Natural climate solutions

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Better stewardship of land is needed to achieve the Paris Climate Agreement goal of holding warming to below 2 °C; however, confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify "natural climate solutions" (NCS): 20 conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We find that the maximum potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO_2 equivalent ($PgCO_2e$) y^{-1} (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 $PgCO_2e$ y^{-1}) represents cost-effective climate mitigation, assuming the social cost of CO_2 pollution is ≥100 USD $MgCO_2e^{-1}$ by 2030. Natural climate solutions can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD $MgCO_2^{-1}$. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change.

climate mitigation | forests | agriculture | wetlands | ecosystems

The Paris Climate Agreement declared a commitment to hold "the increase in the global average temperature to well below 2 °C above preindustrial levels" (1). Most Intergovernmental Panel on Climate Change (IPCC) scenarios consistent with limiting warming to below 2 °C assume large-scale use of carbon dioxide removal methods, in addition to reductions in greenhouse gas emissions from human activities such as burning fossil fuels and land use activities (2). The most mature carbon dioxide removal method is improved land stewardship, yet confusion persists about the specific set of actions that should be taken to both increase sinks with improved land stewardship and reduce emissions from land use activities (3).

The net emission from the land use sector is only 1.5 petagrams of CO_2 equivalent ($PgCO_2e$) y^{-1}, but this belies much larger gross emissions and sequestration. Plants and soils in terrestrial ecosystems currently absorb the equivalent of ∼20% of anthropogenic greenhouse gas emissions measured in CO_2 equivalents (9.5 $PgCO_2e$ y^{-1}) (4). This sink is offset by emissions from land use change, including forestry (4.9 $PgCO_2e$ y^{-1}) and agricultural activities (6.1 $PgCO_2e$ y^{-1}), which generate methane (CH_4) and nitrous oxide (N_2O) in addition to CO_2 (4, 5). Thus, ecosystems have the potential for large additional climate mitigation by combining enhanced land sinks with reduced emissions.

Here we provide a comprehensive analysis of options to mitigate climate change by increasing carbon sequestration and reducing emissions of carbon and other greenhouse gases through conservation, restoration, and improved management practices in forest, wetland, and grassland biomes. This work updates and builds from work synthesized by IPCC Working Group III (WGIII) (6) for the greenhouse gas inventory sector referred to as agriculture, forestry, and other land use (AFOLU). We describe and quantify 20 discrete

Significance

Most nations recently agreed to hold global average temperature rise to well below 2 °C. We examine how much climate mitigation nature can contribute to this goal with a comprehensive analysis of "natural climate solutions" (NCS): 20 conservation, restoration, and/or improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We show that NCS can provide over one-third of the cost-effective climate mitigation needed between now and 2030 to stabilize warming to below 2 °C. Alongside aggressive fossil fuel emissions reductions, NCS offer a powerful set of options for nations to deliver on the Paris Climate Agreement while improving soil productivity, cleaning our air and water, and maintaining biodiversity.

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Data deposition: A global spatial dataset of reforestation opportunities has been deposited on Zenodo (https://zenodo.org/record/883444).

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mitigation options (referred to hereafter as "pathways") within the AFOLU sector. The pathways we report disaggregate eight options reported by the IPCC WGIII and fill gaps by including activities such as coastal wetland restoration and protection and avoided emissions from savanna fires. We also apply constraints to safeguard the production of food and fiber and habitat for biological diversity. We refer to these terrestrial conservation, restoration, and improved practices pathways, which include safeguards for food, fiber, and habitat, as "natural climate solutions" (NCS).

For each pathway, we estimate the maximum additional mitigation potential as a starting point for estimating mitigation potential at or below two price thresholds: 100 and 10 USD $MgCO_2e^{-1}$. The 100 USD level represents the maximum cost of emissions reductions to limit warming to below 2 °C (7), while 10 USD $MgCO_2e^{-1}$ approximates existing carbon prices (8). We aggregate mitigation opportunities at the 100 USD threshold to estimate the overall cost-effective contribution of NCS to limiting global warming to below 2 °C. For 10 of the most promising pathways, we provide global maps of mitigation potential. Most notably, we provide a global spatial dataset of reforestation opportunities (https://zenodo.org/record/883444) constrained by food security and biodiversity safeguards. We also review noncarbon ecosystem services associated with each pathway.

