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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$_2$e) 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$_2$e y^{-1}) represents cost-effective climate mitigation, assuming the social cost of CO$_2$ pollution is ≥100 USD MgCO$_2$e^{-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$_2$e) 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$_2$e y^{-1}) (4). This sink is offset by emissions from land use change, including forestry (4.9 PgCO$_2$e y^{-1}) and agricultural activities (6.1 PgCO$_2$e y^{-1}), which generate methane (CH$_4$) and nitrous oxide (N$_2$O) 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

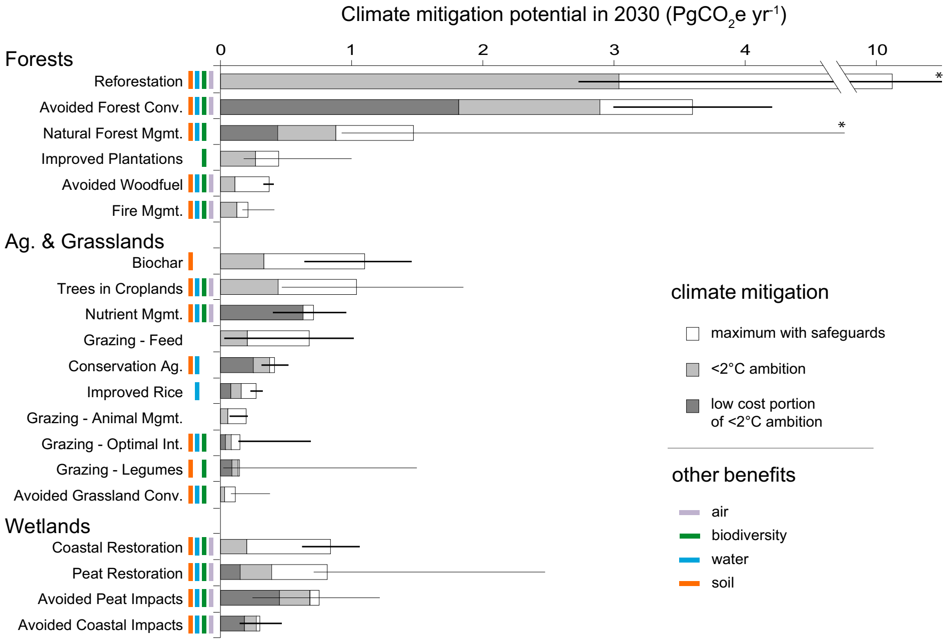

Fig. 1. Climate mitigation potential of 20 natural pathways. We estimate maximum climate mitigation potential with safeguards for reference year 2030. Light gray portions of bars represent cost-effective mitigation levels assuming a global ambition to hold warming to <2 °C (<100 USD $MgCO_2e^{-1}\ y^{-1}$). 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.

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(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.

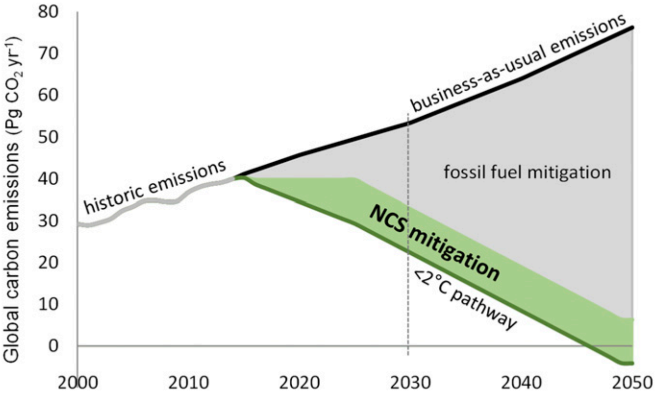

Fig. 2. Contribution of natural climate solutions (NCS) to stabilizing warming to below 2 °C. Historical anthropogenic CO_2 emissions before 2016 (gray line) prelude either business-as-usual (representative concentration pathway, scenario 8.5, black line) or a net emissions trajectory needed for >66% 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.

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, 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

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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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SI Correction

EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES, SUSTAINABILITY SCIENCE

Correction to Supporting Information for “Natural climate solutions,” by Bronson W. Griscom, Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger, David Shoch, Juha V. Siikamäki, Pete Smith, Peter Woodbury, Chris Zganjar, Allen Blackman, João Campari, Richard T. Conant, Christopher Delgado, Patricia Elias, Trisha Gopalakrishna, Marisa R. Hamsik, Mario Herrero, Joseph Kiesecker, Emily Landis, Lars Laestadius, Sara M. Leavitt, Susan Minnemeyer, Stephen Polasky, Peter Potapov, Francis E. Putz, Jonathan Sanderman, Marcel Silvius, Eva Wollenberg, and Joseph Fargione, which was first published October 16, 2017; 10.1073/pnas.1710465114 (*Proc Natl Acad Sci* USA 114:11645–11650).

The authors note that, in the *SI Appendix*, Figs. S1, S2, and S3, and Table S3 appeared incorrectly. The *SI Appendix* has been corrected online.

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Supporting Information Appendix

Natural climate solutions

Bronson W. Griscom, Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger, David Shoch, Juha V. Siikamäki, Pete Smith, Peter Woodbury, Chris Zganjar, Allen Blackman, João Campari, Richard T. Conant, Christopher Delgado, Patricia Elias, Trisha Gopalakrishna, Marisa R. Hamsik, Mario Herrero, Joseph Kiesecker, Emily Landis, Lars Laestadius, Sara M. Leavitt, Susan Minnemeyer, Stephen Polasky, Peter Potapov, Francis E. Putz, Jonathan Sanderman, Marcel Silvius, Eva Wollenberg, Joe Fargione

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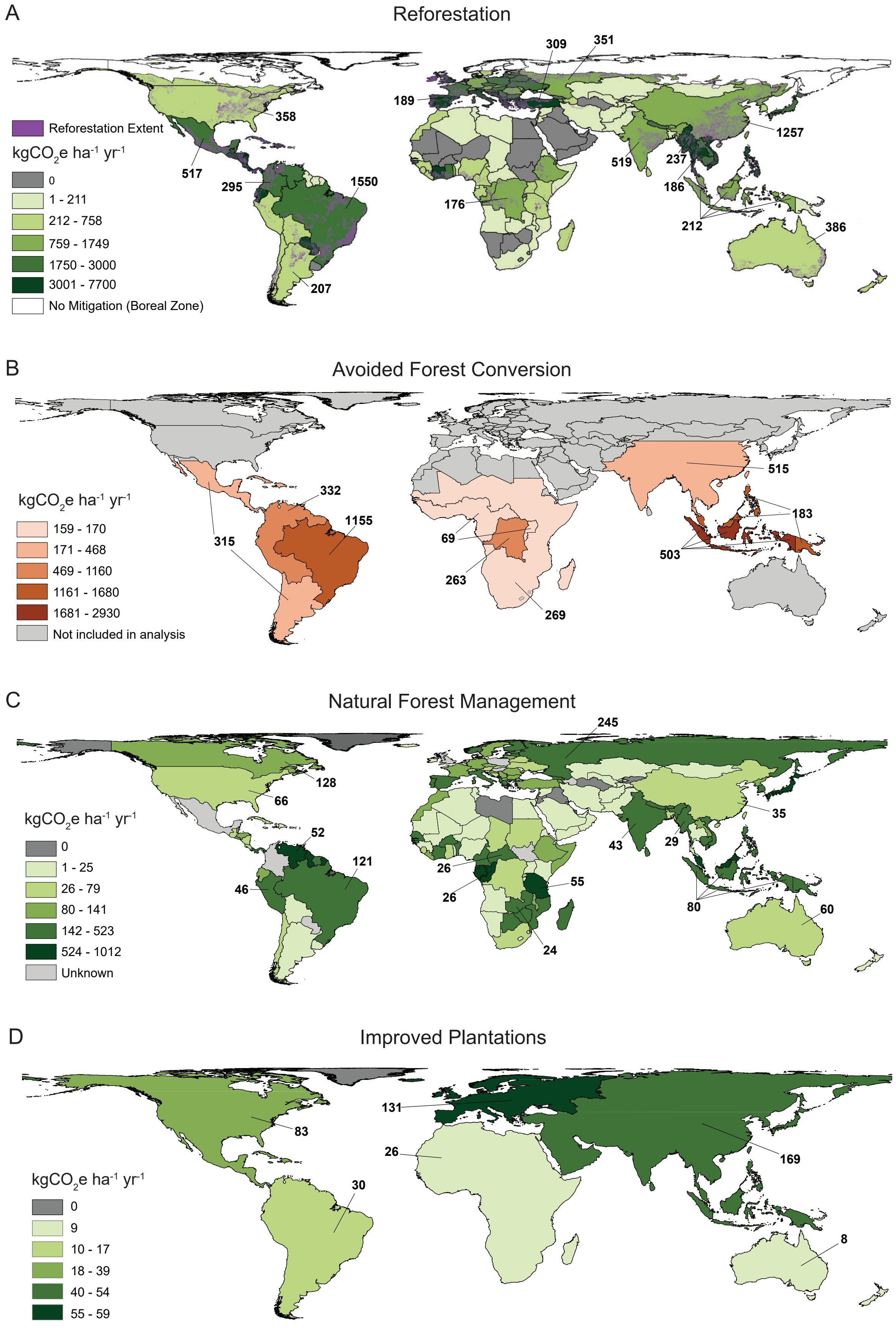
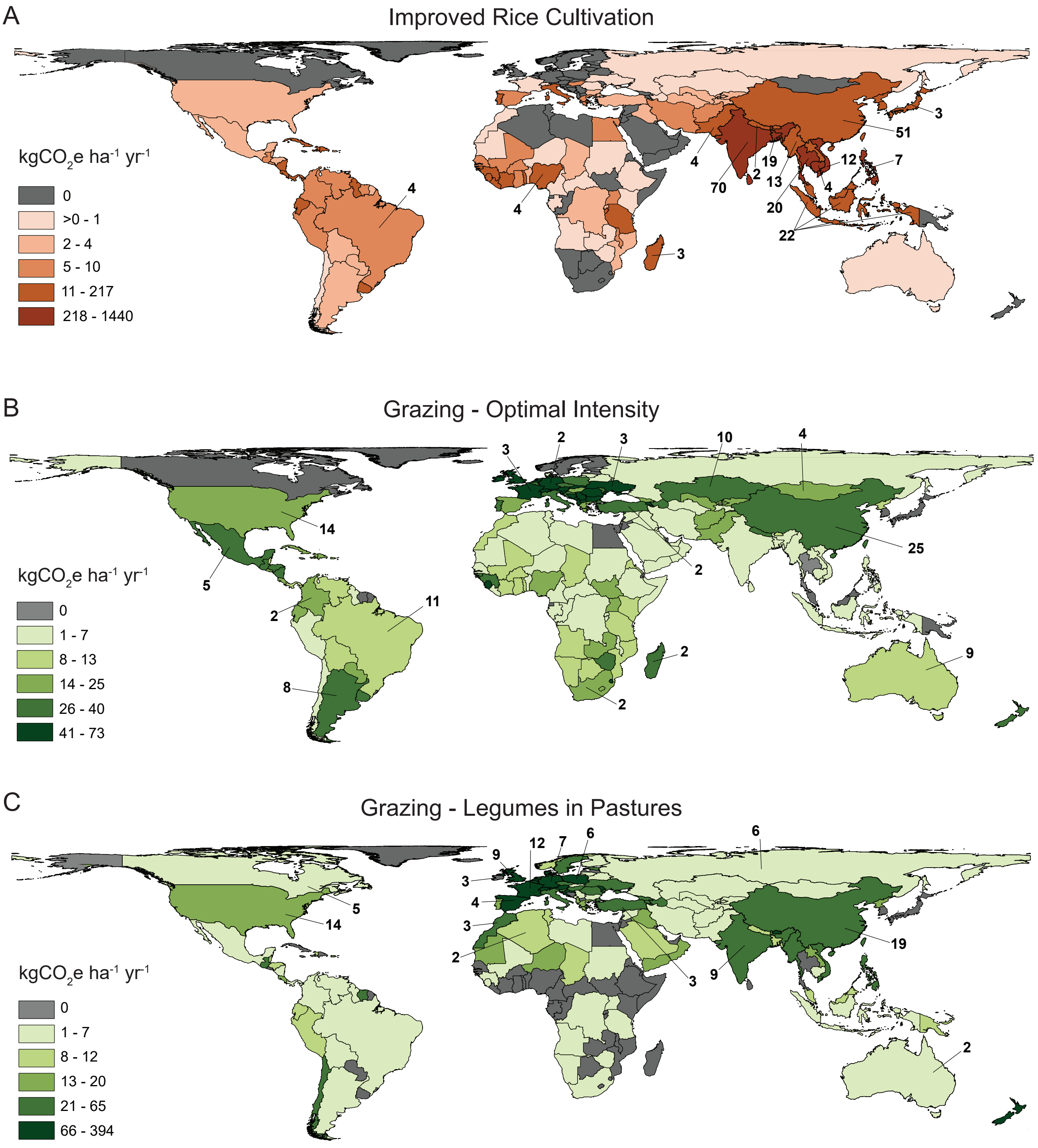
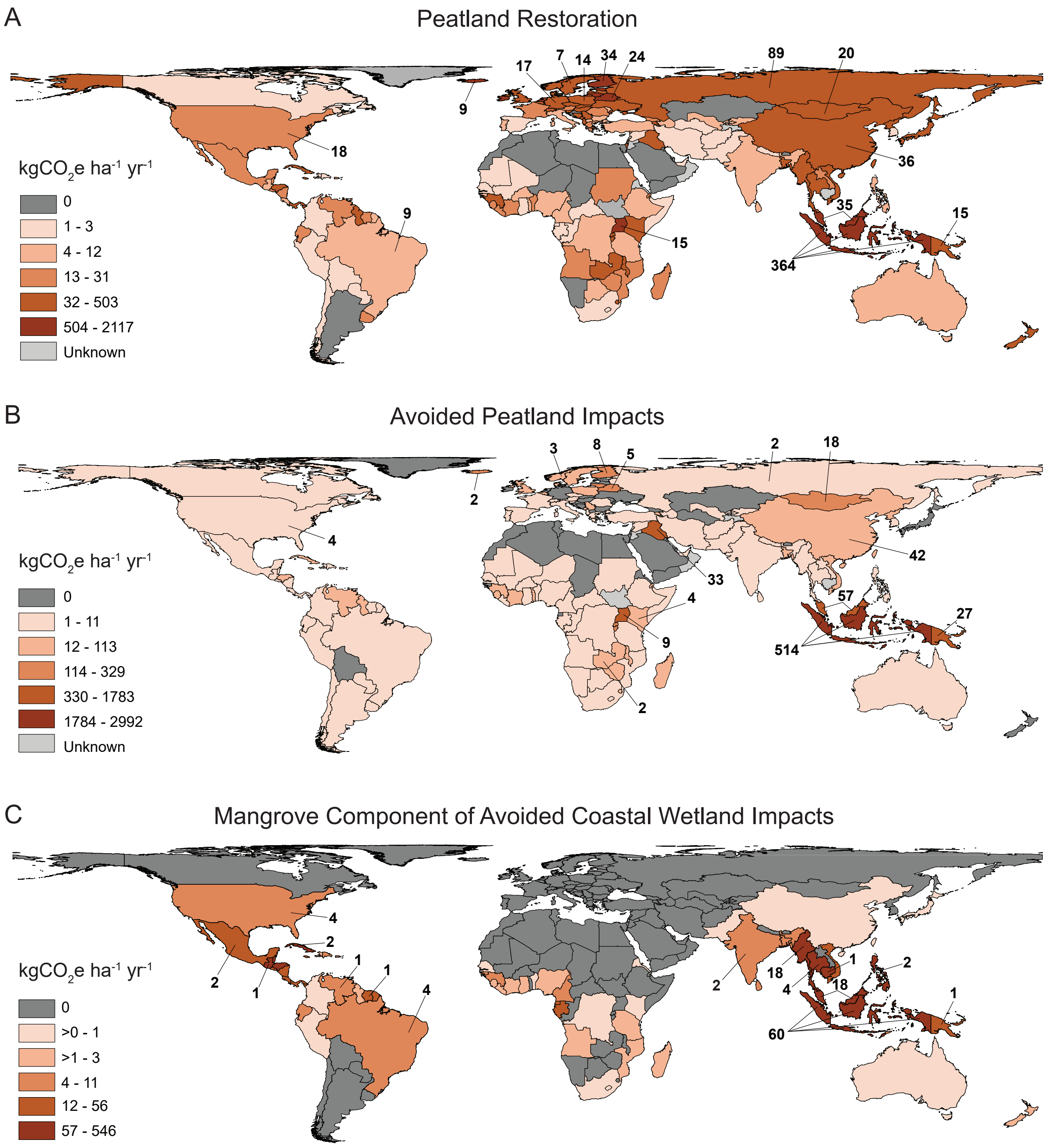


Fig. S1. Distribution of mitigation opportunity for four largest forest pathways. Hues indicate mean density of additional mitigation potential (maximum mitigation with safeguards per country or region divided by ice-free land area). Green hues indicate density of sequestration potential for Reforestation (A), Natural Forest Management (C) and Improved Plantations (D). Orange hues indicate density of avoided emissions potential for Avoided Forest Conversion (B). Boreal zones are excluded from reforestation (A) due to albedo. Numbers in bold indicate total TgCO$_2$e yr^{-1} for the countries/regions with largest mitigation potential. See Table S3 for all country results.



Numbers assigned to countries indicate total TgCO$_2$e yr^{-1}

Fig. S2. Distribution of mitigation opportunity for rice and grazing pathways. Hues indicate mean density of additional mitigation potential (maximum mitigation per country or region divided by ice-free land area). Orange hues indicate density of avoided emissions potential for Improved Rice (A). Green hues indicate density of sequestration potential for Grazing – Optimal Intensity (B) and Legumes in Pastures (C). Numbers in bold indicate total TgCO$_2$e yr^{-1} for the countries/regions with largest mitigation potential. See Table S3 for all country values.



Numbers assigned to countries indicate total TgCO$_2$e yr^{-1}

Fig. S3. Distribution of mitigation opportunity for wetlands pathways. Orange hues indicate density of avoided emissions potential for Peatland Restoration (A), Avoided Peatland Impacts (B), and the Mangrove component of Avoided Coastal Wetlands pathway (C). Note that Peat Restoration (re-wetting) primarily results in avoided peat oxidation (A) although enhanced sequestration can also occur. Numbers in bold indicate total TgCO$_2$e yr^{-1} for the countries/regions with largest mitigation potential. See Table S3 for all country values.

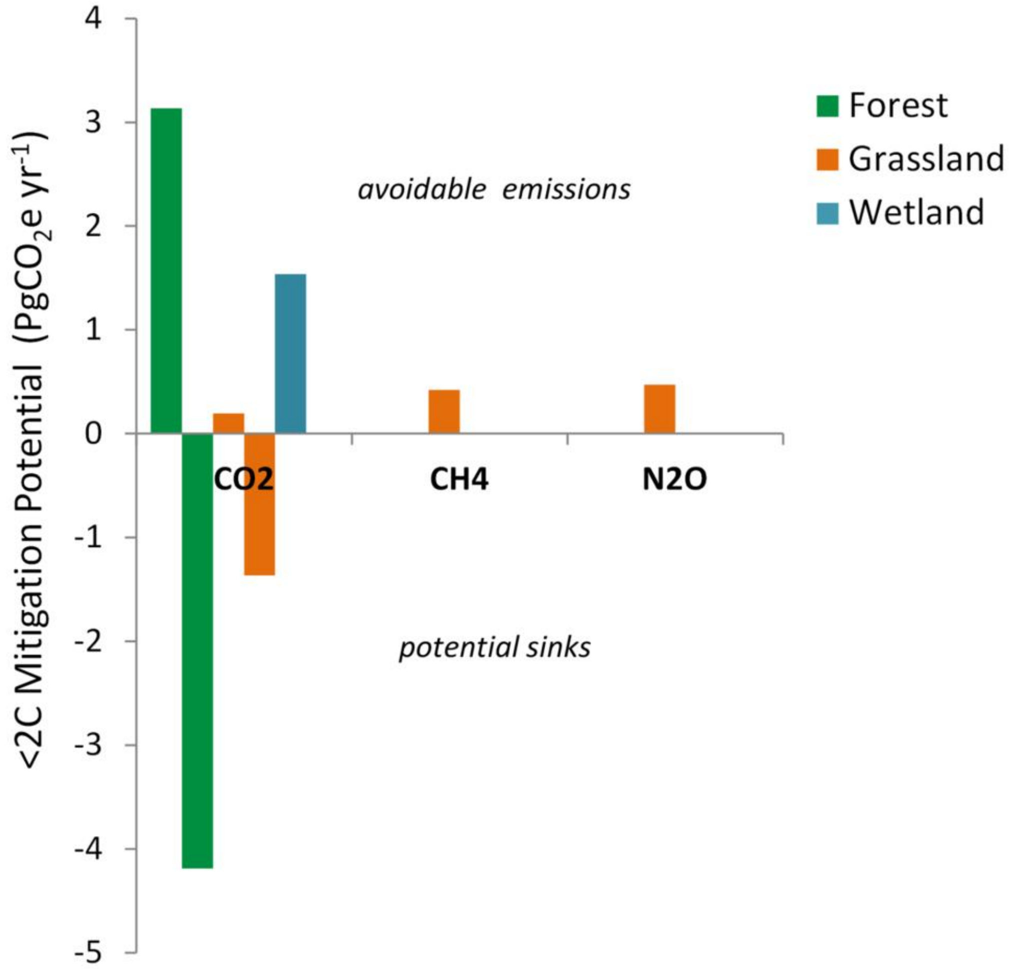


Fig. S4. Mitigation potential by greenhouse gas, biome, and flux type. Total mitigation potential at the <2C° mitigation level (=100 USD cost constraint) across 20 pathways is disaggregated according to biome (forest, grassland & agriculture, wetland), greenhouse gas (CO_2, CH_4, and N_2O), and flux type (avoidable emissions vs. potential sinks).

