savannas as potential sites for restoration using trees is inaccurate and misguided. Earth's savannas and grasslands predate humans by millions of years; their formation is a result of complex ecological and evolutionary interactions among herbaceous plants (grasses and forbs with extensive roots and underground storage organs), environmental change (climatic cooling, drying, changes in atmospheric CO_2), fires (first ignited by lightning, then by people), and large herbivores (5, 6). These ecosystems and their iconic species are already gravely threatened by fire exclusion and afforestation, processes that replace species-diverse biotic communities with lower-diversity forests (14). Carbon-focused tree planting will exacerbate these threats, to the detriment of people who depend on grasslands to provide livestock forage, game habitat, and groundwater and surface-water recharge (11). Moreover, trees planted in grasslands will be prone to carbon loss from fires. Because these detrimental effects should preclude tree planting in grasslands, savannas, and shrublands, we excluded these biomes from Bastin *et al.*'s estimate in Table 1.

In combination, our corrections for SOC and corrections to avoid the unintended consequences of misguided tree planting (i.e., warming and biodiversity loss with afforestation) would reduce Bastin *et al.*'s estimate of potential carbon sequestration by a factor of 5, to the still-substantial amount of ~42 GtC (Table 1). Although ecological restoration, if carefully implemented, can have a role in mitigating climate change, it is no substitute for the fact that most fossil fuel emissions will need to stop to meet the targets of the

Paris Agreement (*15*). Such action should be accompanied by policies that prioritize the conservation of intact, bio-diverse ecosystems, irrespective of whether they contain a lot of trees.

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Table 1. Corrected estimates of the potential for increased tree cover to sequester carbon and mitigate climate change. We corrected Bastin *et al*.'s estimate (205 GtC) to represent realistic gains or losses of soil organic carbon (SOC) that occur with increased tree cover in each biome [based on (*9, 16–21*)]. We then excluded biomes (assigned a value of 0 GtC) where tree planting for climate change mitigation should not occur because of unintended consequences (e.g., net warming from reduced albedo or loss of biodiversity). Although we disagree with several of the carbon density values used by Bastin *et al*. [e.g., they applied values for intact tropical forests (*8*) to estimate second-growth forest biomass, and applied values from humid tropical savannas (*7*) to deserts and tundra], we retained these values to demonstrate the magnitude of the SOC and biome corrections.

	Potential carbon stocks, Bastin *et al.* (*1*)						Correction for soil carbon			Correction to avoid unintended consequences	
Biome*	Canopy cover restoration area (Mha)*	Carbon density (tC/ha)*	Carbon density source*	Carbon gain (GtC)*	ΔC biomass (tC/ha)†	ΔSOC (tC/ha)†	Realistic ΔSOC (tC/ha)	Realistic ΔSOC source	SOC-corrected carbon gain (GtC)¶	Biome-corrected carbon gain (GtC)	Detrimental effects of carbon-focused tree planting
Boreal forests/taiga	178	239	(8)	42.6	85	154	0	(16)‡	15.2		↓albedo (net warming)
Deserts and xeric shrublands	78	202	(7)	15.7	28	174	5.1	(9)§	2.6		↓provisioning of water, ↑fire intensity
Flooded grasslands and savannas	9	202	(7)	1.8	28	174	12.4	(17)	0.4		↓biodiversity
Montane grasslands and shrublands	19	202	(7)	3.9	28	174	−3.3	(18)	0.5		↓biodiversity, ↓albedo (net warming)
Temperate grasslands	73	155	(8)	11.2	81	74	−3.3	(18)	5.6		↓biodiversity, ↓forage production, ↑fire severity
Tropical grasslands	190	283	(8)	53.5	199	84	12.4	(17)	40.0		↓biodiversity, ↓provisioning of water, ↓forage production, ↑fire severity
Tundra	51	202	(7)	10.2	28	174	0	(19)‡	1.4	0	↓albedo (net warming)
Mangroves	3	283	(8)	0.7	199	84	198	(20)	1.0	1.0	
Mediterranean forests	19	202	(7)	3.8	28	174	0	(21)‡	0.5	0.5	↑fire intensity#
Temperate broadleaf	109	155	(8)	16.9	81	74	−3.3	(18)	8.4	8.4	
Temperate conifer forests	36	155	(8)	5.6	81	74	−3.3	(18)	2.8	2.8	↑fire intensity and severity, ↓albedo#
Tropical coniferous forests	7	283	(8)	2.0	199	84	12.4	(17)	1.5	1.5	
Tropical dry broadleaf forests	33	283	(8)	9.3	199	84	12.4	(17)	6.9	6.9	
Tropical moist broadleaf forests	97	283	(8)	27.4	199	84	12.4	(17)	20.5	20.5	
Total	900			205					107	42	

