Environmental Science and Ecotechnology 32 (2026) 100721

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Commentary

Reply to: Beyond carbon sequestration: The critical oversight of emission avoidance in restoration of wetland ecosystems

Wu et al. [1] published a commentary on our study [2], in which we challenged former models on the potential of global ecosystem restoration to mitigate climate change via carbon capture and storage, and came to the conclusions that tree planting [3,4] or ecosystem restoration inclusive of other ecosystem types [5] cannot realistically reduce atmospheric CO_2 levels or offset forecasted emissions. We found that the maximum amount of carbon that can be recaptured by 2100 relative to the amount emitted since the Industrial Revolution is 17.6%. However, emissions will continue throughout the twenty-first century, and if we include them using projected emission scenarios, the number drops to 3.7–12.0%. In addition, if we plan restoration targets (forest, shrubland, grassland, or wetland) to match future climates and consider expected ecosystem state transitions due to climate change in areas currently covered by natural ecosystems, even net-negative values (i.e., carbon emissions) are plausible.

Given the inherent limitations of all global-scale models, we had to make simplifications due to data availability, such as the specificities of non-linear carbon sequestration in certain ecosystem types after restoration [6], and changes in carbon assimilation and decomposition rates under increased atmospheric CO_2 concentrations. In their comment, Wu et al. [1] highlighted that we also ignored avoided emissions, especially in wetlands, which represent a critical nature-based asset, where emission avoidance outweighs carbon sequestration. While we acknowledge that they raised a valid issue, it was a simplification we had to adopt due to the lack of global databases on emission rates from degraded wetlands and other ecosystems. However, we do not see the issue as critical, neither for the predicted effect of global restoration on the atmospheric carbon burden, nor for diverting attention from wetland restoration.

Avoided emissions affect future carbon levels, so they do not change our first numerical result: by 2100, we can capture no more than 17.6% of the carbon emitted between the Industrial Revolution and the present. The other results, however, are affected. We therefore quantified the effect using the value cited by Wu et al. [1], namely that degraded wetlands contribute 4% of annual anthropogenic emissions. Given current annual emissions of around 37 Gt CO_2 [7], this fraction corresponds to about 1.5 Gt CO_2, equivalent to 0.41 Gt C per year. Following the restoration timeline used in our original paper [2], we can schedule the restoration of 20% of the degraded wetlands by 2030, with the remaining 80% distributed evenly through 2100. Assuming the degraded wetlands emit carbon at a constant rate until they are restored at a certain time point, the total avoided emissions would amount to 17.5 Gt C. Accordingly, our previous assumptions of total emissions to 2100, spanning SSP1-2.6 to SSP5-8.5 within the Shared Socioeconomic Pathways framework, would shift from 808 to 2619 Gt C to 790–2601 Gt C. Under this adjustment, the 96.9 Gt C sequestration potential of ecosystem restoration would increase from 3.7–12.0% to 3.7–12.3%, which seems negligible. In addition, incorporating avoided emissions would require considering precluded sequestration. We assumed zero sequestration in all restorable cropland, including non-intensive and marginal croplands, although low-intensity cropland management methods, such as no-till or mulching, can sustain carbon sinks in croplands [8,9]. This simplifying assumption may therefore overestimate the sequestration potential of ecosystem restoration in such areas.

Furthermore, we need to consider the current land use of degraded wetlands to draw conclusions on the climate effects of their restoration. Many wetlands are drained to enable afforestation, and restoration requires tree removal [10], leading to a massive loss of biomass-locked carbon. It is an open question whether this is counterbalanced by avoided emissions from the soil. Wu et al. [1] emphasize that most degraded wetlands are currently under intensive agricultural use, and it is an obsolete view that such areas should be omitted in strategies to meet national climate goals. However, food demand is projected to increase globally in the twenty-first century [11]. Losing cropping area in one place may lead to cropland expansion elsewhere, resulting in direct carbon loss from the destroyed ecosystem [12], and indirect greenhouse gas emissions [13] arising from increased transportation distances as current production is relocated to more distant regions, for example from the Global North to the Global South. In agreement with some of the former global models (e.g., Ref. [3]), we thus maintain our view that intensive croplands should be avoided in predictions, given their importance in food and feed production and the potential leakage effects of restoring them at scale. Finally, some drained wetlands are neither afforested nor used for crop production but still function as wetlands, although degraded. The complete reinstatement of their biotic species composition and water regime is better characterized as improved management rather than restoration [14] and therefore fell outside the scope of our study.

Wu et al. [1] are also concerned that our results would divert attention from wetland restoration. We believe that the opposite is true. Globally, carbon sequestration is still often equated to tree planting [15,16], and our inclusion of all four major terrestrial ecosystem types lends similar leverage to both forested and open ecosystems, including wetlands. We emphasize in the final conclusion of our paper that ecosystem restoration should not be a tool

https://doi.org/10.1016/j.ese.2026.100721

for climate change mitigation but rather to promote biodiversity conservation and the resilience of ecosystem services, including climate change adaptation. It is undisputed that wetland restoration is a prime strategy for all of these; they harbor unique biodiversity, improve water quality, support flood protection, moderate climatic extremes, etc. [17–22].

