CLIMATE MITIGATION

Land availability and policy commitments limit global climate mitigation from forestation

Yijie Wang[1], Yakun Zhu[1]†, Susan C. Cook-Patton[2,3], Wenjuan Sun[4], Wen Zhang[5], Philippe Ciais[6], Tingting Li[5], Pete Smith[7], Wenping Yuan[8], Xudong Zhu[9], Josep G. Canadell[10], Xiaopeng Deng[1], Yifan Xu[1]‡, Hao Xu[8], Chao Yue[11], Zhangcai Qin[1]*

Forestation (afforestation and reforestation) could mitigate climate change by sequestering carbon within biomass and soils. However, global mitigation from forestation remains uncertain owing to varying estimates of carbon sequestration rates (notably in soil) and land availability. In this study, we developed global maps of soil carbon change that reveal carbon gains and losses with forestation, primarily in the topsoil. Constraining land availability to avoid unintended albedo-induced warming and safeguard water and biodiversity (389 million hectares available for forestation globally) would sequester 39.9 petagrams of carbon by 2050, substantially below previous estimates. This estimate drops to 12.5 petagrams of carbon with land further limited to existing policy commitments (120 million hectares). Achieving greater mitigation requires expanding dedicated forestation areas and strengthening commitments from nations with considerable but untapped potential.

Forests deliver multiple economic and environmental benefits to society (*1*, *2*). Yet global forest loss has persisted in recent decades, primarily because of disturbances associated with climate change and human activities (*3*, *4*). Forestation aims to increase forest cover by establishing trees on unforested land through reforestation and afforestation. Reforestation involves land that has recently lost its forest, whereas afforestation focuses on land not covered with forest in recent history (e.g., cropland, bare land). Both practices could capture additional carbon within biomass and soils (*5*, *6*). If strategically implemented with careful consideration of location, timing, tree species, and management, forestation could become a cornerstone natural climate solution (*7*, *8*), contributing substantially to rebuilding land carbon stocks and supporting the Paris Agreement's ambitious climate targets (*9*). Current estimates of climate mitigation from global forestation vary widely, ranging from <1 petagrams of carbon per year (Pg C $year^{-1}$) to >10 Pg C $year^{-1}$ (*7*, *8*, *10*, *11*). In comparison, global fossil CO_2 emissions in 2023 were 10.1 Pg C $year^{-1}$ (*12*).

These disparities arise largely from varying estimates of the annual carbon sequestration rate (per area) and the extent of land deemed suitable for forestation (*7*, *8*). Carbon sequestration potential is often estimated by changes in biomass carbon (aboveground and belowground biomass) and soil stocks over a certain period (e.g., 30 years). Although carbon sequestration in biomass has been relatively well assessed through a synthesis of worldwide field measurements (*13*), soil carbon change as a result of forestation is relatively less represented (*14*, *15*). Additionally, estimates of global area available for forestation show a 10-fold difference, ranging from about 200 Mha to >2000 Mha (*6*, *10*), owing to differences in study objectives and methodologies. Many assessments of land availability inadequately account for critical constraints such as albedo effects, water scarcity, biodiversity trade-offs, and policy limitations (*6*, *10*, *11*). Notably, the spatial mismatch between biophysically suitable land ("supply") and policy-driven forestation commitments ("demand") adds further complexity (*16*–*18*). To unlock forestation's potential as a scalable natural climate solution, two priorities are paramount: advancing integrated assessments of biomass and soil carbon dynamics, and conducting holistic assessments of land availability that reconcile biophysical, ecological, and socioeconomic factors. Together, these steps will provide the foundation for strategically framing future forestation efforts and evaluating climate mitigation impacts (*7*, *18*).

In this study, we developed a machine learning model to quantify soil carbon change after forestation. By integrating these results with biomass sequestration estimates (*13*), we mapped global ecosystem carbon sequestration rates (soil and biomass) resulting from potential forestation. Furthermore, we assessed land availability through the lens of national policy commitments, explicitly addressing the "supply-demand" disconnect, and reevaluated forestation's climate mitigation potential. Our findings provide actionable insights for optimizing land-use policies and forestation strategies to maximize climate benefits.