Table S1. Maximum mitigation potential of natural pathways by 2030. Key literature sources used in estimating values are listed below each value. See Methods Details section for additional sources involved. Mitigation potential given in million tonnes CO_2e per year (Tg CO_2e yr^{-1}). Uncertainty values in grey derived from expert elicitation.

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
Pathway	Pathway Element	Rate of avoidable impact (Mha yr^{-1})	Maximum potential extent of implementation (units as noted)	Extent Uncertainty 95% CI bounds (units as noted)	Avoidable Flux (units as noted)	Additional Sequestration (MgC ha^{-1} yr^{-1})	Flux Uncertainty 95% CI bounds (units as noted)	Baseline Flux in 2030 (TgCO_2e yr^{-1})	Years until saturation	Maximum Additional Mitigation Potential (TgCO_2e yr^{-1})	Maximum Mitigation 95% CI bounds (± TgCO_2e yr^{-1})
Avoided Forest Conversion	Conversion of Natural Forests	5.93			112.80 Mg ha^{-1}			-2,452	>100	2,452	
	References	(1)			(1–3)					(1–3)	
	Clearing for Subsistence Agriculture	3.04			103.29 Mg ha^{-1}			-1,151	>100	1,151	
	References	(1, 4)			(1, 2)					(1, 2)	
	All	8.97		7.95 - 9.98	109.58 Mg ha^{-1}		96 - 123	-3,603	>100	3,603	2,999 - 4,209
Reforestation	Temperate		206 Mha			2.82		202 *	>30	2,100	
	References		(5, 6)			(7–9)		(6)			
	Tropical & Subtropical		472 Mha			4.71		953 *	25	8,025	
	References		(5, 6)			(3, 9, 10)		(6)			
	All		678 Mha	230 - 1125		4.14	2.81 - 5.46	1,132 *	>25	10,124	2,727 - 17,867
Natural Forest Management	Temperate & Boreal		1369 Mha			0.14		0	>50	690	
	References		(11)			(11–14)					
	Tropical & Subtropical		545 Mha			0.39		0	>50	780	
	References		(11)			(15, 16)					
	All		1914 Mha	1247 - 2350		0.21	0.18 - 1.20	0	>50	1,470	921 - 8,224

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
Pathway	Pathway Element	Rate of avoidable impact (Mha yr^{-1})	Maximum potential extent of implementation (units as noted)	Extent Uncertainty 95% CI bounds (units as noted)	Avoidable Flux (units as noted)	Additional Sequestration (MgC ha^{-1} yr^{-1})	Flux Uncertainty 95% CI bounds (units as noted)	Baseline Flux in 2030 (TgCO$_2$e yr^{-1})	Years until saturation	Maximum Additional Mitigation Potential (TgCO$_2$e yr^{-1})	Maximum Mitigation 95% CI bounds (± TgCO$_2$e yr^{-1})
Improved Plantations	Temperate & Boreal		176 Mha			0.47				304	
	References		(11)			(17)					
	Tropical & Subtropical		81 Mha			0.47				139	
	References		(11)			(17)					
	All		257 Mha	199 - 335		0.47	0.20 - 1.00	0	65	443	168 - 1,009
Fire Management	Temperate Fire Prone Forests	0.46			11.13 Mg ha^{-1}			-77		19	7 - 182
	References	(18, 19)								(18, 19)	
	Brazilian Amazon Forests	0.54			34.34 Mg ha^{-1}			-68		68	17 - 117
	References	(20)								(20)	
	Global Savannas	not applicable			not applicable					125	50 - 200
	References									(21, 22)	
	All							-145	>100	212	166 - 411
Avoided Woodfuel Harvest	All		2,800 M people		0.04 MgC person^{-1} yr^{-1}			-748	>100	367	326 - 407
	References		(23)		(23)				(1, 23)		
Forest Subtotal										16,219	11,291- 28,133

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
Pathway	Pathway Element	Rate of avoidable impact (Mha yr^{-1})	Maximum potential extent of implementation (units as noted)	Extent Uncertainty 95% CI bounds (units as noted)	Avoidable Flux (units as noted)	Additional Sequestration (MgC ha^{-1} yr^{-1})	Flux Uncertainty 95% CI bounds (units as noted)	Baseline Flux in 2030 (TgCO$_2$e yr^{-1})	Years until saturation	Maximum Additional Mitigation Potential (TgCO$_2$e yr^{-1})	Maximum Mitigation 95% CI bounds (± TgCO$_2$e yr^{-1})
Avoided Grassland Conversion	Temperate	0.70			18.40 Mg ha^{-1}			-47	>100	47	
	References	(24)			(25, 26)						
	Tropical & Subtropical	1.00			18.80 Mg ha^{-1}			-69	>100	69	
	References	(24)			(25, 26)						
	All	1.70		1.13 - 5.40	18.65 Mg ha^{-1}		15.91 - 21.39	-116	>100	116	75 - 373
Biochar	All		1,670 Tg dm yr^{-1}	939 - 2071		0.18 MgCe (Mg dm)$^{-1}$	0.17 - 0.21	0	>100	1,102	642 - 1,455
	References		(27, 28)			(29–33)					
Cropland Nutrient Management	All		44 Tg N yr^{-1} used	32.6 - 58.0	4.33 MgCe Mg N^{-1}		2.9 - 5.3	-2612 *	>100	706	399 - 959
	References		(34)					(34)		(34–38)	
Conservation Agriculture	All		352 Mha			0.32		28	>50	413	310 - 516
	References		(39)			(39)		(39)	(39)	(39)	
Trees in Croplands	Windbreaks		318 Mha	70.4 - 400		0.20	0.07 - 0.23	0	50	204	
	References		(11, 40, 41)			(42–46)					
	Alley cropping		140 Mha	48.8 - 209		1.20	0.57 - 2.18	0	50	616	
	References		(11, 41)			(47–53)					
	Farmer Managed Natural Regen.		150 Mha	35.0 - 388		0.40	0.22 - 0.76	0	50	220	
	References		(54, 55)			(55)			(55)		
	All		608 Mha			0.37		0	50	1,040	469 - 1,855

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
Pathway	Pathway Element	Rate of avoidable impact (Mha yr^{-1})	Maximum potential extent of implementation (units as noted)	Extent Uncertainty 95% CI bounds (units as noted)	Avoidable Flux (units as noted)	Additional Sequestration (Mg ha^{-1} yr^{-1})	Flux Uncertainty 95% CI bounds (units as noted)	Baseline Flux in 2030 (TgCO$_2$e yr^{-1})	Years until saturation	Maximum Additional Mitigation Potential (TgCO$_2$e yr^{-1})	Maximum Mitigation 95% CI bounds (± Mt CO$_2$e yr^{-1})
Grazing - Optimal Intensity	All		712 Mha			0.06		0	>100	148	148 - 699
	References		(56)			(56)				(56)	
Grazing - Legumes in Pastures	All		72 Mha	61 - 680		0.56	0.26 - 0.84	0	>100	147	14 - 1,500
	References		(56)			(56)					
Grazing - Improved Feed	All		1,400 M head cattle		0.13 MgCe head^{-1}			-2,412	>100	680	35 - 1,014
	References		(57)		(58)			(58)		(58)	
Grazing - Animal Management	All		1,400 M head cattle		0.04 MgCe head^{-1}			-2,412	>100	200	75 - 214
	References		(57)		(58)					(58)	
Improved Rice Cultivation	All		163 Mha		0.44 MgCe ha^{-1} yr^{-1}			-755	>100	265	227 - 319
	References		(59)		(59, 60)			(59)			
Agriculture & Grasslands Subtotal										4,817	4,398 - 6,926
Avoided Coastal Wetland Impacts	Mangrove	0.10		0.04 - 0.16	351.86 MgC ha^{-1}		268 - 436	-130	68	130	
	References	(61, 62)			(63–71)						
	Salt Marsh	0.08		0.04 - 0.12	142.78 MgC ha^{-1}		52 - 234	-42	64	42	
	References	(65)			(65)						
	Seagrass	0.45		0.12 - 0.78	79.95 MgC ha^{-1}		27 - 133	-132	67	132	
	References	(65)			(65, 72)						
	All	0.63			152.02 MgC ha^{-1}			-304	>64	304	141 - 466

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
Pathway	Pathway Element	Rate of avoidable impact (Mha yr^{-1})	Maximum potential extent of implementation (units as noted)	Extent Uncertainty 95% CI bounds (units as noted)	Avoidable Flux (units as noted)	Additional Sequestration (MgC ha^{-1} yr^{-1})	Flux Uncertainty 95% CI bounds (units as noted)	Baseline Flux in 2030 (TgCO$_2$e yr^{-1})	Years until saturation	Maximum Additional Mitigation Potential (TgCO$_2$e yr^{-1})	Maximum Mitigation 95% CI bounds (± TgCO$_2$e yr^{-1})
Avoided Peatland Impacts	Tropical Peatland	0.57			317.54 MgCe ha^{-1}			-664	89	664	
	References	(73)			(73, 74)						
	Temperate Peatland	0.14			146.08 MgCe ha^{-1}			-75	>100	75	
	References	(73)			(73, 75)						
	Boreal Peatland	0.07			59.20 MgCe ha^{-1}			-15	>100	15	
	References	(73)			(73, 75)						
	All	0.78		0.29 - 0.78	266.68 MgCe ha^{-1}		197 - 550	-754	>89	754	237 - 1,212
Coastal Wetland Restoration	Mangrove		11 Mha	9 - 13	8.80 MgCe ha^{-1}yr^{-1}	6.4	12.0 - 18.4	-345	>100	596	
	References		(76, 77)		(63–71)	(76, 78)					
	Salt Marsh		2 Mha	0.2 - 3.2	3.57 Mg Ce ha^{-1}yr^{-1}	2.2	3.43 - 8.07	-22	57	36	
	References		(76)		(65)	(76)					
	Seagrass		17 Mha	8.3 - 25.4	2.00 MgCe ha^{-1}yr^{-1}	1.4	1.87 - 4.89	-124	51	209	
	References		(76)		(65, 72)	(76)					
	All		29 Mha		4.71 MgCe ha^{-1}yr^{-1}	3.3		-491	>51	841	621 - 1,064
Peatland Restoration	Tropical Peatland		17 Mha		7.94 MgCe ha^{-1}yr^{-1}	0.0		-497	20	497	
	References		(73)		(73, 74)	(79–81)					
	Temperate Peatland		20 Mha		3.65 MgCe ha^{-1}yr^{-1}	0.0		-267	20	267	
	References		(73)		(73, 75)	(79–81)					
	Boreal Peatland		9 Mha		1.48 MgCe ha^{-1}yr^{-1}	0.0		-51	20	51	
	References		(73)		(73, 75)	(79–81)					
	All		46 Mha	46.4 - 83.0	4.79 MgCe ha^{-1}yr^{-1}	0.0	3.5 - 9.9	-815	20	815	705 - 2,471
Wetlands Subtotal										2,713	2,415 - 4,502
Total – All Pathways										**23,750**	**20,261– 37,403**

Table S2. Summary of pathway definition, extent, and methods for estimating maximum mitigation potential. See Methods Details section for more information, including pathway-specific methods for uncertainty analysis.

Pathway	**Maximum potential extent**	**Pathway description**	**Areas and fluxes included and excluded, and measures taken to avoid double-counting**
Avoided Forest Conversion	not applicable	Emissions of CO_2 avoided by avoiding forest conversion. Baseline emissions derived from Tyukavina et al. (1), which defined "forest" as >25% tree cover and limits this pathway to predominantly tropical and sub-tropical climate domains where forest conversion is most active.	Boreal forests excluded due to albedo effect. Most temperate forests excluded due to lack of data and to avoid double-counting tree cover loss associated with temperate forestry. Wetland forests (mangroves, peatlands) excluded to avoid double-counting with wetland pathways. Excludes loss of "managed forest" as defined by Tyukavina et al. (1), except for inclusion of emission attributed to conversion to subsistence agriculture. Given these exclusions, this pathway has no spatial overlap with other pathways.
Reforestation	678 Mha	Additional carbon sequestration by converting non-forest (< 25% tree cover) to forest (> 25% tree cover (6)) in areas where forests are the native cover type. Potential reforestation extent calculated by modifying and further constraining a 1 km resolution map from the Atlas of Forest Landscape Restoration Opportunities (FLRO) (82).	Includes conversion of non-forest lands (<25% tree cover) to forest in areas ecologically appropriate for forests. We exclude afforestation, defined here as conversion of native non-forest cover types (i.e. grassland, savanna, and transitional areas with forest) to forest. Boreal biome excluded, due to albedo. All existing cropland area excluded, due to food security safeguard. Impervious surfaces excluded. Other deductions were made to pathway mitigation estimate (but not reflected in spatial dataset) as follows. Projected business-as-usual forest gains through 2030 deducted. We subtracted the maximum mitigation potential of "Grazing-Optimal Intensity" and "Grazing – Legumes" pathways where co-occurring with our Reforestation potential map, to avoid double-counting. The remaining areas accounted here – for maximum estimate – include existing grazing lands, and other non-forest cover types, within forest ecoregions.
Natural Forest Management	1,914 Mha	Additional carbon sequestration in above- and below-ground tree biomass across up to 1,914 Mha of native forests under non-intensive management for wood production (11, 83). Maximum mitigation potential calculated with a scenario of timber harvests deferred for >50 years across all native forests currently under timber production. Wood production lost here is made up by increased yields from Improved Plantations and additional wood production due to Reforestation; however, "cost effective" mitigation potential levels for this pathway can be delivered by practices that continue and possibly increase timber production depending on geography (e.g. reduced-impact logging, limited extension of harvest cycles).	Includes all native forests under timber production in tropical, subtropical, temperate, and boreal climate domains. Does not involve transitions between "forest" and "non-forest" or management for tree species changes, so does not invoke albedo changes. Excludes areas under intensive plantation forestry. Includes areas also included in Fire Management pathway, but double counting avoided because we assume here that no improvements are made in fire management.

Pathway	**Maximum potential extent**	**Pathway description**	**Areas and fluxes included and excluded, and measures taken to avoid double-counting**
Improved Plantations	257 Mha	Additional carbon sequestration in above- and below-ground tree biomass by limited extension of economically optimal rotation lengths (84) to biologically optimal yield rotation lengths in even-aged intensively managed wood production forests. These forests occupy ~7% of global forest area as of 2015, and are assumed to expand by 3 million hectares per year through 2030 (11). Model parameters (e.g. MAI, biomass expansion and conversion factor, rotation lengths, discount rate, yield curve, etc.) were derived from the literature (17, 85–87).	Includes intensively managed production forests (i.e. plantations) subject to even-aged stand management in tropical, subtropical, temperate, and boreal climate domains. Does not involve transitions between "forest" and "non-forest" or management for tree species changes, so does not invoke albedo changes. Excludes areas not under intensive plantation forestry.
Fire Management	not quantified	Additional sequestration and avoided emissions in above- and below-ground tree biomass due to three spatially discrete forms of additional fire management: (i) prescribed fires applied to fire-prone temperate forests in western US (88) and Europe (89) to reduce the likelihood of more intense wildfires, (ii) fire control practices (e.g. fire breaks) applied to edges of moist and wet tropical forests in Amazonia (20), and (iii) use of early season fires in savanna ecosystems to avoid higher emissions from late season fires, drawn from a global estimate of savanna fire emissions (22) and a study extrapolating outcomes demonstrated in northern Australia (21).	Includes (i) naturally fire-prone forests in North America and Europe, (ii) forests adjacent to pasture in Brazilian Amazonia, and (iii) global savannas. Extent of this pathway is conservative because full potential extent of application of this pathway is larger but Unknown. This pathway has spatial overlap with Natural Forest Management; however, no double-counting issues because this pathway assumes no change in harvest levels.
Avoided Woodfuel Harvest	2,800 M people	Avoided emissions due to reduced harvest of woodfuel used for cooking and heating, without reducing heating or cooking utility. Estimate drawn from comprehensive analysis of global unsustainable woodfuel harvest levels (23) which estimates 300 TgCe yr^{-1} woodfuel emissions for the year 2009. We employ their “scenario 2” assumption that improved cookstoves can reduce carbon emissions by 49%.	Extent not spatial – based on number of people, majority in Africa. Potential spatial overlap with savanna burning; however, no double-counting since this pathway and improved savanna fire management are additive. We avoid double counting with Avoided Forest Conversion pathway by subtracting the 32% of baseline woodfuel harvest emissions linked to forest conversion (23).
Avoided Grassland Conversion	not applicable	Avoided soil carbon emissions by avoiding the conversion of grasslands (including savannas and shrublands) to cropland. Mean global rate of grassland conversion to cropland estimated at 1.7 (1.13-5.40) Mha yr^{-1} between 1980 and 1990 (24). We were unable to find sources for more recent time periods. Assumed committed soil carbon losses of 30% from the top 30 cm of soil upon conversion to cropland (26). The soil carbon pool in the top 30 cm estimated at 68.4 MgC ha^{-1} and 62.7 MgC ha^{-1} for temperate and tropical grasslands, respectively (25), and the average loss at 18.65 (15.91-21.39) MgC ha^{-1}.	Includes avoided conversion to cropland of tropical, subtropical, and temperate native grasslands. Spatial overlap with other pathways (e.g. fire management) *de minimis.*

Pathway	Maximum potential extent	Pathway description	Areas and fluxes included and excluded, and measures taken to avoid double-counting
Biochar	1,670 Tg yr^{-1} crop residue	Additional carbon sequestration by amending agricultural soils with biochar, which increases the agricultural soil carbon pool by converting non-recalcitrant carbon (crop residue biomass) to recalcitrant carbon (charcoal) through pyrolysis. Source of biochar production limited to crop residue. From review of several studies that have assessed residue potential for bioenergy uses (27, 28), we identified a mid-range value of 30 EJ/year, about half of current unused above-ground crop residues (90). We assumed that 79.6% of biochar carbon persists on a timescale of >100 years (32, 33). We assume no effects of biochar on emissions of N_2O or CH_4 (91, 92).	Maximum extent assumed to be all global croplands. This pathway has spatial overlap with Cropland Nutrient Management, Conservation Agriculture, and Trees in Croplands; however, accounting is additive so no double-counting deductions needed.
Cropland Nutrient Management	44 TgN yr^{-1} used	Avoided N_2O emissions due to reduced fertilizer use and improved application methods on croplands. By reducing the over-application of fertilizer (improving the timing, placement, and form of fertilizer application and making greater use of manure), significant improvements in efficiency can be made without negatively impacting crop yields. These practices can decrease baseline fertilizer use by 32%, to 95 TgN yr^{-1} (34). Our baseline assumes a projected rise in fertilizer use from 147 TgN in 2010 (116 TgN synthetic fertilizer and 31 TgN manure) to 181 TgN in 2030 (139.5 TgN fertilizer and 41.5 TgN manure) (34). Additional emissions parameters derived from the literature (37, 38).	Applicable extent includes all global croplands, except those already using best nutrient management practices. Spatial overlap with Biochar, Conservation Agriculture, and Trees in Croplands; however, no double-counting because this pathway considers different pools and fluxes (N_2O flux, measured in Mg of fertilizer, rather than soil carbon and biomass carbon pools) and likewise accounting is additive to these other pathways.
Conservation Agriculture	352 Mha	Additional soil carbon sequestration by planting cover crops during the part of the year when the main crop is not growing (39). Area suitable for expansion of cover crops excludes cropland already planted with a perennial or winter crop (39, 93), and excludes cropland where climatic factors and cropping systems require a fallow period or harvest is too late to allow cover crop planting (39). A meta-analysis found a global average sequestration rate of 0.32 +/- 0.08 MgC ha^{-1} yr^{-1} and a global additional mitigation potential of 0.12 +/- 0.03 PgC yr^{-1} applicable for at least 50 years (39). We did not include additional potential benefits from no-till farming given recent reviews concluding that reduced or zero-tillage does not store carbon when considering deeper soil horizons and the potential for higher N_2O emissions following the implementation of no-till (94–98).	Limited to active global cropland areas where cover crops are not currently used but could be given climatic and crop system context. Spatial overlap with Biochar, Nutrient Management, and Trees in Croplands; however, accounting is additive so no double-counting concerns.

