

# Supporting Information Appendix

## Natural climate solutions

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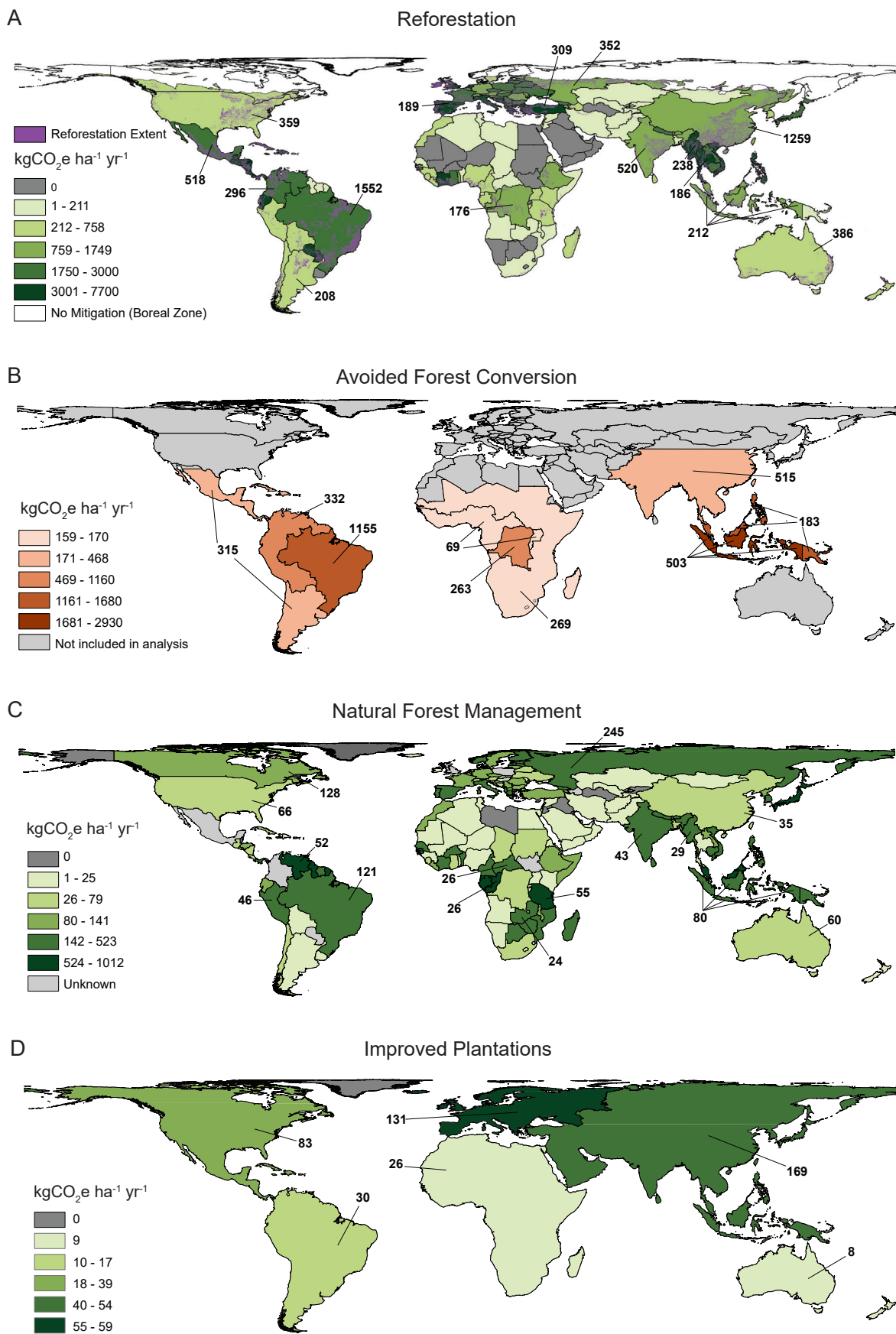
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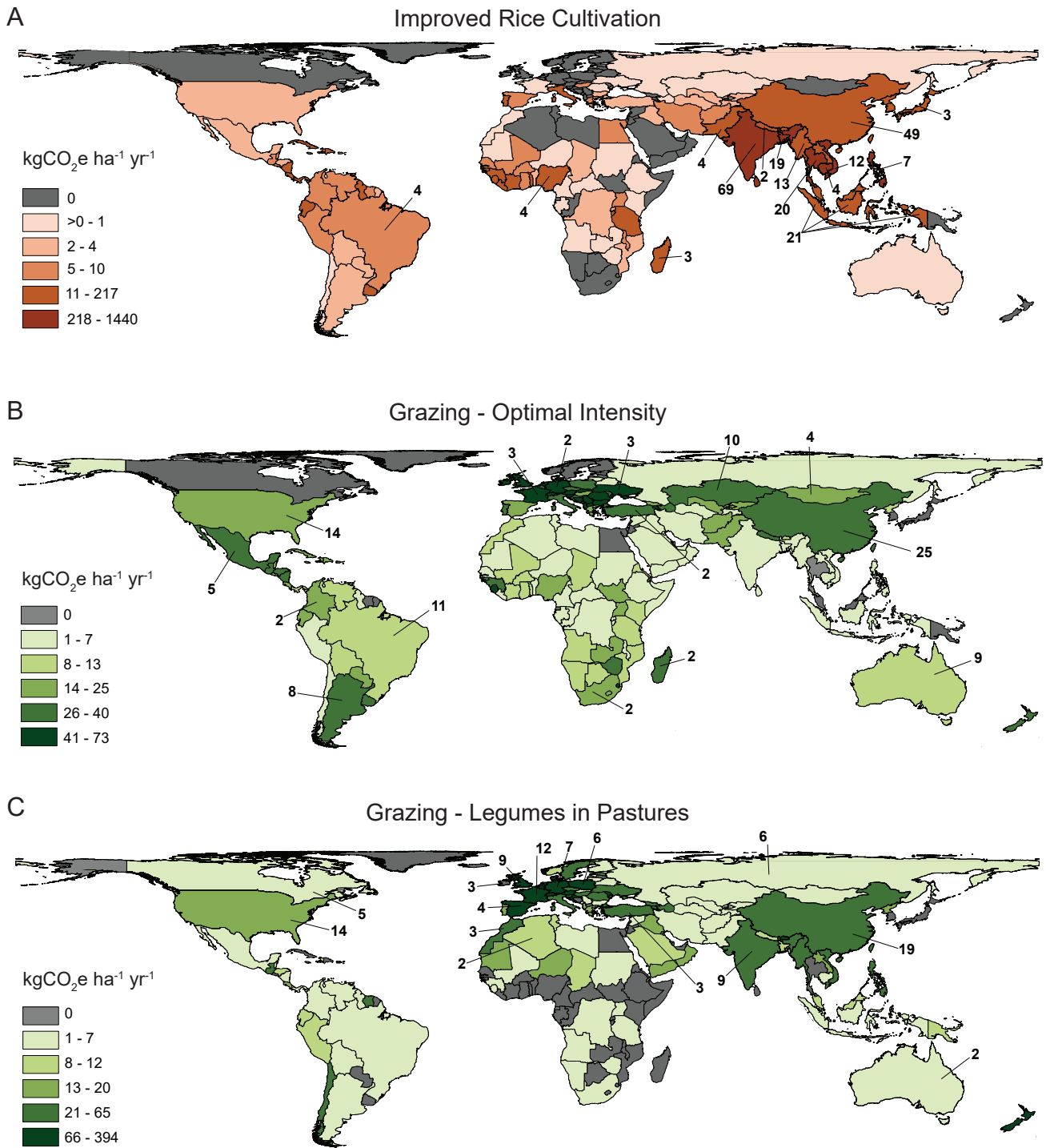
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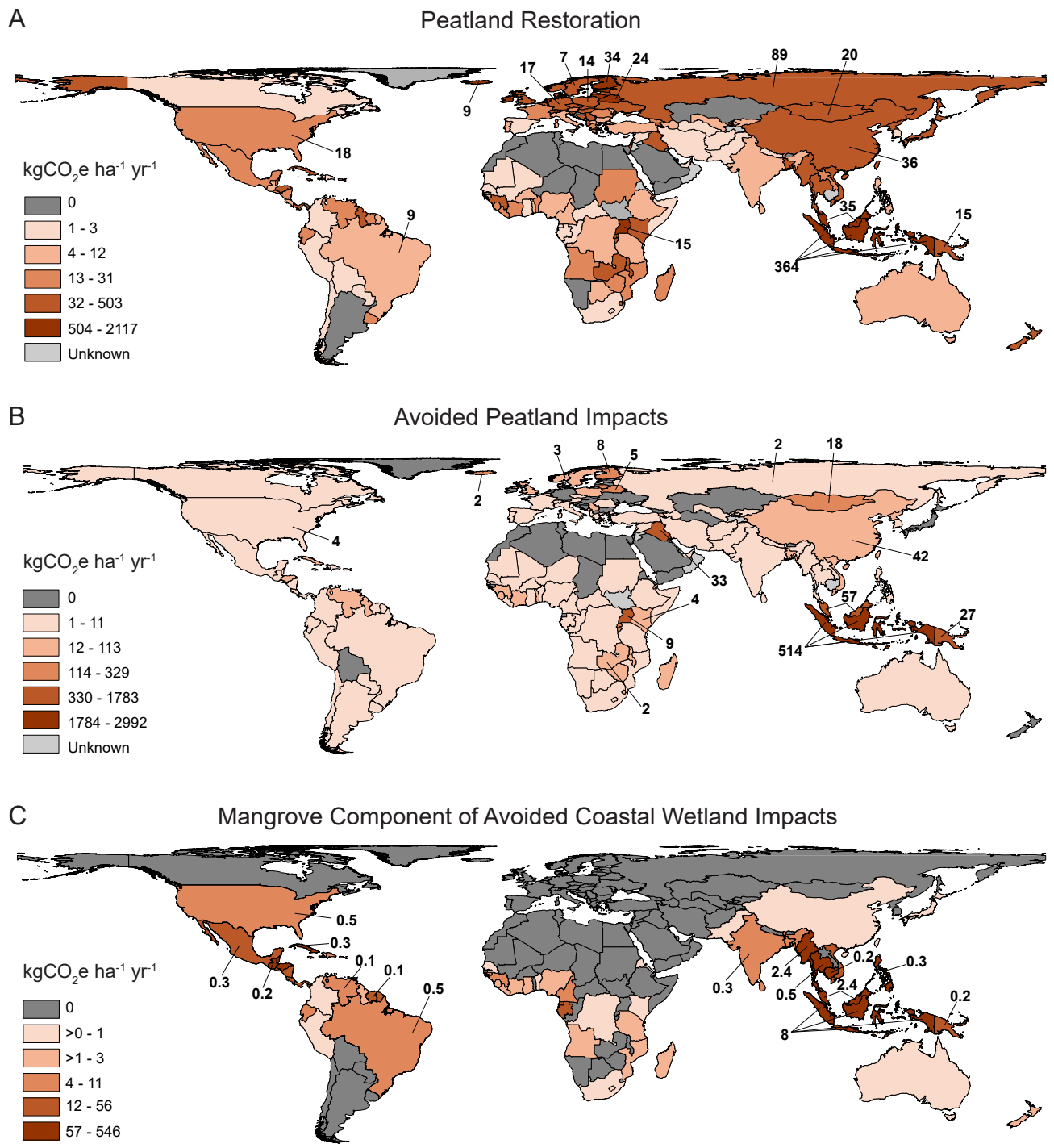
Numbers assigned to countries or regions indicate total TgCO<sub>2</sub>e yr<sup>-1</sup>

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<sub>2</sub>e yr<sup>-1</sup> for the countries/regions with largest mitigation potential. See Table S3 for all country results.