These findings are intended to help translate climate commitments into specific NCS actions that can be taken by government, private sector, and local stakeholders. We also conduct a comprehensive assessment of overall and pathway-specific uncertainty for our maximum estimates to expose the implications of variable data quality and to help prioritize research needs.

Results and Discussion

Maximum Mitigation Potential of NCS with Safeguards. We find that the maximum additional mitigation potential of all natural pathways is 23.8 $PgCO_2e\ y^{-1}$ (95% CI 20.3–37.4) at a 2030 reference year (Fig. 1 and *SI Appendix*, Table S1). This amount is not constrained by costs, but it is constrained by a global land cover scenario with safeguards for meeting increasing human needs for food and fiber. We allow no reduction in existing cropland area, but we assume grazing lands in forested ecoregions can be reforested, consistent with agricultural intensification and diet change scenarios (9, 10). This maximum value is also constrained by excluding activities that would either negatively impact biodiversity (e.g., replacing native nonforest ecosystems with forests) (11) or have carbon benefits that are offset by net biophysical warming (e.g., albedo effects from expansion of boreal forests) (12). We avoid double-counting among pathways (*SI Appendix*, Table S2). We report uncertainty estimated empirically where possible (12 pathways) or from results of an expert elicitation (8 pathways). See Fig. 1 for synthesis of pathway results.

Our estimate of maximum potential NCS mitigation with safeguards is ≥30% higher than prior constrained and unconstrained maximum estimates (5, 9, 13–16). Our estimate is higher, despite our food, fiber, and biodiversity safeguards, because we include a larger number of natural pathways. Other estimates do not include all wetland pathways (5, 9, 13–16), agricultural pathways (13–16), or temperate and boreal ecosystems (13, 14). The next highest estimate (14) (18.3 $PgCO_2\ y^{-1}$) was confined to tropical forests, but did not include a food production safeguard and was higher than our estimate for tropical forest elements of our pathways (12.6, 6.6–18.6 $PgCO_2\ y^{-1}$). Similarly, our estimates for specific pathways are lower than other studies for biochar (17), conservation agriculture (15), and avoided coastal wetland impacts (18). We account for new research questioning the magnitude of potential for soil carbon sequestration through no-till agriculture (19) and grazing land management (20), among other refinements to pathways discussed below. Our estimate for avoided forest conversion falls between prior studies on deforestation emissions (21–24). Our spatially explicit estimate for reforestation was slightly higher compared with a prior nonspatially explicit estimate

