Matters arising

The risks of overstating the climate benefits of ecosystem restoration

https://doi.org/10.1038/s41586-022-04881-0

Received: 26 October 2020

Accepted: 19 May 2022

Published online: 7 September 2022

Check for updates

Jonathan C. Doelman[1,2] ✉ & Elke Stehfest[1]

ARISING FROM B. B. N. Strassburg et al. Nature https://doi.org/10.1038/s41586-020-2784-9 (2020)

Preventing dangerous climate change and halting the global loss of biodiversity are considered crucial goals to ensure a sustainable future on Earth[1,2]. Strassburg et al.[3] present a high-resolution method to identify optimal locations for ecosystem restoration globally for conserving biodiversity and increasing carbon sequestration. Their most prominently presented conclusion is that 30% of the total CO_2 increase in the atmosphere since the Industrial Revolution can be sequestered by restoring 15% of converted lands. Here we argue that this is an overly optimistic message that is partly based on inaccurate assumptions and that this creates unrealistic expectations for the contribution of restoration to the mitigation of climate change.

Our first concern is regarding the area of converted lands and their carbon stocks. The amount of potential carbon sequestration found by Strassburg et al.[3] for the identified 15% priority areas is based on an oversimplified assumption for existing aboveground carbon stocks. For natural vegetation, the estimates of final above- and belowground carbon stocks applied in the study by Strassburg et al.[3] are state of the art (within a wide uncertainty range[4]). For converted lands, Strassburg et al.[3] assume that current aboveground carbon stocks are 6 tonnes of carbon per ha (tC ha^{-1}). However, especially in locations identified as priority areas, such as southeast Asia, the western African coastal area and the Caribbean, carbon stocks in converted lands are in fact much higher because they mostly consist of mosaic and agroforestry-type landscapes. These converted lands are partly detected as mosaic croplands in the European Space Agency Climate Change Initiative (ESA CCI) land-cover data[5] used by Strassburg et al.[3], and are typically assumed to have 40–60% natural vegetation[6]. A previously published analysis[7] showed that these regions, in fact, have high aboveground carbon stocks in agricultural lands, for example, 97 tC ha^{-1} in Indonesia, 46 tC ha^{-1} in Ivory Coast and 49 tC ha^{-1} in Cuba. Because these countries make up a large share of the highlighted 15% priority areas, taking a more realistic reference carbon stock would substantially reduce the carbon-sequestration potential.

This error in estimating current carbon stocks in converted lands arises from confusing land cover with land use. Strassburg et al.[3] use ESA CCI data—a land-cover product—as a 'land-use remote-sensing product' and take a broad view on converted land by including cropland and cultivated grassland classes as well as the two ESA CCI mosaic classes (mosaic cropland (>50%)/natural vegetation (<50%) and mosaic natural vegetation (>50%)/cropland (<50%)). Subsequently, Strassburg et al.[3] use these 'anthropic' land covers synonymously with agricultural land use—that is, cropland and grazing land—and apply the carbon content values as defined for agricultural land use[8]. The difference between ESA-CCI-based converted land as used by Strassburg et al.[3] and a corresponding converted-land estimate based on Food and Agriculture Organization/History Database of the Global Environment (FAO/HYDE) data is substantial, as the estimates are 29 million and 22 million km^2, respectively (Fig. 1 and Supplementary Information). The confusion of land cover and land use leads to a problem when applying land-use-specific carbon contents and it could also distort biodiversity effects.

Our second concern is regarding the misleading comparison between the potential CO_2 uptake and atmospheric CO_2 increase. This issue has also been addressed by Friedlingstein et al.[9] in response to Bastin et al.[10] in *Science* last year that was followed by an erratum[11]. We are happy that Strassburg et al. adjusted their statement[12].