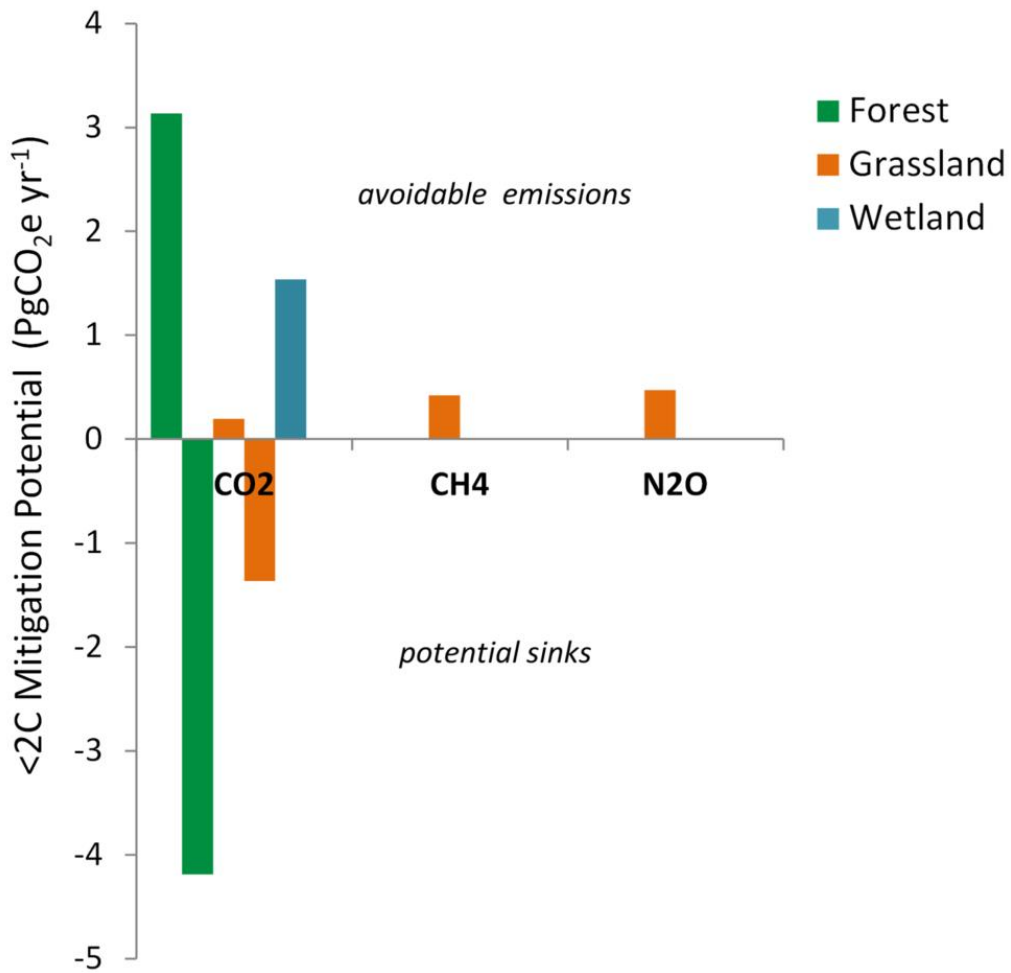
Numbers assigned to countries indicate total TgCO<sub>2</sub>e yr<sup>-1</sup>

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<sub>2</sub>e yr<sup>-1</sup> for the countries/regions with largest mitigation potential. See Table S3 for all country values.



