

Economic potential of land restoration for climate change mitigation

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Abstract

Between 2001 and 2020, the loss of ecosystems worldwide due to land degradation resulted in an economic loss of nearly USD 2 trillion. Restoring degraded lands is essential for mitigating climate change and maintaining biodiversity. Here, we evaluate the potential costs and benefits of restoring degraded lands. We provide unprecedented spatially granular estimates of the carbon removal and broader economic potential of land restoration at a global level and find that restoration of degraded ecosystems such as forests and grasslands can be economically profitable and has considerable carbon sequestration potential, with an average global cost of USD 50 per ton of carbon. The cost of restoring ecosystems degraded between 2001 and 2020 amounts to USD 6.9 trillion. However, each dollar invested is estimated to return USD 2.39 over a 30-year period, and a total of 138 gigatons of carbon would be sequestered.

1. Introduction

Deforestation, overgrazing, mining, urbanization, and expansion of infrastructure have led to the degradation of large areas of land, affecting soil health, biodiversity, and carbon storage capacity (Wuepper et al., 2020). The restoration of degraded lands has become an urgent priority for global efforts to mitigate climate change, maintain biodiversity, and ensure sustainable development (Barbier and Hochard, 2018) – for example, under the UN Decade for Ecosystem Restoration and many related programs and initiatives (Fischer et al., 2021; Aronson et al., 2020).

Restoring degraded lands is important for environmental, economic, and social reasons (Hermans-Neumann et al., 2023; Stringer et al., 2012). One of the most significant reasons is that improved land management can enhance the function of land as carbon sink, helping mitigate climate change (Sha et al., 2022). Degraded lands are often direct and indirect sources of greenhouse gas emissions, mainly carbon dioxide, methane, and nitrous oxide. The historical amount of carbon lost to land degradation has been estimated to be equal to about 3,065 gigatons of carbon dioxide equivalent (GtCO₂e) (Wuepper et al., 2021). According to the Bonn Challenge, a global initiative aimed at restoring 350 million hectares of degraded land by 2030, the restoration of degraded lands has the potential to sequester up to 1.7 GtCO₂e annually. To keep global warming below 1.5°C, there is a need to remove between 561 and 5,970 GtCO₂e from 2020 onwards. To put this into perspective, in 2021, the total amount of greenhouse gas emissions amounted to 40 GtCO₂e, of which 10.1 GtCO₂e were from fossil energy use, and 1.1 GtCO₂e from land use and land cover changes (Friedlingstein et al., 2022), while land ecosystems also absorbed about 3.5 GtCO₂e (IPCC, 2019).

Numerous studies have found land restoration to be an effective means of carbon sequestration. For example, Lewis et al. (2019a) estimate that restoring 350 million hectares of degraded land worldwide could result in the sequestration of 42 GtCO₂e, and Lewis et al. (2019b) indicate that restoring 900 million hectares of degraded land has the potential to sequester 89–108 GtCO₂e. Similarly, Griscom

et al. (2017) find that natural climate solutions, which include land restoration, could provide up to 37% of the emission reductions needed to keep global warming below 2°C.

A variety of ecosystem and land restoration practices have been shown to constitute effective carbon sequestration. Reforestation and afforestation, which involve planting trees on degraded land, have received most attention (Wuepper et al., 2024). Ruiz-Jaen and Aide (2005) find that reforestation of abandoned farming land in Puerto Rico resulted in a significant increase in above-ground carbon storage. Agroforestry, which involves integrating trees into agricultural landscapes, has also been shown to be effective for carbon sequestration. Soil conservation practices such as conservation tillage, cover cropping, and no-till farming have been shown to lead to carbon sequestration. Lal (2004) estimates that adopting conservation tillage practices could sequester between 0.2 and 0.4 GtCO₂e per year globally. Potential carbon sequestration by means of irrigated afforestation on arid land, where irrigation is powered by renewable energy and sea water desalination, has been estimated to hold the potential to sequester 730 GtCO₂ between 2030 and 2100 (Caldera and Breyer, 2023). With this approach, the cost of sequestering one ton of carbon would be equal to USD 457 in 2030, falling to USD 100 by 2100 owing to declining renewable energy costs and growing carbon sequestration by mature trees (Caldera and Breyer, 2023). Carbon removal with afforestation is estimated to cost about USD 17–30 per ton in 2100 (Smith et al., 2016).