Mapping global carbon sequestration rates

We mapped global carbon sequestration rates after forestation at 0.01° resolution (Fig. 1). Ecosystem sequestration rates (Fig. 1A) are expressed as annual net carbon changes in both biomass and soil over the first 30 years of forestation beginning in 2021 (2021–2050) to align with a 2050 carbon neutrality target. Soil organic carbon (SOC) changes (Fig. 1B) are explicitly estimated to complement a prior study that focused only on biomass (*13*). Using an approach similar to that of Cook-Patton *et al.* (*13*), we developed a data-driven machine learning model (mSOC) to map SOC change after forestation (see materials and methods sections M1 and M2 in the supplementary materials). The model was trained using 1595 paired soil layer–specific observations from sites under afforestation (87%) and reforestation (13%) across various forest types (fig. S1 and table S1). The afforestation and reforestation submodels differ in influencing factors (fig. S2), but both demonstrate reasonable performance with cross-validation coefficients of determination (R^2) of 0.88 for afforestation and 0.85 for reforestation (fig. S3).

Across the areas where new forests could potentially be established, forestation leads to SOC changes (Fig. 1B), with >80% of the changes occurring in the top 20 cm of soil (fig. S4A). SOC sequestration rates are generally lower in tropical and some boreal regions. Local SOC losses are predicted for reforestation on carbon-rich soils in tropical areas (-0.46 ± 0.53 Mg C ha^{-1} $year^{-1}$ in Southeast Asia and -0.23 ± 0.31 Mg C ha^{-1} $year^{-1}$ in the Amazon) and in boreal areas (-0.49 ± 0.63 Mg C ha^{-1} $year^{-1}$ in northern Europe). It takes time for SOC to recover to predisturbance levels after reforestation (*15*, *19*). Factors conducive to SOC loss include coarser soil textures (*19*, *20*) and warmer and wetter climates that accelerate SOC decomposition (*21*) (fig. S5). Afforestation is more likely to increase SOC in places where initial SOC is low (e.g., cropland, bare land), including temperate Asia (0.27 ± 0.35 Mg C ha^{-1} $year^{-1}$) and savannas in subtropical Africa (0.18 ± 0.37 Mg C ha^{-1} $year^{-1}$) (Fig. 1B and fig. S4C). This aligns with field observations that recognize the potential for increasing SOC sequestration in carbon-poor soils (*22*). Even though SOC gain is predicted in areas originally covered with savanna, afforestation remains ecologically unsuitable owing to biodiversity risks (*16*, *23*). Note that the SOC prediction errors are generally small and are minimized in data-rich low latitudes (Fig. 1C).

[1]School of Atmospheric Sciences, Key Laboratory of Tropical Atmosphere-Ocean System (Ministry of Education), Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China. [2]The Nature Conservancy, Arlington, VA, USA. [3]Smithsonian Environmental Research Center, Edgewater, MD, USA. [4]Institute of Botany, Chinese Academy of Sciences, Beijing, China. [5]Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China. [6]Laboratoire des Sciences du Climat et de l'Environnement, CEA CNRS UVSQ, Gif-sur-Yvette, France. [7]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, UK. [8]Institute of Carbon Neutrality, College of Urban and Environmental Sciences, Peking University, Beijing, China. [9]College of the Environment and Ecology, Xiamen University, Xiamen, China. [10]Global Carbon Project, CSIRO Environment, Canberra, ACT, Australia. [11]Institute of Soil and Water Conservation, Northwest A&F University, Yangling, China. ***Corresponding author. Email: qinzhangcai@mail.sysu.edu.cn** †Present address: School of the Environment and Sustainable Engineering, Eastern Institute of Technology, Ningbo, China. ‡Present address: School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK.