Numbers assigned to countries indicate total TgCO<sub>2</sub>e yr<sup>-1</sup>

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<sub>2</sub>e yr<sup>-1</sup> 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<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O), 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<sub>2</sub>e per year (Tg CO<sub>2</sub>e yr<sup>-1</sup>). 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 <sup>-1</sup> )	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 <sup>-1</sup> yr <sup>-1</sup> )	Flux Uncertainty 95% CI bounds (units as noted)	Baseline Flux in 2030 (TgCO <sub>2</sub> e yr <sup>-1</sup> )	Years until saturation	Maximum Additional Mitigation Potential (TgCO <sub>2</sub> e yr <sup>-1</sup> )	Maximum Mitigation 95% CI bounds (± TgCO <sub>2</sub> e yr <sup>-1</sup> )
Avoided Forest Conversion	Conversion of Natural Forests	5.93			112.80 Mg ha <sup>-1</sup>			-2,452	>100	2,452	
	<i>References</i>	(1)			(1–3)					(1–3)	
	Clearing for Subsistence Agriculture	3.04			103.29 Mg ha <sup>-1</sup>			-1,151	>100	1,151	
	<i>References</i>	(1, 4)			(1, 2)					(1, 2)	
	All	8.97		7.95 - 9.98	109.58 Mg ha <sup>-1</sup>		96 - 123	-3,603	>100	3,603	2,999 - 4,209
Reforestation	Temperate		206 Mha			2.82		202 *	>30	2,100	
	<i>References</i>		(5, 6)			(7–9)		(6)			
	Tropical & Subtropical		472 Mha			4.71		953 *	25	8,025	
	<i>References</i>		(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	
	<i>References</i>		(11)			(11–14)					
	Tropical & Subtropical		545 Mha			0.39		0	>50	780	
	<i>References</i>		(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 <sup>-1</sup> )	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 <sup>-1</sup> yr <sup>-1</sup> )	Flux Uncertainty 95% CI bounds (units as noted)	Baseline Flux in 2030 (TgCO <sub>2</sub> e yr <sup>-1</sup> )	Years until saturation	Maximum Additional Mitigation Potential (TgCO <sub>2</sub> e yr <sup>-1</sup> )	Maximum Mitigation 95% CI bounds (± TgCO <sub>2</sub> e yr <sup>-1</sup> )
Improved Plantations	Temperate & Boreal <i>References</i>		176 Mha (11)			0.47 (17)				304	
	Tropical & Subtropical <i>References</i>		81 Mha (11)			0.47 (17)				139	
	All		257 Mha	199 - 335		0.47	0.20 - 1.00	0	65	443	168 - 1,009
Fire Management	Temperate Fire Prone Forests <i>References</i>	0.46 (18, 19)			11.13 Mg ha <sup>-1</sup>			-77		19 (18, 19)	7 - 182
	Brazilian Amazon Forests <i>References</i>	0.54 (20)			34.34 Mg ha <sup>-1</sup>			-68		68 (20)	17 - 117
	Global Savannas <i>References</i>	not applicable			not applicable					125 (21, 22)	50 - 200
	All							-145	>100	212	166 - 411
Avoided Woodfuel Harvest	All <i>References</i>		2,800 M people (23)		0.04 MgC person <sup>-1</sup> yr <sup>-1</sup> (23)			-748	>100 (1, 23)	367	326 - 407
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 <sup>-1</sup> )	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 <sup>-1</sup> yr <sup>-1</sup> )	Flux Uncertainty 95% CI bounds (units as noted)	Baseline Flux in 2030 (TgCO <sub>2</sub> e yr <sup>-1</sup> )	Years until saturation	Maximum Additional Mitigation Potential (TgCO <sub>2</sub> e yr <sup>-1</sup> )	Maximum Mitigation 95% CI bounds (± TgCO <sub>2</sub> e yr <sup>-1</sup> )
Avoided Grassland Conversion	Temperate <i>References</i>	0.70 (24)			18.40 Mg ha <sup>-1</sup> (25, 26)			-47	>100	47	
	Tropical & Subtropical <i>References</i>	1.00 (24)			18.80 Mg ha <sup>-1</sup> (25, 26)			-69	>100	69	
	All	1.70		1.13 - 5.40	18.65 Mg ha <sup>-1</sup>		15.91 - 21.39	-116	>100	116	75 - 373
Biochar	All <i>References</i>		1,670 Tg dm yr <sup>-1</sup> (27, 28)	939 - 2071		0.18 MgCe (Mg dm) <sup>-1</sup> (29–33)	0.17 - 0.21	0	>100	1,102	642 - 1,455
Cropland Nutrient Management	All <i>References</i>		44 Tg N yr <sup>-1</sup> used (34)	32.6 - 58.0		4.33 MgCe Mg N <sup>-1</sup>	2.9 - 5.3	-2612* (34)	>100	706 (34–38)	399 - 959
Conservation Agriculture	All <i>References</i>		352 Mha (39)			0.32 (39)		28 (39)	>50 (39)	413 (39)	310 - 516
Trees in Croplands	Windbreaks <i>References</i>		318 Mha (11, 40, 41)	70.4 - 400		0.20 (42–46)	0.07 - 0.23	0	50	204	
	Alley cropping <i>References</i>		140 Mha (11, 41)	48.8 - 209		1.20 (47–53)	0.57 - 2.18	0	50	616	
	Farmer Managed Natural Regen. <i>References</i>		150 Mha (54, 55)	35.0 - 388		0.40 (55)	0.22 - 0.76	0	50 (55)	220	
	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 <sup>-1</sup> )	Maximum potential implementation (units as noted)	Extent of Uncertainty 95% CI bounds (units as noted)	Avoidable Flux (units as noted)	Additional Sequestration (Mg ha <sup>-1</sup> yr <sup>-1</sup> )	Flux Uncertainty 95% CI bounds (units as noted)	Baseline Flux in 2030 (TgCO <sub>2</sub> e yr <sup>-1</sup> )	Years until saturation	Maximum Additional Mitigation Potential (TgCO <sub>2</sub> e yr <sup>-1</sup> )	Maximum Mitigation 95% CI bounds (± Mt CO <sub>2</sub> e yr <sup>-1</sup> )
Grazing - Optimal Intensity	All <i>References</i>		712 Mha (56)			0.06 (56)		0	>100	148 (56)	148 - 699
Grazing - Legumes in Pastures	All <i>References</i>		72 Mha (56)	61 - 680		0.56 (56)	0.26 - 0.84	0	>100	147	14 - 1,500
Grazing - Improved Feed	All <i>References</i>		1,400 M head cattle (57)		0.13 MgCe head <sup>-1</sup> (58)			-2,412 (58)	>100	680 (58)	35 - 1,014
Grazing - Animal Management	All <i>References</i>		1,400 M head cattle (57)		0.04 MgCe head <sup>-1</sup> (58)			-2,412	>100	200 (58)	75 - 214
Improved Rice Cultivation	All <i>References</i>		163 Mha (59)		0.44 MgCe ha <sup>-1</sup> yr <sup>-1</sup> (59, 60)			-755 (59)	>100	265	227 - 319
Agriculture & Grasslands Subtotal										4,817	4,398 - 6,926
Avoided Coastal Wetland Impacts	Mangrove <i>References</i>	0.10 (61, 62)		0.04 - 0.16	351.86 MgC ha <sup>-1</sup> (63-71)		268 - 436	-130	68	130	
	Salt Marsh <i>References</i>	0.08 (65)		0.04 - 0.12	142.78 MgC ha <sup>-1</sup> (65)		52 - 234	-42	64	42	
	Seagrass <i>References</i>	0.45 (65)		0.12 - 0.78	79.95 MgC ha <sup>-1</sup> (65, 72)		27 - 133	-132	67	132	
	All	0.63			152.02 MgC ha <sup>-1</sup>			-304	>64	304	141 - 466