Pathway	**Maximum potential extent**	**Pathway description**	**Areas and fluxes included and excluded, and measures taken to avoid double-counting**
Trees in Croplands	608 Mha	Additional carbon sequestration in above- and below-ground tree biomass and soil carbon due to integration of trees into croplands at levels that do not reduce crop yields. This includes windbreaks/shelterbelts, alley cropping, and farmer managed natural regeneration (FMNR). FMNR is the assisted natural regeneration of scattered trees within cropland for productivity, soil quality and erosion control benefits, and is primarily applied in Africa. 450 Mha of cropland in Africa is suitable for FMNR, extrapolating from a World Resources Institute study (54), and we assume an average sequestration of 0.4 MgC ha^{-1} yr^{-1} in biomass and soils (55). We estimate that 318 Mha of croplands outside of Africa are appropriate for windbreaks. We restricted windbreaks to cropland with little to no existing tree cover (15, 99), excluded African cropland to avoid double counting with FMNR, and applied a deduction to exclude croplands where windbreaks may not have a neutral or positive effect on yield. We estimated that windbreaks provide 0.175 MgC ha^{-1} yr^{-1} additional sequestration in cropland biomass and soils, calculated as the mean of available literature estimates (42–46), and reflecting that windbreaks only cover ~5% of a given hectare of cropland (100). We extrapolated from a US study (41) to estimate that 140 Mha of additional global cropland area, excluding Africa, is suitable for alley cropping. We calculated, as a mean from the available literature (47, 49–52, 101, 102), that alley cropping generates an additional 1.2 MgC ha^{-1} yr^{-1}.	Includes windbreaks, alleycropping, and farmer managed natural regeneration (FMNR), each of which was restricted to non-overlapping relevant cropland areas. Applicable area for windbreaks and/or alleycropping includes annual croplands currently with <10% tree cover, excluding African cropland (where FMNR was exclusively applied). Any production system that exceeds 25% tree cover (e.g. some agroforestry) and all silvopastoral systems (outside of croplands) were excluded to avoid double counting with the Reforestation pathway. Spatial overlap with Biochar, Nutrient Management, Conservation Agriculture; however, accounting is additive, so no double-counting concerns.
Grazing - Optimal Intensity	712 Mha	Additional soil carbon sequestration due to grazing optimization on rangeland and planted pastures, derived directly from a recent global study by Henderson et al. (56). Grazing optimization prescribes a decrease in stocking rates in areas that are over-grazed and an increase in stocking rates in areas that are under-grazed, but with the net result of increased forage offtake and livestock production.	Includes global rangelands and planted pastures. Spatial overlap with Reforestation and Grazing – Legumes. Mitigation potential of this pathway was subtracted from Reforestation mitigation potential to avoid double-counting. Accounting with Grazing – Legumes is additive, so no double-counting concerns.
Grazing - Legumes in Pastures	72 Mha	Additional soil carbon sequestration due to sowing legumes in planted pastures, derived directly from a recent global study by Henderson et al. (56). Restricted to planted pastures and to where sowing legumes would result in net sequestration after taking into account the increases in N_2O emissions associated with the planted legumes.	Restricted to global planted pastures. Spatial overlap with Reforestation and Grazing – Optimal Intensity. Mitigation potential of this pathway was subtracted from Reforestation mitigation potential to avoid double-counting. Accounting with Grazing – Optimal Intensity is additive, so no double-counting concerns.

Pathway	**Maximum potential extent**	**Pathway description**	**Areas and fluxes included and excluded, and measures taken to avoid double-counting**
Grazing - Improved Feed	1,400 M head cattle	Avoided methane emissions due to reduced enteric fermentation from the use of more energy dense feed (cereal grains, improved pastures, cut and carry forages, single cell protein feeds (103, 104)) and the associated reduction in total animal numbers needed to supply the same level of meat and milk demand (103). Maximum mitigation estimate derived from Herrero et al. (105) and Gerber et al (106). We do not include changes in feed additives given feasibility constraints (105, 107).	Spatial overlap with other grazing pathways, but accounting additive so no double-counting concerns. This pathways has the added benefit of sparing land as a result of the reductions in the extent of land needed for livestock production (108); however, this benefit is not accounted for here to avoid double-counting with avoided deforestation and reforestation pathways.
Grazing - Animal Management	1,400 M head cattle	Avoided methane emissions due to reduced enteric fermentation as a result of improved livestock breeds and management techniques that increase reproductive performance, animal health, and weight gain, and the associated reduction in total animal numbers needed to supply the same level of meat and milk demand (103). Maximum mitigation estimate derived from Herrero et al. (105) and Gerber et al (106). We do not include changes in manure management given feasibility constraints (105, 107).	Spatial overlap with other grazing pathways, but accounting additive so no double-counting concerns. This pathways has the added benefit of sparing land as a result of the reductions in the extent of land needed for livestock production (108); however, this benefit is not accounted for here to avoid double-counting with avoided deforestation and reforestation pathways.
Improved Rice Cultivation	163 Mha	Avoided emissions of methane and N_2O associated with anaerobic decomposition by employing periodic draining of rice soils and removal of rice residues in flooded and upland rice production lands (109). Projected total global emissions associated with rice cultivation in 2030 are estimated to be 755 $TgCO_2e\ yr^{-1}$ (110). This includes 473 $TgCO_2e\ yr^{-1}$ of methane and 341 $TgCO_2e\ yr^{-1}$ of nitrous oxide, offset by soil carbon sequestration of 16 T Ce yr^{-1}.	Global upland and flooded rice lands included – area projected to 2030. Limited spatial overlap with Biochar, Trees in Croplands, and Nutrient Management pathways; however, accounting is additive, so no double-counting concerns.
Avoided Coastal Wetland Impacts	not applicable	Avoided emissions of above- and below-ground biomass and soil carbon due to avoided degradation and/or loss of salt-water wetlands (mangroves, salt marshes, and seagrass beds). For mangroves, we calculate the extent of baseline degradation and/or conversion based on an estimate of current extent (13.8 ±1.24 Mha, (77)), and recently reported loss rate (0.7% (66)). We calculate mangrove carbon stocks by combining the mean of seven above and below-ground vegetation biomass estimates from the literature (194 ±76 MgC ha^{-1} (65–71), with the most recent and comprehensive global estimate of soil organic carbon (SOC) density in the top meter (369 ± 6.8 MgC ha^{-1} (63)). For salt marshes and seagrasses, we follow estimates of loss rate and carbon stocks from Pendleton et al. (65).	Includes global mangroves, salt marshes, and coastal seagrass. Mangroves were excluded from Avoided Forest Conversion pathway to avoid double-counting.

Pathway	**Maximum potential extent**	**Pathway description**	**Areas and fluxes included and excluded, and measures taken to avoid double-counting**
Avoided Peatland Impacts	not applicable	Avoided emissions of above- and below-ground biomass and soil carbon due to avoided degradation and/or loss of freshwater wetlands (tropical, temperate, and boreal peatlands). We calculate degradation and/or loss rates from the International Mire Conservation Group Global Peatland Database IMCGGPD (73, 111, 112). To calculate the flux per hectare of peatland impacts, we combine soil organic carbon (SOC) emissions and vegetation emissions using IMCGGPD data aggregated to climate domains. Tree biomass fluxes are drawn from peatland woody biomass estimates from the literature (74, 75) but applied only to the proportion of peatland loss attributed to forested peatlands by IMCGGPD.	Includes all non-tidal freshwater forested and non-forested wetlands. Forested wetlands were excluded from Avoided Forest Conversion pathway to avoid double-counting.
Coastal Wetland Restoration	29 Mha	Avoided oxidation of soil carbon and enhanced soil carbon sink due to soil re-wetting in mangroves, salt marshes, and seagrass beds. Additional sequestration also included for mangroves due to restored tree growth. We use published carbon burial rates (76) and mangrove vegetation sequestration rates (78) to calculate rates of soil carbon sequestration. Maximum extent of potential restoration is derived from estimated areas of “degraded” wetlands globally (65, 73, 76, 77). We assume degraded wetlands have already lost 50% of their original carbon stocks, reasoning that the global aggregate of degraded wetlands represents a balanced chronosequence of all phases of carbon depletion.	Includes restoration of global mangroves, salt marshes, and coastal seagrass.
Peatland Restoration	46 Mha	Avoided oxidation of soil carbon due to soil re-wetting in freshwater wetlands (tropical, temperate, and boreal peatlands). Maximum extent of potential restoration is derived from estimated areas of “degraded” wetlands globally (65, 73, 76, 77). Due to controversy in the literature about the timing and net atmospheric effect of methane emissions in restored peatlands, we omit a sequestration benefit from peatland restoration and assume they are offset by methane emissions (79–81). We assume degraded wetlands have already lost 50% of their original carbon stocks, reasoning that the global aggregate of degraded wetlands represents a balanced chronosequence of all phases of carbon depletion.	Includes restoration of global non-tidal freshwater forested and non-forested wetlands.

Table S3. Country level maximum mitigation potential with safeguards for 8 NCS pathways. Units are in $TgCO_2e\ yr^{-1}$. Absence of a value indicates that either the value is unknown, or it is <0.01.

Country	Reforestation	Natural Forest Management	Improved Rice Cultivation	Grazing - Optimal Intensity	Grazing - Legumes	Peatland Restoration	Avoided Peatland Impacts	Avoided Coastal Impacts - Mangroves
Afghanistan	0.64	1.63	0.34	1.21	0.31	0.12	0.03	
Alaska (United States)					0.01	0.06	0.01	
Albania	18.84	0.65		0.14	0.03	0.21		
Algeria	19.6	1.62		0.19	2.37	0.01		
Andorra	0.05				0.02			
Angola	13.45			1.12	0.06	2.94	0.62	0.24
Antigua & Barbuda								
Argentina	207.41	3.08	0.34	8.27	0.77	0.07	0.05	
Armenia	4.31	0.23		0.14	0.08	0.15	0.09	
Australia	385.67	60.35	0.28	8.95	2.43	2.5	0.21	0.77
Austria	12.52	0.41		0.55	0.86	0.16	0.03	
Azerbaijan	4.87		0.01	0.24	0.2	0.03	0.01	
Bahamas						0.09	0.02	0.02
Bahrain								
Bangladesh	0.42	0.63	18.74	0.06	0.1	1.11	0.22	0.08
Barbados		0.01						
Belarus	44.72	1.29		0.13	0.02	24.17	4.83	
Belgium	5.29	0.15		0.09	0.47	0.21	0.04	
Belize	5.38		0.01	0.02	0.02	0.03	0.01	0.27
Benin	0.33	3.87	0.04	0.05		0.15	0.03	
Bhutan	3.12	1.94	0.05	0.04	0.35			
Bolivia	64.37	0.03	0.38	0.89	0.26	0.04	0.01	
Bosnia & Herzegovina	17.77	0.18		0.24		0.17		
Botswana		13.07		0.46		0.29	0.06	
Brazil	1549.72	121.39	4.38	10.52	0.23	8.74	1.75	3.79
Brunei Darussalam	0.51	0.26				0.41	0.32	0.06
Bulgaria	26.38	1.01	0.04	0.46	0.01	0.09		
Burkina Faso		4.35	0.22	0.34		0.15	0.03	
Burundi	0.6	0.03	0.03			0.18	0.31	
Cambodia	42.29	4.5	4.44	0.05	0.07			1.19
Cameroon	29.74	18.93	0.05	0.13		0.29	0.06	0.4
Canada	54.58	127.86			5.32	0.99	0.2	
Cape Verde	3.44	0.01						
Central African Rep.	6.7	26.43	0.02	0.21		0.03	0.01	
Chad	0.55	4.46	0.19	0.93	1.36	0.02		
Chile	36.32	2.51	0.08	0.53	1.88	0.15	0.09	
China	1256.71	35.27	51.42	25.04	19.4	36.32	42.47	0.05
Colombia	295.04		0.71	1.84	0.77	0.09	0.1	0.16
Comoros	0.04	0.04						
Costa Rica	26.09	0.24	0.14	0.13	0.1	0.03	0.01	0.09
Cote d'Ivoire	101.23	10.72	0.8	0.26		0.87	0.47	0.05
Croatia	10.34	0.72		0.15	0.39			
Cuba	86.68	0.65	0.32	0.21		2.07	0.56	2.34

Country	Reforestation	Natural Forest Management	Improved Rice Cultivation	Grazing - Optimal Intensity	Grazing - Legumes	Peatland Restoration	Avoided Peatland Impacts	Avoided Coastal Impacts - Mangroves
Curacao								
Cyprus	0.78	0.08						
Czech Rep.	21.25	0.85		0.25	0.43	0.3	0.06	
Dem. People's Rep. of Korea	13.97	1.46	0.95	0.14	0.17	1.35	0.27	
Dem. Rep. of the Congo	175.96	14.77	0.85	0.64	0.16	1.75	0.94	0.07
Denmark (except Greenland)	4.26	0.09		0.02	0.91	1.84	0.37	
Djibouti		0.01				0.05	0.03	
Dominica	0.01							
Dominican Rep.	35.64	0.1	0.34	0.1		0.01	0.01	0.05
Ecuador	76.72	2.42	0.74	0.38	0.19	0.29	0.06	0.14
Egypt		0.04	0.65			0.02		
El Salvador	11.87	0.24	0.01	0.05		0.06	0.01	0.06
Equatorial Guinea	0.22	1.56				0.01		0.1
Eritrea	0.02	0.02		0.08				
Estonia	6.83	0.73			0.17	6.56		
Ethiopia	97.48	14.14		0.56		0.44	0.38	
Fiji	2.27	1.04				0.06	0.01	0.06
Finland	1.69	13.71			0.12	34.32	8.35	
France (except French Guiana)	111.5	4.88	0.03	2.84	12.22	1.5	0.31	
French Guiana (France)	0.4	5.02	0.02			0.03	0.01	0.43
Gabon	9.31	22.89		0.04		0.06	0.07	0.35
Gambia	0.69	0.03	0.02	0.01		0.06	0.01	
Georgia	17.92	3.28		0.17	0.21	0.09		
Germany	42	3.06		2.01	6.63	17.41		
Ghana	48.04	1.51	0.17	0.27		0.06	0.01	0.07
Greece	92.43	4.2	0.07	0.23	0.18	0.16	0.01	
Greenland (Denmark)								
Grenada	0.03							
Guatemala	50.84	0.63	0.04	0.33	0.62	0.04	0.04	1.4
Guinea	10.82	0.62	1.33	0.73	0.03	1.46	0.29	0.14
Guinea-Bissau	7.92	0.71	0.26	0.11		0.02		0.03
Guyana	3.35	19.93	0.31			2.91	0.58	0.04
Haiti	21.21	0.03	0.13	0.05	0.03			0.01
Honduras	57.68	1.33	0.02	0.29	0.12	1.09	0.66	0.8
Hungary	21.92		0.09	0.19	0.53	0.39		
Iceland						9.43	1.86	
India	519.47	42.58	69.66	0.93	8.58	1.46	0.29	2.18
Indonesia	212.02	80.25	21.56	0.24	0.43	363.85	514.24	60.2
Iran	19.37	1.07	0.92	0.74	0.23	0.18	0.03	
Iraq			0.08	0.25	0.52	3.2	32.99	
Ireland	87.65	0.09		0.45	3.32	5.01		
Israel	0.49	0.07				0.12		
Italy	111.47	4.2	0.36	1.01	0.73	0.29	0.06	
Jamaica	4.82	0.02				0.07	0.04	0.06
Japan	67.06	22.01	2.65			2.47		
Jordan	0.01							

Country	Reforestation	Natural Forest Management	Improved Rice Cultivation	Grazing - Optimal Intensity	Grazing - Legumes	Peatland Restoration	Avoided Peatland Impacts	Avoided Coastal Impacts - Mangroves
Kazakhstan	11.75	0.75	0.16	9.72	0.12	0.01		
Kenya	12.59	0.2	0.01	0.64		2.91	3.88	0.03
Kiribati								
Kuwait								
Kyrgyzstan	0.6		0.02	0.33	0.01	0.18	0.01	
Laos	44.17	3.16	1.38	0.05	0.43	0.29	0.06	
Latvia	11.68	0.91				2.65		
Lebanon	1.78	0.11						
Lesotho		0.04		0.02		0.05	0.03	
Liberia	5.57	1.28	0.13	0.07		0.12	0.08	0.02
Libya	0.57			0.03	1.06	0.03	0.01	
Liechtenstein	0.03				0.01			
Lithuania	11.95	0.53		0.01	0.03	3.67	0.9	
Luxembourg	0.23	0.03						
Macedonia (FYROM)	7.06	0.31		0.16		0.03		
Madagascar	26.9	8.61	2.77	1.78		1.78	0.94	0.17
Malawi	0.99	1.05	0.05	0.06		0.87	0.18	
Malaysia	29.38	19.14	1.1		0.36	34.93	57.01	17.94
Maldives								
Mali		0.7	1.05	0.9	0.78	0.15	0.03	
Malta	0.01							
Marshall Islands		0.01						
Mauritania		0.14	0.05	0.51	1.46	0.09	0.03	
Mauritius	1.63	0.01						
Mexico	516.96		0.26	5.23	1.09	2.91	0.58	2.33
Micronesia		0.06				0.02		
Moldova	2.57	0.08		0.1	0.31	0.01		
Monaco								
Mongolia	9.69	1.35		3.85	0.7	20.22	17.58	
Montenegro	8.72	0.81		0.08		0.31	0.14	
Morocco	11.51	4.14	0.02	0.46	2.51	0.02		
Mozambique	5.97	24.22	0.11	0.79		2.33	0.76	0.2
Myanmar	237.27	28.89	13.03	0.2	1.59	2.91	0.58	18.4
Namibia		1.93		0.95	0.57	0.03	0.01	
Nauru								
Nepal	26.23	2.44	2.37	0.43	0.11	0.02		
Netherlands	12.21	0.12		0.17	1.01	3.08		
New Zealand	14.29	0.05		0.91	2.31	1.81		0.07
Nicaragua	78.44	0.75	0.22	0.37	0.08	0.29	0.06	0.35
Niger		0.96	0.07	0.66	1.9	0.03	0.07	
Nigeria	68.97	1.9	3.93	1.3		0.87	0.71	0.24
Norway	0.43	4.38			0.23	2.88	2.56	
Oman				0.04	0.51			
Pakistan	6.17	1.23	3.85	1.01	0.07	0.03	0.01	
Palau	0.01	0.05						0.01
Panama	39.78	3.75	0.18	0.09	0.03	0.29	0.06	0.31

Country	Reforestation	Natural Forest Management	Improved Rice Cultivation	Grazing - Optimal Intensity	Grazing - Legumes	Peatland Restoration	Avoided Peatland Impacts	Avoided Coastal Impacts - Mangroves
Papua New Guinea	9.78	13.81			0.5	14.55	27.22	1.35
Paraguay	150.16		0.07	1.01		0.06	0.01	
Peru	32.88	45.61	0.62	0.86	1.43	0.29	0.06	
Philippines	118.84	6.47	7.08	0.09	0.74	0.23	0.05	2.03
Poland	75.22			1.24	5.7	13.66	1.11	
Portugal	64.95	2.35	0.14	0.36	0.16	0.04		
Qatar								
Rep. of Congo	46.09	25.67		0.11		0.03	0.01	
Rep. of Korea	3.24	1.58	1.47			0.01		
Romania	30	2.72	0.02	1.27	0.52	0.56	0.11	
Russian Federation	351.33	245.05	0.33	0.78	6.14	89	2.07	
Rwanda		0.1	0.01	0.01		0.6	0.71	
Saint Kitts & Nevis	0.07	0.01						
Saint Lucia	0.03							
Saint Vincent & the Grenadines	0.05							
Samoa		0.07						
San Marino	0.03							
Sao Tome & Principe								
Saudi Arabia		1.18		0.15	2.33			
Senegal	0.4	7.62	0.12	0.14		0.02	0.02	0.01
Serbia	16.69	0.69		0.42	0.02	0.31	0.14	
Seychelles								
Sierra Leone	5.13	0.27	0.81	0.33		0.12	0.08	0.02
Singapore	0.04	0.02				0.4	0.05	
Slovakia	8.34	0.28		0.2		0.15		
Slovenia	2.31			0.15	0.08	0.09	0.01	
Solomon Islands	0.28	0.42				0.01		0.15
Somalia	7.36	7.67		0.24		0.15	0.03	
South Africa	5.03	8.31		1.78	0.08	0.21	0.16	0.01
South Sudan	0.03			1.06				
Spain	188.73	12.13	0.2	1.05	3.72	0.11	0.03	
Sri Lanka	2.71	1.5	1.73	0.04		0.06		0.03
Sudan		5.92		1.04	1.22	2.91	0.58	
Suriname	1.41	3.24	0.06		0.36	0.29	0.06	0.89
Swaziland				0.08		0.1	0.05	
Sweden	6.84	5.33			1.92	7.1	1.42	
Switzerland	3.19	0.1		0.22	0.98	0.17	0.04	
Syrian Arab Rep.	2.39	0.36		0.12	0.11	0.01		
Taiwan								
Tajikistan	0.17	0.01	0.05	0.09	0.01			
Tanzania	66.73	55.26	1.72	0.95	0.05	0.26	0.11	0.16
Thailand	186.18	0.8	19.7			1.57	0.25	3.74
Timor-Leste		0.24		0.01				0.01
Togo	7.44	0.11	0.06	0.05		0.06	0.07	
Tonga								
Trinidad & Tobago	1.43	0.17				0.01	0.01	0.12

Country	Reforestation	Natural Forest Management	Improved Rice Cultivation	Grazing - Optimal Intensity	Grazing - Legumes	Peatland Restoration	Avoided Peatland Impacts	Avoided Coastal Impacts - Mangroves
Tunisia	3.23	0.06		0.1	0.13			
Turkey	308.96	7.91	0.16	2.01	2.61	0.31	0.03	
Turkmenistan			0.1	0.33		0.12		
Tuvalu								
Uganda	5.09	0.37	0.09	0.31	0.03	14.55	8.8	
Ukraine	104.69	1.88	0.05	2.81	1.7	3.08		
United Arab Emirates		0.14		0.01				
United Kingdom	153.05			1.31	8.53	5.76	1.15	
United States (except Alaska)	357.98	65.72	2.35	13.73	13.79	17.58	3.54	3.8
Uruguay		0.19	0.28	0.6		0.29	0.05	
Uzbekistan	0.02		0.06	0.67	0.01	0.48	0.08	
Vanuatu	1.76							
Venezuela	165.53	52.04	0.48	0.94	0.37	2.62	1.11	0.97
Vietnam	128.2	5.4	12.16	0.21	0.63	3.81	0.76	0.65
Yemen		0.66		0.1	0.8			
Zambia	3.72	24.44	0.02	1.11		3.49	1.88	
Zimbabwe		15.5		1.08	0.1	0.73	0.44	

Table S4. Cost effective NCS mitigation levels contributing to holding global warming below 2°C. Literature sources used in setting both <2°C and Low Cost targets are listed below <2°C targets. See Table S1 for key sources used for estimating maximum additional mitigation potential. See Methods Details section for additional sources and narrative on target assignments for each pathway.