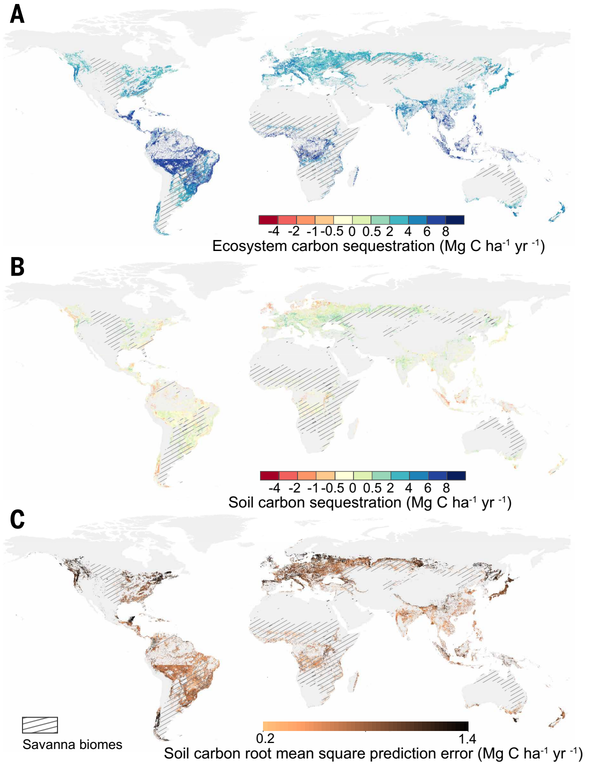

Fig. 1. Estimated carbon sequestration rates with forestation across potential lands. (**A**) Ecosystem carbon sequestration rate (soil and biomass combined). (**B**) Soil carbon sequestration rate (0 to 60 cm). (**C**) Uncertainty of soil carbon sequestration rate (0 to 60 cm). The positive values [(A) and (B)] show carbon gain, and negative values show loss. The color-shaded areas show potential lands estimated in this study (regardless of savanna biome boundaries); the areas under savanna are further constrained. Data are available in data S1 (*24*).

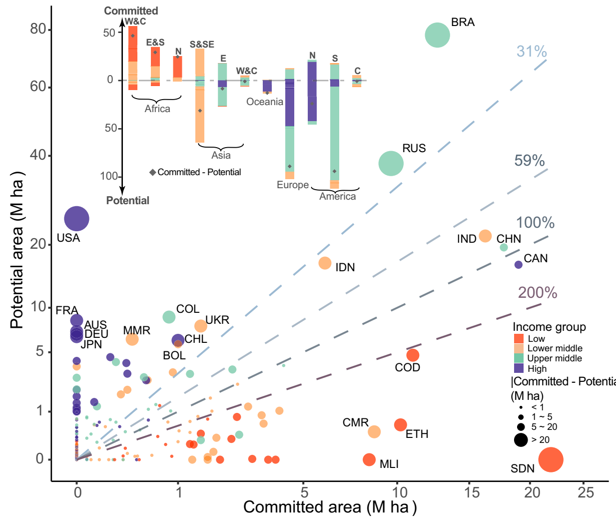

Fig. 2. Potential and committed land for forestation by country and region. The dashed lines indicate the percentage of *x* axis in *y* axis. The 31% and 59% lines refer to the global average proportion of currently achievable (with both potential and commitment) and committed area over total potential area estimated in Qin24, respectively. The inset figure illustrates land availability by region. Country codes are shown for those with forestation potential or commitment >5 Mha. Region names, country codes, and income groups can be found in table S6. Specific country-level data are available in data S2 (*24*).

Ecosystem carbon sequestration varies spatially (Fig. 1A), generally with a larger contribution from biomass than soil (fig. S4B). Globally, the 30-year average potential carbon sequestration rate from both biomass and soil (including savanna) is 3.15 (±1.76) Mg C ha^{-1} year^{-1}, with 2.86 (±1.49) and 3.35 (±1.89) Mg C ha^{-1} year^{-1} for afforestation and reforestation, respectively. Within the tropics (between 23°N and 23°S), the total potential sequestration ranges from 0.14 to 8.53 Mg C ha^{-1} year^{-1}, with an average of 5.28 (±1.20) Mg C ha^{-1} year^{-1}. The highest rate is associated with wet tropical forest ecosystems, with 5.66 (±1.11) Mg C ha^{-1} year^{-1}, 5.80 (±1.32) Mg C ha^{-1} year^{-1}, and 4.66 (±1.13) Mg C ha^{-1} year^{-1} in South America, Africa, and Southeast Asia, respectively, reflecting high biomass growth rates (fig. S4, C and D). Boreal forests show minimal potential in either biomass or soil carbon sequestration. The spatial variability of ecosystem sequestration is primarily driven by the variability in biomass (fig. S4B). The actual ecosystem carbon sequestration should be further evaluated with dedicated extent of land.