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

**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 <sub>2</sub> 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 TgC yr <sup>-1</sup> 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 <sup>-1</sup> 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 <sup>-1</sup> and 62.7 MgC ha <sup>-1</sup> for temperate and tropical grasslands, respectively (25), and the average loss at 18.65 (15.91-21.39) MgC ha <sup>-1</sup> .	Includes avoided conversion to cropland of tropical, subtropical, and temperate native grasslands. Spatial overlap with other pathways (e.g. fire management) <i>de minimis</i> .

Pathway	Maximum potential extent	Pathway description	Areas and fluxes included and excluded, and measures taken to avoid double-counting
Biochar	1,670 Tg yr <sup>-1</sup> 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 <sub>2</sub> O or CH <sub>4</sub> (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 <sup>-1</sup> used	Avoided N <sub>2</sub> O 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 <sup>-1</sup> (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 <sub>2</sub> O 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 <sup>-1</sup> yr <sup>-1</sup> and a global additional mitigation potential of 0.12 +/- 0.03 PgC yr <sup>-1</sup> 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 <sub>2</sub> O 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 <sup>-1</sup> yr <sup>-1</sup> 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 <sup>-1</sup> yr <sup>-1</sup> 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 <sup>-1</sup> yr <sup>-1</sup> .	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 <sub>2</sub> O 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 <sub>2</sub> O 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 <sub>2</sub> e yr <sup>-1</sup> (110). This includes 473 TgCO <sub>2</sub> e yr <sup>-1</sup> of methane and 341 TgCO <sub>2</sub> e yr <sup>-1</sup> of nitrous oxide, offset by soil carbon sequestration of 16 T Ce yr <sup>-1</sup> .	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 <sup>-1</sup> (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 <sup>-1</sup> (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 TgCO<sub>2</sub>e yr<sup>-1</sup> unless otherwise specified. “Ukn” refers to Unknown.

Country	Reforestation	Natural Forest Mgmt.	Grazing - Optimal Intensity	Grazing - Legumes	Improved Rice Cult.	Avoided Coastal Impacts - Mangroves	Avoided Peatland Impacts	Peatland Restoration
Afghanistan	0.64	1.63	1.21	0.31	0.34	0	0.03	0.12
Alaska (United States)	0	0	0	0.01	0	0	0.01	0.06
Albania	18.84	0.65	0.14	0.03	0	0	0	0.21
Algeria	19.60	1.62	0.19	2.37	0	0	0	0.01
Andorra	0.05	0	0	0.02	0	0	0	0
Angola	13.45	0	1.12	0.06	0	0.24	0.62	2.94
Antigua & Barbuda	0	0	0	0	0	0	0	0
Argentina	207.41	3.08	8.27	0.77	0.34	0	0.05	0.07
Armenia	4.31	0.23	0.14	0.08	0	0	0.09	0.15
Australia	385.67	60.35	8.95	2.43	0.28	0.77	0.21	2.50
Austria	12.52	0.41	0.55	0.86	0	0	0.03	0.16
Azerbaijan	4.87	0	0.24	0.20	0.01	0	0.01	0.03
Bahamas	0	0	0	0	0	0.02	0.02	0.09
Bahrain	0	0	0	0	0	0	0	0
Bangladesh	0.42	0.63	0.06	0.10	18.74	0.08	0.22	1.11
Barbados	0	0.01	0	0	0	0	0	0
Belarus	44.72	1.29	0.13	0.02	0	0	4.83	24.17
Belgium	5.29	0.15	0.09	0.47	0	0	0.04	0.21
Belize	5.38	0	0.02	0.02	0.01	0.27	0.01	0.03
Benin	0.33	3.87	0.05	0	0.04	0	0.03	0.15
Bhutan	3.12	1.94	0.04	0.35	0.05	0	0	0
Bolivia	64.37	0.03	0.89	0.26	0.38	0	0.01	0.04
Bosnia & Herzegovina	17.77	0.18	0.24	0	0	0	0	0.17
Botswana	0	13.07	0.46	0	0	0	0.06	0.29
Brazil	1549.72	121.39	10.52	0.23	4.38	3.79	1.75	8.74
Brunei Darussalam	0.51	0.26	0	0	0	0.06	0.32	0.41
Bulgaria	26.38	1.01	0.46	0.01	0.04	0	0	0.09
Burkina Faso	0	4.35	0.34	0	0.22	0	0.03	0.15
Burundi	0.60	0.03	0	0	0.03	0	0.31	0.18
Cambodia	42.29	4.50	0.05	0.07	4.44	1.19	Ukn	Ukn
Cameroon	29.74	18.93	0.13	0	0.05	0.40	0.06	0.29
Canada	54.58	127.86	0	5.32	0	0	0.20	0.99
Cape Verde	3.44	0.01	0	0	0	0	0	0
Central African Rep.	6.70	26.43	0.21	0	0.02	0	0.01	0.03
Chad	0.55	4.46	0.93	1.36	0.19	0	0	0.02
Chile	36.32	2.51	0.53	1.88	0.08	0	0.09	0.15
China	1256.71	35.27	25.04	19.40	51.42	0.05	42.47	36.32
Colombia	295.04	0	1.84	0.77	0.71	0.16	0.10	0.09
Comoros	0.04	0.04	0	0	0	0	0	0
Costa Rica	26.09	0.24	0.13	0.10	0.14	0.09	0.01	0.03
Cote d'Ivoire	101.23	10.72	0.26	0	0.80	0.05	0.47	0.87
Croatia	10.34	0.72	0.15	0.39	0	0	0	0
Cuba	86.68	0.65	0.21	0	0.32	2.34	0.56	2.07
Curacao	0	0	0	0	0	0	0	0