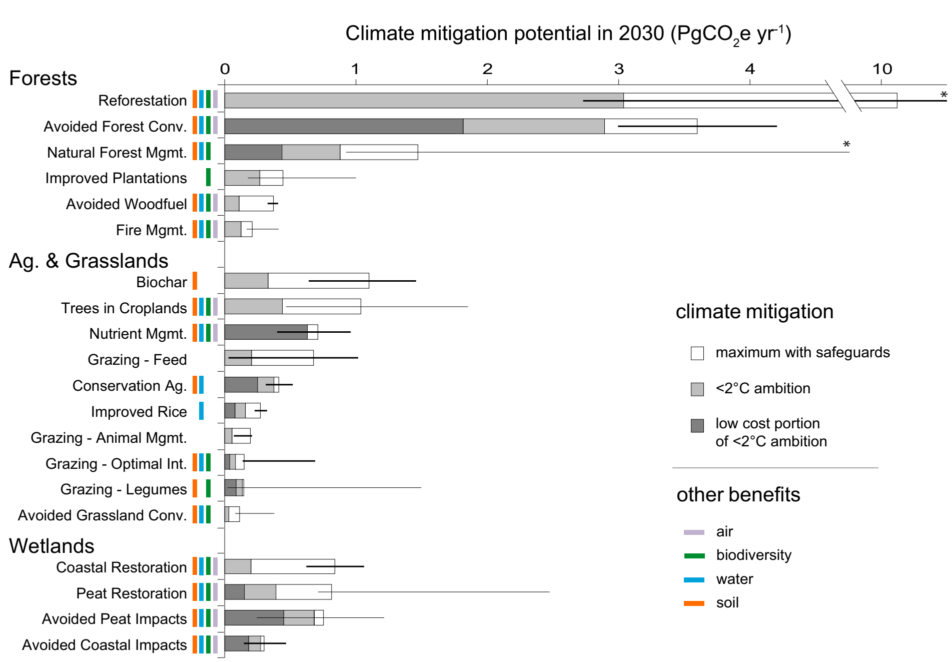

Fig. 1. Climate mitigation potential of 20 natural pathways. We estimate maximum climate mitigation potential with safeguards for reference year 2030. Light gray portions of bars represent cost-effective mitigation levels assuming a global ambition to hold warming to <2 °C (<100 USD $MgCO_2e^{-1}\ y^{-1}$). Dark gray portions of bars indicate low cost (<10 USD $MgCO_2e^{-1}\ y^{-1}$) portions of <2 °C levels. Wider error bars indicate empirical estimates of 95% confidence intervals, while narrower error bars indicate estimates derived from expert elicitation. Ecosystem service benefits linked with each pathway are indicated by colored bars for biodiversity, water (filtration and flood control), soil (enrichment), and air (filtration). Asterisks indicate truncated error bars. See *SI Appendix*, Tables S1, S2, S4, and S5 for detailed findings and sources.

(9). Natural pathway opportunities differ considerably among countries and regions (*SI Appendix*, Figs S1–S3 and Table S3).

Cost-Effective and Low-Cost NCS. We explore the proportion of maximum NCS mitigation potential that offers a cost-effective contribution to meeting the Paris Climate Agreement goal of limiting warming to below 2 °C. We define a <2 °C "cost-effective" level of mitigation as a marginal abatement cost not greater than ∼100 USD $MgCO_2^{-1}$ as of 2030. This value is consistent with estimates for the avoided cost to society from holding warming to below 2 °C (7, 25). We find that about half (11.3 $PgCO_2e\ y^{-1}$) of the maximum NCS potential meets this cost-effective threshold. To estimate the portion of NCS that are cost effective for holding warming to below 2 °C, we estimated the fraction of the maximum potential of each natural pathway (high = 90%, medium = 60%, or low = 30%) that could be achieved without exceeding costs of ∼100 USD $MgCO_2^{-1}$, informed by published marginal abatement cost curves. Our assignment of these indicative high, medium, and low cost-effective mitigation levels reflects the coarse resolution of knowledge on global marginal abatement costs for NCS. These default levels structured our collective judgment where cost curve data were incomplete (*SI Appendix*, Table S4). Using parallel methods, we find that more than one-third of the "<2 °C cost effective" levels for natural pathways are low cost (<10 USD $MgCO_2^{-1}$; 4.1 $PgCO_2e\ y^{-1}$; Fig. 1 and *SI Appendix*, Table S4).

The "low-cost" and cost-effective NCS carbon sequestration opportunities compare favorably with cost estimates for emerging technologies, most notably bioenergy with carbon capture and storage (BECCS)—which range from ∼40 USD $MgCO_2^{-1}$ to over 1,000 USD $MgCO_2^{-1}$. Furthermore, large-scale BECCS is untested and likely to have significant impacts on water use, biodiversity, and other ecosystem services (2, 26).

Our 100 USD constrained estimate (11.3 $PgCO_2e\ y^{-1}$) is considerably higher than prior central estimates (6, 14, 27, 28), and it is somewhat higher than the upper-end estimate from the IPCC Fifth Assessment Report (AR5) (10.6 $PgCO_2e\ y^{-1}$). Aside from our inclusion of previously ignored pathways as discussed above, this aggregate difference belies larger individual pathway differences between our estimates and those reported in the IPCC AR5. We find a greater share of cost-constrained potential through reforestation, forestry, wetland protection, and trees in croplands than the IPCC AR5, despite our stronger constraints on land availability, biodiversity conservation, and biophysical suitability for forests (14, 29).