		Mitigation Potential					
Pathway	Pathway Element	Maximum Additional Mitigation Potential ($TgCO_2e$ yr^{-1})	Max. Mitigation Uncertainty 95% CI bounds ($TgCO_2e$ yr-1)	<2°C Target (% of max)	<2°C Mitigation ($TgCO_2e$ yr^{-1})	Low Cost Target (% of max)	Low Cost Mitigation ($TgCO_2e$ yr^{-1})
Avoided Forest Conversion	Conversion of Natural Forests	2,452		90%	2206	60%	1,471
	References			(113, 114)		(113, 114)	
	Clearing for Subsistence Agriculture	1,151		60%	691	30%	345
	References						
	All	3,603	2,999 – 4,209	80%	2,897	50%	1,816
Reforestation	Temperate	2,100					
	References						
	Tropical & Subtropical	8,025					
	References						
	All	10,124	2,727 – 17,867	30%	3,037	0%	0
	References			(115)		(115)	
Natural Forest Management	Temperate & Boreal	690					
	References						
	Tropical & Subtropical	780					
	References						
	All	1,470	921 – 8,224	60%	882	30%	441
	References			(60, 116)		(60, 116)	
Improved Plantations	Temperate & Boreal	304					
	References						
	Tropical & Subtropical	139					
	References						
	All	443	168 – 1,009	60%	266	0%	0
	References			(60, 116)		(60, 116)	

Pathway	Pathway Element	*Mitigation Potential* Maximum Additional Mitigation Potential (TgCO$_2$e yr^{-1})	Max. Mitigation Uncertainty 95% CI bounds (TgCO$_2$e yr-1)	<2°C Target (% of max)	<2°C Mitigation (TgCO$_2$e yr^{-1})	Low Cost Target (% of max)	Low Cost Mitigation (TgCO$_2$e yr^{-1})
Fire Management	Temperate Fire Prone Forests	19	7 – 182				
	References						
	Brazilian Amazon Forests	68	17 – 117				
	References						
	Global Savannas	125	50 – 200				
	References						
	All	212	166 – 411	60%	127	0%	0
	References						
Avoided Woodfuel Harvest	All	367	326 – 407	30%	110	0%	0
	References						
Forest Subtotal		16,219	11,291 – 28,133		7,320		2,257
Avoided Grassland Conversion	Temperate	47					
	References						
	Tropical & Subtropical	69					
	References						
	All	116	75 - 373	30%	35	0%	0
Biochar	All	1,102	642 – 1,455	30%	331	0%	0
	References						
Cropland Nutrient Management	All	706	399 - 959	90%	635	90%	635
	References						
Conservation Agriculture	All	413	310 - 516	90%	372	60%	248
	References			(117)		(117)	

		Mitigation Potential					
Pathway	Pathway Element	Maximum Additional Mitigation Potential ($TgCO_2e\ yr^{-1}$)	Max. Mitigation Uncertainty 95% CI bounds ($TgCO_2e$ yr-1)	<2°C Target (% of max)	<2°C Mitigation ($TgCO_2e\ yr^{-1}$)	Low Cost Target (% of max)	Low Cost Mitigation ($TgCO_2e\ yr^{-1}$)
Trees in Croplands	Windbreaks	204		60%	122	0%	
	References						
	Alleycropping	616		30%	185	0%	
	References						
	Farmer Managed Natural Regen.	220		60%	132	0%	
	References						
	All	1,040	469 – 1,855	42%	439	0%	0
	References			(117)		(117)	
Grazing - Optimal Intensity	All	148	148 - 699	60%	89	30%	45
	References			(58)		(58)	
Grazing - Legumes in Pastures	All	147	14 - 1500	90%	132	60%	88
	References			(58)		(58)	
Grazing - Improved Feed	All	680	35 - 1014	30%	204	0%	0
	References			(58)		(58)	
Grazing - Animal Management	All	200	75 - 214	30%	60	0%	0
	References						
Improved Rice Cultivation	All	265	227 - 319	60%	159	30%	80
	References			(60, 117–119)		(60, 117–119)	
Agriculture & Grasslands Subtotal		4,817	4,398 – 6,926	51%	2,456	23%	1,095

		Mitigation Potential					
Pathway	Pathway Element	Maximum Additional Mitigation Potential ($\text{TgCO}_2\text{e yr}^{-1}$)	Max. Mitigation Uncertainty 95% CI bounds (TgCO_2e yr-1)	<2°C Target (% of max)	<2°C Mitigation ($\text{TgCO}_2\text{e yr}^{-1}$)	Low Cost Target (% of max)	Low Cost Mitigation ($\text{TgCO}_2\text{e yr}^{-1}$)
Avoided Coastal Wetland Impacts	Mangrove	130		90%	117	60%	78
	References						
	Salt Marsh	42		90%	38	60%	25
	References						
	Seagrass	132		90%	119	60%	79
	References						
	All	304	141 – 466	90%	273	60%	182
Avoided Peatland Impacts	Tropical Peatland	664					
	References						
	Temperate Peatland	75					
	References						
	Boreal Peatland	15					
	References						
	All	754	237 – 1,212	90%	678	60%	452
	References			(62)		(62)	
Coastal Wetland Restoration	Mangrove	596		30%	179	0%	0
	References						
	Salt Marsh	36		60%	22	0%	0
	References						
	Seagrass	209		0%	0	0%	0
	References						
	All	841	621 – 1,064	24%	200	0%	0
	References			(120)		(120)	

		Mitigation Potential					
Pathway	Pathway Element	Maximum Additional Mitigation Potential ($\text{TgCO}_2\text{e yr}^{-1}$)	Max. Mitigation Uncertainty 95% CI bounds (TgCO_2e yr-1)	<2°C Target (% of max)	<2°C Mitigation ($\text{TgCO}_2\text{e yr}^{-1}$)	Low Cost Target (% of max)	Low Cost Mitigation ($\text{TgCO}_2\text{e yr}^{-1}$)
Peatland Restoration	Tropical Peatland	497		60%	298	30%	149
	References						
	Temperate Peatland	267		30%	80	0%	0
	References			(121)		(121)	
	Boreal Peatland	51		30%	15	0%	0
	References						
	All	815	705 – 2,471	48%	394	18%	149
	References			(117)		(117)	
Wetlands Subtotal		2,713	2,415 – 4,502	57%	1,546	29%	784
Total		**23,750**	**20,261 – 37,403**	**48%**	**11,321**	**17%**	**4,136**

Table S5. Co-benefits associated with natural pathways. We summarize publications providing evidence that a given type of ecosystem service is enhanced due to implementation of a pathway. Cells in white indicate cases where we did not identify clear evidence of enhanced ecosystem services. See Methods Details section for definition of each of the four service types (biodiversity, water, soil, air).

Pathway	**Biodiversity** (alpha, beta, gamma)	**Water** (filtration, flood control)	**Soil** (enrichment)	**Air** (filtration)
Forests				
Avoided Forest Conversion	"Results indicate the irreplaceable value of continuous primary forests for conserving biodiversity" (122).	Improved availability of water for crop irrigation, drought mitigation; avoided sedimentation and water regulation for hydroelectric dams (123).	Water retention and flow regulation (123). Maintains soil biological and physical properties ensuring health and productivity of forests (124).	Ozone abatement benefits of reforestation (125). Multiple modeling studies describe health benefits of air filtration by forests (126, 127).
Reforestation	Tree plantings can create wildlife corridors and buffer areas that enhance biological conservation (128).	Improved availability of water for crop irrigation, drought mitigation; avoided sedimentation and water regulation for hydroelectric dams (123).	Measured increase in soil fauna in reforested sites. During drought conditions earthworms only survived in reforested areas (129).	Ozone abatement benefits of reforestation (125). Multiple modeling studies describe health benefits of air filtration by forests (126, 127).
Natural Forest Management	"Species richness of invertebrates, amphibians, and mammals decreases as logging intensity increases" (130).	Harvesting that removes large proportions of biomass increases water flows and flooding thereby altering freshwater ecosystem integrity (131).	Timber harvesting that removes large amounts of woody debris reduces soil biological and physical properties thereby reducing health and productivity (124).	
Improved Plantations	Forest plantations that consider community type such as polycultures over monocultures, native over exotics, disturbance pattern replication, longer rotations, and early thinning can enhance biodiversity (132).			
Fire Management	Fire management that mimics natural historic fire regimes can improve forest biodiversity (133).	Forests that survive fires (i.e. reduced catastrophic wild fires) contain more organic matter, improved soil properties, and lower recovery times enhance water infiltration and retention (134)	Forests that survive fires (i.e. reduced catastrophic wild fires) contain more organic matter, improved soil properties, and lower recovery times enhance water infiltration and retention (135).	"Possibility of small increases in mortality due to abrupt and dramatic increases in particulate matter concentrations from wildfire smoke" (136).
Avoided Woodfuel Harvest	Woodfuel collection reduces saproxylic material used as food and habitat for forest organisms and fauna (137).	Limiting soil compaction during woodfuel harvest reduces runoff and increases forest water retention (137).	Fuel wood harvest causes soil compaction and disturbance that can change soil chemical properties (137).	More efficient cook stoves improve indoor air quality and "reduces the incidence of mortality and disease" (138, 139).

Pathway	**Biodiversity** (alpha, beta, gamma)	**Water** (filtration, flood control)	**Soil** (enrichment)	**Air** (filtration)
Agriculture & Grasslands				
Avoided Grassland Conversion	Important habitat for nesting and foraging birds (140).	Permanent grasslands provide "biological flood control" and maintain ecosystem water balance assuring adequate water resources (141).	"Soil macroinvertebrates are important prey for breeding wading birds on lowland wet grassland" (140).	
Biochar			The addition of biochar enhances soil quality and fertility in temperate regions (142).	
Cropland Nutrient Management	Increased fish species richness and abundance (143).	Benefits associated with improved drinking water quality, increased opportunities for recreation, and health benefits (143).	Better nutrient management maintains soil fertility (144).	"Precision management of soil nutrients can reduce ammonia and nitric oxide emissions" (144).
Conservation Agriculture		Reduces agricultural water demands with appropriate cover crops (145).	Reduces soil erosion and redistribution maintaining soil depth and water retention (144).	
Trees in Croplands	Agroforestry provides habitat for species and supports connectivity (146).	Erosion control and water recharge (146).	Decreased soil erosion (147).	Tree planting helps capture airborne particles and pollutant gasses (144).
Grazing - Animal Management				
Grazing - Optimal Intensity	A gradient of intensive to extensively grazed pastures reduces overall disturbance to plant-insect interactions (148).	Nearly 70% of water use for cattle occurs during farm grazing, managed grazing practices can reduce water use on managed pastures (149).	Over grazing can reduce the soils ability to trap contaminants and cause a release of these and other suspended sediments (144).	
Grazing - Legumes in Pastures	The presence of legumes in prairie leads to higher insect herbivore and insect predator diversity (150).		"Legumes provide other ecological services including improved soil structure, erosion protection and greater biological diversity" (151).	
Grazing - Improved Feed				
Improved Rice Cultivation		Alternating wet dry and midseason drainage of irrigated rice fields reduces water demands for agriculture (152). The use of gray water in agriculture can reduce gross water consumption (153).		

Pathway	Biodiversity (alpha, beta, gamma)	Water (filtration, flood control)	Soil (enrichment)	Air (filtration)
Wetlands				
Avoided Coastal Wetland Impacts	Maintains the provision of structure, nutrients and primary productivity and nurseries for commercially important fish and shrimp (70, 154–156).	Coastal wetlands have an assessed economic value of $785-$34,700 in waste water treatment value (157).	Benefits of cross-system nutrient transfer to coral reefs, coastal protection, and water quality regulation (158).	Tree planting helps capture airborne particles and pollutant gasses (144).
Avoided Peatland Impacts	"Boreal peat bogs contain distinctive insects in addition to widely distributed generalists" (156, 159).	Wetlands and wetland soils attenuate flooding (156, 160)	Wetlands and wetland soils attenuate flooding (160).	Draining and forest clearing increases peat fire risk (161). Exposure to pollutants from peat fires increases in the need for health services to treat lung and pulmonary disorders (162).
Coastal Wetlands Restoration	Maintains the provision of structure, nutrients and primary productivity and nurseries for commercial fish and shrimp (70, 154–156).	Flood control and water filtration benefits of mangroves (70, 163) and other coastal wetlands (156).	Benefits of cross-system nutrient transfer to coral reefs, coastal protection, and water quality regulation (158).	Tree planting helps capture airborne particles and pollutant gasses (144).
Peatland Restoration	Regeneration of peatlands re-establishes diverse communities (164)	Waste water treatment and storm water remediation (156, 165).	Restoring degraded lands to high productivity depend on faunal species that help develop soil structure and fertility (166).	Exposure to pollutants from peat fires increases in the need for health services to treat lung and pulmonary disorders (162). Rewetting peatlands reduces fire risk (167).

Table S6. Alignment of multilateral announcements of global environmental efforts with <2°C mitigation levels for 20 natural pathways. See Table S4 for quantitative NCS <2°C targets for each pathway.

Multilateral announcements of global environmental efforts related to NCS	Pathway(s)	Relationship to NCS <2°C targets
United Nations New York Declaration on Forests		
"..halve the rate of loss of natural forests globally by 2020... end natural forest loss by 2030."	Avoided forest conversion	More ambitious than NCS targets, if interpreted as ending gross natural forest loss.
"Restore 150 million hectares of degraded landscapes and forestlands by 2020... restore at least an additional 200 million hectares by 2030."	Reforestation	NCS 2030 target is moderately more ambitious. The UN target of 350 Mha by 2030 includes some agroforestry, silviculture etc. in addition to likely 200-250 Mha of reforestation.
Bonn Challenge		
"…a global aspiration to restore 150 million hectares of the world's deforested and degraded lands by 2020."	Reforestation	Similar ambition to NCS target, assuming forest C sequestration rates/ha reflect global means (150 Mha of reforestation and other forest restoration vs. ~100 Mha of reforestation only for the NCS target by 2020).
United Nations Convention on Biological Diversity, Aichi Targets		
Target 5: "By 2020, the rate of loss of all natural habitats…is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced."	Avoided forest conversion, coastal impacts, and peat impacts	"brought close to zero" is aligned with NCS targets for forests, wetlands. It is more ambitious for avoided grassland conversion, which we assume to involve more expensive opportunity costs per $MgCO_2$ abatement.
Target 11:"By 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas…are conserved through…systems of protected areas and other…area-based conservation measures…" Target 15:"By 2020, … restoration of at least 15 per cent of degraded ecosystems…"	All restoration pathways	Targets 11 and 15 are important contributions to NCS targets, but alone not sufficient.
4 pour 1000		
"The goal of the initiative is to engage stakeholders in a transition towards a productive, resilient agriculture, based on a sustainable soil management and generating jobs and incomes, hence ensuring sustainable development…A 4% annual growth rate of the soil carbon stock would make it possible to stop the present increase in atmospheric CO_2"	Reforestation, natural forest management, improved plantations, fire management, avoided woodfuel harvest, biochar, conservation agriculture, trees in croplands, grazing – optimal intensity, grazing – legumes in pastures, coastal wetland restoration, peatland restoration	More ambitious than NCS targets, if interpreted as attempting to increase soil carbon by 4% per year. However, 4% is an aspirational goal, and there is no date associated with the goal, and the application to forest and wetland systems is unclear.

United Nations Global Goals		
Goal 6: "By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes."	Avoided forest conversion, coastal impacts, and peat impacts; Reforestation; Coastal restoration; Peat restoration	Aligned with NCS targets; however, cannot compare ambition levels without greater clarity on quantitative thresholds for achieving goal.
Goal 15: "By 2030…strive to achieve a land degradation-neutral world."*	Natural forest management and improved plantations; Fire management; Avoided woodfuel harvest; Grazing optimal intensity, legumes in pastures, and improved feed	Aligned with NCS targets; however, cannot compare ambition levels without greater clarity on quantitative thresholds for achieving "land degradation-neutral world."
The Convention on Wetlands of International Importance (Ramsar Convention)	All four wetlands pathways	Convention concept can help achieve NCS targets; however, cannot compare ambition levels without greater clarity on quantitative thresholds for achieving Ramsar outcomes.
World Business Council on Sustainable Development Vision 2050		
"Doubling of agricultural output without increasing the amount of land or water used: ...reduce the land area under agricultural production… increase the carbon sequestration in soils, and emissions…from agriculture…are radically reduced."	Nutrient management; Conservation agriculture; Trees in croplands; Grazing optimal intensity, legumes in pastures, improved feed, and animal management; Improved rice cultivation	"without increasing amount of land…used" is aligned with NCS assumption of no reduction in current cropland area. Ambition to "reduce the land area under agricultural production" would allow for higher "maximum" potential for reforestation pathway. Soil carbon and ag emissions statement are aligned with NCS targets, however, cannot compare ambition levels without greater clarity on quantitative thresholds for achieving these outcomes.
"Halting deforestation and increasing yield from planted forests"	Avoided forest conversion; Improved plantations	Halting deforestation entirely is more ambitious than NCS target, if interpreted as ending gross natural forest loss (which would need to be specified). Increasing yield from planted (plantation) forests is an outcome of our Improved Plantations pathway.
"Restoration of degraded land for production of food, biofuel crops and timber is a common practice across the globe"	Natural forest management and improved plantations; Trees in croplands	Statement aligned with NCS targets; however, cannot compare ambition levels without greater clarity on quantitative thresholds for achieving these outcomes.
"[By 2050]: Forests cover 30% of world land area. The total stock of carbon sequestered in forests is more than 10% greater than 2010 levels. Primary forest coverage is held intact and expanded somewhat. Primary forests are no longer used for wood, wood products, new farmland, or biomass. Yield and harvest from planted forests have increased threefold from 800 million cubic meters to 2.7 billion cubic meters…and the land area has increased by 60%."	Avoided forest conversion; Reforestation; Avoided woodfuel harvest	Holding & expanding primary forest cover (assuming primary = "natural forest" cover(1)) is more ambitious than NCS target. Stop logging in "primary forests" is consistent with our improved forestry pathway. The extent of spatial overlap depends on definition of "primary."

Tropical Forest Alliance 2020		
"…contribute to mobilizing and coordinating actions by governments, the private sector and civil society to reduce tropical deforestation related to key agricultural commodities by 2020."	Avoided forest conversion	Statement aligned with NCS targets; however, cannot compare ambition levels without greater clarity on quantitative thresholds for achieving these outcomes.

*According to the United Nations Convention to Combat Desertification, "land degradation neutrality can be monitored and communicated in terms of increased productivity, vegetative cover, biodiversity and the resulting socio-economic benefits"

Table S7. Activities associated with pathways. Activities represent specific conservation, restoration, and/or improved land management actions that practitioners may take to avoid emissions and/or enhance sequestration.

Pathway	Conservation Action (168)	Example Activities
Forests		
Avoided Forest Conversion	1.1, 1.2, 2.1, 5.1, 5.2, 5.3, 5.4	Protected areas establishment and improved enforcement; improved citing of non-forest land use; forest certification; improved land tenure; zero deforestation commitments; sustainable intensification of subsistence agriculture; avoided loss of high carbon forests.
Reforestation	2.3, 5.1.2, 5.2, 5.3, 5.4.4, 6.1, 6.2	Conversion from non-forest to forest in areas ecologically appropriate for tree growth through agricultural certification programs and impact mitigation frameworks that prioritize restoration; regulations that advance minimum forest cover requirements; integration of trees into grazing lands (i.e. silvopastoral systems); reduced consumption of land-extensive food types (e.g. beef).
Natural Forest Management	1.2, 2.3, 4.2, 5.1.3, 5.3, 2.3, 4.2, 5.3, 6.3	Extension of logging rotations; reduced-impact logging practices that avoid damage to non-commercial trees; voluntary certification programs; regulatory requirements that limit impacts from logging; improved land tenure; stop-logging.
Improved Plantations	2.3, 4.2, 5.3, 6.3	Extension of logging rotation lengths to achieve maximum yield while increasing average landscape carbon stocks; certification systems; multi-species plantation systems.
Fire Management	2.2 2.3, 4.2, 5.3, 6.3	Advance prescribed fires to reduce the likelihood of more intense wildfires in fire-adapted forests; advance fire control practices in tropical moist forests such as fire breaks between pasture and forest edges; regulations and certification programs that promote improved fires management; improved forest management practices that reduce slash and improve resiliency to natural disturbance.
Avoided Woodfuel Harvest	1.1, 2.1 2.2, 4.2, 5.3, 6.1, 6.2, 6.3	Reduce woodfuel harvest levels by adoption of improved efficiency cook stoves or stoves using alternative fuel (e.g. solar, methane from agricultural waste).
Agriculture & Grasslands		
Avoided Grassland Conversion	1.1,1.2, 2.1, 5.1, 5.2, 5.3, 5.4	Protected areas establishment and improved enforcement to prevent conversion of grasslands to tilled croplands; improved land tenure; intensification of existing croplands.
Biochar	1.2, 2.3, 4.2, 5.1.3, 5.3	Extension programs to build capacity on biochar management; improved land tenure; certification systems; incentives programs.
Cropland Nutrient Management	1.2, 2.3, 4.2, 5.1.3, 5.3	Certification programs that seek to maintain water quality by reducing excessive fertilizer; water quality/pollution mitigation; credit trading programs; removal of regulations creating perverse incentives to apply excessive fertilizer; improved manure management.
Conservation Agriculture	1.2, 2.3, 4.2, 5.1.3, 5.3	Cultivation of additional cover crops in fallow periods; shift to reduced-tillage or zero-tillage systems and other conservation agriculture practices may enhance soil carbon benefits of cover crops.
Trees in Croplands	1.2, 2.3, 4.2, 5.1.3, 5.3	Regulations and certification programs that promote integration of trees into agricultural lands; agroforestry certification systems; increasing the quantity of trees in croplands by introducing windbreaks (also called shelterbelts), alley cropping, and farmer managed natural regeneration (FMNR).