However, and although afforestation is one of the most frequently used methods for carbon dioxide removal, planting trees in areas where there were no trees before can have negative environmental and ecological impacts (Olsson et al., 2019). Afforestation of arid grasslands or savannas, which would harm these ecosystems, does not make sense (Mirzabaev et al., 2019). A more environmentally sustainable approach is reforestation—that is to say, planting trees in deforested areas. The more recent the deforestation, the more environmentally suitable an area is for reforestation.

The 2019 IPCC report on climate change and land emphasizes the need for further research to improve the understanding of the trade-offs and synergies between land restoration, carbon sequestration, biodiversity conservation, and other ecosystem services, in order to inform effective and sustainable land management strategies (IPCC, 2019). There is growing political emphasis on accounting for synergies and trade-offs among the three Rio Conventions—the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), and the United Nations Convention to Combat Desertification (UNCCD). Therefore, our first objective is to contribute to filling this critical gap by helping to identify the potential costs and benefits of restoring degraded lands for climate change mitigation through increased carbon sequestration. Secondly, as carbon sequestration is only one of the many benefits of land restoration, our analysis seeks to capture how land restoration affects the full range of values of ecosystem services. Finally, we identify the parts of the world where land restoration activities will make most environmental and economic sense. We also conduct sensitivity analyses to test the robustness of our findings against potential risks and uncertainties.

The novelty of this study consists in identifying those land restoration opportunities that make both environmental and economic sense and estimating their carbon removal and broader economic potentials at the global level with an unprecedented level of spatial granularity. Previous studies measuring the carbon sequestration potential of land-based approaches usually modeled all the potential areas where specific land management actions could be carried out, without fully accounting for the environmental and economic sustainability of these land restoration activities (Wolff et al., 2018; Bastin et al., 2019).

The four specific research questions that this study seeks to answer are: (1) What is the extent and cost of land degradation globally during the two decades between 2001 and 2020? (2) What is the total financing needed to restore these degraded lands? (3) Which degraded lands does it make both environmental and economic sense to restore? (4) What is the carbon sequestration potential of these land restoration activities, both in tons of CO₂ and monetary value?

2. Results

There have been considerable changes in global land use and land cover in the two decades after the year 2000. Figure 1 details the loss and gain of land area by terrestrial ecosystems, as well as the corresponding economic values for each ecosystem type.

There was a significant net loss in the area of evergreen needleleaf and evergreen broadleaf forests. The world's evergreen needleleaf forests experienced a loss of 63 million hectares and a gain of 53 million hectares, resulting in a net loss of 10 million hectares, corresponding to an economic value net loss of USD 120 billion. Similarly, the evergreen broadleaf forests lost 123 million hectares and gained 66 million hectares, leading to a net loss of 57 million hectares and a net economic loss of USD 334 billion. Deciduous needleleaf forests and deciduous broadleaf forests also exhibited net combined losses of USD 20 billion.

On the other hand, there was also significant expansion of mixed forests (usually plantations) (USD 135 billion), woody savannas (USD 175 billion), croplands (USD 44 billion), and agroforestry systems in the natural mosaics (USD 40 billion). As a result, the net economic loss from land degradation was around USD 22 billion during 2001–2020 (Figure 1).

Table 1. Environmentally sustainable and economically profitable land restoration opportunities (in USD bln)

Ecosystem to be restored	Cost of restoration	Cost if not restored	Benefit–cost ratio
Forests	3,436	9,779	2.8
Wetland	1,675	1,886	1.1
Shrublands, woody savannas, and savannas	11,088	9,331	0.8
Cropland with agroforestry	547	481	0.9
Standard cropland	156	154	1.0
Grassland	1,763	4,786	2.7
Total of profitable restoration opportunities	6,874	16,451	2.4

Our analysis shows that about USD 6.9 trillion are needed to restore these ecosystems that were degraded over the last two decades (see the Methods section for underlying data and methods). On average, each dollar invested in land restoration was estimated to return USD 2.39 over a 30-year period. The most profitable restoration options are restoring lost forests through reforestation, recovering wetlands, and restoring grasslands. These benefit-cost ratios, however, show average values at the global level. Region-specific benefit-cost ratios can be different (see Supplementary Materials). For example, in terms of global averages, restoring lost agroforestry systems is not economically profitable. However, at the regional level in Africa, for example, restoring degraded agroforestry systems is one of the most profitable land restoration options.