Finally, we want to comment on the feasibility of the restoration options presented. Quantifying potential biodiversity and carbon gains of ecosystem restoration is scientifically very valuable. The realization of the proposed restoration, however, would have severe feasibility constraints. The high priority locations are mostly located in tropical regions, where about 50% of all agricultural land in southeast Asia, Central Africa, the Caribbean and Mesoamerica would need to be restored (as shown in the most prominently presented case, see figure 1e and extended data figure 3e of Strassburg et al.[3]). Although Strassburg et al.[3] acknowledge these feasibility constraints in a section of their paper using various sensitivity tests, the figures and abstract only feature the unconstrained cases. Such unconstrained restoration with large-scale abandonment of agriculture in these regions would have enormous impacts on the agricultural system, and beyond. Moreover, business-as-usual projections show major increases in population, food demand and agricultural production in Latin America, sub-Saharan Africa and southern Asia[13,14], further increasing the pressure on land systems. Various studies have shown that large reductions in agricultural land in these regions could lead to major effects on food security[15,16]. Testing the sensitivity of their results, Strassburg et al.[3] reveal that national- and landscape-level assumptions substantially diminish the sequestration potential (by 29% and 49%, respectively). In our view, the case with national targets (a maximum of 15% agricultural abandonment) represents a more-realistic approach to restoration because it considers some level of effort sharing and therefore should have been presented more prominently.

We agree that ecosystem restoration is important for carbon sequestration and biodiversity conservation. However, overstating the role of restoration in preventing climate change may undermine mitigation efforts and distract from the core task of reducing carbon emissions by energy and industry.

[1]PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands. [2]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands.
✉e-mail: jonathan.doelman@pbl.nl