Country	Reforestation	Natural Forest Mgmt.	Grazing - Optimal Intensity	Grazing - Legumes	Improved Rice Cult.	Avoided Coastal Impacts - Mangroves	Avoided Peatland Impacts	Peatland Restoration
Cyprus	0.78	0.08	0	0	0	0	0	0
Czech Rep.	21.25	0.85	0.25	0.43	0	0	0.06	0.30
Dem. People's Rep. of Korea	13.97	1.46	0.14	0.17	0.95	0	0.27	1.35
Dem. Rep. of the Congo	175.96	14.77	0.64	0.16	0.85	0.07	0.94	1.75
Denmark (except Greenland)	4.26	0.09	0.02	0.91	0	0	0.37	1.84
Djibouti	0	0.01	0	0	0	0	0.03	0.05
Dominica	0.01	0	0	0	0	0	0	0
Dominican Rep.	35.64	0.10	0.10	0	0.34	0.05	0.01	0.01
Ecuador	76.72	2.42	0.38	0.19	0.74	0.14	0.06	0.29
Egypt	0	0.04	0	0	0.65	0	0	0.02
El Salvador	11.87	0.24	0.05	0	0.01	0.06	0.01	0.06
Equatorial Guinea	0.22	1.56	0	0	0	0.10	0	0.01
Eritrea	0.02	0.02	0.08	0	0	0	0	0
Estonia	6.83	0.73	0	0.17	0	0	0	6.56
Ethiopia	97.48	14.14	0.56	0	0	0	0.38	0.44
Fiji	2.27	1.04	0	0	0	0.06	0.01	0.06
Finland	1.69	13.71	0	0.12	0	0	8.35	34.32
France (except French Guiana)	111.50	4.88	2.84	12.22	0.03	0	0.31	1.50
French Guiana (France)	0.40	5.02	0	0	0.02	0.43	0.01	0.03
Gabon	9.31	22.89	0.04	0	0	0.35	0.07	0.06
Gambia	0.69	0.03	0.01	0	0.02	0	0.01	0.06
Georgia	17.92	3.28	0.17	0.21	0	0	0	0.09
Germany	42.00	3.06	2.01	6.63	0	0	0	17.41
Ghana	48.04	1.51	0.27	0	0.17	0.07	0.01	0.06
Greece	92.43	4.20	0.23	0.18	0.07	0	0.01	0.16
Greenland (Denmark)	0	0	0	0	0	0	0	0
Grenada	0.03	0	0	0	0	0	0	0
Guatemala	50.84	0.63	0.33	0.62	0.04	1.40	0.04	0.04
Guinea	10.82	0.62	0.73	0.03	1.33	0.14	0.29	1.46
Guinea-Bissau	7.92	0.71	0.11	0	0.26	0.03	0	0.02
Guyana	3.35	19.93	0	0	0.31	0.04	0.58	2.91
Haiti	21.21	0.03	0.05	0.03	0.13	0.01	0	0
Honduras	57.68	1.33	0.29	0.12	0.02	0.80	0.66	1.09
Hungary	21.92	0	0.19	0.53	0.09	0	0	0.39
Iceland	0	0	0	0	0	0	1.86	9.43
India	519.47	42.58	0.93	8.58	69.66	2.18	0.29	1.46
Indonesia	212.02	80.25	0.24	0.43	21.56	60.20	514.24	363.85
Iran	19.37	1.07	0.74	0.23	0.92	0	0.03	0.18
Iraq	0	0	0.25	0.52	0.08	0	32.99	3.20
Ireland	87.65	0.09	0.45	3.32	0	0	0	5.01
Israel	0.49	0.07	0	0	0	0	0	0.12
Italy	111.47	4.20	1.01	0.73	0.36	0	0.06	0.29
Jamaica	4.82	0.02	0	0	0	0.06	0.04	0.07
Japan	67.06	22.01	0	0	2.65	0	0	2.47
Jordan	0.01	0	0	0	0	0	0	0
Kazakhstan	11.75	0.75	9.72	0.12	0.16	0	0	0.01