Table 2. Environmentally sustainable and economically profitable carbon sequestration potential from restoring ecosystems degraded between 2001 and 2020 (in GtCO₂e)

Region	Carbon sequestration potential		
	Above-ground biomass	Below-ground biomass	Total
Africa	16	2	18
Asia	16	4	20
Europe	5	2	7
Russia	20	5	25
North America	21	5	26
Central America Oceania and Caribbean	4	2	6
South America	31	5	36
Total	97	25	138

Table 2 presents the environmentally sustainable and economically profitable carbon sequestration potential of restoring ecosystems degraded between 2001 and 2020, disaggregated by region and categorized into above-ground and below-ground biomass. The total carbon sequestration potential across all regions is 138 GtCO₂e, with 97 GtCO₂e in above-ground biomass and 25 GtCO₂e in below-ground biomass. South America exhibits the highest potential for carbon sequestration at 36 GtCO₂e, followed by North America and Russia, with the substantial potentials of 26 and 25 GtCO₂e, respectively.

Our estimates show that the average global cost of carbon sequestration by land restoration is USD 50 per ton of carbon (at a 10% discount rate).

3. Discussion

Land restoration is the only viable strategy currently available for achieving negative emissions to meet the goals of the Paris Agreement, particularly through afforestation and reforestation efforts (Minx et al., 2018). Our findings on changes in global land use and land cover, as well as the economic impacts, align with the recent literature that highlights the role of land restoration in improving ecosystem services (Veldman et al., 2019), in carbon sequestration, and in biodiversity conservation (Anderson et al., 2019). Previously, Bastin et al. (2019) estimated that restoring forests on degraded lands worldwide could sequester up to 205 gigatons of carbon. Lewis et al. (2019a) estimated that restoring 350 million hectares of degraded land worldwide under the Bonn Challenge could sequester 42 GtCO₂e. Similarly, Griscom et al. (2017) found that natural climate solutions, which include land restoration, could provide up to 37% of the emissions reduction needed to keep global warming below 2°C.

However, several studies present contrasting perspectives and emphasize the social, economic, and environmental constraints that limit the viability of land restoration projects. Moreover, the potential for

land-based climate change mitigation may be lower than previously estimated, owing to the complex interplay of biophysical and socioeconomic factors affecting land use and management. In this study, we provide an *ex ante* modeling of land restoration potential when land restoration is conducted in a way that is both environmentally sustainable and economically profitable. We find that after the application of these two important criteria, about 138 gigatons of carbon could still be sequestered through land restoration activities.

Our findings contribute to the ongoing debate surrounding the effectiveness and feasibility of land restoration for mitigating climate change and providing valuable ecosystem services. While our results align with previous studies that emphasize the potential benefits of land restoration, it is essential to consider the complexity of factors involved in land use and management, as well as the costs and challenges associated with land restoration. Further research is needed to better understand the trade-offs and synergies between land restoration and broader social development objectives, such as, for example, declining social inequalities (Barbier and Di Falco, 2021). This may involve incorporating insights from disciplines such as ecology, economics, and other social sciences to develop a more comprehensive understanding of the interdependencies and potential co-benefits associated with land restoration initiatives.

4. Methods and Data

4.1. Methodological framework

4.1.1. Methods for answering Research Question 1: The extent and costs of land degradation (2001–2020)

Following the IPCC special report on climate change and land, we define land degradation as “a negative trend in land condition, caused by direct or indirect human-induced processes, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans” (Olsson et al., 2019, p. 347).

In this study, we focus on land degradation through land use and land changes. Therefore, we first identify changes in ecosystems between 2001 and 2020 based on the global maps of land use and cover at 500-meter spatial resolution (Friedl and Sulla-Menashe, 2019), with each pixel size equaling 25 hectares. The land uses and covers considered are given in Table M1.

The assessment of the extent and cost of land degradation incorporates the total economic values (TEV) of both direct-use and indirect-use ecosystem services derived from each of these land ecosystems. We identify the changes in the areas of each land use and land cover (hereafter referred to as “ecosystem”) between 2001 (baseline) and 2020 (end line). Following this, we estimate the changes in the total economic values of ecosystem services due to the expansion or reduction of the areas of each ecosystem, so that:

$$\gamma = (\alpha - \lambda) * \theta \quad (1)$$

where γ is the net change in the value of ecosystem services; α is a vector of total economic values of one hectare of the ecosystems present in each location in 2001 (Table M1); λ is a vector of total economic values of one hectare of each ecosystem in each location in 2020; and θ is a vector of ecosystem area changes in each location between 2001 and 2020. The estimations depicted by Eq. 1 give us the net economic value of changes in ecosystem services due to the expansion/reduction of the areas under each of these ecosystems between 2001 and 2020. This also allows us to identify the extent of land degradation during this period. Land degradation occurs in those areas where $\gamma < 0$.