In conclusion, we welcome the comment by Wu et al. [1], and their constructive critique can help further improve future models provided that relevant, comprehensive, and truly global databases become readily available. We acknowledge that incorporating empirical data on avoided emissions and precluded sequestration will improve future models. As datasets expand [20], this will help reduce uncertainty, while maintaining model interpretability. However, ignoring avoided emissions does not have a remarkable effect on the predicted figures and thus, our main conclusion, stating that global strategies of ecosystem restoration should prioritize biodiversity conservation, climate change adaptation, and the maintenance of resilient ecosystem services in a geographically balanced and equitable way rather than carbon capture and storage, remains solid. Beyond restoration, wetland conservation outcomes depend on solid governance frameworks, including water management, land-use planning, and cross-sector coordination to enhance biodiversity, ecosystem resilience, and the provision of ecosystem services.

CRediT authorship contribution statement

Csaba Tölgyesi: Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Nándor Csikós:** Writing – review & editing. **Vicky M. Temperton:** Writing – review & editing. **Elise Buisson:** Writing – review & editing. **Fernando A.O. Silveira:** Writing – review & editing. **Caroline E.R. Lehmann:** Writing – review & editing. **Péter Török:** Writing – review & editing, Funding acquisition. **Zoltán Bátori:** Writing – review & editing, Funding acquisition. **Ákos Bede-Fazekas:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The contribution of C.T., Z.B. and P.T. was supported by the NKFIH K 146137, FK 142428 and KKP 144068 grants, respectively. Á.B.-F. was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. This work has been implemented by the National Multidisciplinary Laboratory for Climate Change (RRF-2.3.1-21-2022-00014) project within the framework of Hungary's National Recovery and Resilience Plan supported by the Recovery and Resilience Facility of the European Union.

References

[1] S. Wu, R.R.E. Artz, A. Barthelmes, S. Cui, D.V. Adetsu, V. Eory, M.S. Reed, F. Humpenöder, T.S. Heuts, C. Fritz, A. Klimkowska, A. Lohila, Beyond carbon sequestration: the critical oversight of emission avoidance in restoration of wetland ecosystems, Environ. Sci. Ecotechnol. 29 (2025) 100658.
[2] C. Tölgyesi, N. Csikós, V.M. Temperton, E. Buisson, F.A. Silveira, C.E. Lehmann, Á. Bede-Fazekas, Limited carbon sequestration potential from global ecosystem restoration, Nat. Geosci. 18 (2025) 761–768.
[3] J.F. Bastin, Y. Finegold, C. Garcia, D. Mollicone, M. Rezende, D. Routh, T.W. Crowther, The global tree restoration potential, Science 365 (6448) (2019) 76–79.
[4] L. Mo, C.M. Zohner, P.B. Reich, J. Liang, S. De Miguel, G.J. Nabuurs, E. Ortiz-Malavasi, Integrated global assessment of the natural forest carbon potential, Nature 624 (7990) (2023) 92–101.
[5] B.B. Strassburg, A. Iribarrem, H.L. Beyer, C.L. Cordeiro, R. Crouzeilles, C.C. Jakovac, P. Visconti, Global priority areas for ecosystem restoration, Nature 586 (7831) (2020) 724–729.
[6] T. Zhou, P. Shi, G. Jia, Y. Dai, X. Zhao, W. Shangguan, Y. Luo, Age-dependent forest carbon sink: estimation via inverse modeling, J. Geophys. Res. Biogeosci. 120 (12) (2015) 2473–2492.
[7] Z. Deng, B. Zhu, S.J. Davis, P. Ciais, D. Guan, P. Gong, Z. Liu, Global carbon emissions and decarbonization in 2024, Nat. Rev. Earth Environ. 6 (4) (2025) 231–233.
[8] C. Bayer, L. Martin-Neto, J. Mielniczuk, A. Pavinato, J. Dieckow, Carbon sequestration in two Brazilian Cerrado soils under no-till, Soil Tillage Res. 86 (2) (2006) 237–245.
[9] Y. Li, Y. Chai, J. Ma, R. Li, H. Cheng, L. Chang, S. Chai, Straw strip mulching in a semiarid rainfed agroecosystem achieves carbon sequestration and emission reduction from winter wheat fields, Agric. Ecosyst. Environ. 334 (2022) 107990.
[10] P.P. Gaffney, M.H. Hancock, M.A. Taggart, R. Andersen, Restoration of afforested peatland: effects on pore-and surface-water quality in relation to differing harvesting methods, Ecol. Eng. 177 (2022) 106567.
[11] B.L. Bodirsky, S. Rolinski, A. Biewald, I. Weindl, A. Popp, H. Lotze-Campen, Global food demand scenarios for the 21 st century, PLoS One 10 (11) (2015) e0139201.
[12] A. Balmford, T.S. Ball, B. Balmford, I.J. Bateman, G. Buchanan, G. Cerullo, D.R. Williams, Time to fix the biodiversity leak, Science 387 (6735) (2025) 720–722.
[13] A. Foong, P. Pradhan, O. Frör, J.P. Kropp, Adjusting agricultural emissions for trade matters for climate change mitigation, Nat. Commun. 13 (1) (2022) 3024.
[14] S.C. Cook-Patton, C.R. Drever, B.W. Griscom, K. Hamrick, H. Hardman, T. Kroeger, P.W. Ellis, Protect, manage and then restore lands for climate mitigation, Nat. Clim. Change 11 (12) (2021) 1027–1034.
[15] C. Tölgyesi, E. Buisson, A. Helm, V.M. Temperton, P. Török, Urgent need for updating the slogan of global climate actions from “tree planting” to “restore native vegetation”, Restor. Ecol. 30 (3) (2022) e13594.
[16] C.L. Parr, M. Te Beest, N. Stevens, Conflation of reforestation with restoration is widespread, Science 383 (6684) (2024) 698–701.
[17] P. Denny, Biodiversity and wetlands, Wetl. Ecol. Manag. 3 (1) (1994) 55–611.
[18] J.H. Janse, A.A. Van Dam, E.M. Hes, J.J. De Klein, C.M. Finlayson, A.B. Janssen, J.T. Verhoeven, Towards a global model for wetlands ecosystem services, Curr. Opin. Environ. Sustain. 36 (2019) 11–19.
[19] J. Loisel, A. Gallego-Sala, Ecological resilience of restored peatlands to climate change, Commun. Earth Environ. 3 (1) (2022) 208.
[20] I. Ascenzi, J. Seuren, S. van der Hooft, G.J. van Duinen, G. Granath, J.P. Hilbers, S.V. Hanssen, WaterLANDS: a database of carbon stocks, GHG fluxes and biodiversity indicators in restored European wetlands, Global Ecol. Biogeogr. 35 (1) (2026) e70199.
[21] B. Misteli, D. Morant, A. Camacho, M. Adamo, G. Bachi, N. Bègue, K. Attermeyer, Coastal wetland restoration and greenhouse gas pathways: a global meta-analysis. https://doi.org/10.31223/X51B39, 2025.
[22] L.S. Verona, A.E. Zanne, S. Trumbore, P.N. Bernardino, G.M. Alencar, T. Andreuccetti, Oliveira, Vast, overlooked peat, and organic soils in Brazil's Cerrado: carbon storage, dynamics, and stability, New Phytol. 250 (2026) 2946–2965.