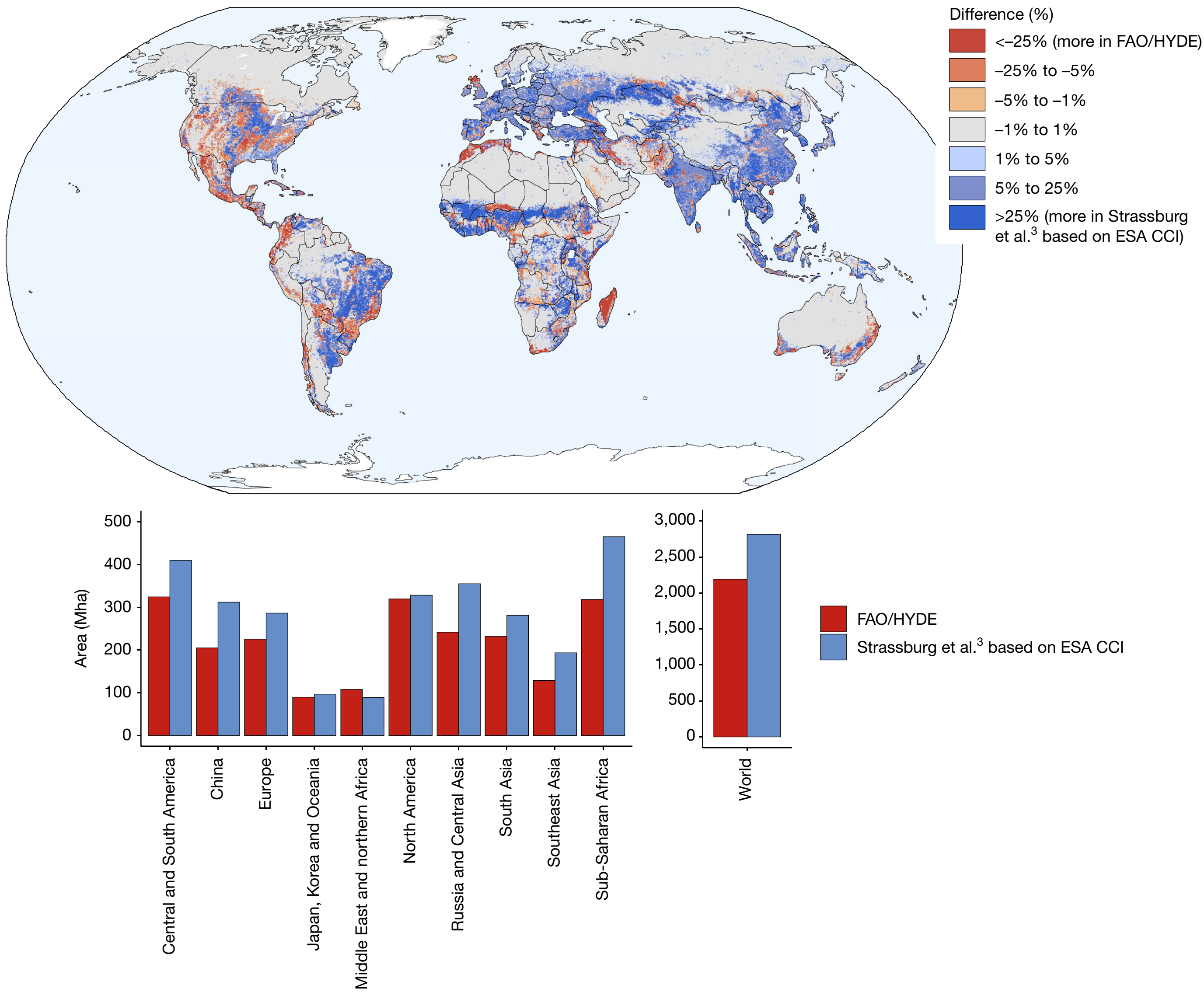

Fig. 1 | Difference between converted land according to Strassburg et al.[3] based on ESA CCI and according to FAO/HYDE. The comparison shows substantial differences both on the grid (top) and global scale (bottom), resulting from a different interpretation of land use and land cover data, with 29 million km^2 of converted land using Strassburg et al.[3] based on ESA CCI, and 22 million km^2 of converted land using FAO/HYDE. Both datasets are compared on the basis of the assumptions made by Strassburg et al.[3]. Mha, megahectare. For details, see Supplementary Information.

Data availability

All input datasets are available from the references cited. The data generated for this study are available from the corresponding author upon request.

Code availability

MATLAB and R codes developed for and used in this analysis are available upon request from the corresponding author.

1. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2014).
2. IPBES. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES Secretariat, 2019).
3. Strassburg, B. B. N. et al. Global priority areas for ecosystem restoration. *Nature* **586**, 724–729 (2020).
4. Erb, K.-H. et al. Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* **553**, 73–76 (2018).
5. ESA CCI. *Land Cover CCI Climate Research Data Package* (2017); https://maps.elie.ucl.ac.be/CCI/viewer/download.php
6. Poulter, B. et al. Plant functional type classification for earth system models: results from the European Space Agency's Land Cover Climate Change Initiative. *Geosci. Model Dev.* **8**, 2315–2328 (2015).
7. Zomer, R. J. et al. Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. *Sci. Rep.* **6**, 29987 (2016).
8. IPCC. *IPCC Guidelines for National Greenhouse Gas Inventories* 48–56 (2006).
9. Friedlingstein, P., Allen, M., Canadell, J. G., Peters, G. P. & Seneviratne, S. I. Comment on "The global tree restoration potential". *Science* **366**, eaay8060 (2019).
10. Bastin, J.-F. et al. The global tree restoration potential. *Science* **365**, 76–79 (2019).
11. Bastin, J.-F. et al. Erratum for the Report: "The global tree restoration potential" by J.-F. Bastin, Y. Finegold, C. Garcia, D. Mollicone, M. Rezende, D. Routh, C. M. Zohner, T. W. Crowther and for the Technical Response "Response to Comments on 'The global tree restoration potential'" by J.-F. Bastin, Y. Finegold, C. Garcia, N. Gellie, A. Lowe, D. Mollicone, M. Rezende, D. Routh, M. Sacande, B. Sparrow, C. M. Zohner, T. W. Crowther. *Science* **368**, eabc8905 (2020).
12. Strassburg, B. B. N. et al. Author Correction:Global priority areas forecosystem restoration. *Nature* https://doi.org/10.1038/s41586-022-05178-y (2022).
13. KC, S. & Lutz, W. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Change* **42**, 181–192 (2017).
14. Popp, A. et al. Land-use futures in the shared socio-economic pathways. *Glob. Environ. Change* **42**, 331–345 (2017).