NCS Contribution to a <2 °C Pathway. To what extent can NCS contribute to carbon neutrality by helping achieve net emission targets during our transition to a decarbonized energy sector? Warming will likely be held to below 2 °C if natural pathways are implemented at cost-effective levels indicated in Fig. 1, and if we avoid increases in fossil fuel emissions for 10 y and then drive them down to 7% of current levels by 2050 and then to zero by 2095 (Fig. 2). This scenario (14) assumes a 10-y linear increase of NCS to the cost-effective mitigation levels, and a >66% likelihood of holding warming to below 2 °C following a model by Meinshausen et al. (30). Under this scenario, NCS provide 37% of the necessary CO_2e mitigation between now and 2030 and 20% between now and 2050. Thereafter, the proportion of total mitigation provided by NCS further declines as the proportion of necessary avoided fossil fuel emissions increases and as some NCS pathways saturate. Natural climate solutions are thus particularly important in the near term for our transition to a carbon neutral economy by the middle of this century. Given the magnitude of fossil fuel emissions reductions required under any <2 °C scenario, and the risk of relying heavily on negative emissions technologies (NETs) that remain decades from maturity (3), immediate action on NCS should not delay action on fossil fuel emissions reductions or investments in NETs.

Half of this cost-effective NCS mitigation is due to additional carbon sequestration of 5.6 $PgCO_2e\ y^{-1}$ by nine of the pathways,

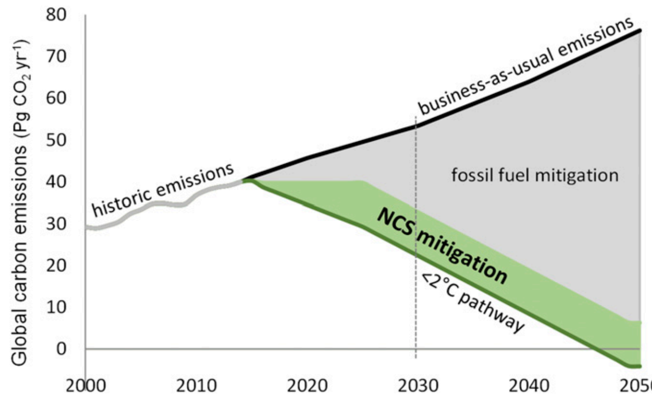

Fig. 2. Contribution of natural climate solutions (NCS) to stabilizing warming to below 2 °C. Historical anthropogenic CO_2 emissions before 2016 (gray line) prelude either business-as-usual (representative concentration pathway, scenario 8.5, black line) or a net emissions trajectory needed for >66% likelihood of holding global warming to below 2 °C (green line). The green area shows cost-effective NCS (aggregate of 20 pathways), offering 37% of needed mitigation through 2030, 29% at year 2030, 20% through 2050, and 9% through 2100. This scenario assumes that NCS are ramped up linearly over the next decade to <2 °C levels indicated in Fig. 1 and held at that level (=10.4 $PgCO_2\ y^{-1}$, not including other greenhouse gases). It is assumed that fossil fuel emissions are held level over the next decade then decline linearly to reach 7% of current levels by 2050.

while the remainder is from pathways that avoid further emissions of CO_2, CH_4, and N_2O (*SI Appendix*, Fig. S4 and Table S1). Aggregate sequestration levels begin to taper off around 2060, although most pathways can maintain the 2030 mitigation levels we report for more than 50 years (Fig. 2 and pathway-specific saturation periods in *SI Appendix*, Table S1). The NCS scenario illustrated in Fig. 2 will require substantial near-term ratcheting up of both fossil fuel and NCS mitigation targets by countries to achieve the Paris Climate Agreement goal to hold warming to below 2 °C. Countries provided nationally determined contributions (NDCs) with 2025 or 2030 emissions targets as a part of the Paris Climate Agreement. While most NDCs indicate inclusion of land sector mitigation, only 38 specify land sector mitigation contributions, of 160 NDCs assessed (31). Despite these limitations, analyses indicate that if NDCs were fully implemented, NCS would contribute about 20% of climate mitigation (31) and about 2 $PgCO_2e\ y^{-1}$ mitigation by 2030 (31, 32). As such, a small portion of the 11.3 $PgCO_2e\ y^{-1}$ NCS opportunity we report here has been included in existing NDCs. Across all sectors, the NDCs fall short by 11–14 $PgCO_2e\ y^{-1}$ of mitigation needed to keep 2030 emissions in line with cost-optimal 2 °C scenarios (33). Hence, NCS could contribute a large portion—about 9 $PgCO_2e\ y^{-1}$—of the increased ambition needed by NDCs to achieve the Paris Climate Agreement.