4.1.2. Methods for answering Research Questions 2 and 3: The total financing needs to restore ecosystems degraded between 2001 and 2020, and economic rationale for restoration

We calculate the costs and benefits of investments directed at restoration of ecosystems degraded between 2001 and 2020 by their net present value (NPV) in year t for the land user's planning horizon T :

$$\pi_t^i = \frac{1}{\rho^t} \sum_{t=0}^T \left(PY_t^i + IV_t^i - lm_t^i \right)$$

2

where π_t^c represent the NPV of ecosystems restoration in year t over the planning period T ; ρ is define as $1 + r$; with r being the discount rate applied by the land user; Y_t^i indicates the output of direct use provisioning services post-restoration, including items like food, fodder, timber, and non-timber products; P is price per unit of the direct use provisioning services Y_t^i ; IV_t^i refers to the value of indirect use ecosystem services such as carbon sequestration, biodiversity habitats, and cultural values; and lm_t^i represent the costs incurred for ecosystem restoration. Superscript i denotes that the values pertain to a restored ecosystem.

If land users choose not to engage in land restoration, the net present value (NPV) is calculated as follows:

$$\pi_t^d = \frac{1}{\rho^t} \sum_{t=0}^T \left(PY_t^d + IV_t^d \right)$$

3

where $\pi_t^d =$ NPV of the ecosystem services obtained from a less valuable ecosystem that has supplanted a more valuable one. Superscript d indicates a degraded ecosystem.

The benefit of land restoration is calculated as:

$$BA = \pi_t^c - \pi_t^d \quad (4)$$

The difference $\pi_t^c - \pi_t^d$ returns the profitability of land restoration. If the returns from restoring ecosystems, after accounting for restoration costs, are lower than the returns from the new ecosystem

in 2020 that replaced the old ecosystem in 2001, land restoration activities are not economically profitable. The costs of restoring degraded higher-value ecosystems are comprised of establishment costs, maintenance costs, as well as the opportunity costs of the lower-value ecosystem that is being replaced by restoration.

We track the outcomes of restoring ecosystems with a time horizon of 30 years into the future. The assessment uses discount rates differentiated by country, ranging from 1–10%, to capture differences in country risks and the time value of money across populations with different income levels. The survival rate of planted trees is set at 60% (Mirzabaev et al., 2021). Furthermore, after restoration activities are implemented, the newly re-established ecosystems will not immediately achieve their full potential but will require time to mature. Consequently, a phased period was established for restored ecosystems, during which they will gradually attain their complete ecosystem potential. (Table M2).

4.1.3. Methods for answering Research Question 4 on carbon sequestration potentials from land restoration

The findings from the above analyses give us the locations where land restoration makes environmental and economic sense, which ecosystems will replace each other after restoration, and what will be the costs and benefits of land restoration activities. Carbon sequestration is included as part of climate regulation ecosystem services, and available data will enable us to estimate the monetary value of these carbon sequestration services when restoration is carried out. The price of carbon would be equal to the amount that local land users will be willing to pay in those locations where land restoration is happening. However, those estimates of carbon sequestration values are usually based on willingness to pay (WTP) studies, and reflect neither the social cost of carbon nor the prevailing international prices for each sequestered ton of carbon. Moreover, the use of carbon sequestration economic values from the WTP-based studies does not allow evaluation of the physical amount of carbon that can be sequestered through land restoration. We seek to address these issues in this part of the study.

To do so, we combine a highly granular and rigorously compiled database on above-ground and below-ground biomass carbon from Spawn et al. (2020) with MODIS Land Cover Type global maps of land use and cover. Since the above-ground and below-ground biomass carbon data are for the year 2010, for best compatibility we use MODIS land use data for the same year. As a result, we have information on the carbon density of each ecosystem in any given location. We use this information to estimate the physical above-ground and below-ground biomass carbon amount that will be sequestered after the restoration of each valuable ecosystem at each specific pixel. The analysis is conducted for a 30-year period from 2020 to 2050.

$$t = \sum_{ij} (a_{ij} - b_{ij}) * c_{ij} \quad (5)$$

a - above-ground and below-ground biomass carbon density of new ecosystem after restoration

b - above-ground and below-ground biomass carbon density of old ecosystem

c - the total area of ecosystem restoration

t - total amount of sequestered carbon

Sub-scripts *i* and *j* represent different ecosystems and locations, respectively.