Csaba Tölgyesi[a,b,*], Nándor Csikós[a,c], Vicky M. Temperton[d], Elise Buisson[e], Fernando A.O. Silveira[f], Caroline E.R. Lehmann[g,h], Péter Török[b,i,j], Zoltán Bátori[k], Ákos Bede-Fazekas[l,m]

[a] *MTA-SZTE Applied Ecology Research Group, University of Szeged, 6720, Szeged, Hungary*

[b] *HUN-REN-UD Functional and Restoration Ecology Research Group, 4032, Debrecen, Hungary*

[c] *HUN-REN Centre for Agricultural Research, Institute for Soil Sciences, 1116, Budapest, Hungary*

[d] *Institute of Ecology, School of Sustainability, Leuphana University Lüneburg, 21335, Lüneburg, Germany*

[e] *Avignon University, Aix Marseille Univ, CNRS, IRD, IMBE, Avignon, 84911, France*

[f] *Department of Genetics, Ecology and Evolution, Federal University of Minas Gerais, 31270-901, Minas Gerais, Brazil*

[g] *Taxonomy and Macroecology, Royal Botanic Garden Edinburgh, EH3 5LR, Edinburgh, United Kingdom*

[h] *School of GeoSciences, University of Edinburgh, EH8 3FF, Edinburgh, United Kingdom*

[i] *University of Debrecen, Department of Ecology, 4032, Debrecen, Hungary*

[j] *Balaton Limnological Research Institute, HUN-REN, Tihany, 8237, Hungary*

[k] *Department of Ecology, University of Szeged, 6720, Szeged, Hungary*

[l] *HUN-REN Centre for Ecological Research, Institute of Ecology and Botany, Vácrátót, 2163, Hungary*

[m] *Department of Environmental and Landscape Geography, Institute of Geography and Earth Sciences, ELTE Eötvös Loránd University, 1117, Budapest, Hungary*

[*] Corresponding author. MTA-SZTE Applied Ecology Research Group, University of Szeged, 6720, Szeged, Hungary.
E-mail address: tolgyesi.csaba@szte.hu (C. Tölgyesi).

26 January 2026