Our assessment of the potential contribution of NCS to meeting the Paris Agreement is conservative in three ways. First, payments for ecosystem services other than carbon sequestration are not considered here and could spur cost-effective implementation of NCS beyond the levels we identified. Natural climate solutions enhance biodiversity habitat, water filtration, flood control, air filtration, and soil quality (Fig. 1) among other services, some of which have high monetary values (34–36) (see *SI Appendix*, Table S5 for details). Improved human health from dietary shifts toward plant-based foods reduce healthcare expenses and further offset NCS costs (37).

Second, our findings are conservative because we only include activities and greenhouse gas fluxes where data were sufficiently robust for global extrapolation. For example, we exclude no-till agriculture (Conservation Agriculture pathway), we exclude improved manure management in concentrated animal feed operations (Nutrient Management pathway), we exclude adaptive multipaddock grazing (Grazing pathways), and we exclude soil carbon emissions that may occur with conversion of forests to pasture (Avoided Forest Conversion pathway). Future research may reveal a robust empirical basis for including such activities and fluxes within these pathways.

Third, the Paris Agreement states goals of limiting warming to "well below 2 °C" and pursuing "efforts to limit the temperature increase to 1.5 °C." Our analysis specifies a >66% chance of holding warming to just below 2 °C (30). Additional investment in all mitigation efforts (i.e., beyond ∼100 USD $MgCO_2^{-1}$), including NCS, would be warranted to keep warming to well below 2 °C, or to 1.5 °C, particularly if a very likely (90%) chance of success is desired.

Specific Pathway Contributions. Forest pathways offer over two-thirds of cost-effective NCS mitigation needed to hold warming to below 2 °C and about half of low-cost mitigation opportunities (*SI Appendix*, Table S4). Reforestation is the largest natural pathway and deserves more attention to identify low-cost mitigation opportunities. Reforestation may involve trade-offs with alternative land uses, can incur high costs of establishment, and is more expensive than Avoided Forest Conversion (38). However, this conclusion from available marginal abatement cost curves ignores opportunities to reduce costs, such as involving the private sector in reforestation activities by establishing plantations for an initial commercial harvest to facilitate natural and assisted forest regeneration (39). The high uncertainty of maximum reforestation mitigation potential with safeguards (95% CI 2.7–17.9 $PgCO_2e\ y^{-1}$) is due to the large range in existing constrained estimates of potential reforestation extent (345–1,779 Mha) (14, 16, 40–42). As with most forest pathways, reforestation has well-demonstrated cobenefits, including biodiversity habitat, air filtration, water filtration, flood control, and enhanced soil fertility (34). See *SI Appendix*, Table S5 for detailed review of ecosystem services across all pathways.

Our maximum reforestation mitigation potential estimate is somewhat sensitive to our assumption that all grazing land in forested ecoregions is reforested. If we assume that 25%, 50%, or 75% of forest ecoregion grazing lands were not reforested, it would result in 10%, 21%, and 31% reductions, respectively, in our estimate of reforestation maximum mitigation potential. While 42% of reforestation opportunities we identify are located on lands now used for grazing within forest ecoregions, at our <2 °C ambition mitigation level this would displace only ∼4% of global grazing lands, many of which do not occur in forested ecoregions (20). Grazing lands can be released by shifting diets and/or implementing Grazing-Feed and Grazing-Animal Management pathways, which reduce the demand for grazing lands without reducing meat and milk supply (43).