15. Hasegawa, T. et al. Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Change* **8**, 699–703 (2018).
16. Doelman, J. C. et al. Afforestation for climate change mitigation: potentials, risks and trade-offs. *Glob. Change Biol.* **26**, 1576–1591 (2019).

Author contributions Both authors contributed to developing the ideas presented in this study and to writing this Comment. Both authors approved the final submitted version.

Competing interests The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41586-022-04881-0.
Correspondence and requests for materials should be addressed to Jonathan C. Doelman.

Reply to: The risks of overstating the climate benefits of ecosystem restoration

https://doi.org/10.1038/s41586-022-04882-z

Published online: 7 September 2022

Check for updates

Bernardo B. N. Strassburg[1,2,3,4] ✉, Alvaro Iribarrem[1,2], Hawthorne L. Beyer[5], Carlos Leandro Cordeiro[1,2], Renato Crouzeilles[1,2,3], Catarina Jakovac[1,2,6], André Braga Junqueira[1,2,7], Eduardo Lacerda[1,2,8], Agnieszka E. Latawiec[1,2,9,10], Andrew Balmford[11], Thomas M. Brooks[12,13,14], Stuart H. M. Butchart[11,15], Robin L. Chazdon[2,16,17,18], Karl-Heinz Erb[19], Pedro Brancalion[20], Graeme Buchanan[21], David Cooper[22], Sandra Díaz[23], Paul F. Donald[11,15,21], Valerie Kapos[24], David Leclère[25], Lera Miles[24], Michael Obersteiner[25], Christoph Plutzar[19,26], Carlos Alberto de M. Scaramuzza[2], Fabio R. Scarano[3] & Piero Visconti[25]

REPLYING TO J. C. Doelman & E. Stehfest *Nature* https://doi.org/10.1038/s41586-022-04881-0 (2022).

In the associated Comment, Doelman et al.[1] suggest that findings from our recent paper[2] overestimate the potential contribution of restoration to climate change mitigation, and suggest that our assumptions were incorrect and that we did not consider practical constraints to the implementation of the scenarios that we presented. We welcome their interest and agree with Doelman et al.[1] that realizing the full potential contributions of large-scale restoration to the mitigation of climate change (and conservation of biodiversity) will be challenging. We strongly disagree, however, that we have overestimated the scale of plausible contributions or failed to consider practical limitations to their delivery.

The central argument of Doelman et al.[1] is that a fraction of each pixel in the subcategory of cropland mosaics from the land-cover product[3] that we used[1] contains natural vegetation (they cite 40–60%) and a higher current carbon content than we considered, and that accounting for this would significantly affect our estimates of the contribution of restauration to the mitigation of climate change. Although an analysis within our 300 m pixels was beyond the original scope of our global analysis, we decided to investigate the effect on our estimates by accounting for natural vegetation within our mosaic pixels.

The previously published dataset[4] that Doelman et al.[1] base their arguments on does not distinguish between natural vegetation and tree plantations in cropland mosaics. Whereas the former would not fit our definition of restorable, the latter would. For instance, in southeast Asia, where the previously published study[4] found the highest biomass per hectare, oil palm tree plantation is widespread and widely considered a threat to addressing climate change and biodiversity conservation[5]. Instead, we used another dataset of 30 m products by the US Geological Survey (USGS)[6–13]. These datasets directly identify croplands to disaggregate the fraction of each 300 m cropland-mosaic pixel from the European Space Agency Climate Change Initiative (ESA CCI) dataset that is cropland from the fraction that is natural vegetation. For this sensitivity analysis, we subtracted, from our original croplands map, the fraction classified as natural vegetation to generate an alternative croplands map. We then reclassified these subtracted areas as one of our five broad natural vegetation classes according to the 'original ecosystem type' (OET_i) calculation described in the original study[2]. These operations yielded a new set of land-cover/land-use maps that were used to run our optimization algorithm for the central scenario (that is, the 'multiple benefits' scenario).