Operator \sum means that we are summing up all ecosystem- and location-specific sequestration amounts.

Data

Extent of ecosystems

The changes in the extent of ecosystems during the period 2001–2020 are identified using MODIS data of land use and cover at 500-meter spatial resolution (Friedl and Sulla-Menashe, 2019). The 500-meter spatial resolution implies that each analyzed pixel contains 25 hectares.

Economic values of ecosystem services

The data on economic values of ecosystem services come from the Ecosystem Services Valuation Database (ESVD) (<https://www.esvd.net>). The database contains about 10,000 valuation data points of ecosystem services. The data on cropland values comprise the net per hectare production value of croplands in each country for the latest available year (2016) from FAOSTAT. However, these net per hectare production values for croplands do not account for the non-provisioning ecosystem services provided by croplands. The values for these non-provisioning services are sourced from the ESVD and combined with the provisioning service values obtained from FAOSTAT.

Data on costs of restoring ecosystems

The data on the costs of (re-)establishment of ecosystem come from the ECON-WOCAT dataset (Mirzabaev et al., 2021) and Economics of Land Degradation Initiative (Nkonya et al., 2016).

Data on carbon sequestration potentials from ecosystem restoration

The information on carbon sequestration potentials from ecosystem restoration is sourced from the database of above-ground and below-ground biomass carbon Spawn et al. (2020).

References

1. Anderson, C. M., et al. (2019). Global adoption of novel ecosystem restoration solutions must target the world's most vulnerable regions. *Nature Ecology & Evolution*, 3(12), 1611–1613.
2. Aronson, J., Goodwin, N., Orlando, L., Eisenberg, C., & Cross, A. T. (2020). A world of possibilities: six restoration strategies to support the United Nation's Decade on Ecosystem Restoration. *Restoration Ecology*, 28(4), 730–736.

3. Barbier, E. B., & Hochard, J. P. (2018). Land degradation and poverty. *Nature Sustainability*, 1(11), 623-631.
4. Barbier, E. B., & Di Falco, S. (2021). Rural populations, land degradation, and living standards in developing countries. *Review of Environmental Economics and Policy*, 15(1), 115-133.
5. Bastin, J. F., et al. (2019). The global tree restoration potential. *Science*, 365(6448), 76–79.
6. Berzaghi, F., et al. (2019). Carbon stocks in central African forests enhanced by elephant disturbance. *Nature Geoscience*, 12(9), 725–729.
7. Bonn Challenge. (2021). The Bonn Challenge: A global effort to bring degraded and deforested lands into restoration. <https://www.bonnchallenge.org/>
8. Griscom, B. W., et al. (2020). National mitigation potential from natural climate solutions in the tropics. *Philosophical Transactions of the Royal Society B*, 375(1794), 20190126.
9. IPCC, 2019: Summary for Policymakers. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. <https://doi.org/10.1017/9781009157988.001>
10. Caldera, U., & Breyer, C. (2023). Afforesting arid land with renewable electricity and desalination to mitigate climate change. *Nature Sustainability*. <https://doi.org/10.1038/s41893-022-01056-7>
11. Fischer, J., Riechers, M., Loos, J., Martin-Lopez, B., & Temperton, V. M. (2021). Making the UN decade on ecosystem restoration a social-ecological endeavour. *Trends in ecology & evolution*, 36(1), 20-28.
12. Food and Agriculture Organization of the United Nations. (2015). Global Soil Partnership: Rome Declaration on Soil. <https://www.fao.org/global-soil-partnership/resources/highlights/detail/en/c/318817/>
13. Friedl, M., & Sulla-Menashe, D. (2019). MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC.
14. Friedlingstein, P., O'sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., ... & Zheng, B. (2022). Global carbon budget 2022. *Earth System Science Data Discussions*, 2022, 1-159.
15. Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., ... & Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, 114(44), 11645-11650.
16. Hermans-Neumann, K., Müller, D., O'Byrne, D., Olsson, L., & Stringer, L. C. (2023). Land degradation and migration. *Nature Sustainability*, 6, 1503–1505. Advance online publication. <https://doi.org/10.1038/s41893-023-01231-4>
17. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *science*, 304(5677), 1623-1627.