Avoided Forest Conversion offers the second largest maximum and cost-effective mitigation potential. However, implementation costs may be secondary to public policy challenges in frontier landscapes lacking clear land tenure. The relative success of Brazil's efforts to slow deforestation through a strong regulatory framework, accurate and transparent federal monitoring, and supply chain interventions provides a promising model (44), despite recent setbacks (45). We find relatively low uncertainty for Avoided Forest Conversion (±17%), reflecting considerable global forest monitoring research in the last decade stimulated by interest in reducing emissions from deforestation and forest degradation (REDD) (46).

Improved forest management (i.e., Natural Forest Management and Improved Plantations pathways) offers large and cost-effective mitigation opportunities, many of which could be implemented rapidly without changes in land use or tenure. While some activities can be implemented without reducing wood yield (e.g., reduced-impact logging), other activities (e.g., extended harvest cycles) would result in reduced near-term yields. This shortfall can be met by implementing the Reforestation pathway, which includes new commercial plantations. The Improved Plantations pathway ultimately increases wood yields by extending rotation lengths from the optimum for economic profits to the optimum for wood yield.

Grassland and agriculture pathways offer one-fifth of the total NCS mitigation needed to hold warming below 2 °C, while maintaining or increasing food production and soil fertility. Collectively, the grassland and agriculture pathways offer one-quarter of low-cost NCS mitigation opportunities. Cropland Nutrient Management is the largest cost-effective agricultural pathway, followed by Trees in Croplands and Conservation Agriculture. Nutrient Management and Trees in Croplands also improve air quality, water quality, and provide habitat for biodiversity (*SI Appendix*, Table S5). Our analysis of nutrient management improves upon that presented by the IPCC AR5 in that we use more recent data for fertilizer use and we project future use of fertilizers under both a "business as usual" and a "best management practice" scenario. Future remote sensing analyses to improve detection of low-density trees in croplands (47) will constrain our uncertainty about the extent of this climate mitigation opportunity. The addition of biochar to soil offers the largest maximum mitigation potential among agricultural pathways, but unlike most other NCS options, it has not been well demonstrated beyond research settings. Hence trade-offs, cost, and feasibility of large scale implementation of biochar are poorly understood. From the livestock sector, two improved grazing pathways (Optimal Intensity and Legumes) increase soil carbon, while two others (Improved Feed and Animal Management) reduce methane emission.

Wetland pathways offer 14% of NCS mitigation opportunities needed to hold warming to <2 °C, and 19% of low-cost NCS mitigation. Wetlands are less extensive than forests and grasslands, yet per unit area they hold the highest carbon stocks and the highest delivery of hydrologic ecosystem services, including climate resilience (47). Avoiding the loss of wetlands—an urgent concern in developing countries—tends to be less expensive than wetland restoration (49). Improved mapping of global wetlands—particularly peatlands—is a priority for both reducing our reported uncertainty and for their conservation and restoration.

Challenges. Despite the large potential of NCS, land-based sequestration efforts receive only about 2.5% of climate mitigation dollars (50). Reasons may include not only uncertainties about the potential and cost of NCS that we discuss above, but also concerns about the permanence of natural carbon storage and social and political barriers to implementation. A major concern is the potential for Reforestation, Avoided Forest Conversion, and Wetland/Peatland pathways to compete with the need to increase food production. Reforestation and Avoided Forest Conversion remain the largest mitigation opportunities despite avoiding reforestation of mapped croplands and constraints we placed on avoiding forest conversion driven by subsistence agriculture (*SI Appendix*, Table S1). A large portion (42%) of our maximum reforestation mitigation potential depends on reduced need for pasture accomplished via increased efficiency of beef production and/or dietary shifts to reduce beef consumption. On the other hand, only a ∼4% reduction in global grazing lands is needed to achieve <2 °C ambition reforestation mitigation levels, and reduced beef consumption can have large health benefits (51). A portion of wetland pathways would involve limited displacement of food production; however, the extremely high carbon density of wetlands and the valuable ecosystem services they provide suggest that protecting them offers a net societal benefit (52).