Suitable area for potential forestation

Estimates of overall climate mitigation from forestation heavily rely on the considered available land area. From a land "supply" point of view, Bastin *et al.* (2019) (BA19) found that about 900 Mha were biophysically suitable for increasing tree cover, even beyond current forest biomes (*10*) (fig. S6A). Excluding areas with risks of biodiversity loss in natural grasslands and albedo-induced warming in the boreal region, Griscom *et al.* (2017) (GR17) estimated the potential to be 678 Mha (*8*) (fig. S6B). In this study, we developed a new dataset, referred to as "Qin24" (*24*), and identified that only ~390 Mha of "potential area" could be supplied for forestation (fig. S6C) after excluding areas with potential biodiversity loss (*16*, *23*, *25*), biophysical warming (*26*), and exacerbated water stress (*27*) (see materials and methods section M3). Most of the Qin24 potential area is concentrated in the Americas (42%) and Europe (26%), with Brazil, Russia, and the USA contributing to 36% of the total (Fig. 2). Brazil alone represents one-fifth of the potentially suitable area (78 Mha), primarily consisting of recently deforested regions of the Amazon (*28*). Low- and middle-income countries (LMICs) hold about 71% of this potential (table S2).

From the land "demand" perspective, global commitments across all countries have pledged 229.7 Mha of forestation during 2021–2030, 59% of the global potential area (fig. S6D). Notably, 90% of the committed area is contributed by LMICs with limited potential area (Fig. 2). Africa, with only 4% of the global potential area (16.0 Mha), has committed 50% of forestation pledges (115.5 Mha) (table S2); this limited potential area is mainly due to biodiversity concerns (*16*, *23*), suggesting that commitments may exceed its potential area by more than six times. The commitments in 38 out of 41 African countries were more than double the estimated potential area (Fig. 2, 200% line). Sudan, the Democratic Republic of the Congo, and Ethiopia account for 43 Mha of overcommitments (Fig. 2), likely relying on lands that we excluded in this study, such as savanna. Commitments ("demand") exceed the estimated potential area ("supply") in 57 out of 105 countries across the globe, including 54 LMICs. This leaves only 119.7 Mha, which is 31% of "supply" or 52% of "demand," to be currently "achievable" from the intersection of committed and suitable land availability, with 84% in LMICs and mostly in Asia (50.5 Mha).

Europe and South America have only committed 12.8 and 16.1% of their potential area, respectively, far less than the global average of 59% (Fig. 2). The top 15 countries, representing 70% of the global potential area, have only committed 31% their estimated potential to forestation (84 Mha) (fig. S6E). Notably, Canada, China, and India have contributed to 62% of the top 15 countries' commitments. By contrast, the last 10 of these 15 countries with high potential area have either made no or extremely limited commitments, totaling 8 Mha.

Global climate change mitigation

Under a hypothetical scenario of worldwide forestation over a period of 10 years starting from 2021, the carbon sequestration in biomass and soil could reach a theoretical amount of 39.9 Pg C by 2050 on 389 Mha of potential lands estimated in this study (excluding savanna). This would equate to about 1.3 Pg C year^{-1}, which is 63% of the current net annual land sink from 2014 to 2023 (i.e., 2.1 Pg C year^{-1}) (*12*). This amount is much lower than the 91.1 and 63.4 Pg C over 30 years, on 891 and 678 Mha of land, predicted by Bastin *et al.* (*10*) and Griscom *et al.* (*8*), respectively (Fig. 3A). For all these three estimates from the land "supply" perspective, carbon sequestration is dominated by South America, where a large area of previously cleared forests could potentially be regrown (e.g., Brazil, Colombia), followed by Asia, particularly China and India, where potential area is available.

Taking into account only current commitments (materials and methods section M3), the "committed" mitigation potential significantly declines, to 21.4 Pg C by 2050, at a rate of 0.71 Pg C year^{-1} (Fig. 3A). When further considering these commitments along with our land availability limitations, the resulting currently "achievable" mitigation potential drops to 12.5 Pg C, with an average rate of 0.42 Pg C year^{-1}. For comparison, the carbon uptake by land over the period 2014–2023 is 3.2 Pg C year^{-1} (*12*), and halting global forest loss by 2030 could avoid emissions of between 1.1 and 1.3 Pg C year^{-1} (2021–2050) (*17*, *18*). Land-use change causes about 1.1 Pg C year^{-1} carbon emissions globally (*12*) and −0.14 Pg C year^{-1} carbon sink in China (*29*). It should be noted that 95% of the achievable mitigation is contributed by LMICs, mainly Brazil, India, and China. High-income countries only contribute a cumulative 0.9 Pg C, with Canada being the largest contributor (74%) owing to its highly ambitious commitments. Asia alone contributes the most mitigation (5 Pg C, or 40%), with India and China accounting for more than half, followed by South America and Africa (Fig. 3B).