Pathway	Conservation Action(168)	Example Activities
Grazing - Animal Management		Animal management practices such as improved health; reduced mortality; improved genetics; live weight gain.
Grazing - Optimal Intensity	1.2, 2.3, 4.2, 5.1.3, 5.3	Maintaining forage consumption rates that enable maximum forage production; certification programs.
Grazing - Legumes in Pastures	1.2, 2.3, 4.2, 5.1.3, 5.3	Sowing legumes in existing planted pastures.
Grazing - Improved Feed		Inclusion of cereal grains in feed to improve feed quality and reduce methane emissions.
Improved Rice Cultivation	1.2, 2.3, 4.2, 5.1.3, 5.3	Adopting water management techniques such as alternate wetting and drying (AWD) and midseason drainage (MSD); residue incorporation; fertilizer management.
Wetlands		
Avoided Coastal Wetland Impacts	1.1, 1.2, 2.1, 5.1, 5.2, 5.3, 5.4, 6.3	Protected areas establishment and improved enforcement; improved land tenure; no-net-loss mitigation regulations; avoided harvest of mangroves for charcoal; avoided consumption of food products with acute impacts on coastal wetlands (e.g. mangrove replacing shrimp farms).
Avoided Peatland Impacts	1.1, 1.2, 2.1, 5.1, 5.2, 5.3, 5.4, 6.4	Protected areas establishment and improved enforcement; improved land tenure; no-net-loss mitigation regulations; re-siting of oil palm plantation permits to non-peat locations.
Coastal Wetlands Restoration	2.3, 5.1.2, 5.2, 5.3, 5.4.4, 6.1, 6.3	Re-wetting and re-planting with native salt-water wetlands; wetland mitigation programs.
Peatland Restoration	2.3, 5.1.2, 5.2, 5.3, 5.4.4, 6.1, 6.4	Re-wetting and re-planting with native freshwater wetlands species; wetland mitigation programs.

Methods Details

We address three questions in this analysis:

1. What is the maximum climate mitigation potential of Natural Climate Solutions (NCS), with safeguards for food and fiber security and biodiversity conservation?
2. What proportion of maximum potential NCS is needed as a contribution to limiting global warming below 2°C?
3. What proportion of NCS has the lowest cost barrier?

Our methods for addressing these questions for 20 natural pathways across three biomes (forests, grasslands + croplands, and wetlands) are as follows.

Estimating maximum mitigation potential with safeguards for 20 natural pathways by 2030

As described in the main text, we estimate the maximum additional annual mitigation potential at a 2030 reference year (Table S1). By "additional" we mean mitigation outcomes due to actions taken beyond business-as-usual land use activities, and not including existing land fluxes not attributed to human activities. We constrained this estimate to be consistent with meeting human needs for food and fiber. For food, we allow no reduction in existing cropland area, but do allow the potential to reforest all grazing lands in forested ecoregion, as consistent with agricultural intensification scenarios (169) and potential for dietary changes in meat consumption (170). 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 limit our estimate of maximum mitigation potential by avoiding activities that would negatively impact biodiversity, such as establishing forests where they are not the native cover type (171).

For most pathways, we generated new 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 $M_x = A_x * F_x$. Our estimates for the reforestation pathway involved new geospatial analyses. For most pathways the applicable extent was in terms of area (hectares); however, for five of the pathways (Biochar; Cropland Nutrient

Management; Grazing – Improved Feed; Grazing – Animal Management; Avoided Woodfuel Harvest) other units of extent were used (Table S1). For three pathways (Avoided Woodfuel Harvest; Grazing – Optimal Intensity; Grazing – Legumes in Pastures) estimates were derived directly from an existing published estimate. In these cases, we found no other estimates of similar credibility and we concluded that it was beyond the scope of this analysis to improve upon the single source. Our specific methods for estimating maximum mitigation potential are described for each pathway below, and results are summarized in Tables S1 and S4.

Estimating uncertainty of our maximum mitigation potential estimates

We estimated uncertainty for maximum mitigation potential estimates for each pathway. The following methods, consistent with Intergovernmental Panel on Climate Change (IPCC) good practice guidance (172), build on those described by Griscom et al. (173) to empirically estimate uncertainty where possible. Where available data were insufficient for empirical uncertainty estimates we conducted an expert elicitation. More specifically, for each pathway, we employed one of the following options to assign pathway uncertainties to our maximum estimate of extent (A_x) and flux intensity (F_x) Options 1-3 were explored before proceeding to option 4.

Option 1: If A_x and F_x are calculated from formulae with independent error estimates for each variable, calculate uncertainty of A_x and/or F_x using IPCC Uncertainty Approach 1 (172).

Option 2: If one good study exists with its own estimate of uncertainty for A_x and/or F_x, convert this uncertainty to 95% confidence interval.

Option 3: If three or more studies exist with comparable published estimates of A_x and/or F_x, but no good embedded estimates of uncertainty, check distribution of A_x and F_x estimates for normality and symmetry, and calculate 95% confidence interval of distribution.

Option 4: If option 1-3 conditions cannot be met, assign uncertainty estimates to A_x and/or F_x using expert elicitation, with a minimum of three respondents. The results of this method are distinguished from empirical methods (Options 1-3) with gray text in Table S1 and with wider error bars in Fig. 1.

We used the Delphi method (174) of expert elicitation. Experts were contacted individually via email with detailed instructions on the task, definition of terms, units, flux constraints, baseline assumptions, and a list of key studies we consider most relevant to answering the questions. We requested anonymous responses to six questions for each pathway (unless specified otherwise below). Three questions were asked about the uncertainty of extent values (A_x), and three about the uncertainty of flux intensity values (F_x), as follows:

1. What do you think is the lowest this value could be? This is your best estimate of the lower end of a 95% confidence interval (~2.5% chance the true value is lower than this value)?
2. What do you think is the highest this value could be? This is your best estimate of the upper end of a 95% confidence interval (~2.5% chance the true value is lower than this value)?
3. In arriving at your estimates, did you consider any additional peer-reviewed papers that we did not list? If so please provide full reference or pdf. If you would like to describe methods you used to arrive at your estimates, please note them here. Also, if you believe the median value is substantially skewed towards the upper or lower value above, please provide your median value. Response to this methods & skewness question is optional. It is understood that your methods involve both awareness of existing data and your judgement given the limited availability of data. Let us know if you have any questions about our questions.

In a second email we anonymously reported to each expert the mean of upper and lower values reported by all experts for each pathway and we provided to all any additional papers received and clarifications to questions asked. We gave each expert the chance to provide revised estimates. The mean values from respondents' final answers to questions were averaged to derive the upper and lower bounds of 95% confidence intervals.

We received responses from 21 of 90 topic experts contacted. Each was identified on the basis of their authorship of relevant peer-reviewed publications. The following individuals provided expert responses for one or two pathways: Shawn Archibeque, Mark Bonner, Rich Conant, Peter Ellis, Joe Fargione, Alan Franzluebbers, Holly Gibbs, Bronson Griscom, Richard Houghton, Matthew Hurteau, Tyler Lark, Guy

Lomax, Megan Machmuller, Susan Page, Jack Putz, David Shoch, Marcel Silvius, Pete Smith, Penka Tsonkova, Guido van der Werf, and Chris Zganjar.

Uncertainty ranges we derived from expert elicitation were expected to be skewed with respect to our maximum mitigation potential estimates – which we derived from published data. In two cases we extended the mean expert elicitation based uncertainty ranges to include key published estimates.

We combined A_x and F_x uncertainties within pathways from each of the four methods options above to calculate overall inter-pathway uncertainty using IPCC Approach 2: Monte Carlo simulation. Applying the central limits theorem, we converted 95% confidence intervals to standard errors of the mean (SEM) by dividing by 1.96. Input parameter SEMs were used to define distributions used in Monte Carlo simulations ((175), 100,000 iterations). The simulation randomly selected a single value from defined normal distributions, for each parameter and at each simulation, and passed values into the emissions equation to calculate uncertainty at the pathway and biome level. The mean of normal distributions for expert elicitation uncertainty values were not tied to our literature-based estimates of mitigation potential.

Assigning cost-constrained mitigation levels

We assumed that a maximum marginal cost of approximately 100 US dollars per Mg of carbon dioxide equivalent emitted per year (~100 USD $MgCO_2e^{-1}$) in 2030 would be required across all mitigation options (fossil fuel emissions reductions and NCS) to hold warming below 2°C (176). To calibrate natural pathway mitigation levels with a goal of holding warming 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 $MgCO_2e^{-1}$ (Table S4).

This ensures that the marginal (per unit) cost of emissions reductions from NCS does not exceed the marginal benefit of avoiding carbon emissions. The marginal benefit of emissions reductions is represented by estimates of the social cost of carbon, which is the value to society of the avoided marginal damage of CO_2 emissions due to climate change and is obtained through welfare-maximizing emissions pricing models (177, 178). The social cost of carbon in 2030 is estimated to be 82-260 USD $MgCO_2e^{-1}$ to meet the 1.5-2°C climate target(176). This estimate is based on an updated version of the Dynamic Integrated Climate-Economy model to allow for endogenous capital and improved models of the damage from climate change. The exact value depends on the assumptions related to the convexity of the damage function, the discount rate and climate sensitivity parameter. The model does not allow for adjustments costs and hence is likely to underestimates the values.

100 USD $MgCO_2e^{-1}$ is also in line with the 95th percentile of the estimated distribution from the White House (https://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf) and is consistent with the values used in other modelling studies (113, 179). Based on a 3% discount rate, the values reported in the White House reports in 2007 USD are 72.8 $MgCO_2^{-1}$ and 100 $MgCO_2^{-1}$ for 2015 and 2030, respectively. This value represents a conservative estimate, as using a lower discount rate would result in a larger value. For simplicity and alignment with other parts of the analysis in this paper, we use the value 100 USD $MgCO_2e^{-1}$ for 2030.

We assign low (30%), medium (60%), and high (90%) default cost-constrained mitigation levels, as a percentage of maximum levels, informed by marginal abatement cost (MAC) curve literature and the 100 USD $MgCO_2e^{-1}$ cost threshold. 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 (see Table S4 and section below for literature reviewed). Also, for some pathways we saw a need to adjust levels to consider barriers to implementation beyond costs. Mitigation level assignments for each pathway are discussed further below.

We also assessed the proportion of NCS mitigation towards a <2°C outcome 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 reductions efforts underway and current prices on existing carbon markets.

We supplemented the authors' knowledge of the literature by searching for MAC curves for each pathway using Google Scholar, including key words "supply curve" or "marginal abatement cost curve" in addition to the name of the pathway. In addition, we also searched for the studies citing the studies included in our database. Where global studies were not available, we searched for regional (e.g., country-specific) studies and assumed a similar percentage of mitigation was available at the USD 100 and USD 10 price points in related geographies. If multiple curves were presented on a graph, we used the one matching the year 2030 and the maximum associated with a specific pathway. The list of studies included in our database is reported in Table S4. We converted all emissions units to $TgCO_2e$ and the marginal cost estimates to 2015 USD, using US Consumer Price Calculator ((180), available at https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=1&year1=199501&year2=200501). Where suitable MAC studies were not available, we relied on our expert opinion to judge probable costs of mitigation – and compared costs to the most similar pathways with MAC information.

Projecting NCS contribution to climate mitigation through 2100

We projected the potential contributions of NCS to overall CO_2e mitigation action needed for a 'likely' (greater than 66%) chance of holding warming below 2°C (181) 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 Tables S1 and 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 prior to saturation reported in 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 (182), with model parameters derived from Meinshausen et al. (183). 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 Co-Benefits

We identified mitigation activities and non-carbon ecosystem services associated with each of the 20 natural pathways (Tables S5 and S7). We used a taxonomy of conservation actions developed by the International Union for Conservation of Nature (IUCN) and the Conservation Measure Partnership (168) 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 (Table S7). Activities represent specific conservation, restoration, and improved land management actions that practitioners may take to avoid emissions and/or enhance sequestration.

We considered four generalized types of ecosystem services (biodiversity, water, soil, air) that may be enhanced as a result of the implementation of natural pathways (Table S5). We identify types of ecosystem services as linked to a pathway in Fig. 1 and Table S5 only where one or more peer-reviewed publication confirms that the type of ecosystem service is enhanced by an additional pathway activity. For example, the existence of additional forest area – which is generated by avoided forest conversion and reforestation pathways – has been linked to improved air quality (125); however, our two forest management pathways (natural forest management, improved plantations) do not directly change forest area, so we did not identify a link between forestry management pathways and improved air quality. Such a link may exist, but we were unable to identify a peer-reviewed publication demonstrating it.

We define biodiversity benefits as any increases in alpha, beta, and/or gamma diversity as is described in the Convention on Biological Diversity (184). Water ecosystem benefits include water regulation, water purification, and storm protection as defined in the Millennium Ecosystem Assessment (185). Soil benefits are characterized by improvement in metrics of soil quality that enhance productivity, maintain nutrient cycling, and improve plant growth (186) as well as the improved potential food provision and reduced soil erosion services described in the Millennium Ecosystem Assessment (185). We define air benefits as the "air quality regulation" ecosystem service described in the Millennium Ecosystem Assessment (185).

The following are pathway-specific methods:

Avoided Forest Conversion

Our estimates for avoided forest conversion extent and flux per ha were derived from a recent University of Maryland (UMD) study of carbon loss in natural and managed tropical forests (1). Other studies either rely on inconsistent source data (187, 188) from the Forests Resources Assessment (189–192); coarse, time-limited forest loss data convolved with coarser, spatially incongruent pixel-based biomass maps (193); or a limited sample-based estimate of forest loss (194). The UMD authors also employ a “stratify and multiply” approach to biomass mapping (195) that uses 9 million GLAS shots biomass measurements from Baccini et al. (190), providing the most consistent assessment of forest loss emissions to date (196). Further, the differentiation between natural and managed forests in the UMD product (1) holds the advantage of allowing us to treat subsistence agriculture differently, and avoid double-counting with forest management pathways, as described below. While datasets, like the UMD product, that rely on optical sensors for activity data are limited by cloud cover, an independent accuracy assessment (173) found that the UMD product performed well, and better than alternatives, in an aseasonal region of Indonesia with heavy cloud cover.

In defining the boundaries of forest loss, we relied on the UMD definition of “forest” (>25% tree cover), and their tropical/subtropical study area (Fig. S5). The omission of boreal forests is justified by research on the countervailing effect of albedo warming (197), but large portions of temperate and subtropical zones remain un-accounted for. Few reliable, large-scale studies quantify deforestation emissions in these zones. Nevertheless, we believe the opportunity for avoided forest loss mitigation in these areas is much smaller than in the UMD study area, because carbon stocks are significantly lower (198), the ratio of regrowth to loss is much higher (0.57 versus 0.22), and a higher proportion of loss does not reflect conversion to other land uses (i.e. natural disturbance such as boreal wildfires and forestry activities). Tyukavina et al. include non-anthropogenic forest loss (hurricanes, storms, wildfire) in their analysis, but in the tropical regions assessed, the influence of these drivers is likely *de minimis* (199).

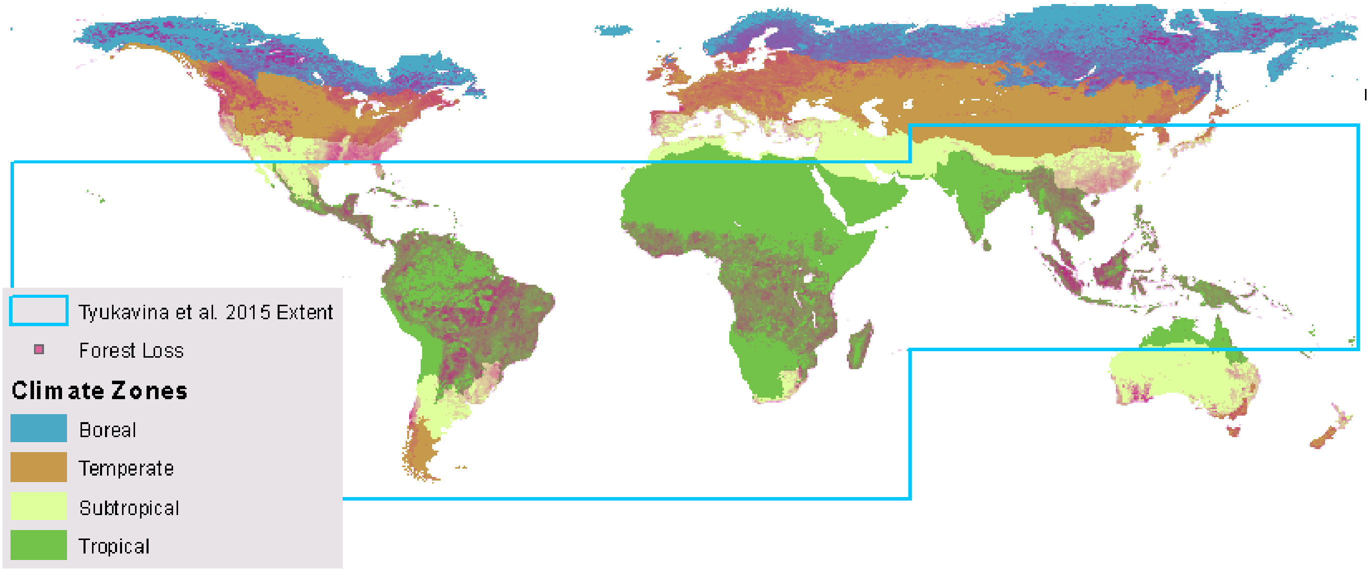


Fig. S5. Extent of historic forest loss captured by Tyukavina et al. (1) inform our Avoided Forest Conversion pathway – thus limited primarily to tropical and subtropical climate zones, as defined by FAO (57).

To calculate the area of avoided loss we assume a constant rate of forest loss through 2030, based on an historical baseline of 5.9 Mha yr^{-1} drawn from the UMD sample-based estimate of natural forest loss 2000-2012, after removing forested wetlands (see below). Our mean historic baseline approach here and for other pathways is consistent with research finding that more sophisticated approaches tend to generate inflated outcomes (200), and with international accounting frameworks that prefer or require historic mean baselines (201). Our exclusion of nationally determined contributions (NDC's) from our baseline scenario is aligned with "no policy baseline" scenarios being used for integrated assessment models (202). UMD defines natural forest loss as occurring in "forests cleared for the first time in recent history." The inverse, termed "managed forest loss" by UMD, occurs on "forest plantations, agroforestry systems and areas of subsistence farming due to shifting cultivation practices." UMD's estimate is an improvement upon a previous UMD study (6) because it utilizes an extensive validation sample of 3000 forest loss pixels stratified across continents and forest cover strata, following a remote sensing validation procedure outlined in Olofsson et al. (203). We use UMD's estimate of natural unmanaged forest loss to exclude forest loss from plantation forestry – a source of controversy in previous forest loss assessments (6, 204–206).

To calculate forest loss emissions, we adjust UMD's gross above- and below-ground natural forest loss emissions estimate (750 Tg yr^{-1}) by accounting for elemental charcoal carbon and wood product carbon retention, overlap with forested wetlands, and soil emissions. We assume that – in conjunction with the deforestation process – 2.0% of initial biomass is stored in long-term charcoal, and 2.4% is stored in long term wood products (2). To prevent double counting with the avoided wetland loss pathway, we further deduct historic mangrove and forested peatland loss from UMD's area and carbon loss estimates (65, 73, 207, 208). We take a committed emissions approach (209) to assume 100% loss of carbon from the remaining "slash" biomass pool, a reasonable assumption for tropical forests given a 20 year time horizon, since even a conservative 0.3 yr^{-1} decay constant results in >99% decay within 15 years (2, 210). We assume 54% of natural forest lost is converted to commercial agriculture (4), resulting in an additional 13 Mg ha^{-1} of soil carbon emissions from tilling (3). This is a conservative estimate compared to other meta-analyses (211).

We estimate that an additional 314 TgC are emitted every year as a result of subsistence agriculture in the tropics, based on UMD's estimates of the loss of managed forest (1), and an assessment of the proportion of this loss attributable to subsistence agriculture (4). Using data from Hansen et al. (6) and a stratified random sample of 3000 loss pixels, UMD calculate 5.3 Mha yr^{-1} of managed forest loss, including plantation forestry and subsistence agriculture. A pan-tropical assessment of deforestation drivers (4) estimates that 32% of deforestation is a result of subsistence agriculture, translating to 26% of all forest loss (3.0 Mha), given that the authors do not account for plantation forestry in their definition of deforestation. UMD calculates 553 Tg yr^{-1} of carbon emissions resulting from managed forest loss, or 105 Mg ha^{-1}. Applying a 2% deduction for charcoal storage after burning (2), the total historic flux from subsistence agriculture is 314 TgC yr^{-1} or 103 MgC ha^{-1}.

Recent research suggests that standing forests provide an additional sequestration benefit between 1.3 and 2.6 PgC yr^{-1} not accounted for in traditional avoided forest loss estimates (192, 212–214). There is disagreement about the nature and magnitude of this carbon sink, and how it will respond to future changes in atmospheric CO_2 levels, water availability, seasonality, weather, and pests/pathogens (215–221). Based on our estimated natural forest loss conversion rate, this carbon sink could provide an additional 3.4 – 8.8 TgC yr^{-1}, but we exclude this from our maximum mitigation estimate until more conclusive evidence is available, such as from NASA's Orbiting Carbon Observatory-2 (222), available at http://oco.jpl.nasa.gov/.