We found that accounting for the native vegetation fraction in each mosaic pixel would reduce the carbon sequestration estimate by 4.6% and the biodiversity benefits by 4.0% when running our central scenario using the same target area (430 megahectare (Mha)). Both results are well within the margin of error of the original estimates. And even this modest effect is probably an overestimation of the error, because, in this sensitivity analysis, we removed only restorable areas found to be natural vegetation at 30 m (389 Mha) and did not include other cropland areas identified at 30 m (188 Mha) that were not included in the original analysis.

We performed another, more-conservative estimate of the potential effects of the issue raised by Doelman et al.[1]. We allocated a value of 40 tonnes of carbon per ha (tC ha^{-1}) to the current carbon stocks of all mosaic areas selected in the central scenario of the original paper[2], and measured the associated reduction in climate sequestration. This value assumes that all of these mosaics would have the current carbon content of palm oil plantations[14], which is well above the woody biomass carbon of perennial croplands suggested by the IPCC (21 tC ha^{-1})[15] for the predominantly moist tropical climate regions in which our priority areas in the central scenario are located. Crucially, we did not run the optimization again, which would allow our algorithm to choose other areas with improved net gains for carbon. Even with these conservative

[1]Rio Conservation and Sustainability Science Centre, Department of Geography and the Environment, Pontifical Catholic University, Rio de Janeiro, Brazil. [2]International Institute for Sustainability, Rio de Janeiro, Brazil. [3]Programa de Pós Graduacão em Ecologia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil. [4]Botanical Garden Research Institute of Rio de Janeiro, Rio de Janeiro, Brazil. [5]School of Biological Sciences, University of Queensland, St Lucia, Queensland, Australia. [6]Agricultural Science Center, Federal University of Santa Catarina, Florianópolis, Brazil. [7]Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Barcelona, Spain. [8]Department of Geography, Fluminense Federal University, Niterói, Brazil. [9]Department of Production Engineering, Logistics and Applied Computer Science, Faculty of Production and Power Engineering, University of Agriculture in Kraków, Kraków, Poland. [10]School of Environmental Sciences, University of East Anglia, Norwich, UK. [11]Department of Zoology, University of Cambridge, Cambridge, UK. [12]International Union for Conservation of Nature (IUCN), Gland, Switzerland. [13]World Agroforestry Center (ICRAF), University of The Philippines, Los Baños, The Philippines. [14]Institute for Marine & Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia. [15]BirdLife International, Cambridge, UK. [16]Department of Ecology and Evolutionary Biology, University of Connecticut, Storrs, CT, USA. [17]World Resources Institute, Global Restoration Initiative, Washington, DC, USA. [18]Tropical Forests and People Research Centre, University of the Sunshine Coast, Sippy Downs, Queensland, Australia. [19]Institute of Social Ecology, University of Natural Resources and Life Sciences Vienna, Vienna, Austria. [20]Department of Forest Sciences, 'Luiz de Queiroz' College of Agriculture, University of São Paulo, Piracicaba, Brazil. [21]RSPB Centre for Conservation Science, Royal Society for the Protection of Birds, Edinburgh, UK. [22]Secretariat of the Convention on Biological Diversity (SCBD), Montreal, Quebec, Canada. [23]Instituto Multidisciplinario de Biología Vegetal, CONICET and Universidad Nacional de Córdoba, Córdoba, Argentina. [24]United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, UK. [25]Biodiversity and Natural Resources (BNR) program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. [26]Division of Conservation Biology, Vegetation Ecology and Landscape Ecology, University of Vienna, Vienna, Austria. ✉e-mail: b.strassburg@iis-rio.org

assumptions, the reduction in carbon sequestration is equivalent to 8.6% of our original estimates, again well within the margin of error of the estimates. It is important to note that, had we combined both approaches (excluding natural vegetation fraction from these mosaics and applying a value of 40 tC ha^{-1} to current carbon content of the remaining cropland areas) and run the optimization again, the reduction in carbon sequestration would necessarily be smaller than 8.6%, as it assumes that all mosaic areas selected in the original paper[2] would still be selected. In the first sensitivity analysis, when we removed the natural fraction from the restorable pool, the area of mosaics in the solution decreased by approximately half (to around 20% of the selected priority areas), even when the carbon content of the cropland fraction was kept at 6 tC ha^{-1}.