*From materials and methods and table S2 of Bastin *et al*. (*1*): Carbon gain = canopy cover restoration area × carbon density.

†Portion of carbon density attributable to biomass and soil, from the same sources used by Bastin *et al*. [i.e., (*7, 8*)].

‡Studies that report no statistically significant change in SOC.

§Mean of two sites with annual precipitation < 300 mm.

¶SOC-corrected carbon gain = canopy cover restoration area × (ΔC biomass + realistic ΔSOC).

#Strength of effects depends on ecological context, but effects are not universal enough to exclude the biome.

Science

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Comment on "The global tree restoration potential"

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Bastin *et al.* (Reports, 5 July 2019, p. 76) state that the restoration potential of new forests globally is 205 gigatonnes of carbon, conclude that "global tree restoration is our most effective climate change solution to date," and state that climate change will drive the loss of 450 million hectares of existing tropical forest by 2050. Here we show that these three statements are incorrect.

Bastin *et al.* (*1*) provide an assessment of the potential to expand the area of Earth allocated to forests to sequester carbon to mitigate climate change. They (i) produce a data-driven model to estimate the potential area of Earth where trees will grow, then exclude existing forest, croplands, and urban areas, estimating that the remaining 900 Mha of new tree cover is the global "restoration potential"; (ii) estimate that the resulting carbon sequestration from foresting this area is 205 GtC; (iii) suggest that this will offset two-thirds of the "global anthropogenic carbon burden," making it the "most effective climate change solution to date"; and finally (iv) extend their spatial model of restoration potential in time, showing a net 223 Mha decrease in global tree cover by 2050. We consider the last three of these results to be fundamentally flawed.

The stated 205 GtC restoration potential is 0.22 GtC Mha⁻¹ new forest cover, double previously published estimates (*2–5*). This anomaly is not noted by the authors (*1*). Four alternative approaches show that this number is almost certainly too high:

1) Anthropogenic land-use change, since 1750, has emitted 200 GtC, which suggests that it is highly unlikely that restoring only a fraction of previously deforested land will itself sequester 205 GtC (*5*). The 900 Mha that Bastin *et al.* suggest restoring is 39% of formerly tree-covered land (*1*), hence historical evidence suggests that restoring this proportion of it would lead to 78 GtC uptake. Add the fraction of the 200 GtC land sink since 1750 attributable to the 900 Mha (14% of once tree-covered land and today's existing forests), and from first principles we expect 107 GtC uptake from restoring 900 Mha of new tree cover (0.12 GtC Mha⁻¹).

2) Using a fully coupled climate model to restore 100% of agricultural land (*2*) predicts 240 GtC uptake on 2020 Mha of land (0.12 GtC Mha⁻¹). This converts to 107 GtC for

restoring 900 Mha.

3) Using mapped restoration areas regenerating to climatically supportable carbon stock levels (*3*) results in 108 GtC sequestered over 900 Mha (0.12 GtC Mha⁻¹).

4) A mapping exercise that identified restoration areas, with no economic constraints and published sequestration rates, gave a median estimate of 89 GtC when scaled to 900 Mha (*4*) (0.10 GtC Mha⁻¹).