Mapping Country-Level Mitigation

We were unable to map avoided forest conversion maximum mitigation to individual countries because Tyukavina et al. assess managed and natural forest loss at regional levels only (1). We mapped pan-tropical maximum additional mitigation potential reported here into regions using the proportion of natural forest above-ground and below-ground carbon loss for each region reported by Tyukavina et al. (1).

Uncertainty

Reported uncertainty from the UMD dataset is low, based on a large sample-based estimate of forest loss extent (±11%), carbon stock variability, and quantified GLAS model error. Flux uncertainty is approximated by UMD as a function of natural intra-stratum variation in carbon stocks (±5.0%). However, this uncertainty estimate does not account for field measurement error (including wood density), tree allometry error, or error in the model to predict biomass from the GLAS LIDAR sensor analysis (190) – reported by UMD as ±22.6 Mg ha^{-1}, or ±5.5%, but not incorporated into their model. We therefore follow option 1 uncertainty method and propagate this error together with errors from wood product/charcoal (assumed "high" or ±75%), and soil at ±38% (3) to achieve an estimated flux uncertainty of ±12%.

To check this uncertainty estimate against the literature, we compared UMD's reported pan-tropical above- and below-ground forest carbon loss (3.7 $PgCO_2$ yr^{-1}) to four recent estimates from the literature (Table S8). All estimates are within 18% of the mean, providing further justification for our combined area-flux uncertainty estimate of 17%.

Table S8. Comparison of recent pan-tropical studies of gross forest loss emissions.

Study	Gross Deforestation Emissions ($PgCO_2e\ yr^{-1}$)
Tyukavina et al. 2015 (1)	3.7
Harris et al. 2012 (193)	3.0
Baccini et al. 2012 (190)	4.2
Houghton et al. 2013 (189)	3.5
Achard et al. 2014 (194)	3.2
Mean	3.5
95% CI	0.41 (12%)

Mitigation Targets

We estimated our <2°C and low cost mitigation targets for avoided “natural” forest loss based on two global marginal abatement cost curves relevant to this pathway (113, 114). These sources are also consistent with values reported by the IPCC (116).

Our <2°C target of 90% of maximum potential avoided forest conversion is closely aligned with, the UN Declaration on Forest agreement “to end natural forest loss by 2030” (223), and the UNFCCC Paris Agreement “to conserve and enhance…sinks and reservoirs of greenhouse gases…including forests” (224). Following (225), we allocate the remaining 10% of forest loss to low-carbon density land (56 Mg ha^{-1}, when accounting for below-ground biomass, charcoal, wood product storage, and soil carbon).

We set a lower cost-effective mitigation potential (60%) for avoided subsistence agriculture than indicated for other drivers of forest conversion in the cost curve literature (113, 114) given the complex challenges involved with achieving socially and culturally responsible and sustainable changes in subsistence agricultural practices.

For example, despite MAC curve information indicating that the Avoided Forest Conversion pathway can be implemented at ~90% (see Table S4), we do not believe the available literature has sufficiently considered implementation barriers to avoiding forest conversion driven by subsistence agriculture.

Reforestation

We define reforestation as conversion from non-forest (< 25% tree cover) to forest (> 25% tree cover (6)) in areas ecologically appropriate and desirable for forests. We exclude afforestation (the growth of forests in non-forest biomes) from our analysis to avoid adverse impacts to biodiversity (226, 227). Our exclusion of croplands from reforestation while assuming that all grazing lands in forested ecoregions can be reforested is consistent with recent analyses finding a variety of options for improving the efficiency of livestock production and/or diet change (228, 229).

To calculate the extent of reforestation potential, we modify a 1 km resolution map from the Atlas of Forest Landscape Restoration Opportunities (FLRO) (82). This map uses ecoregional data and bioclimatic modeling of the following criteria to identify areas with opportunities for forest landscape restoration: potential forest cover (230, 231) minus existing forests (232) minus areas incompatible with returning to forests (233–235). The potential forest cover map combined data on climate, soils, elevation, current and historical forest extent, and potential forest composition and density (5, 40, 231, 236, 237). The existing forest map was derived from MODIS 250m data from 2000 to 2009, which maps forest extent, and MODIS vegetation continuous fields data, which maps tree canopy density (232, 238). We excluded areas incompatible with returning to forests, included locations with dense rural population (>100 person km^{-2}), agricultural and other intensively used areas (233, 235, 239). Note that the FLRO map classifies forests as either closed forest (canopy density >45%), open forest (canopy density between 25-45%), and woodlands (canopy density between 10-25%).

We applied additional spatially explicit filters to avoid double-counting among pathways, avoid overlap with wetlands, exclude boreal ecoregions, remove native non-forest ecosystems, and improve estimates of additionality as follows:

- Deductions to avoid double-counting with forest management pathways: To adjust the estimated restoration opportunity area to our definition of reforestation opportunities (where non-forests can be converted to forests >25% tree cover), we removed (i) areas identified by FLRO based on Olson ecoregions (231) as having potential forest cover with <25% tree canopy cover, and (ii) Hansen pixels (6) identifying existing forest cover >25% tree canopy cover. This modification avoids double-counting between reforestation and other forest restoration pathways (e.g. natural forest management), and reduces the substantial remote sensing error associated with more subtle changes in vegetation in forests remaining forests and non-forests remaining non-forests (240).

- Boreal albedo exclusion: We excluded boreal forest ecoregions (10%) given biophysical effects of forest cover that may offset carbon sequestration (i.e. albedo warming (197)).
- Biodiversity safeguard: To avoid negative impacts to biodiversity, we excluded areas in grassy biomes where forests naturally transition to grassland and savannah ecosystems. As indicated in the literature (241, 242) , the potential vegetation cover data used by the FLRO map (231) does not accurately delimit grass-dominated ecosystems. We make use of a new study (NESCent grasslands working group, unpublished) to map the extent of grassy biomes globally, which excludes 47% of the 2.5 Gha FLRO area identified by WRI.
- Baseline adjustment: To account for baseline reforestation between the FLRO base year 2000 and present, we apply the mean forest “gain” rate for 2000-2012 from the UMD dataset (6) to the intervening period. To appropriately account for additionality, we use the same rate to exclude baseline reforestation during the 2016-2030 period.

We also applied a non-spatial deduction to eliminate double counting: we deducted the unmapped area of forested peatlands and mangrove forests (66, 73, 76, 77) (see wetland restoration methods below). We note that our definition of agroforestry in this analysis (use of trees in cropping systems where tree cover <25%), excludes agroforestry interventions as defined here from the reforestation pathway, thereby eliminating double-counting. We assumed that potential reforestation areas do not compete with future areas of cropland expansion, as croplands were already excluded from the FLRO map, and we assume that the current extent of agricultural land can effectively feed projected future populations ((191) “yield growth” scenario).

To calculate rates of forest carbon sequestration, we conducted a literature review of plantation and natural forest growth studies in different climate domains (Table S9). Our analysis indicates that the majority of potential reforestation area is located in the tropics (70%), where growth rates are higher, thereby representing an even greater proportion of the mitigation potential (79%).

Table S9. Summary of maximum potential extent and sequestration rates for reforestation pathway. We used current plantation extent (11) to estimate the proportion of future reforestation allocated to plantations. Growth rates include aboveground biomass (sources listed), belowground biomass (9), and soil organic carbon sequestration (tropical forest only, (3)).

Climate Domain (57)	WRI 2014 Estimate: Potential Reforestation Area (Mha)	This study: Max Extent Potential Reforestation Area (Mha)	Natural Forest Growth Rate (MgC ha^{-1} yr^{-1})	Plantation Forest Growth Rate (MgC ha^{-1} yr^{-1})	Percent of regrowth allocated to plantations (11)	Literature Sources
Boreal	238	0	0	0	NA	Albedo offset (197)
Temperate	403	206	2.0	5.8	22%	(3, 7, 8)
Tropical	1,849	472	4.8	6.2	4%	(10)
Total	2,489	678	4.0	6.1	7%	

We eliminate double-counting of mitigation potential with grazing pathways as follows. We calculate the proportion of lands with mitigation potential from improved grazing and sowing legumes (56) that overlap our reforestation map (13% and 15%, respectively). We deduct the corresponding mitigation potential from our reforestation maximum (158 $TgCO_2e$), representing a 1.5 % deduction.

We assessed the requirements for reforestation to deliver additional global wood yield in order to make up for lack of wood yield from natural forests under maximum implementation of the natural forest pathway. We estimate 2.2 billion m^3 of wood (woodfuel and industrial roundwood) provided by natural production forests would need to be generated instead from new forests associated with the reforestation pathway. This could be generated if 144 million hectares of the maximum reforestation area (= 21% of 678 M ha) was in the form of plantations with the mean growth rate of 6.1 MgC ha^{-1} yr^{-1} (see Table S9 for sources). Given mean harvest rotation length of 45 years for commercial plantations, the additional sequestration in new plantations would saturate after about two decades (see Table S1). The saturation period would be much longer for the majority of reforestation from which commercial timber harvest would not be necessary.

For the purposes of calculating maximum reforestation mitigation potential, we assumed no change in the proportion of forest cover in the form of commercial plantations (7%). This avoids assumptions about controversial implications of intensification of the forestry sector, and it results in a conservative reforestation mitigation potential estimate, since natural regeneration sequestration rates are lower than in commercial plantations. Once we arrive at feasible levels of reforestation mitigation (30% of maximum), it is not necessary for more than 7% of additional reforestation area to be in the form of plantations. For example, a proportion of the natural forest management pathway, given 60% mitigation at <2C° ambition, could be delivered through reduced impact logging practices that do not involve reductions in wood yields from natural forests.

Mapping Country-Level Mitigation

To map reforestation mitigation potential, we combined country-level estimates of extent and flux per ha. We calculated country-level estimates of reforestation extent by deducting background gain reported in (6) (excluding boreal areas) from the area of purple pixels displayed in Fig. S1A. We calculated country-level mean flux using the natural and plantation forest growth rates reported in Table S9 and country-level percent of regrowth allocated to plantations from the Forest Resources Assessment (FRA) (11).

Uncertainty

Following uncertainty option 3, we reviewed five estimates of reforestation mitigation potential from the literature (116, 179, 182, 243, 244) to assign 66% extent uncertainty and 32% flux per ha uncertainty.

Mitigation Targets

We set the <2°C target at 30%, or 1.2 PgC yr^{-1}. This corresponds to approximately 200 Mha of implementation area. This level of mitigation exceeds 100 USD $MgCO_2^{-1}$ according to an analysis of the marginal abatement cost of reforestation with commercial plantations (115). However, we assigned a 30% mitigation level considering that large extents of reforestation could be achieved at lower costs by halting intentional burning of marginal grazing lands in places like the Amazon basin to allow natural forest regeneration (245).

The Bonn Challenge and United Nations New York Declaration on Forests (223) commit to restore at least 350 Mha of "degraded landscapes and forestlands" by 2030. Because this target area includes silviculture, agroforestry, improved fallow, and mangrove restoration strategies in addition to the tree planting, watershed protection, and assisted natural regrowth included in our definition of reforestation, its restoration implementation area is more expansive, and our 275 Mha is therefore on par with the target. A review of 28 country reforestation pledges indicates that 61% of the committed area (213 Mha) falls within our definition of reforestation (246).

Natural Forest Management

This pathway involves improved forest management practices in native forests under timber production. This pathway applies to naturally-regenerated forests designated for production or multiple-use as defined by the Food and Agriculture Organization of the United Nations Global Forest Resources Assessments (FAO GFRA) 2015 (11). Planted forests under intensive even-aged management are excluded to avoid double counting with the Improved Plantations pathway. We estimate the maximum mitigation potential under a scenario where timber harvests are halted during this century across all native forests currently under timber production. It is assumed that lost wood production is made up by a combination of increased yields from the Improved Plantations pathway, and commercial harvest from a portion of the Reforestation pathway. Feasible mitigation potential levels may involve any number of improved management practices that may continue timber production (e.g. reduced-impact logging, extended harvest rotations, liana cutting).

The FAO GFRA are the only global datasets on native forest production forest areas. The total area under consideration is 1,914 Mha as of 2015, of which 545 million ha occurs in tropical and sub-tropical climate domains, and 1,369 Mha occurs in temperate and boreal climate domains (11, 83). This naturally regenerating production forest area is assumed to be constant between now and our reference baseline year of 2030.

On average, we estimate that the effective mean net additional carbon sequestration rate across all current production forests during the next 50 years is 0.39 MgC ha^{-1} yr^{-1} for tropical forests and 0.14 MgC ha^{-1} yr^{-1} for temperate and boreal forests, based on the following literature-based assumptions. We assume no change in soil carbon. In determining sequestration rates associated with age of stands or age-classes, we assume that the average business as usual cutting cycle is 30 years in tropical forests and 50 years in temperate and boreal forests. We assume that selectively-logged tropical forests maintain stock levels on average 76% of those of never-logged primary forest, and that on average cutting cycles must be extended by 75 years for complete recovery of original stocking levels (16). Global tropical average initial above- and belowground stocks in natural production forests are estimated to be 126.5 MgC ha^{-1} (1), and global average "fully recovered" stocks are assumed to be 166.4 MgC ha^{-1} (= 126.5 MgC ha^{-1} * 1 / 76%).

This rate is derived assuming that forests subject to logging maintain ~50% of stock levels of old-growth forest, and that old-growth stock levels require several hundred years to recover (12–14). Global temperate average initial above- and belowground stocks in natural production forests are estimated to be 49.4 MgC ha^{-1} (11, 83), and global average "fully recovered" stocks are assumed to be 98.8 MgC ha^{-1}.

We note that the sequestration rates we derived above, 0.39 to 0.14 MgC ha^{-1} yr^{-1}, are low compared to growth rates from site-specific post-logging studies we reviewed (173, 247–250), most of which estimate re-growth rates within the first 10-20 years following harvest. In large part, the low rates we derived result from an assumed length of the full recovery period (from 75 to 200 years) and the application of a constant growth rate over that period. Hence, our maximum mitigation potential estimates can be considered conservative with respect to an initial 50-year period of halting global timber harvests within natural production forests. On the other hand, with only 0.6% annual average removals (= 3 * 10^{9} m^{3} global removals in 2011 / 431 * 10^{9} m^{3} global growing stock in 2015; (11)) vast areas of global natural production forests have not been subject to recent harvest, so until new studies are available on the landscape-scale growth rate of forests older than 30 to 50 years, we believe it is best assumed that global natural production forest area is growing at slow rates typical of stands approaching mature, uneven-aged conditions.

Mapping Country-Level Mitigation

To map natural forest management at the country scale, we removed plantation forest extent from country-level estimates of natural forest management extent by regionally allocating proportional deductions of intensively managed plantation forest areas (251) from the sum of FRA production and multi-use forest area (11). We calculated maximum mitigation by multiplying these extents by the tropical and temperate/boreal sequestration rates reported in Table S1.

Uncertainty

Available published data did not permit options 1-3 described above for empirical estimation of uncertainty, so we employed expert elicitation (N = 4 experts elicited) to estimate the uncertainty of (i) the extent of naturally regenerating production forests, and (ii) growth rates of forest stands that have aged beyond business-as-usual harvest cycles.

Mitigation Targets

Our mitigation targets are based on reported marginal abatement costs (60, 116). While these studies present global estimates of the impact of modifications to intensive and extensive forest management, they do not distinguish between natural and plantation forests. Our low cost mitigation target (30%) is also informed by studies indicating that at least one practice included in this pathway, reduced-impact logging, is reported to have low or negative costs (252).

Improved Plantations

This pathway involves extending harvest rotation lengths on intensively managed production forests (i.e. plantations) subject to even-aged stand management. Unlike the Natural Forest Management pathway, we constrain the Improved Plantations to increases in carbon stocks associated with maximizing wood volume yields. We assume baseline rotation lengths are at the economic optimum, which is generally shorter than the optimum rotation for wood yield (biological optimum). In contrast to the biological optimum based simply on the optimization of the tree species growth function, the economic optimum balances discounted costs with discounted stream of revenues from timber production, given a tree species growth function (84). In our modeling exercise, we set the target extended rotation length based on the biological optimum, i.e. the point that maximizes the Mean Annual Increment (MAI) for timber. Shifting rotations from an economic to a biological optimum will increase timber volumes harvested from stands in the long run, as the biological optimum rotation length yields the highest mean annual productivity.

The extent of this pathway is limited to “planted forests” as defined by the FAO GFRA, which includes plantations and semi-natural planted forests, and should encompass the majority of intensively-managed even-aged production forests worldwide. These planted forests occupied ~ 7% of the estimated global forest area in 2015. We source data from the most recent FAO GFRA and from a detailed global thematic study on planted forests carried out by FAO in 2006 (86, 251), hereafter referred to as “thematic study.” The thematic study provided data on rotation lengths, MAI, ownership and other parameters incorporated in our analysis, derived from a sample of 61 countries representing 95% of the 2005 planted forest land base.

This pathway is constrained to the subset of planted forests managed for timber. This subset does not include small-scale planted forest with end uses for bioenergy or non-timber forest products. We estimated the proportion of planted forest managed for timber based on the 2006 thematic study.

We derived area data on planted forests from the 2015 GFRA and projected it forward to 2030 (Table S10) assuming a constant rate of increase in planted forest area of 3 million ha per year (rate 2010-2015; GFRA 2015). After 2030, we do not consider further expansion of planted forest area. This is a conservative assumption, given anticipated continuing trends of increasing plantation forest area. Plantation forest area has been increasing globally in recent decades at around 2% per year (253).

Table S10. Area of planted forests from GFRA 2015.

	Total planted ha 2015	Estimated productive planted ha 2015	Projected productive planted ha 2030
Africa	16,000,000	12,766,141	14,753,948
Asia	129,000,000	84,223,754	97,338,180
Europe	82,000,000	65,366,375	75,544,531
N and C America	43,000,000	41,237,074	47,658,072
Oceania	4,000,000	3,966,882	4,584,563
S America	15,000,000	14,929,998	17,254,739
		Global total	257,134,032

We calculated the ratio of biological optimum rotation age: economic optimum rotation age to be 1.45. This was calculated using a generalized Chapman Richards form yield curve and assuming a global average discount rate of 8% (85).

All existing rotations were increased by a factor of 1.45, to produce the new (extended) rotation regime scenarios. In both business-as-usual and extended rotation scenarios, the total long-term average stock of above- and belowground biomass carbon in $MgCO_2e$ was calculated for each rotation length class as:

Area (ha) * MAI (m^3 ha^{-1} yr^{-1}) * midpoint of rotation length (yrs) * BCEF (Mg $AGBm^{-3}$) * 0.47 (carbon fraction) * (44/12) * (1+ R:S ratio)

A single biomass conversion and expansion factor (BCEF) for temperate pines (17) was applied in all calculations, which we consider reasonably appropriate in the context of global planted production forests, where most above ground biomass (AGB) is contained in stem wood. Similarly justified, root:shoot (R:S) ratios for temperate conifers (17) were applied in all calculations. Our analysis is focused on difference in stocks, rather than absolute magnitude of stocks, such that any bias introduced should have limited influence. We employ the minimum values of rotation length and MAI reported in the thematic study (251), which for rotation length should align with revenue-driven management of planted forests under productive use considered here, and for MAI should produce conservative estimates of growth and yield.

For the extended rotation scenarios, MAI of the original rotation regime is applied through the length of the new extended rotation (a conservative assumption). The derived long-term average stock estimate further assumes constant productivity across rotations (i.e. no increases in productivity due to introduction of new technologies or improved genetic material, or decrease due to soil degradation). Our estimates ignore net emissions from harvests, which are not expected to significantly differ between the two scenarios. We also conservatively ignore carbon stored in wood products, which can be expected to be slightly higher in the extended rotation scenario due to higher MAI. We assume the same end wood products are generated in both scenarios, i.e. no change in market demand is assumed.

Using these methods, we estimate that the potential benefit of extended rotations globally is 27.0 $PgCO_2e$, which is the estimated difference in long-term average stocks between the two scenarios assessed. To interpret this value as a rate, we assume that the time to transition the global landscape to the new long-term average stocking state is equal to the length of the new (extended rotation) in years, for each rotation length class. This is the shortest possible timeframe to transition all age cohorts across a landscape. For the 2030-2045 assessment timeframe, we estimate an unconstrained maximum biophysical potential benefit of extended rotations of 0.443 $PgCO_2e$ per year, sequestered as additional long-term average stocks in plantation forests worldwide.

Mapping Country-Level Mitigation

We mapped improved plantations maximum mitigation by multiplying FAO estimates of intensively managed plantation forest extent at continental scales (251) times the sequestration rate of 0.47 MgC ha^{-1} yr^{-1} reported above.

Uncertainty

Available published data did not permit options 1-3 described above for empirical estimation of uncertainty, so we employed expert elicitation (N = 4 experts elicited) to estimate the uncertainty of (i) the extent of naturally regenerating production forests, and (ii) growth rates of forest stands that have aged beyond business-as-usual harvest cycles.

Mitigation Targets

We assigned the same mitigation target for <2°C ambition as the natural forest management pathway, while noting that the marginal abatement curve sources (60, 116) are less directly applicable. We assigned 0% low cost mitigation opportunities, anticipating that low cost mitigation opportunities for improved plantations will be more limited than for natural forest management, given that additional mitigation requires a shift away from economic optimum harvest rotations.