18. Lewis, S. L., Wheeler, C. E., Mitchard, E. T., & Koch, A. (2019a). Restoring natural forests is the best way to remove atmospheric carbon. *Nature*, 568(7750):25-28. doi: 10.1038/d41586-019-01026-8
19. Lewis, S. L., Mitchard, E. T. A., Prentice, C., Maslin, M. & Poulter, B. (2019b) Comment on “The global tree restoration potential”. *Science* 366, eaaz0388 (2019)
20. Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-being: Biodiversity Synthesis*.
21. Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., ... & Dominguez, M. D. M. Z. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, 13(6), 063001.
22. Mirzabaev, A., J. Wu, J. Evans, F. García-Oliva, I.A.G. Hussein, M.H. Iqbal, J. Kimutai, T. Knowles, F. Meza, D. Nedjraoui, F. Tena, M. Türkeş, R.J. Vázquez, M. Wertz, 2019: Desertification. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. <https://doi.org/10.1017/9781009157988.005>
23. Mirzabaev, A., Sacande, M., Motlagh, F., Shyroka, A., & Martucci, A. (2021). Economic efficiency and targeting of the African Great Green Wall. *Nature Sustainability*. <https://doi.org/10.1038/s41893-021-00801-8>
24. Nkonya, E., Anderson, W., Kato, E., Koo, J., Mirzabaev, A., von Braun, J., & Meyer, S. (2016). Global Cost of Land Degradation. In *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development* (pp. 117–165). Springer International Publishing. https://doi.org/10.1007/978-3-319-19168-3_6
25. Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., Delusca, K., Flores-Renteria, D., Hermans, K., Jobbagy, E., Kurz, W., Li, D., Sonwa, D., & Stringer, L. C. (2019). Land Degradation. In *Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
26. Ruiz-Jaén, M. C., & Aide, T. M. (2005). Vegetation structure, species diversity, and ecosystem processes as measures of restoration success. *Forest Ecology and Management*, 218(1-3), 159-173.
27. Sha, Z., Bai, Y., Li, R. et al. The global carbon sink potential of terrestrial vegetation can be increased substantially by optimal land management. *Commun Earth Environ* 3, 8 (2022). <https://doi.org/10.1038/s43247-021-00333-1>
28. Smith, P., Davis, S., Creutzig, F. et al. Biophysical and economic limits to negative CO2 emissions. *Nature Clim Change* 6, 42–50 (2016). <https://doi.org/10.1038/nclimate2870>
29. Spawn, S.A., and H.K. Gibbs. 2020. *Global Aboveground and Belowground Biomass Carbon Density Maps for the Year 2010*. ORNL DAAC, Oak Ridge, Tennessee, USA.

<https://doi.org/10.3334/ORNLDAAC/1763>

30. Stringer, L. C., Dougill, A. J., Thomas, A. D., Spracklen, D. V., Chesterman, S., Speranza, C. I., ... & Kopolov, G. (2012). Challenges and opportunities in linking carbon sequestration, livelihoods and ecosystem service provision in drylands. *Environmental science & policy*, 19, 121-135.
31. United Nations Convention to Combat Desertification. (2018). Land Restoration. <https://www.unccd.int/actions/land-restoration>
32. Wolff, S., Schrammeijer, E. A., Schulp, C. J., & Verburg, P. H. (2018). Meeting global land restoration and protection targets: What would the world look like in 2050?. *Global Environmental Change*, 52, 259-272.
33. Wuepper, D., Borrelli, P., & Finger, R. (2020). Countries and the global rate of soil erosion. *Nat. Sustain.* 3, 51–55.
34. Wuepper, D., Borrelli, P., Panagos, P., Lauber, T., Crowther, T., Thomas, A., & Robinson, D. A. (2021). A 'debt'based approach to land degradation as an indicator of global change. *Global Change Biology*, 27(21), 5407-5410.
35. Wuepper, D., Crowther, T., Lauber, T., Routh, D., Le Clec'h, S., Garrett, R. D., & Börner, J. (2024). Public policies and global forest conservation: Empirical evidence from national borders. *Global Environmental Change*, 84, 102770.