Although Bastin *et al.* use tree cover area as their metric, this is directly comparable to the above land area estimates, because their methods account for this; for example, 10% tree cover is only 10% of the per-hectare carbon sequestration. The four published estimates above are similar, with a mean of 103 GtC (range, 89 to 108), just 50% the Bastin *et al.* estimate.

Bastin *et al.*'s anomalous result arises because their multiplication of tree cover area by mature ecosystem carbon stock levels is incorrect. First, they assume, incorrectly, that soil carbon stocks are zero prior to restoration. The original carbon density values used in (*1*) show that 37 to 86% of the carbon sequestration in each vegetation class is new soil carbon, a total of 113 GtC. This is not credible: It is equivalent to all the soil organic carbon lost globally since the advent of farming, ~116 GtC (*6*). Critically, when converting grassland or pasture to tree-covered land [the majority of the new tree cover (*1*)], meta-analyses show no overall trend in soil carbon stocks (*7, 8*). Alternatively, if the global average 3.6% loss of soil organic carbon was assumed to return to these soils, that would add 4 GtC, not 113 GtC as Bastin *et al.* claim. Thus, the total sequestration, when accounting for the prior existence of carbon in soil, is ~96 GtC, in line with published estimates.

Bastin *et al.* secondly assume that live stem, leaf, root, and necromass are all also zero prior to restoration. This is

not correct: All of the 900 Mha they highlight as available has plants growing on it, and a substantial proportion will have some trees already. Carbon removed from the atmosphere by restoration is only that added to the system from new additional vegetation growth. To illustrate the likely magnitude of this error, a recent restoration potential analysis showed 42.1 GtC uptake from restoring 350 Mha of forest, in addition to the 10.6 GtC already in biomass on the land prior to restoration (*3*). Using the Bastin *et al.* method, sequestration would thus have been overreported by ~25%.

The third Bastin *et al.* assumption is that future environmental change will have no impact on forest carbon stocks. Typically, higher atmospheric CO_2 concentrations increase carbon stocks more than higher temperatures and altered rainfall reduce it (*9*, *10*). Given the intrinsic uncertainty of future emissions, this impact could be as low as ~7% under a low-emission scenario (*3*), or as high as a ~20% increase under a mid-range scenario for the tropical forest biome (*11*). Assuming the latter and taking all three biases into account (initial soil, initial biomass, changing environment), ~92 GtC is expected to be sequestered in 900 Mha of new forest cover (92 GtC on the land after restoration, minus 23 GtC already on the land, plus 4 GtC added to the soil, plus 19 GtC added from the changing environment). This corrected 92 GtC value is similar to the four independent sequestration estimates detailed above, but is less than half the Bastin *et al.* estimate.

The authors then compound their overestimate of the importance of forest restoration by asserting that "reaching this maximum restoration potential [205 GtC] would reduce a considerable proportion of the global anthropogenic carbon burden (~300 GtC) to date." This 67% reduction is not correct. Human actions have added 640 GtC since 1750; thus, 205/640 is 32%. The authors appear to have confused the increase in atmospheric carbon dioxide concentration since 1750 with total anthropogenic emissions. The difference is because ~55% of anthropogenic CO_2 emissions were removed from the atmosphere into land and ocean sinks. Reversing the atmospheric increase via restoration concomitantly weakens the sink strength (*2*, *5*, *12*). Thus, overall, restoration over 900 Mha is ~100 GtC, which would reduce the anthropogenic burden by ~15% [i.e., (100 × 0.45)/300 from an atmospheric perspective, or 100/640 from an emissions perspective), not ~67% as Bastin *et al.* claim. Furthermore, 15% overestimates the climate impact of Bastin *et al.*'s restoration potential, because 25% of the new tree cover is in tundra and boreal regions, where warming from forests' lower surface albedo can offset the cooling from new carbon uptake (*13*).