Fire Management

This pathway integrates three spatially discrete and distinct forms of fire management (i) prescribed fires applied to fire-prone temperate forests to reduce the likelihood of more intense wildfires, and (ii) fire control practices (e.g. fire breaks) applied in moist and wet tropical forests to avoid understory fires that enter at edges with lands converted to non-forest cover types (primarily pasture maintained with fire), and (iii) use of early season fires in savanna ecosystems to avoid higher emissions late season fires.

Our estimate of the maximum mitigation potential for temperate forests is drawn as the sum of estimates from two studies that modelled carbon benefits from prescribed burns. One study modelled mitigation potential of prescribed burns across 26.3 million ha of fire prone coniferous forests of the western United States (88). The other study modelled mitigation potential of prescribed burns across a variety of forest types across Balkan, Western European, Eastern European, Scandinavian, and Mediterranean countries – but not Russia (89). These studies report baseline wildfire emissions about four times higher than the potential avoided emissions from prescribed burning treatments. This reflects that (i) prescribed burns generate their own, albeit lower, emissions, and (ii) prescribed burns reduce but do not eliminate the likelihood of wildfires.

Our estimate for avoiding tropical forest degradation by escaped fires was drawn from Alencar et al. for the Brazilian Amazon (20). Given the occurrence of an El Niño Southern Oscillation (ENSO) year during Alencar et al.'s estimates, we deducted from their mean annual reported emissions by assuming a seven year ENSO return rate. Note that we only included understory degradation fires accounted for by Alencar et al., since more intense fires associated with deforestation would be double-counting with our

Avoided Forest Conversion pathway. We limited the maximum extent of improved fire management to the areas covered by each of these studies, as we are unaware of a credible basis for extrapolating these studies.

Our estimate for reducing emissions through improved savanna fire management was drawn from a study of potential global savanna fire emissions reductions if indigenous fire management methods from northern Australia were applied more broadly, particularly in Africa (21). This study drew on a global estimate of savanna fire emissions (22).

Uncertainty

Available published data did not permit options 1-3 described above for empirical estimation of uncertainty, so we employed expert elicitation (N = 3 experts elicited). Uncertainty in estimated savanna fire emissions reductions is based on a reported range (21) adjusted to approximate 95% confidence intervals based on expert elicitation methods described above. We used reported 95% confidence intervals (20) for uncertainty of avoided understory fires in the Brazilian Amazon.

Mitigation Targets

We are unaware of available literature on marginal abatement cost curves applicable to this pathway. We assumed this is a relatively expensive pathway in the context of other forest pathways and based on conversations with practitioners. We assigned 30% mitigation at ~100 USD $MgCO_2^{-1}$ and 0% mitigation at ~10 USD $MgCO_2^{-1}$.

Avoided Woodfuel Harvest

Our maximum mitigation potential for avoided woodfuel harvest was drawn from a recent comprehensive analysis of global unsustainable woodfuel harvest levels (23). This analysis estimates 300 TgCe yr^{-1} woodfuel emissions for the year 2009, but qualifies that approximately 32% of these emissions originate from land cover change byproducts. We omit this proportion of baseline emissions from our analysis to avoid double counting with other avoided forest loss pathways, and follow their assumption that improved cookstoves can reduce carbon emissions by 49% (Scenario 2), resulting in an overall maximum mitigation potential of 100 TgCe yr^{-1}.

Uncertainty

Following uncertainty option 1, we calculate 11% uncertainty of maximum woodfuel mitigation potential, based on propagation of 9% uncertainty in baseline woodfuel emissions, 6% uncertainty in land cover change overlap, and 3% uncertainty in cookstove efficiency as report in (23).

Mitigation Targets

We are unaware of available literature on marginal abatement cost curves applicable to this pathway. We assumed this is a relatively expensive pathway in the context of other forest pathways and based on conversations with practitioners and assigned a 30% mitigation at ~100 USD $MgCO_2^{-1}$ and 0% mitigation at ~10 USD $MgCO_2^{-1}$.

Avoided Grassland Conversion

Grasslands here include temperate grasslands, tropical savannahs, and shrublands. We focus on conversion of grasslands to cropland, as the carbon emission implications of the conversion to other habitat types are unclear. Using satellite observations of land cover from the DIScover (1km resolution) (254), Ramankuty et al. (24) modelled the historical area of croplands globally. Combined with the BOIME3 dataset showing the potential vegetation in the “absence of human activity” (255), Ramankuty et al. were able to estimate the area of land conversion driven by the expansion of cropland in different habitat types. They found a global grassland conversion rate of 1.7 Mha yr^{-1} based on the area lost between 1980 and 1990 (24) (Table S11).

Table S11. Global grassland conversion rates and carbon stocks

Grassland Type	Conversion rate	Carbon Stocks	C deduction from cultivation	Committed emissions	Maximum potential
	Mha yr^{-1}	MgC ha^{-1} (0-30cm depth)	%	MgC ha^{-1}	TgC
Temperate	0.7	61.4	30	18.4	12.9
Tropical	1.0	62.7	30	18.8	18.8
Total (Mean)	1.7	(62.2)	(30)	(18.65)	32

We considered soil carbon losses in the 0-30cm soil depth, where carbon losses are greatest and best measured (26). The percent loss of carbon in the top 30cm of grassland soils upon conversion to agriculture is generally between 20 and 40 percent (26, 256–258). We assumed committed soil carbon losses of 30% from the 0-30cm horizon upon grassland conversion to tilled agricultural land (26).

We use findings from Jobbagy (25) to estimate the soil carbon pool in the top 30 cm. They estimate a carbon pool of 68.4 MgC ha^{-1} and 62.7 MgC ha^{-1} for temperate and tropical grasslands, respectively. Their analysis is based on a synthesis of a global database of >2700 studies, with 121 studies in temperate grasslands and 35 studies in tropical grasslands. Based on the above numbers, current global rates of grassland conversion to cropland have committed emissions of 32 TgC yr^{-1} (Table S11).

Uncertainty

We used expert elicitation to estimate uncertainty of the extent of grassland conversion to agriculture (cropland) (N=3 experts). We used reported 95% confidence intervals of flux uncertainty (25). Our overall maximum mitigation potential estimate is likely conservative because it does not include net avoided emissions from root biomass.

Mitigation Targets

In the absence of available MAC curves applicable to this pathway, we assumed a 30% mitigation level for <2°C ambition. The ongoing demand for arable land, and the relatively small emissions per ha compared with forest and wetland biomes, suggests a relatively high cost per Mg of avoided CO_2 emissions.

Biochar

Our estimate is derived from the amount of crop residue available for pyrolysis, assuming that this will form the bulk of the resource for any biochar industry. Crop residue availability for biochar in 2030 was estimated from assumptions about global crop production, competing demands for residue, and the fraction of residue that must be left in fields to maintain soil condition and carbon levels. Based on a review of several studies that have assessed residue potential for bioenergy uses (27, 28), we identified a mid-range value of 30 EJ yr^{-1}. We converted this value to 1.67 Pg yr^{-1} dry matter (dm) available by 2050, assuming 18

GJ Mg^{-1} average specific energy (259). Woolf et al. (90) report above-ground residues generated in 2009, less those fed to livestock, as 3.36 Pg dm yr^{-1} (assuming 45% carbon content). Thus, 1.67 Pg yr^{-1} is about half of current unused above-ground crop residues.

We assume the average carbon content of residues is 45% (29) and the amount of carbon retained in biochar is 50% (32, 33). 97% of biochar carbon represents the recalcitrant fraction, with a long but highly uncertain mean residence time of 556 years in soils (32, 33). 79.6% of char carbon is estimated to persist on a timescale of >100 years. As such, we estimate "long-term" mitigation at 0.18 MgCe per Mg dm of dry feedstock. We do not assume that the pyrolysis process is used to offset fossil fuel use. We also do not include any second order effects of biochar on soil organic matter or emissions of N_2O or CH_4, based on recent meta-analyses showing these effects to be neutral or weakly beneficial on average (91, 92).

We estimate total mitigation potential as:

$$1{,}670 \text{ Tg dm yr}^{-1} * 0.18 \text{ MgCe (Mg dm)}^{-1} = 300 \text{ TgCe yr}^{-1}$$

Our new maximum estimate of potential carbon sequestration, derived from independent data for available crop residues and experimental measurements of the fraction of biomass carbon that becomes recalcitrant to decomposition, is 70-87% lower than those of Woolf et al. (90), largely owing to our exclusion of energy crops and estimated mitigation from energy generation and reductions in non-CO2 GHGs.

Uncertainty

To estimate uncertainty in the amount of resource available for biochar, we compiled nine estimates of sustainable availability of agricultural residues for bioenergy either today or in 2050 (27, 260–263). We use these estimates to inform an option 3 estimate, calculating a 95% confidence interval range of 0.94-2.07 Pg dry biomass resource in 2030.

To estimate uncertainty in the mitigation per unit biomass, we assess confidence intervals for each term of the following equation:

$$M = F_C * Y_C * f_R * F_{100}$$

Where M is mitigation per unit biomass, F_C is carbon content of residue feedstocks, Y_C is "carbon yield" (% of feedstock carbon retained in char during pyrolysis), f_R is the fraction of char carbon that is recalcitrant, and F_{100} is the fraction of recalcitrant carbon remaining after 100 years. f_R and F_{100} are drawn directly from a recent meta-analysis of 121 data points (92). We used option 3 to generate confidence intervals for F_C and Y_C based on studies of residue feedstocks (29, 264–267) and pyrolysis (264, 265, 267, 268). We used IPCC Uncertainty Approach 1 to combine these into a single figure, with a final 95% confidence interval range of 16.7-20.6%.

Mitigation Targets

In the absence of available global MAC curves applicable to this pathway, we assumed relatively high costs per Mg of avoided CO_2 emissions, given the labor and technical requirements of implementing biochar across extensive and often remote agricultural landscapes. Our assignments are consistent with a MAC curve for biochar in Germany (269).

Cropland Nutrient Management

We derive the business as usual emissions level for this pathway (2,612 $TgCO_2e$ yr^{-1}, 22% increase from 2010) from Bodirsky et al. (34), who use a range of development scenarios to project total food and feed demand to 2050. Bodirsky et al. develop country-specific nitrogen budgets balancing nutrient demand (crop and livestock production) and supply (atmospheric deposition, manure, legumes etc.). Based on a series of assumptions about nitrogen use efficiency, they then estimate the amount of synthetic and manure fertilizer needed to meet nutrient shortfalls in different regions. The end result is a projected amount of nitrogen fertilizer applied in order to meet global food demand in 2050.

We use as our baseline the more pessimistic of the three development scenarios, “SSP3”, since this tracks closest to a “business as usual” scenario. This reflects significant population growth and increased consumption, and only minimal increases in nitrogen use efficiency. Total fertilizer use rises from 116 TgN in 2010 to 163 TgN in 2050, and manure generated from confined livestock also increases substantially from 31 TgN to 52 TgN. Interpolating linearly, this implies a baseline use of 139.5 TgN fertilizer and 41.5 TgN manure in 2030.

Translating into business as usual (BAU) N_2O emissions, we follow Davidson (37) in using an emissions factor of 2.54% for fertilizer N and 2.03% for manure N, or 11.9 and 9.5 $MgCO_2e$ per MgN applied. This is slightly higher than IPCC emissions factors (2% direct + indirect), but consistent with range of estimates reviewed by Snyder et al. (38) of 2-5%. Total N_2O emissions from fertilizer and manure are therefore 2,054 $TgCO_2e$ yr^{-1}.

Finally, we acknowledge that fertilizer production itself is a significant source of greenhouse gas emissions, both through CO_2 emitted during ammonia production and excess nitrous oxide during nitric acid production. Snyder et al. (38), reviewing a range of estimates, report an overall upstream emissions factor of about 4 $kgCO_2e$ kgN^{-1} averaged over the mix of different fertilizers used in North America. Assuming no major technology change under a business as usual scenario to 2030, this adds 34% to in-field emissions from synthetic fertilizer, bringing the business as usual total in 2030 to 2,612 $TgCO_2e$ yr^{-1}.

Saving in N_2O emissions under max mitigation: 706 $TgCO_2e$ yr^{-1}

To model the effect of more efficient nutrient management, Bodirsky et al. (34). use a factor called “Soil Nutrient Uptake Efficiency” (SNUPE). SNUPE refers to how efficiently humanity manages nutrients within soils, including biologically fixed or deposited nitrogen as well as fertilizer. They estimate SNUPE at about 53% globally today, and predict it rises to 55% in the BAU scenario for 2050.

In the maximum mitigation scenario, they assume SNUPE can be increased globally to a 75% maximum in 2050. This mainly represents more efficient use of fertilizer, but also better use of other N flows such as manure and legumes to reduce the total amount of synthetic fertilizer needed. This 75% maximum, halving relative losses, is similar to that quoted by Oenema et al. (35) (70%) and less than that implied by Mueller et al. (36).

Assuming again that humanity approaches this maximum linearly towards 2050, SNUPE would reach 65% globally in 2030, which is 5% higher than the current European average. The amount of fertilizer used would decrease by 32% (compared to the BAU) to 95 TgN yr^{-1}, leading to total emissions of 1,906 $TgCO_2e$ yr^{-1} and a saving of 706 $TgCO_2e$ yr^{-1} (= 192.6 TgCe yr^{-1}). Note that this assumes no change in the emissions per Tg from fertilizer production.

Uncertainty

Given the relative complexity of our calculation, we approximate the uncertainty in this pathway with a simplified version of the calculation. The equation used is:

$$Potential = F * x * (EF_{N20} + EF_{CO2})$$

Where F is total nitrogen in synthetic fertilizer use in 2030, x is the percentage by which we are technically able to reduce synthetic fertilizer use through better fertilizer and manure management, EF_{N20} is the N_2O released Mg^{-1} of nitrogen in fertilizer used and EF_{CO2} is the CO_2 released Mg^{-1} of nitrogen in fertilizer produced. We follow option 3 approaches for each term using figures drawn or calculated from other sources that best reflect the suite of efficiency measures captured by this pathway.

To capture measurement uncertainties rather than uncertainties in assumptions of future fertilizer use, we construct a distribution out of six estimates for the year 2000 (270–272) and apply the resulting relative uncertainty of 7.2% to our assumed 2030 estimate of 139.5 Tg yr^{-1}. We construct similar confidence intervals for x (35, 36, 273–275), EF_{N20} (37, 38) and EF_{CO2} (38) from literature estimates. IPCC Approach 1 uncertainty calculations were used to generate confidence intervals for total avoided N use $F * x$ (32.6-58.0 TgN yr^{-1}) and overall emissions flux per ha $EF_{N20} + EF_{CO2}$ (10.5-19.5 $MgCO_2e$ MgN^{-1}) for Monte Carlo propagation.

Mitigation Targets

We assigned mitigation targets based on our expert opinion as MAC curve studies matching our definition of the pathway were not available. For example, the MAC curves for Cropland Nutrient Management from EPA (119) includes only emission reductions due to mineral-based cropland soils processes. This omits other contributors to emission reductions considered here, such as from fertilizer manufacturing, increased use of manures, residue N, mineralization and asymbiotic fixation, as well as increased use of cover crops and crop rotations. We observed low or negative costs associated with avoiding unnecessary use of excessive fertilizers, particularly in the context of countries (e.g. China) where regulations have created perverse subsidies for excessive fertilizer applications.

Conservation Agriculture

Changing agricultural practices and cropping systems can have widely varying effects on soil carbon (95, 276). However, among the practices with the most consistent positive recorded effects on carbon sequestration is the cultivation of additional cover crops in fallow periods between main crops (39).

Poeplau & Don (39) cite a study by Siebert et al. (93) that investigates global cropland use intensity, and relative fallow periods, in the year 2000. Based on this dataset, they identify approximately 800 million hectares of active cropland that is not already planted with a winter crop or under permanent perennial cropping, and thus currently have an off-season fallow period that may be suitable for additional cover crop planting. They further discount this value by 50% (= 400 Mha) to exclude land where climatic factors require a fallow period or otherwise preclude a cover crop, and cropping systems where harvest is too late to allow cover crop planting.

In our baseline/BAU case, we assume the area planted with cover crops remains roughly constant at 2000 levels. Poeplau & Don (39) cite several regional studies from 2007-2013 reporting low uptake of cover crops, qualitatively supporting this assumption.

Poeplau & Don (39) is the most comprehensive and rigorous meta-analysis of carbon sequestration due to cover crops to date, and finds an average effect that is remarkably consistent across crop choice, tillage regime and climate. It is also consistent with the Eagle et al. (276) mean value of 0.37 MgC ha^{-1} yr^{-1}. These estimates refer to cover crops that left in the field as green manure or mulch rather than harvested. Poeplau and Don's estimate is based on field observations of cover crop implementation for up to 54 years. Their model suggests that a new equilibrium is reach after 155 years. We assume that their sequestration rate applies for at least 50 years.

No-till agriculture not included in our estimate

A second often-cited driver of soil carbon gains in agricultural soils is a shift to reduced-tillage or zero-tillage systems. Originally developed to reduce soil erosion, no-till has been promoted widely as a carbon sequestration practice (277–281). However, several more recent expert reviews of the evidence base have concluded that the evidence behind consistent carbon sequestration through practicing reduced or zero-tillage is weak or inconclusive (96), and that most reports of strong positive effects on soil carbon levels were at least partly due to inherent biases in soil sampling technique (94, 95, 97, 98).

For example, Baker et al. (97) found that in all cases where soil had been sampled to >30cm depth, apparent gains in carbon in shallow depths were offset by *decreases* at greater depths, leading to no net gain over the whole soil profile. Powlson et al. (94) also suggest that many experiments introduce systematic overestimates by measuring the change in soil carbon concentration (%C by mass) without also accounting for changes in the soil bulk density profile (mass of soil per cm^3) under no-till.

In addition, no-till may result in an increase in N_2O emissions, eliminating any net greenhouse gas mitigation benefit (282, 283). Specifically, N_2O emissions tend to increase, compared to conventional tillage, in the first ten years of no-till, but then tend to be reduced compared to conventional tillage. However, no-till is often not implemented continuously for longer than ten years. For fields where no-till has been implemented, the average time in no-till before tillage in the corn belt is less than three years. Less than 14% of no-till fields have been in continuous no till for at least 6 years (284).

For the purposes of calculations here, we therefore do not attempt to calculate a global figure for carbon sequestration through adoption of zero-tillage. While it is likely that cropping systems including reduced or zero tillage do indeed have some potential to sequester carbon in soils, it is not currently possible to reliably estimate such potential.

Uncertainty

We use a global estimate of SOC sequestration and associated uncertainty of 0.12 ± 0.03 PgC yr^{-1} (39).

Mitigation Targets

Our maximum estimate described above already discounted areas where cover crops would be displacing more profitable crops or would otherwise be unsuitable, therefore we assume a 90% mitigation rate is possible at 100 USD CO_2e^{-1} and a 60% mitigation rate at 10 USD CO_2e^{-1}. Experience to date suggests that cover crops outside these contexts, especially leguminous crops, tend to provide net economic value in reduced soil erosion, improved fertility and additional crop value (285). Our assigned mitigation target was also informed by IPCC (117) cost estimates for the <2°C ambition level (<100 USD $MgCO_2$).

Trees in Croplands

We consider three ways in which trees can be increased in cropland: windbreaks (also called shelterbelts), alley cropping, and farmer managed natural regeneration (FMNR). There are other types of trees in agriculture that represent important opportunities for climate mitigation, but are not counted here to avoid double-counting with the reforestation pathway. Specifically, silvopastoralism and forested riparian buffers both involve planting sufficient tree cover to be included within our reforestation pathway, and are accounted for there.

Windbreaks

Windbreaks can help reduce soil erosion, evaporation and wind stress on crops, and have been shown in a variety of contexts and climates to benefit yields in the sheltered area (286–290). However, this is not always the case, depending on the crop, climate and windbreak configuration (288–290). We assume first that windbreaks would be most suitable on cropland with little to no existing tree cover. Zomer et al. (99) estimate that 54% of agricultural lands have <10% tree cover. Globally, there is about 1.4 Gha of annual cropland (11)). To avoid double counting with FMNR, we exclude African cropland, leaving an estimated area of 635 Mha. In the absence of any global assessment of current windbreak use, or of other factors determining windbreak viability, we assumed only 50% of this remaining area could support additional windbreaks with neutral or positive effects on overall yield: a total of 318 Mha.

Our review of the literature found an average of 0.175 MgC ha^{-1} yr^{-1} additional sequestration in biomass and soils (42–46). These numbers reflect the fact that windbreaks only cover ~5% of the cropland (i.e. the sequestration rates just on the portion of the field with the windbreak would be 20 times higher; (100)).

Alley Cropping

Alley cropping refers to planting trees in rows with crops in between. Udawatta and Jose (41) estimate that 22% of cropland in the USA is suitable for alley cropping. We applied this to the area of 635 Mha of treeless, annual cropland, outside of Africa, calculated for the maximum area for windbreaks. This yields a 140 Mha maximum area of implementation for alley cropping.

Our review of the literature found an average of 1.2 MgC ha^{-1} yr^{-1} in biomass and soils (47, 49–53, 101). We restricted our studies to those with a paired comparison of cropland without alley cropping.

Farmer Managed Natural Regeneration (FMNR)

FMNR is the assisted natural regeneration of scattered trees within cropland, especially in drylands, for productivity, soil quality and erosion control benefits. The end state of FMNR is comparable to the traditional African dryland agriculture system of agroforestry parklands (291). Application of FMNR in this analysis is considered specific to Africa.WRI analysis identifies 300 Mha of dry cropland in Africa with rainfall between 400-1,000 mm yr^{-1} (54). Areas suitable for additional FMNR would have very low current tree cover, but require a stock of existing live stumps and root systems to act as sources of regeneration. As with windbreaks, we assume 50% of this cropland area (150 Mha) is thus technically suitable for such regeneration.