Forestation action: faster, higher, stronger—together

The effectiveness of forestation as a natural climate solution ultimately depends on taking action: acting faster, setting higher targets, prioritizing areas with greater benefits, and coordinating global efforts for the right places with suitable species (*8*, *30*). Actual climate mitigation is heavily influenced by the time taken to reach full potential considering ecological and social delays (*30*). Most current commitments aim to accomplish forestation by 2030, which leaves about 5 years for action starting from 2025. If forestation action is delayed, the potential 21.4 Pg C of sequestration by 2050 would be reduced by 0.41 (0.37–0.45) Pg C for each year of delay (fig. S7). Acting faster could lower the risk of reduced efficacy of human actions (*31*), decreasing the likelihood of severe climate damages (*9*).

Greater mitigation could also be achieved with more ambitious forestation goals. Currently, about 59% of the potential area is designated for global forestation, but only half of that area (120 Mha) aligns with our estimate of land availability. Many high-income countries have not made explicit official commitments to the major forestation projects surveyed here (Fig. 2). To meet a higher target of forestation, like the current global commitment of 59% of the potential area, even more ambitious commitments and actions are urgently needed, especially for countries that have made limited commitments despite their high potential as estimated in Qin24 (Fig. 2). In addition, even with the same area of committed land, prioritizing locations with a stronger capability to sequester carbon can maximize the overall mitigation magnitude. Across the 229.7 Mha of committed global area, total carbon sequestration could be 20% higher if prioritizing locations with stronger rather than lower sequestration rates (fig. S7). Tropical regions, Brazil for example, could boost their mitigation, given their higher carbon sequestration rate compared with other regions, if the potential area permits (Fig. 1A). In contrast, for regions with high potential areas but smaller carbon sequestration rates, such as the USA and Russia, more ambitious commitments are needed to result in equivalent amounts of mitigation (Fig. 4).

Lastly, the asymmetry in mitigation potential and overall socioeconomic development among countries and regions necessitates global and collective action (Fig. 4). Globally, 83.9% of the 39.9 Pg C mitigation potential (on 389 Mha of land) is concentrated in LMICs, which represent only 37.4% of the global gross domestic product. Despite considerable mitigation potential, many LMICs struggle with limited resources for deploying large-scale forestation projects. Countries such as Indonesia and Brazil have potential for forestation but are still losing large amounts of forest land to agricultural and commodity production (e.g., palm oil, wood fiber) (*3*, *32*). The essential involvement of tropical regions, especially LMICs, requires as much local and national commitment as international involvement in financing projects (*33*, *34*). Maximizing effective climate mitigation requires global cooperation, including financing, technology transfer, carbon markets, and mechanisms such as the United Nations Green Climate Fund (*2*, *34*, *35*). Equitable support must address power asymmetries in different regions (e.g., North–South) and actors, such as the state versus local communities and Indigenous peoples and rights (*2*, *36*, *37*). Global and collective action is needed to ensure projects benefit regional and Indigenous communities, including some LMICs that are least responsible for climate change but with high forestation potential.

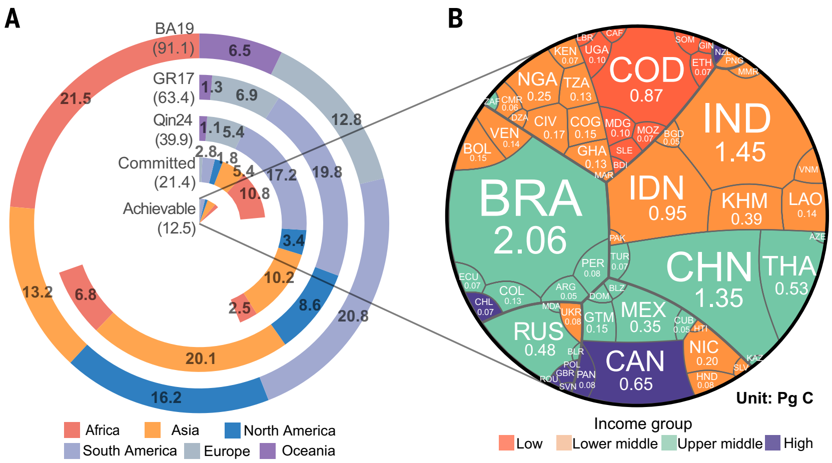

Fig. 3. Estimated mitigation potential from forestation varies with land availability assumptions. (**A**) Global and regional ecosystem carbon sequestration. BA19 (*10*), GR17 (*8*), and Qin24 (*24*) refer to respective assumptions of land potentially available for forestation. The "committed" assumption considers only national commitments, and "achievable" shows currently achievable land limited by availability defined in Qin24 (see materials and methods section M3). (**B**) The currently achievable mitigation potential varies among countries and income groups. Country-specific data are available in data S3 (*24*). Country codes and corresponding income groups can be found in table S6.