Country	Reforestation	Natural Forest Mgmt.	Grazing - Optimal Intensity	Grazing - Legumes	Improved Rice Cult.	Avoided Coastal Impacts - Mangroves	Avoided Peatland Impacts	Peatland Restoration
Kenya	12.59	0.20	0.64	0	0.01	0.03	3.88	2.91
Kiribati	0	0	0	0	0	0	0	0
Kuwait	0	0	0	0	0	0	0	0
Kyrgyzstan	0.60	0	0.33	0.01	0.02	0	0.01	0.18
Laos	44.17	3.16	0.05	0.43	1.38	0	0.06	0.29
Latvia	11.68	0.91	0	0	0	0	0	2.65
Lebanon	1.78	0.11	0	0	0	0	0	0
Lesotho	0	0.04	0.02	0	0	0	0.03	0.05
Liberia	5.57	1.28	0.07	0	0.13	0.02	0.08	0.12
Libya	0.57	0	0.03	1.06	0	0	0.01	0.03
Liechtenstein	0.03	0	0	0.01	0	0	0	0
Lithuania	11.95	0.53	0.01	0.03	0	0	0.90	3.67
Luxembourg	0.23	0.03	0	0	0	0	0	0
Macedonia (FYROM)	7.06	0.31	0.16	0	0	0.17	0	1.78
Madagascar	26.90	8.61	1.78	0	2.77	0	0.94	0.87
Malawi	0.99	1.05	0.06	0	0.05	17.94	0.18	34.93
Malaysia	29.38	19.14	0	0.36	1.10	0	57.01	0
Maldives	0	0	0	0	0	0	0	0.15
Mali	0	0.70	0.90	0.78	1.05	0	0.03	0
Malta	0.01	0	0	0	0	0	0	0
Marshall Islands	0	0.01	0	0	0	0	0	0.09
Mauritania	0	0.14	0.51	1.46	0.05	0	0.03	0
Mauritius	1.63	0.01	0	0	0	2.33	0	2.91
Mexico	516.96	0	5.23	1.09	0.26	0	0.58	0.02
Micronesia	0	0.06	0	0	0	0	0	0.01
Moldova	2.57	0.08	0.10	0.31	0	0	0	0
Monaco	0	0	0	0	0	0	0	20.22
Mongolia	9.69	1.35	3.85	0.70	0	0	17.58	0.31
Montenegro	8.72	0.81	0.08	0.00	0	0	0	0.02
Morocco	11.51	4.14	0.46	2.51	0.02	0.20	0	2.33
Mozambique	5.97	24.22	0.79	0	0.11	18.40	0.76	2.91
Myanmar	237.27	28.89	0.20	1.59	13.03	0	0.58	0.03
Namibia	0	1.93	0.95	0.57	0	0	0.01	0
Nauru	0	0	0	0	0	0	0	0.02
Nepal	26.23	2.44	0.43	0.11	2.37	0	0	3.08
Netherlands	12.21	0.12	0.17	1.01	0	0.07	0	1.81
New Zealand	14.29	0.05	0.91	2.31	0	0.35	0	0.29
Nicaragua	78.44	0.75	0.37	0.08	0.22	0	0.06	0.03
Niger	0	0.96	0.66	1.90	0.07	0.24	0.07	0.87
Nigeria	68.97	1.90	1.30	0	3.93	0	0.71	2.88
Norway	0.43	4.38	0	0.23	0	0	2.56	0
Oman	0	0	0.04	0.51	0	0	0	0.03
Pakistan	6.17	1.23	1.01	0.07	3.85	0.01	0.01	0
Palau	0.01	0.05	0	0	0	0.31	0	0.29
Panama	39.78	3.75	0.09	0.03	0.18	1.35	0.06	14.55
Papua New Guinea	9.78	13.81	0	0.50	0	0	27.22	0.06

Country	Reforestation	Natural Forest Mgmt.	Grazing - Optimal Intensity	Grazing - Legumes	Improved Rice Cult.	Avoided Coastal Impacts - Mangroves	Avoided Peatland Impacts	Peatland Restoration
Paraguay	150.16	0	1.01	0	0.07	0	0.01	0.29
Peru	32.88	45.61	0.86	1.43	0.62	2.03	0.06	0.23
Philippines	118.84	6.47	0.09	0.74	7.08	0	0.05	13.66
Poland	75.22	0	1.24	5.70	0	0	1.11	0.04
Portugal	64.95	2.35	0.36	0.16	0.14	0	0	0
Qatar	0	0	0	0	0	0	0	0.03
Rep. of Congo	46.09	25.67	0.11	0	0	0	0.01	0.01
Rep. of Korea	3.24	1.58	0	0	1.47	0	0	0.56
Romania	30	2.72	1.27	0.52	0.02	0	0.11	89.00
Russian Federation	351.33	245.05	0.78	6.14	0.33	0	2.07	0.60
Rwanda	0	0.10	0.01	0	0.01	0	0.71	0
Saint Kitts & Nevis	0.07	0.01	0	0	0	0	0	0
Saint Lucia	0.03	0	0	0	0	0	0	0
Saint Vincent & the Grenadines	0.05	0	0	0	0	0	0	0
Samoa	0	0.07	0	0	0	0	0	0
San Marino	0.03	0	0	0	0	0	0	0
Sao Tome & Principe	0	0	0	0	0	0	0	0
Saudi Arabia	0	1.18	0.15	2.33	0	0.01	0	0.02
Senegal	0.40	7.62	0.14	0	0.12	0	0.02	0.31
Serbia	16.69	0.69	0.42	0.02	0	0	0	0
Seychelles	0	0	0	0	0	0.02	0	0.12
Sierra Leone	5.13	0.27	0.33	0	0.81	0	0.08	0.40
Singapore	0.04	0.02	0	0	0	0	0.05	0.15
Slovakia	8.34	0.28	0.20	0	0	0	0	0.09
Slovenia	2.31	0	0.15	0.08	0	0.15	0.01	0.01
Solomon Islands	0.28	0.42	0	0	0	0	0	0.15
Somalia	7.36	7.67	0.24	0	0	0.01	0.03	0.21
South Africa	5.03	8.31	1.78	0.08	0	0	0.16	0
South Sudan	0.03	0	1.06	0	0	0	0	0.11
Spain	188.73	12.13	1.05	3.72	0.20	0.03	0.03	0.06
Sri Lanka	2.71	1.50	0.04	0	1.73	0	0	2.91
Sudan	0	5.92	1.04	1.22	0	0.89	0.58	0.29
Suriname	1.41	3.24	0	0.36	0.06	0	0.06	0.10
Swaziland	0	0	0.08	0	0	0	0.05	7.10
Sweden	6.84	5.33	0	1.92	0	0	1.42	0.17
Switzerland	3.19	0.10	0.22	0.98	0	0	0.04	0.01
Syrian Arab Rep.	2.39	0.36	0.12	0.11	0	0	0	0
Taiwan	0	0	0	0	0	0	0	0
Tajikistan	0.17	0.01	0.09	0.01	0.05	0.16	0	0.26
Tanzania	66.73	55.26	0.95	0.05	1.72	3.74	0.11	1.57
Thailand	186.18	0.80	0	0	19.70	0	0.25	0.03
Timor-Leste	0	0.24	0.01	0	0	0.01	0	0
Togo	7.44	0.11	0.05	0	0.06	0	0.07	0.06
Tonga	0	0	0	0	0	0	0	0
Trinidad & Tobago	1.43	0.17	0	0	0	0.12	0.01	0.01
Tunisia	3.23	0.06	0.10	0.13	0	0	0	0