Although further research that combines more-refined estimates of the current carbon content with higher-resolution datasets can improve our estimates, we are reassured by these findings. Furthermore, there are other factors that make our estimates conservative. We probably underestimated the carbon-sequestration potential of carbon pools other than aboveground biomass. Whereas, in our estimate, these pools account for 8.6% of the gain in aboveground biomass, the IPCC recommends an adjustment fraction of 27% of the aboveground biomass gain to account for gains in other carbon pools[15]. This factor alone is several times larger than the estimated effects presented here.

As for the overall potential of restoration to contribute to climate mitigation, we certainly underestimated it as we did not account for the carbon-sequestration potential of restoring existing but degraded native ecosystems. This potential is estimated to be similar to the potential sequestration from restoring converted lands[16].

Therefore, we disprove the central argument made by Doelman et al.[1] that we overestimated the contribution of restauration to the mitigation of climate change.

Doelman et al.[1] suggest that we confused land cover and land use. We did not, and neither did other groups who also used the ESA CCI land-cover database as a basis to assess land use[17,18]. Doelman et al.[1] then provide an analysis in which they compare our estimates of converted lands with the HYDE database, which they produced with colleagues[19], and suggest that the difference between the two analyses is substantial (2.87 billion ha (Bha) in our original paper[2] compared with 2.2 Bha in the HYDE database). First, this difference is comparable to differences between other available estimates[17,18,20]. Second, our estimate is actually closer to the centre of the range of available estimates[17–20], whereas the HYDE database provides one of the smallest available estimates for converted lands. As an illustration, the recent high-resolution cropland products from USGS[6–13] estimate that there are 1.9 Bha of croplands alone (compared with the HYDE estimate of croplands and pasturelands of 2.2 Bha). There is a great need of further data and research to provide more-precise estimates of converted and degraded lands worldwide, but we believe our estimate is compatible with the current state of the art.

The final point by Doelman et al.[1] is related to the practical feasibility of achieving these effects, and the concentration of priority areas for restoration in developing countries. These are valid considerations, but we disagree that we did not address them. Indeed, these considerations occupy 40% of our results section, and 30 of the 52 scenarios presented in the main text (figure 3 in ref. [2]). Doelman et al.[1] suggest that achieving effects for the climate similar to the ones reported in our central scenarios would involve the large-scale abandonment of agriculture in some tropical regions. Our estimates contradict this argument. The unconstrained global scenarios indeed identify very high proportions of some regions as priority areas for restoration, as we have noted in the opening of the "Scale and feasibility constraints" section of our results[2]. However, constraining the optimization so that each country or even 5 km by 5 km landscape could restore areas only up to a level that is compatible with maintaining the current agricultural production (when coupled with a partial closure of the yield gap) would reduce the potential for climatechange mitigation by 3% or less (scenarios VIII and IX in figure 3 of ref. [2]). Furthermore, as stated, future increases in demand can be met by complementary measures such as food-waste reduction, improved trade and a shift in consumption away from higher-footprint food. Another recent analysis[19] showed that about 10 million km^2 (that is, about one-third of the area that we identified as converted land) could be restored and still meet future agricultural demand by 2050. This further suggests that the 15% target of our central scenarios is within feasible boundaries. Even in the extreme scenario in which restoration is equally distributed across all countries (so that each restored 15% of its converted lands), climate mitigation benefits would be reduced by a maximum of 29%. These results show that, in contrast to what Doelman et al.[1] suggest, we did not ignore practical constraints that would make the climate change mitigation or biodiversity conservation benefits that we reported exaggerated or unrealistic.

Achieving ecosystem restoration at planetary scales targeted by multiple international agreements and processes will be very complex, involving multiple practical, ecological, social and ethical considerations that need to be dealt with appropriately. However, the resulting contributions to some of our greatest global challenges, as shown in our Article[2] and reaffirmed in the analyses summarized here, are vast and can hopefully motivate all relevant stakeholders to take appropriate actions towards realizing this potential.