Figures

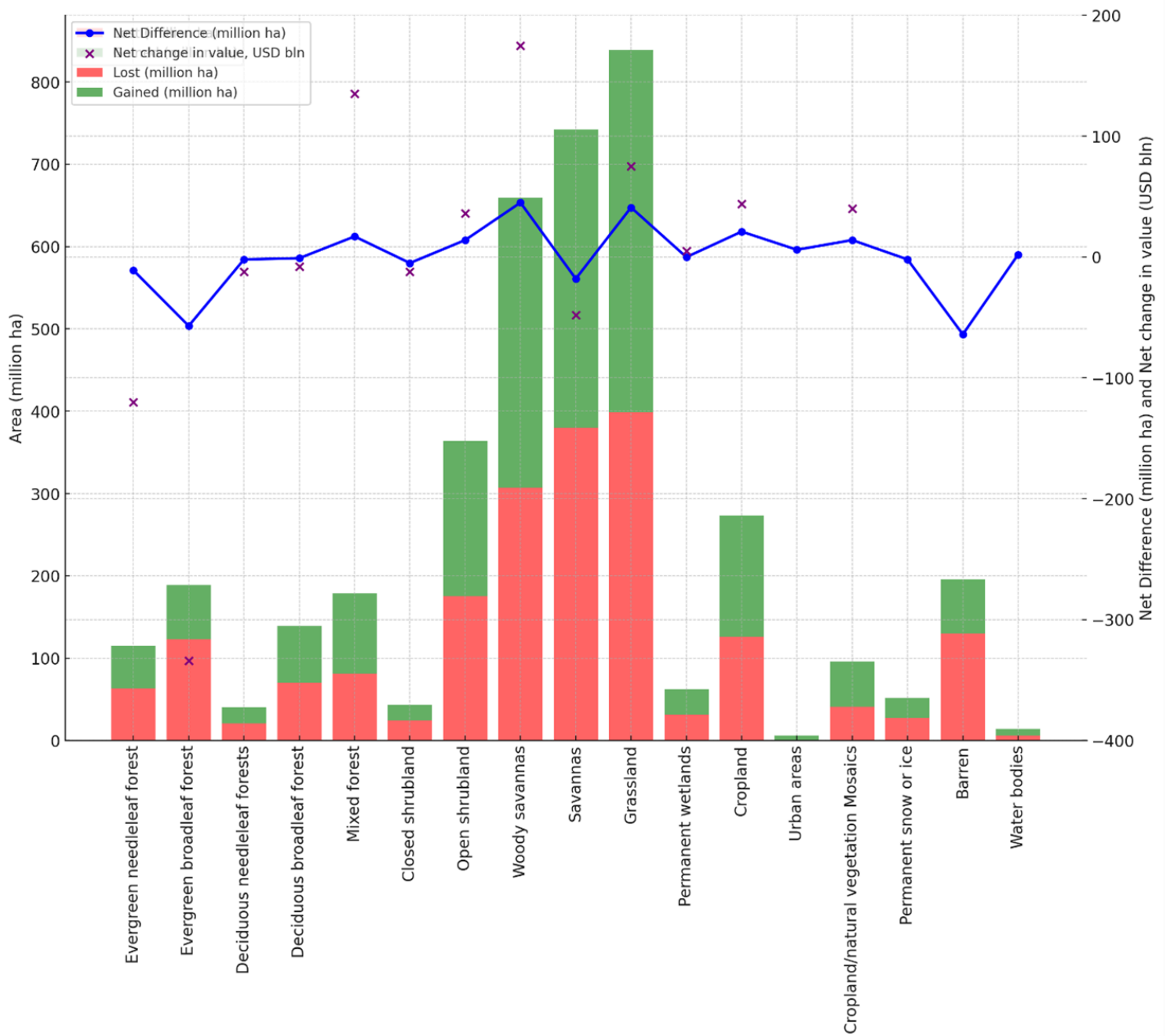


Figure 1

Changes in ecosystems extent and values, 2001–2020

Sources: MODIS land use and land cover data (Friedl and Sulla-Menashe, 2019), and authors' calculations.