Bastin *et al.* state in their abstract that "[our study] highlights global tree restoration as our most effective climate change solution to date." This statement is not sup-

ported by the evidence provided. Furthermore, such a statement can never be supported because (i) in physical terms, keeping fossil carbon in its original geological storage is self-evidently a more effective solution to climate change than releasing it and capturing it later in trees; (ii) allowing trees to grow where they once grew is largely merely replacing carbon that was previously lost through land-use change, and so does not address fossil fuel emissions; and (iii) sequestering ~100 GtC into new forests is equivalent to just 10 years of current emissions, which clearly shows that forest restoration is of lower importance than rapidly reducing fossil fuel emissions.

Finally, Bastin *et al.* model the future, concluding that "global potential canopy cover may shrink by ~223 million hectares by 2050, with the vast majority of losses occurring in the tropics." The authors state that their results are "in stark contrast to most current model predictions" but give no explanation for this. The reason is that they first parameterize an environment–tree cover association in space for the recent past, and then apply it over time into the future, giving an erroneous result. This arises because there are no current areas of Earth today that are as hot as will exist in the core wet tropics in 2050. Thus, when 2050 climate output shows higher temperatures in areas of current tropical forest, the Bastin *et al.* machine-learning model fills in the tree cover from areas with the closest match from today—but these are open forest and savanna areas that are also considerably drier than climate models predict for future tropical forest areas. This upper temperature limit problem is a well-recognized error within bioclimatic envelope-type modeling (*14*). Thus, although the intact Amazon carbon sink is declining, there is no hint of a decline in canopy cover (*15*) and a switch due to climate change alone, in the absence of deforestation and logging (which were not modeled), to swathes of open forest within the next 30 years is highly unlikely, even under the most pessimistic of climate-driven vegetation models (*11*).

One further contributory reason why the 2050 results that Bastin *et al.* report are in "stark contrast" to other models is because their spatial correlations exclude any impact of rising atmospheric CO_2. Given that no place on Earth today has 2050-level CO_2 concentrations, their machine-learning approach is not an appropriate approach. Tropical forests' response to global change is the net of a negative impact of high temperatures, a positive impact of rising CO_2, and the impacts of any changes in rainfall or its distribution (*9*). The pivotal role of CO_2 for photosynthesis is well known, evidenced from theory, observations, and experiments (*9*). The decision to ignore this evidence means that the reported net 46 GtC loss from forest cover by 2050 is also incorrect.

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Comment on "The global tree restoration potential"

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Comment on "The global tree restoration potential"

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Bastin *et al.* (Reports, 5 July 2019, p. 76) neglect considerable research into forest-based climate change mitigation during the 1980s and 1990s. This research supports some of their findings on the area of land technically suitable for expanding tree cover, and can be used to extend their analysis to include the area of actually available land and operational feasibility.

The paper by Bastin *et al.* (*1*) is to be welcomed for drawing fresh attention to the potential for expanding forest and tree cover to mitigate global climate change by sequestering CO_2 from the atmosphere. Unfortunately, it fails to acknowledge the huge amount of research in this field during the 1980s and 1990s. This is a common problem because the UN Framework Convention on Climate Change did not begin negotiations on a REDD+ (Reducing Emissions from Deforestation and Degradation) mechanism until 2007, and research to support REDD+ has grown rapidly since then. As Bastin *et al.* emphasize, time is short. So it is vital that new forest mitigation programs build on preexisting knowledge and do not try to "reinvent the wheel." Here, we use key achievements of this early research to assess the contributions and limitations of Bastin *et al.*'s findings.

Bastin *et al.* find "room for an extra 0.9 billion hectares of canopy cover, which could store 205 gigatonnes of carbon" and relate this to the net amount of carbon transferred into the atmosphere since pre-industrial times. Early estimates, however, focused on the size of a new forest sink needed to sequester a meaningful amount of carbon on a continuing basis. They included (i) 500 Mha to absorb gross emissions in the 1980s of 5 gigatonnes of carbon per year (GtC year^{-1}) (*2*), and (ii) 465 Mha with a growth rate of 15 m^3 ha^{-1} year^{-1} to sequester only the net annual rise of 2.9 GtC year^{-1} in the atmosphere (*3*) after uptake by terrestrial and oceanic sinks.