1. Doelman, J. C. & Stehfest, E. The risks of overstating the climate benefits of ecosystem restoration. *Nature* https://doi.org/10.1038/s41586-022-04881-0 (2022).
2. Strassburg, B. B. N. et al. Global priority areas for ecosystem restoration. *Nature* **586**, 724–729 (2020).
3. ESA CCI. *Land Cover CCI Climate Research Data Package* https://www.esa-landcovercci.org/?q=node/158 (2017).
4. Zomer, R. J. et al. Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. *Sci. Rep.* **6**, 29987 (2016).
5. Meijaard, E. et al. *Oil Palm and Biodiversity: A Situation Analysis by the IUCN Oil Palm Task Force* (IUCN, 2018).
6. Xiong, J. et al. *NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Global Food Security-support Analysis Data (GFSAD) @ 30-m Africa: Cropland Extent Product (GFSAD30AFCE)* (NASA EOSDIS Land Processes DAAC, 2017).
7. Xiong, J. et al. Nominal 30-m cropland extent map of continental Africa by integrating pixel-based and object-based algorithms using Sentinel-2 and Landsat-8 data on Google Earth Engine. *Remote Sens.* **9**, 1065 (2017).
8. Teluguntla, P. et al. *NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Global Food Security-support Analysis Data (GFSAD) @ 30-m for Australia, New Zealand, China, and Mongolia: Cropland Extent Product (GFSAD30AUNZCNMOCE)* (NASA EOSDIS Land Processes DAAC, 2017).
9. Oliphant, A. J. et al. *NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Global Food Security-support Analysis Data (GFSAD) @ 30-m for Southeast and Northeast Asia: Cropland Extent Product (GFSAD30SEACE)* (NASA EOSDIS Land Processes DAAC, 2017).
10. Gumma, M. K. et al. *NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Global Food Security-support Analysis Data (GFSAD) @ 30-m for South Asia, Afghanistan and Iran: Cropland Extent Product (GFSAD30SAAFGIRCE)* (NASA EOSDIS Land Processes DAAC, 2017).
11. Phalke, A. et al. *NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Global Food Security-support Analysis Data (GFSAD) @ 30-m for Europe, Middle-East, Russia and Central Asia: Cropland Extent Product (GFSAD30EUCEARUMECE)* (NASA EOSDIS Land Processes DAAC, 2017).
12. Massey, R. et al. *NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Global Food Security-support Analysis Data (GFSAD) @ 30m for North America: Cropland Extent Product (GFSAD30NACE)* (NASA EOSDIS Land Processes DAAC, 2017).
13. Zhong, Y. et al. *NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Global Food Security-support Analysis Data (GFSAD) @ 30-m for South America: Cropland Extent Product (GFSAD30SACE)* (NASA EOSDIS Land Processes DAAC, 2017).
14. Khasanah, N., van Noordwijk, M. & Ningsih, H. Aboveground carbon stocks in oil palm plantations and the threshold for carbon-neutral vegetation conversion on mineral soils. *Cogent Environ. Sci.* https://doi.org/10.1080/23311843.2015.1119964 (2015).
15. IPCC. *Guidelines for National Greenhouse Gas Inventories* (2006).
16. Erb, K.-H. et al. Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* **553**, 73–76 (2018).
17. Li, W. et al. Gross and net land cover changes in the main plant functional types derived from the annual ESA CCI land cover maps (1992–2015). *Earth Syst. Sci. Data* **10**, 219–234 (2018).

18. Poulter, B. et al. Plant functional type classification for earth system models: results from the European Space Agency's Land Cover Climate Change Initiative. *Geosci. Model Dev.* **8**, 2315–2328 (2015).
19. Goldewijk, K. K., Beusen, A., Doelman, J. & Stehfest, E. Anthropogenic land use estimates for the Holocene — HYDE 3.2. *Earth Syst. Sci. Data* **9**, 927–953 (2017).
20. Leclère, D. et al. Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551–556 (2020).

Author contributions B.B.N.S. wrote the first version of the paper. All authors provided input on subsequent versions of the Reply.

Competing interests The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to Bernardo B. N. Strassburg.