We assume an average sequestration of 0.4 MgC ha^{-1} yr^{-1} in biomass and soils based on a review of agroforestry parklands by Luedeling et al. (55).

Uncertainty

Available published data did not permit options 1-3 for empirical estimation of uncertainty, so we employed expert elicitation (N = 3 experts) to estimate the uncertainty of (i) the potential extent of each form of the three agroforestry systems described above (assuming FMNR exclusively applicable in Africa), and (ii) mean anticipated tree biomass sequestration for each system.

Mitigation Targets

Our target assignments are consistent with previous studies on the emission abatement from agroforestry reported by the IPCC (Chapter 11 Fig 11.13) (117). Since we have tried to limit our windbreak and FMNR adoption to areas where yield effects are positive, we assign these a higher economic mitigation target than for alley cropping.

Grazing Pathways: Optimal Intensity, Legumes in Pastures, Improved Feed, Animal Management

Improved grazing management can increase soil carbon pools, and can also reduce greenhouse gas emissions from other aspects of the life cycle of livestock production. First, we consider changes in soil carbon based on 1) grazing optimization on rangeland, and planted pastures, and 2) sowing legumes in planted pastures. Grazing optimization was defined "as the offtake rate that led to maximum forage production" (56). This prescribes a decrease in stocking rates in areas that are over-grazed and an increase in stocking rates in areas that are under-grazed, but with the net result of increased forage offtake and livestock production (56). The legume sowing estimate is restricted to planted pastures and to where sowing legumes would have net sequestration, taking into account the increases in N_2O emissions associated with the planted legumes (56).

Non-soil carbon improvements in management can also reduce emissions. We include reductions in emissions from improved feed digestibility and animal management (292). Improved feed management represents "inclusion of energy-dense feeds (e.g. cereal grains) in the ration, with the greatest potential in production systems that utilize little or no grain to feed animals, which are common in many parts of the world." (292). While this reduces methane emissions from enteric fermentation, more importantly this allows a reduction in total animal numbers needed to supply the same level of meat and milk demand (103). Improved animal management includes use of improved livestock breeds, and increased reproductive performance, health, and liveweight gain. Both Improved Feed and Animal Management pathways assume that demand for livestock products is relatively inelastic, such that improved efficiency of production reduces livestock numbers and emissions. We do not include changes in manure management or feed additives. The costs of reducing emissions via manure management have been estimated at 200 USD $MgCO_2e^{-1}$ (107) and the total potential is below 100 $TgCO_2e\ yr^{-1}$ (292). Feed additives have uncertain long-term effects on emissions due to adaptation of rumen microbial systems, potential environmental and health impacts have not yet been adequately studied, and public acceptance is uncertain.

Mapping Country-Level Mitigation

For grazing optimization and legumes in pastures, we mapped maximum mitigation to countries by using spatial data from (56). Improved feed management and improved animal management pathways were not mapped.

Uncertainty

Uncertainty for animal management and grazing optimization are drawn from Herrero et al. (292). Uncertainty for improved feed was calculated using option three (see above) using estimates from Havlik et al (108), Herrero et al. (292) and Gerber et al (106). Uncertainty for the legumes in pastures pathway was obtained via expert elicitation (N=3 experts). The mean estimate for the climate mitigation potential for sowing legumes in planted pastures is conservative (and toward the lower end of stated confidence intervals) because Henderson et al. (56) quantified soil C sequestration potential only in areas where sowing legumes would lead to net greenhouse gas benefits (i.e., soil C sequestration exceeded increased CO_2e due to greater N_2O emissions).

Mitigation Targets

Target assignments for optimal intensity, legumes, and improved feed are based on global model MAC curves (293). Our target assignments for animal management were informed by IPCC and EPA studies (117, 119) while noting that sources did not fully match our grazing animal management pathway definition.

Improved Rice Cultivation

Much of the world's rice is typically grown in standing water, generating anaerobic conditions in the soil, which causes methane and N_2O emissions, comprising 10-14% of anthropogenic methane emissions (152, 294). Water management techniques such as alternate wetting and drying (AWD) and midseason drainage (MSD) limit the time rice paddies spend in an anaerobic state thereby reduce annual methane emissions while at the same time saving water (152). Additional management techniques applied to upland rice such as fertilizer applications, residue and tillage management practices reduce the amounts of nitrogen and carbon emissions (295).

Projected total global emissions associated with rice cultivation in 2030 are estimated to be 755 $TgCO_2e$ yr^{-1} (59). This includes 473 $TgCO_2e$ yr^{-1} methane and 341 $TgCO_2e$ yr^{-1} nitrous oxide offset by soil carbon sequestration of 16 TgCe yr^{-1}. Using twenty-six mitigation scenarios produced from the Denitrification-Decomposition (DNDC) model for both dryland and flooded rice the US EPA 2013 study reports a 35% reduction in combined Ce emissions from improved cultivation techniques. We apply the EPA's 35% mitigation potential value to the EPA's estimated total global emissions from rice production in 2030 (755 $TgCO_2e$ yr^{-1}) to arrive at a maximum mitigation potential of 265 $TgCO_2e$ yr^{-1} from improving rice cultivation (59). Compared to an IPCC, 2006 study (296) that reports a 40% reduction in methane from midseason drainage, this EPA-derived estimate is conservative while being more inclusive, since it includes nitrous oxide and carbon flux in stated mitigation potential.

Uncertainty

Using option three we calculated a ±17% uncertainty to the maximum mitigation potential of flooded and upland rice management practices based on a comparison of our primary source (59) and three other sources (117, 294, 297) scaled to our 2030 baseline year.

Mitigation Targets

Our mitigation targets are based on the averages of Golub et al. (298), Beach et al. (118) and EPA (119) and are aligned with the values reported by the IPCC (117).

Avoided Coastal Wetland Impacts

We define coastal wetland conversion as the anthropogenic loss of organic carbon stocks in mangroves, saltmarshes, and seagrass ecosystems. For mangroves, we calculate the extent of conversion based on best estimates of current extent (13.8 ±1.24 Mha, (77)), and recently reported loss rates loss rate (0.7% (66)). We estimated mangrove carbon stocks by combining the mean of seven above and below-ground vegetation biomass estimates from the literature (194 ±76 MgC ha^{-1}, (65–69, 71, 299)), with the most recent and comprehensive global estimate of soil organic carbon (SOC) density in the top meter (369

± 6.8 MgC ha^{-1} (63)). For saltmarshes and seagrasses, we follow estimates of loss rate and carbon stocks from Pendleton et al. (65).

For all three coastal wetland ecosystems, flux is the sum of vegetation biomass emissions (assuming 100% committed emissions within a 20-year time horizon), and SOC emissions – calculated as the product of SOC stocks and percent carbon stock released into the atmosphere post disturbance (63% ± 25% (65, 66, 300)), and percent committed emissions released in the first 20 years post-disturbance. Like all our avoided loss pathways (avoided forest conversion, avoided woodfuel harvest, avoided peatland conversion, and avoided grassland loss), avoided coastal wetland conversion is calculated based on 20 year "committed emissions" accounting approach (209). Given that coastal wetland soil organic carbon pools are lost over a long time frame, the 20 year accounting window captures 86% ± 11% of SOC emissions based on estimated half-life of 7.5 years (65). Therefore, 54% of carbon in coastal wetlands is lost within in 20 years.

Mapping Country-Level Mitigation

Only the mangroves component of this pathway was mapped. We mapped our mangrove maximum mitigation potential using the annual proportion of mangroves lost in each country per year reported in (301).

Uncertainty

To calculate uncertainty, we follow option 1 uncertainty approach, defining 95% confidence intervals for all variables based on direct error estimates from the literature (e.g. mangrove SOC (63)) or variation between 3 or more studies (e.g. mangrove vegetation carbon stocks).

Mitigation Targets

Our coastal wetland mitigation targets are informed by a recent study (62) reporting that a large percentage of mangrove conversion is possible at costs <10 USD $MgCO_2^{-1}$. In the absence of cost curve literature for other pathway elements (salt marsh, sea grass) we assumed similar cost-effectiveness as mangrove systems.

Avoided Peatland Impacts

We estimated emissions from conversion of peatlands in three climate zones: boreal, temperate, and tropical. For each type, we calculated annual loss rates and annual emission rates to determine the total emissions upon conversion using a 20-year time horizon. To determine the recent annual conversion rate of freshwater peatlands we used The International Mire Conservation Group Global Peatland Database (73, 111, 112). We aggregated the reported peatland area by climate zone to determine the change in intact tropical, temperate, and boreal peatland during the 18 year period between 1990 and 2008 (73). We calculated the rate of decrease of intact (versus degraded) peatlands between 1990 and 2008. We also used the peatland database for information on the extent of forested peatlands and country level CO_2 emissions (Table S12).

Table S12. Carbon stocks and conversion rates for global peatlands

	Conversion Rate Mha yr^{-1}	Carbon Stocks Biomass MgC ha^{-1}	 Soil MgC ha^{-1}	 Total MgC ha^{-1}
Tropical Peatland	0.57 (73)	100.1 (208)	217.5 (73)	317.54
Temperate Peatland	0.14 (73)	4.1 (75)	141.9 (73)	146.08
Boreal Peatland	0.07 (73)	2.6 (75)	56.6 (73)	59.20
Weighted Average		75.96	190.71	266.67

Our accounting of peatland carbon stock estimates includes both biomass (above ground and belowground) and soil carbon. Based on Joosten (73) we calculated the percentage of forested peatlands from all peatlands for each climate zone (Tropical Peatland 55.7%, Temperate Peatland 20.7%, Boreal Peatland 13%) and adjusted the above ground biomass carbon estimates based on this percentage in our total carbon stocks per unit area (Table S12). We assumed that within 20 years all biomass and soil carbon to a one meter depth would be emitted following conversion (302).

We calculated a per area annual emission rate for each country using country-level data on area of degraded (drained and deforested) peatlands and emissions in 2008 (73). We calculated a per area annual emission rate for each climate zone based on the weighted average of these country-level emissions. Using this rate, we calculated the 'committed emissions' over a 20-year time horizon by multiplying the annual rate by twenty (Table S12). Although Joosten (73) does not include emissions from tropical peatland fires, the loss of carbon stocks resulting from fire is likely to be similar to carbon losses from decomposition over our 20 year time-horizon.

Mapping Country-Level Mitigation

We mapped avoided peatland impacts using country-level estimates of the extent of peatland lost (73), and the avoidable flux reported in Table S12.

Uncertainty

Available published data did not permit options 1-3 described above for empirical estimation of uncertainty, so we employed expert elicitation (N = 3 experts elicited) to estimate the uncertainty of (i) the global mean rate of peatland conversion, and (ii) soil carbon stocks to 1-meter depth (which we assumed would decompose within 20 years if drained to that depth).

Mitigation Targets

We were not able to identify cost curve literature directly applicable to this pathway, so we assumed similar cost-effectiveness for the analogous coastal wetlands pathway.

Coastal Wetland Restoration and Peatland Restoration

We consider coastal wetland and peatland restoration mitigation separately. In each of these wetland types, restoration alters both the rate of carbon sequestration through soil accumulation and carbon loss through oxidation and combustion.

We estimate potential extent of wetland restoration based on the extent of “degraded” wetlands. For peatlands, this is derived from Joosten (73), a review of country-level peatland statistics. We use peatland area estimates for 2008, representing a snapshot of peatlands in various states of degradation. For mangroves and saltmarshes, we calculate the total historic area lost by combining estimates of global extent (described in coastal wetlands avoided conversion pathway methods above) and percent of original extent disturbed (76).

To calculate the rate of soil carbon sequestration in restored coastal wetlands, we use published carbon burial rates (76) and mangrove vegetation sequestration rates (78), assuming negligible vegetation sequestration in saltmarshes and seagrass. Due to controversy in the literature about the timing and net atmospheric effect of methane emissions in restored peatlands, we choose to omit a sequestration benefit from peatland restoration in our calculations (79–81). This conservative assumption has a small impact on the overall estimate of biophysical mitigation potential, as total sequestration is heavily outweighed by avoided loss. Wetland vegetation biomass growth rates for mangroves and peatlands were added to soil carbon sequestration based on available estimates in the literature (7, 10, 78).

The majority of wetland restoration mitigation is avoided emissions from re-wetting (peatlands) and revegetation (coastal wetlands). To calculate these avoided emissions, we assume degraded wetlands have already lost 50% of their original carbon stocks, based on the reasoning that the global aggregate of degraded wetlands represents a balanced chronosequence of all phases of carbon depletion. This assumption avoids the problematic application of an average rate of global wetland carbon loss, which has very high uncertainty (302–304). Therefore, our wetlands restoration avoided emissions flux factors are 50% of avoided wetlands conversion flux for corresponding ecosystems.

Carbon accounting for the coastal wetland restoration pathways contains both a sequestration component, and an avoided emissions component. Therefore, the maximum potential mitigation expressed here is a mixture of two accounting methods: (i) an annual rate of carbon sequestration per unit area (coastal wetlands only), and (ii) total avoided loss of carbon per unit area (all wetlands). Therefore, to combine (i) and (ii), we divide the SOC avoided emissions by 20 years (our committed emissions time horizon), to achieve our avoided emissions flux rate.

Saturation of annual mitigation potential occurs after about 20 years, at which point we assume the rate of avoided SOC emissions (4.79 MgCe $ha^{-1}yr^{-1}$) decline, because SOC stocks held in drained peatlands would be mostly oxidized after two decades in the absence of re-wetting.

Mapping Country-Level Mitigation

Like avoided peatland impacts, we mapped peatland restoration using the country-level estimates of the extent of degraded peatlands (73) and the avoidable flux reported in Table S11. The coastal wetland restoration pathway was not mapped.

Uncertainty

We used an option 1 approach to calculate uncertainty of coastal wetland restoration – similar to coastal wetland avoided conversion uncertainty described above. We applied literature-based uncertainties to certain variables (e.g. carbon burial (76)) and inter-study variance to others (e.g. seagrass loss rate).

Available published data did not permit options 1-3 for empirical estimation of uncertainty of the global area of degraded peatlands, so we employed expert elicitation for this component of uncertainty (N = 3 experts elicited). Results of expert elicitation for avoided peatland impacts also informed our estimate of peatland restoration mitigation potential uncertainty.

Mitigation Targets

In the absence of prior studies reporting marginal abatement cost (MAC) curves to assign mitigation targets, we constructed them using a comprehensive project database (120), available at https://www.researchgate.net/publication/284714306_Restoration_database . This database contains separate data for saltmarsh, seagrass, and mangrove restoration projects from the published and gray literature. The costs included are the technical costs of restoration (capital and operating costs), but no opportunity or transaction costs, and, hence, they are likely underestimates of the true restoration costs. We retained only the observations with non-missing values for both the area of the project and the cost per ha.

The emissions reductions from a project were calculated using the total project area from the database and a CO_2 sequestration rate per year per ha based on our database. The restoration costs per $MgCO_2$ were calculated by dividing the per ha sequestration rate by the per ha restoration cost. Since all costs had been converted to 2010 values, we used a conversion factor of 1.09 based on CPI to get them to 2015 values.

We used 55 mangrove studies from both developed and developing countries (American Samoa, Australia, Bangladesh, China, Colombia, Ecuador, Hong Kong, India, Indonesia, Malaysia, Philippines, Puerto Rico, Thailand, USA, Venezuela, and Vietnam). We used the sum of emissions abated from all projects to determine the maximum abatement (Fig. S6).

We constructed a saltmarsh cost curve with 51 observations (Fig. S7). In contrast to the mangrove restoration studies, projects were all based in developed countries (UK, US, Australia) and, hence, are likely to overestimate global restoration costs.

The seagrass constructed cost curve (Fig. S8) is based on 35 observations from developed countries only (UK, US, Australia) and is therefore likely to overestimate the global restoration costs. However, seagrass restoration projects tend to be much more expensive than other types of restoration projects (e.g., mangroves) (120). Our assignment of individual mitigation targets based on these constructed cost curves for mangroves, saltmarshes, and seagrass are reported in Table S4.

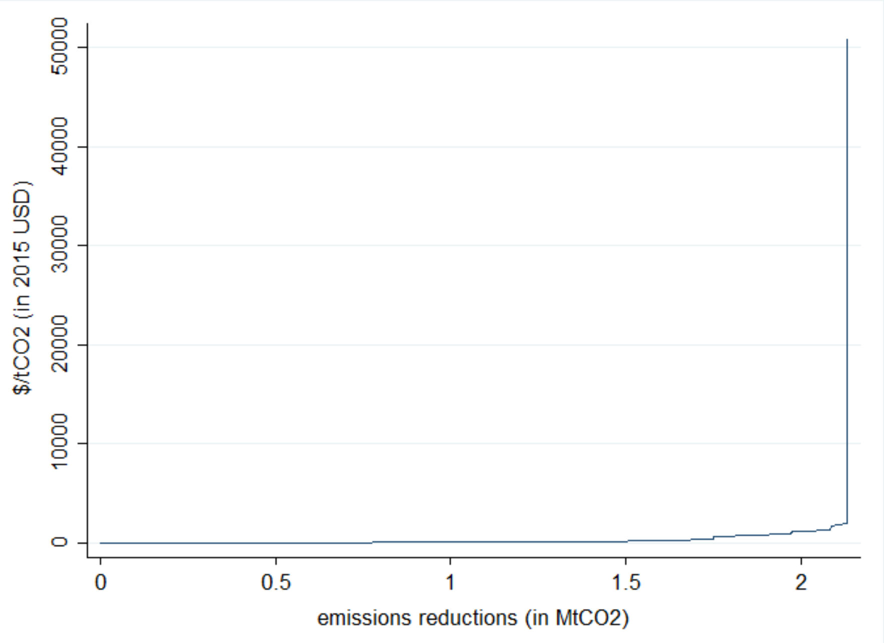


Fig. S6. Cost curve for mangrove restoration.

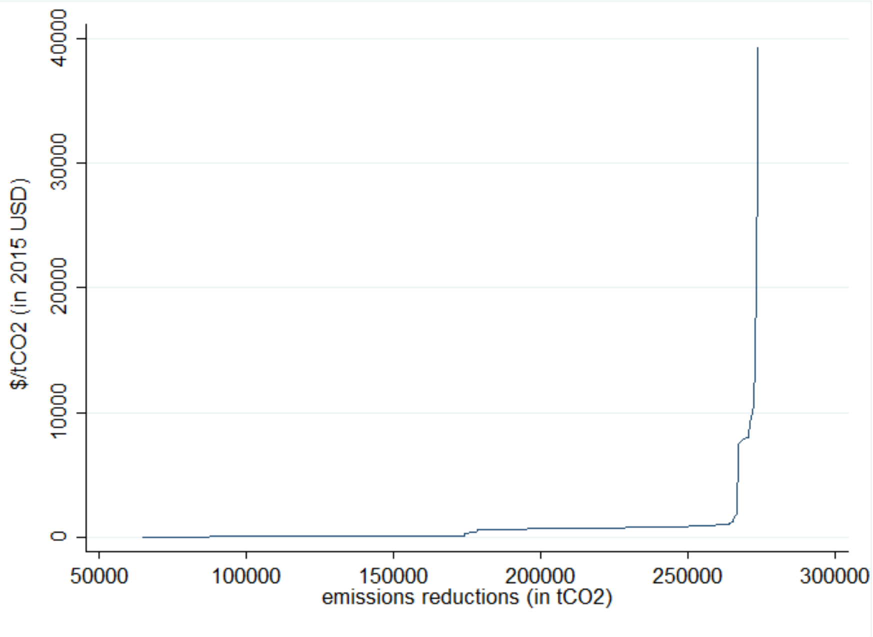


Fig. S7. Cost curve for salt marsh restoration. Two observations with very high values excluded from the graph, but not the calculations.

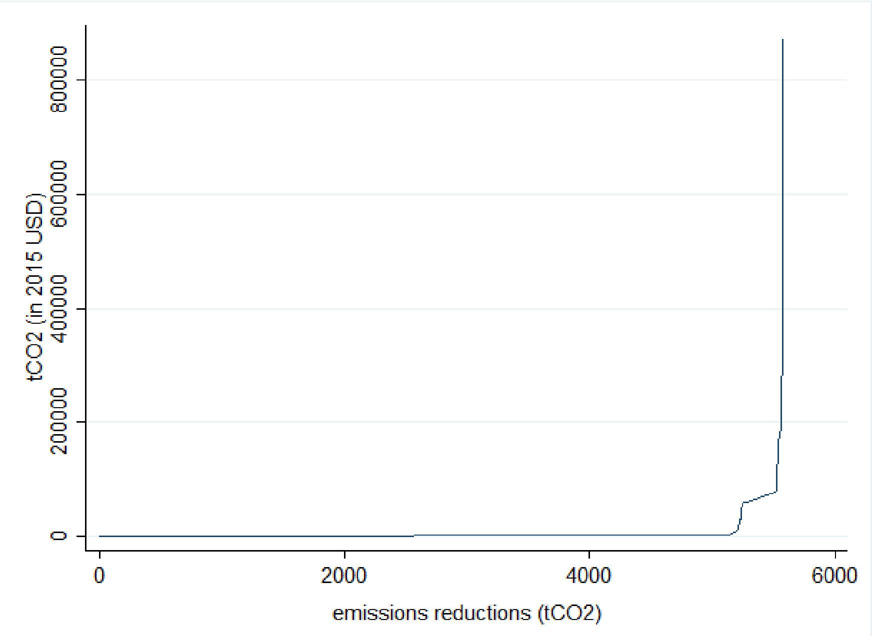


Fig. S8. Cost curve for seagrass restoration.

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