Feedbacks from climate change on terrestrial carbon stocks are uncertain. Increases in temperature, drought, fire, and pest outbreaks could negatively impact photosynthesis and carbon storage, while CO_2 fertilization has positive effects (53). Unchecked climate change could reverse terrestrial carbon sinks by midcentury and erode the long-term climate benefits of NCS (54). Thus, climate change puts terrestrial carbon stocks (2.3 exagrams) (55) at risk. Cost-effective implementation of NCS, by increasing terrestrial carbon stocks, would slightly increase (by 4%) the stocks at risk by

2050. However, the risk of net emissions from terrestrial carbon stocks is less likely under a <2 °C scenario. As such, NCS slightly increase the total risk exposure, yet will be a large component of any successful effort to mitigate climate change and thus help mitigate this risk. Further, most natural pathways can increase resilience to climate impacts. Rewetting wetlands reduces risk of peat fires (56). Reforestation that connects fragmented forests reduces exposure to forest edge disturbances (57). Fire management increases resilience to catastrophic fire (58). On the other hand, some of our pathways assume intensification of food and wood yields—and some conventional forms of intensification can reduce resilience to climate change (59). All of these challenges underscore the urgency of aggressive, simultaneous implementation of mitigation from both NCS and fossil fuel emissions reductions, as well as the importance of implementing NCS and land use intensification in locally appropriate ways with best practices that maximize resilience.

While the extent of changes needed in global land stewardship is large (*SI Appendix*, Tables S1 and S4), we find that the environmental ambition reflected in eight recent multilateral announcements is well aligned with our <2 °C NCS mitigation levels. However, only four of these announcements are specific enough for quantitative comparison: The New York Declaration on Forests, the Bonn Challenge, the World Business Council on Sustainable Development Vision 2050, and the "4 pour 1000" initiative (*SI Appendix*, Table S6). The first three of these have quantitative targets that are somewhat more ambitious than our <2 °C mitigation levels for some pathways, while the 4 pour 1000 initiative is considerably more ambitious for soil carbon storage. More explicit and comprehensive policy targets for all biomes and natural pathways are needed to clarify the role of NCS in holding warming to below 2 °C.

Next Steps. Considerable scientific work remains to refine and reduce the uncertainty of NCS mitigation estimates. Work also remains to refine methods for implementing pathways in socially and culturally responsible ways while enhancing resilience and improving food security for a growing human population (60). Nevertheless, our existing knowledge reported here provides a solid basis for immediately prioritizing NCS as a cost-effective way to provide 11 $PgCO_2e\ y^{-1}$ of climate mitigation within the next decade—a terrestrial ecosystem opportunity not fully recognized by prior roadmaps for decarbonization (15, 61). Delaying implementation of the 20 natural pathways presented here would increase the costs to society for both mitigation and adaptation, while degrading the capacity of natural systems to mitigate climate change and provide other ecosystem services (62). Regreening the planet through conservation, restoration, and improved land management is a necessary step for our transition to a carbon neutral global economy and a stable climate.

Methods

Estimating Maximum Mitigation Potential with Safeguards. We estimate the maximum additional annual mitigation potential above a business-as-usual baseline at a 2030 reference year, with constraints for food, fiber, and biodiversity safeguards (*SI Appendix*, Tables S1 and S2). For food, we allow no reduction in existing cropland area, but do allow the potential to reforest all grazing lands in forested ecoregions, consistent with agricultural intensification scenarios (9) and potential for dietary changes in meat consumption (10). For fiber, we assume that any reduced timber production associated with implementing our Natural Forest Management pathway is made up by additional wood production associated with Improved Plantations and/or Reforestation pathways. We also avoid activities within pathways that would negatively impact biodiversity, such as establishing forests where they are not the native cover type (11).

For most pathways, we generated estimates of the maximum mitigation potential (M_x) informed by a review of publications on the potential extent (A_x) and intensity of flux (F_x), where $M_x = A_x \times F_x$. Our estimates for the reforestation pathway involved geospatial analyses. For most pathways the applicable extent was measured in terms of area (hectares); however, for five of the pathways (Biochar, Cropland Nutrient Management, Grazing—Improved Feed, Grazing—Animal Management, and Avoided Woodfuel Harvest) other units of extent were used (*SI Appendix*, Table S1). For five pathways (Avoided Woodfuel Harvest; Grazing—Optimal Intensity, Legumes, and Feed; and Conservation Agriculture) estimates were derived directly from an existing published estimate. An overview of pathway definitions, pathway-specific methods, and adjustments made to avoid double counting are provided in *SI Appendix*, Table S2. See *SI Appendix*, pp 36–79 for methods details.