Uncertainties and pathways

Global forestation's mitigation potential hinges on carbon sequestration rates and land availability, in addition to finances, governance, and sociopolitical considerations (*8*, *30*, *38*). SOC modeling needs more field data for validation and model development, particularly for longer-term (>30 years), deeper soils (>60 cm) and regions with lack of data such as the Amazon and Congo Basin (*14*, *15*). Land availability assessments require further examination and consolidation to better reflect consistently defined, spatially explicit, biome- and region-specific forestation opportunities (*39*, *40*). Sociopolitical challenges, such as contested land tenure (*41*), power asymmetries, unfairness, and injustice in forest governance (*37*), should be further examined to align local forestation opportunities with global studies (*11*, *42*, *43*). Future mitigation estimates should consider mechanisms and factors missing in current carbon sequestration modeling (*15*, *44*–*46*). Our estimates (see materials and methods section M4) suggest that CO_2 fertilization could boost biomass carbon sequestration and increase estimated mitigation by 11 to 12%. Albedo

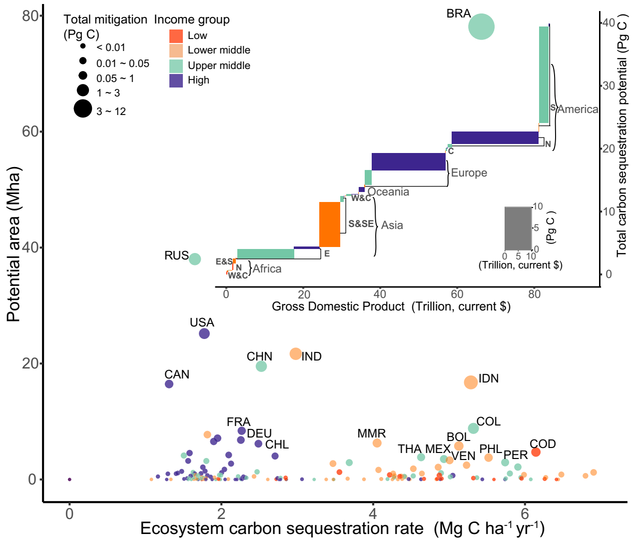

Fig. 4. The ecosystem carbon sequestration rate, potential area, and mitigation potential vary spatially. The countries with large potential areas may not necessarily exhibit high carbon sequestration rates. The inset graph illustrates carbon sequestration potential among regions with varying economic situations. The carbon sequestration is based on potential area estimated in this study (*24*). Country codes are shown for those with mitigation potential exceeding 0.5 Pg C. The ecosystem carbon sequestration rate data are available in data S4 (*24*). Region names, country codes, and income groups can be found in table S6.

change could lead to an overall warming effect, offsetting 1.3 Pg C of achievable mitigation. Studies show that the net impacts of CO_2 fertilization and climate change on biomass productivity vary from a 30% loss to a 60% gain of regional carbon stocks (*47*). Negative impacts such as ozone damage, drought, and nitrogen and phosphorus limitation may often negate CO_2 fertilization effects (*2*, *48*–*50*). Numerous natural (e.g., wildfires, insect herbivores, and fungal pathogens) and anthropogenic disturbances (e.g., catastrophic failure of planted stands) as well as forest harvest or wood extraction may further reduce the potential achievable mitigation (*51*–*53*).