Later studies showed that more than enough degraded tropical land existed to support forest expansion on this scale. Two papers presented to an Intergovernmental Panel on Climate Change (IPCC) conference in January 1990 estimated that in the tropics, (i) 620 Mha of degraded lands were physically suitable for establishing this new "carbon-forest," and another 137 Mha of degraded forests could be restored (*4*); and (ii) 500 Mha of land could be afforested by

2100, with a further 365 Mha of forest fallows having potential for restoration (*5*). Both studies were summarized in the First IPCC Assessment Report (*6*). The comparability of these findings with those of Bastin *et al.* is remarkable, given that Bastin *et al.* use very high (≤1 m)–resolution satellite data and cloud-based machine-learning algorithms, whereas early estimates depended largely on United Nations statistics—although one 1990 estimate did use low (≥1 km)–resolution satellite data (*5*).

Bastin *et al.* also relate their principal finding to a recent IPCC estimate (*7*) that 950 Mha of new forests could help to "limit global warming to 1.5°C" by 2050. Because this estimate is based on the current net annual rise in CO_2 in the atmosphere, which is twice as high (~5.7 GtC year^{-1}) as in the 1980s, it is consistent with the 465 Mha considered appropriate 30 years ago (*3*).

Bastin *et al.* do not evaluate the operational feasibility of expanding tree cover in time to tackle global warming promptly. Nor does the recent IPCC report, which discusses planting 950 Mha of new forests in just 30 years (*7*). Yet one early study (*4*) argued that to afforest 600 Mha over a 30-year period would require a planting rate 20 times the contemporary rate of 1 Mha year^{-1}. It anticipated REDD+ by showing that more modest planting rates could suffice if afforestation proceeded in parallel with programs to reduce the rate of tropical deforestation, which is a major source of carbon emissions (*4*).

Bastin *et al.* assess the potential to increase carbon density in existing forests, using carbon densities in protected areas as benchmarks, but do not mention a pioneering methodology for making restoration assessments that was devised in the early 1990s and applied to all of tropical Asia. Starting with an FAO map of tropical forest area in Asia in 1980 derived from medium-resolution Landsat satellite data, the distribution of potential forest carbon density was de-

termined by using Geographical Information System modeling to combine forest inventory data (*8*) with multiple environmental datasets. Using degradation factors developed as a function of human population density for each ecofloristic zone along a moisture gradient, actual carbon density was then mapped to identify the distribution of degraded forests that could be restored. This map agreed well with an alternative map of a global vegetation index quantified using low-resolution satellite data (*9, 10*).

Commenting on Bastin *et al.*'s paper, Chazdon and Brancalion (*11*) wisely stress the need to address "social and environmental issues" in tree restoration. The importance of integrating afforestation with forest conservation was recognized in 1991 (*12*). Early studies also estimated the costs of afforestation; for example, just to plant a 300 Mha carbon-forest over 30 years would cost US$4 billion annually (*4*). These costs would be offset by income from converting the wood produced in the new forests into energy and harvested wood products (HWP), so these forests would be sustainable carbon sinks. The potential role of HWP in climate change mitigation is still poorly understood.

Increasingly sophisticated tools for feasibility analysis were then developed. The "technical suitability" of land for afforestation was distinguished from the "actual availability" of land on which afforestation might be socially, economically, and politically acceptable (*10, 13*), and the link between the level of national development (i.e., "developmental time") and the area of actually available land was recognized in the new concept of "national forest carbon transition functions" (*14*). Now that climate change is shifting the potential locations of biome boundaries (*15*), Bastin *et al.* rightly allow for the influence of "climatic time" on their assessment by including alternative climate change scenarios.

If Bastin *et al.*'s paper gives new impetus to using forests to mitigate climate change, then the results of this early research can finally be used for the purpose for which they were originally intended.

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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-

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	90	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	90	202.4
Montane grasslands and shrublands	19.3	90	100	100	202.4
Temperate broadleaf and mixed forests	109	86	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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