Uncertainty Estimates. We estimated uncertainty for maximum mitigation estimates of each pathway using methods consistent with IPCC good practice guidance (63) for the 12 pathways where empirical uncertainty estimation was possible. For the remaining eight pathways (indicated in Fig. 1), we used the Delphi method of expert elicitation (64) following best practices outline by Mach et al. (65) where applicable and feasible. The Delphi method involved two rounds of explicit questions about expert opinion on the potential extent (A_x) and intensity of flux (F_x) posed to 20 pathway experts, half of whom were not coauthors (see *SI Appendix*, pp 38–39 for names). We combined A_x and F_x uncertainties using IPCC Approach 2 (Monte Carlo simulation).

Assigning Cost-Constrained Mitigation Levels. We assumed that a maximum marginal cost of ∼100 US dollars $MgCO_2e^{-1}\ y^{-1}$ in 2030 would be required across all mitigation options (including fossil fuel emissions reductions and NCS) to hold warming to below 2 °C (7). This assumption is consistent with the values used in other modeling studies (16, 66) and was informed by a social cost of carbon in 2030 estimated to be 82–260 USD $MgCO_2e^{-1}$ to meet the 1.5–2 °C climate target (7).

To calibrate individual NCS pathways with a goal of holding warming to below 2 °C, we assessed which of three default mitigation levels—30%, 60%, or 90% of maximum—captures mitigation costs up to but not more than ∼100 USD $MgCO_2e^{-1}$, informed by marginal abatement cost (MAC) curve literature. Our assignment of these default levels reflects that the MAC literature does not yet enable a precise understanding of the complex and geographically variable range of costs and benefits associated with our 20 natural pathways. We also assessed the proportion of NCS mitigation that could be achieved at low cost. For this we used a marginal cost threshold of ∼10 USD $MgCO_2e^{-1}$, which is consistent with the current cost of emission reduction efforts underway and current prices on existing carbon markets. For references and details see *SI Appendix*.

Projecting NCS Contribution to Climate Mitigation. We projected the potential contributions of NCS to overall CO_2e mitigation action needed for a "likely" (greater than 66%) chance of holding warming to below 2 °C between 2016 and 2100. We compared this NCS scenario to a baseline scenario in which NCS are not implemented. In our NCS scenario, we assumed a linear ramp-up period between 2016 and 2025 to our <2 °C ambition mitigation levels reported in *SI Appendix*, Table S4. During this period, we assumed fossil fuel emissions were also held constant, after which they would decline. We assumed a maintenance of <2 °C ambition NCS mitigation levels through 2060, allowing for gradual pathway saturation represented as a linear decline of natural pathway mitigation from 2060 to 2090. We consider this a conservative assumption about overall NCS saturation, given the time periods we estimate before saturation reported in *SI Appendix*, Table S1. This scenario and the associated action on fossil fuel emissions reductions needed are represented in Fig. 2 through 2050. Scenario construction builds from ref. 14, with model parameters from Meinshausen et al. (30). The proportion of CO_2 mitigation provided by NCS according to the scenario described above is adjusted to a proportion of CO_2e with the assumption that non-CO_2 greenhouse gases are reduced at the same rate as CO_2 for NCS and other sectors.

Characterizing Activities and Cobenefits. We identified mitigation activities and noncarbon ecosystem services associated with each of the 20 natural pathways (*SI Appendix*, Tables S5 and S7). We used a taxonomy of conservation actions developed by the International Union for Conservation of Nature (IUCN) and the Conservation Measures Partnership (67) to link pathways with a known set of conservation activities. The IUCN taxonomy does not identify activities that are specific to many of our pathways, so we list examples of more specific activities associated with each pathway (*SI Appendix*, Table S7). We identify four generalized types of ecosystem services (biodiversity, water, soil, and air) that may be enhanced by implementation of activities within each natural pathway—but only where one or more peer-reviewed publication confirms the link (Fig. 1 and *SI Appendix*, Table S5).

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