Furthermore, social and economic development, conservation priorities, and the needs and interests of local communities should also be factored into the accounting of regional land supply and productivity, to determine the "practical," not just "theoretical," mitigation potential by country and region (*54*). In the forest sector, halting forest loss and protecting and managing existing forests are just as important as, if not more important than, creating new forests (*7*, *8*, *17*, *18*). From a life-cycle perspective, long-term carbon dynamics (>30 years) involving plantation, wood harvest, and biomass utilization should be explored, especially for net-negative emissions needs beyond ecosystem boundaries (e.g., bioenergy) (*55*–*57*). Natural climate solutions could bridge the gap between national decarbonization pledges (nationally determined contributions, or NDCs) and the efforts required to limit warming within 1.5° or 2°C (*7*, *9*), but rapid decarbonization in industry and other fossil-related sectors remains the priority (*9*, *12*, *58*).

REFERENCES AND NOTES

1. J. Busch *et al.*, *Nat. Clim. Chang.* **9**, 463–466 (2019).
2. J. G. Canadell, M. R. Raupach, *Science* **320**, 1456–1457 (2008).
3. P. G. Curtis, C. M. Slay, N. L. Harris, A. Tyukavina, M. C. Hansen, *Science* **361**, 1108–1111 (2018).
4. Z. Qin *et al.*, *One Earth* **7**, 835–847 (2024).
5. G. M. Domke, S. N. Oswalt, B. F. Walters, R. S. Morin, *Proc. Natl. Acad. Sci. U.S.A.* **117**, 24649–24651 (2020).
6. W. S. Walker *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2111312119 (2022).
7. S. C. Cook-Patton *et al.*, *Nat. Clim. Chang.* **11**, 1027–1034 (2021).
8. B. W. Griscom *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 11645–11650 (2017).
9. S. Deng *et al.*, *Glob. Change Biol.* **29**, 289–291 (2023).
10. J.-F. Bastin *et al.*, *Science* **365**, 76–79 (2019).
11. S. Rohatyn, D. Yakir, E. Rotenberg, Y. Carmel, *Science* **377**, 1436–1439 (2022).
12. P. Friedlingstein *et al.*, *Earth Syst. Sci. Data* **17**, 965–1039 (2025).
13. S. C. Cook-Patton *et al.*, *Nature* **585**, 545–550 (2020).
14. L. E. Nave *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **115**, 2776–2781 (2018).
15. E. Veldkamp, M. Schmidt, J. S. Powers, M. D. Corre, *Nat. Rev. Earth Environ.* **1**, 590–605 (2020).
16. C. L. Parr, M. Te Beest, N. Stevens, *Science* **383**, 698–701 (2024).
17. Y. Zhu *et al.*, *Innovation (Camb.)* **3**, 100307 (2022).
18. T. Gasser, P. Ciais, S. L. Lewis, *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2200519119 (2022).
19. J. Laganière, D. A. Angers, D. Paré, *Glob. Change Biol.* **16**, 439–453 (2010).
20. W. M. Post, K. C. Kwon, *Glob. Change Biol.* **6**, 317–327 (2000).
21. R. Lal, *For. Ecol. Manage.* **220**, 242–258 (2005).
22. S. Hong *et al.*, *Nat. Sustain.* **3**, 694–700 (2020).
23. R. C. R. Abreu *et al.*, *Sci. Adv.* **3**, e1701284 (2017).
24. Z. Qin, Forestation: land availability and climate change mitigation, Figshare (2025); https://doi.org/10.6084/m9.figshare.28377266.
25. G. Hayman, *Science* **383**, 833–834 (2024).
26. N. Hasler *et al.*, *Nat. Commun.* **15**, 2275 (2024).
27. A. J. Hoek Van Dijke *et al.*, *Nat. Geosci.* **15**, 363–368 (2022).
28. P. Potapov *et al.*, *Front. Remote Sens.* **3**, 856903 (2022).
29. Y. Zhu *et al.*, *Nat. Clim. Chang.* **15**, 428–435 (2025).
30. Z. Qin *et al.*, *Glob. Change Biol.* **27**, 215–217 (2021).
31. J. P. Dunne, R. J. Stouffer, J. G. John, *Nat. Clim. Chang.* **3**, 563–566 (2013).
32. M. C. Hansen *et al.*, *Science* **342**, 850–853 (2013).
33. J. T. Erbaugh *et al.*, *Nat. Ecol. Evol.* **4**, 1472–1476 (2020).
34. S. Roe *et al.*, *Nat. Clim. Chang.* **9**, 817–828 (2019).
35. Y. Zeng *et al.*, *Nat. Clim. Chang.* **10**, 842–844 (2020).
36. C. M. Anderson *et al.*, *Science* **363**, 933–934 (2019).
37. D. Kleinschmit, C. Wildburger, N. Grima, B. Fisher, *International Forest Governance: A Critical Review of Trends, Drawbacks, and New Approaches*, vol. 43 of *IUFRO World Series* (International Union of Forest Research Organizations, 2024).
38. L. Mo *et al.*, *Nature* **624**, 92–101 (2023).
39. C. R. Drever *et al.*, *One Earth* **8**, 101177 (2025).
40. L. Yao *et al.*, *Nat. Commun.* **15**, 8398 (2024).
41. O. S. Rakotonarivo *et al.*, *Commun. Earth Environ.* **4**, 179 (2023).
42. C. A. Williams, H. Gu, T. Jiao, *Sci. Adv.* **7**, eaax8859 (2021).
43. M. G. Windisch, E. L. Davin, S. I. Seneviratne, *Nat. Clim. Chang.* **11**, 867–871 (2021).
44. R. B. Jackson *et al.*, *Annu. Rev. Ecol. Evol. Syst.* **48**, 419–445 (2017).
45. F. Tao *et al.*, *Nature* **618**, 981–985 (2023).
46. C. Terrer *et al.*, *Nature* **591**, 599–603 (2021).
47. S. L. Lewis, C. E. Wheeler, E. T. A. Mitchard, A. Koch, *Nature* **568**, 25–28 (2019).
48. L. Xia *et al.*, *One Earth* **4**, 1752–1763 (2021).
49. W. R. Wieder, C. C. Cleveland, W. K. Smith, K. Todd-Brown, *Nat. Geosci.* **8**, 441–444 (2015).
50. W. R. L. Anderegg *et al.*, *Science* **368**, eaaz7005 (2020).
51. L. Peng, T. D. Searchinger, J. Zionts, R. Waite, *Nature* **620**, 110–115 (2023).
52. K.-H. Erb *et al.*, *Nature* **553**, 73–76 (2018).
53. C. T. J. Roebroek, G. Duveiller, S. I. Seneviratne, E. L. Davin, A. Cescatti, *Science* **380**, 749–753 (2023).
54. P. Smith *et al.*, *Nat. Clim. Chang.* **6**, 42–50 (2016).
55. E. J. Forster, J. R. Healey, C. Dymond, D. Styles, *Nat. Commun.* **12**, 3831 (2021).
56. Y. Xu, P. Smith, Z. Qin, *iScience* **27**, 110232 (2024).
57. S. Liang *et al.*, *Sci. Adv.* **11**, eadn7915 (2025).
58. W. Steffen *et al.*, *Science* **280**, 1393–1394 (1998).