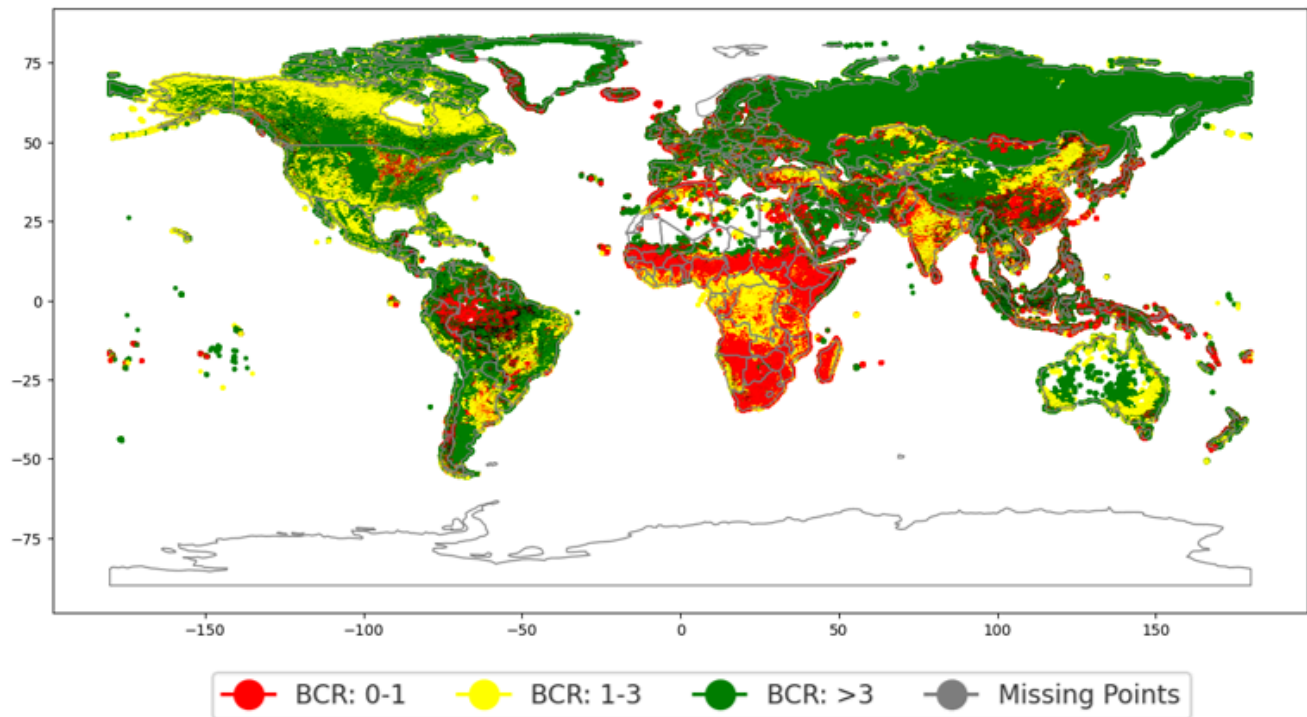


Figure 2

Global mapping of profitable and sustainable land restoration opportunities, showing their costs and benefit ratios). Note: BCR: benefit-cost ratios.

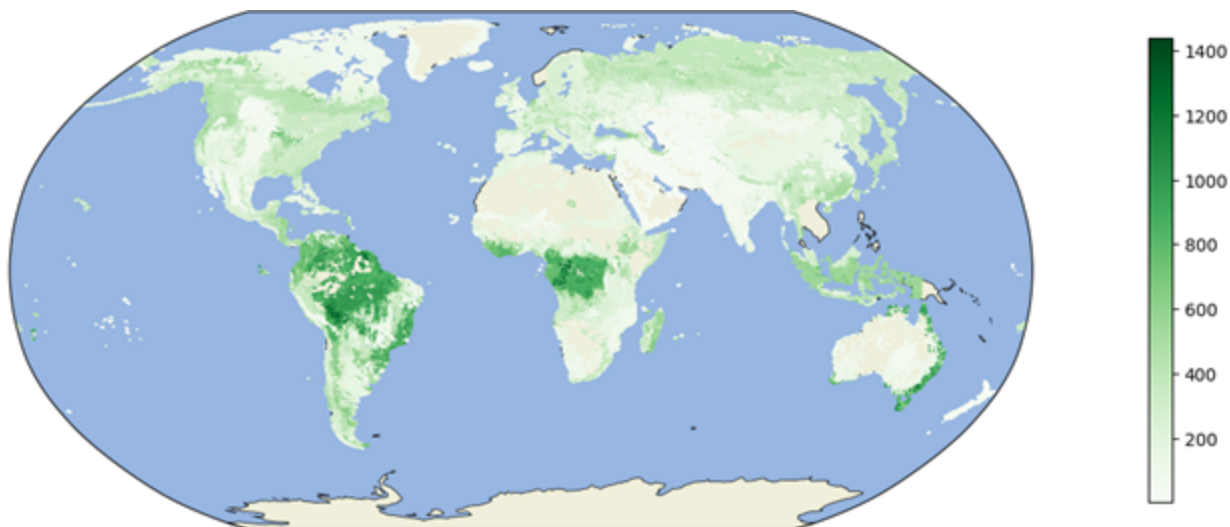


Figure 3

Global carbon sequestration potentials from land restoration (tons per pixel)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SUPPLEMENTARYMATERIALS.docx](#)
- [TableM1M2.docx](#)