ACKNOWLEDGMENTS

We thank B. Griscom for his active contributions to data resources and many valuable discussions during the early stages of our research, and the members of the Qin lab for their many helpful discussions throughout this project. **Funding:** This work was supported by the National Natural Science Foundation of China (U21A6001, 42141020) fund outdated. Y.W. and Y.Z. were partially supported by the Science and Technology Program of Guangdong (2024B1212070012). P.C. acknowledges support from the Carbon Loss In Plants, Soils and Oceans (CALPSO) funded by the Schmidt Sciences. C.Y. was funded by the National Key Research and Development Program of China (2023YFB3907403) and the Second Tibetan Plateau Scientific Expedition and Research Program (2022QZKK0101). **Author contributions:** Conceptualization: Z.Q. Methodology: Z.Q., Y.W. Investigation: Y.W., Z.Q., W.S., W.Z. Resources: Z.Q., S.C.C.-P., P.C., T.L., P.S., W.Y., X.Z., J.G.C. Data curation: Y.W., Y.Z., X.D., Y.X., H.X., C.Y. Formal analysis: Y.W., Z.Q. Visualization: Y.W., Z.Q., Y.Z. Supervision: Z.Q. Project administration: Z.Q. Writing – original draft: Z.Q. Writing – review & editing: All authors. **Competing interests:** S.C.C.-P. serves on the technical advisory board for the Symbiosis Coalition and the science advisory group for Restor and as a science adviser for CTrees. All other authors declare that they have no competing interests. **Data and materials availability:** All data and code needed to replicate and extend the analysis are available on Figshare (*24*).

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adj6841
Materials and Methods; Figs. S1 to S7; Tables S1 to S8; References (*59*–*342*)

Submitted 24 August 2023; resubmitted 3 December 2024; accepted 11 July 2025
10.1126/science.adj6841