Country	Reforestation	Natural Forest Mgmt.	Grazing - Optimal Intensity	Grazing - Legumes	Improved Rice Cult.	Avoided Coastal Impacts - Mangroves	Avoided Peatland Impacts	Peatland Restoration
Turkey	308.96	7.91	2.01	2.61	0.16	0	0.03	0.31
Turkmenistan	0	0	0.33	0	0.10	0	0	0.12
Tuvalu	0	0	0	0	0	0	0	0
Uganda	5.09	0.37	0.31	0.03	0.09	0	8.80	14.55
Ukraine	104.69	1.88	2.81	1.70	0.05	0	0	3.08
United Arab Emirates	0	0.14	0.01	0	0	0	0	0
United Kingdom	153.05	0	1.31	8.53	0	0	1.15	5.76
United States (except Alaska)	357.98	65.72	13.73	13.79	2.35	3.80	3.54	17.58
Uruguay	0	0.19	0.60	0	0.28	0	0.05	0.29
Uzbekistan	0.02	0	0.67	0.01	0.06	0	0.08	0.48
Vanuatu	1.76	0	0	0	0	0	0	0
Venezuela	165.53	52.04	0.94	0.37	0.48	0.97	1.11	2.62
Vietnam	128.20	5.40	0.21	0.63	12.16	0.65	0.76	3.81
Yemen	0	0.66	0.10	0.80	0	0	0	0
Zambia	3.72	24.44	1.11	0	0.02	0	1.88	3.49
Zimbabwe	0	15.50	1.08	0.10	0	0	0.44	0.73

**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.

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

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



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

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

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

**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)
<b>Forests</b>				
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)
<b>Agriculture &amp; Grasslands</b>				
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).		

<b>Pathway</b>	<b>Biodiversity</b> (alpha, beta, gamma)	<b>Water</b> (filtration, flood control)	<b>Soil</b> (enrichment)	<b>Air</b> (filtration)
<b>Wetlands</b>				
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.

<b>Multilateral announcements of global environmental efforts related to NCS</b>	<b>Pathway(s)</b>	<b>Relationship to NCS &lt;2°C targets</b>
<i>United Nations New York Declaration on Forests</i>		
"...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.
<i>Bonn Challenge</i>		
"...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).
<i>United Nations Convention on Biological Diversity, Aichi Targets</i>		
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 <sub>2</sub> 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.
<i>4 pour 1000</i>		
"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 <sub>2</sub> "	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.

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\*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”

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**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
<b>Forests</b>		
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).
<b>Agriculture &amp; Grasslands</b>		
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.
<b>Wetlands</b>		
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.

## 1 **Methods Details**

2 We address three questions in this analysis:

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

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

10

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

12 As described in the main text, we estimate the maximum additional annual mitigation potential at a  
13 2030 reference year (Table S1). By “additional” we mean mitigation outcomes due to actions taken beyond  
14 business-as-usual land use activities, and not including existing land fluxes not attributed to human  
15 activities. We constrained this estimate to be consistent with meeting human needs for food and fiber. For  
16 food, we allow no reduction in existing cropland area, but do allow the potential to reforest all grazing lands  
17 in forested ecoregion, as consistent with agricultural intensification scenarios (169) and potential for dietary  
18 changes in meat consumption (170). For fiber, we assume that any reduced timber production associated  
19 with implementing our Natural Forest Management pathway is made up by additional wood production  
20 associated with improved plantations and/or reforestation pathways.

21 We also limit our estimate of maximum mitigation potential by avoiding activities that would  
22 negatively impact biodiversity, such as establishing forests where they are not the native cover type (171).

23 For most pathways, we generated new estimates of the maximum mitigation potential ( $M_x$ ) informed by  
24 a review of publications on the potential extent ( $A_x$ ) and intensity of flux ( $F_x$ ), where  $M_x = A_x * F_x$ . Our  
25 estimates for the reforestation pathway involved new geospatial analyses. For most pathways the applicable  
26 extent was in terms of area (hectares); however, for five of the pathways (Biochar; Cropland Nutrient

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

34

### 35 **Estimating uncertainty of our maximum mitigation potential estimates**

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

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

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

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

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

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

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

70 In a second email we anonymously reported to each expert the mean of upper and lower values  
71 reported by all experts for each pathway and we provided to all any additional papers received and  
72 clarifications to questions asked. We gave each expert the chance to provide revised estimates. The mean  
73 values from respondents' final answers to questions were averaged to derive the upper and lower bounds of  
74 95% confidence intervals.

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

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

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

84 We combined  $A_x$  and  $F_x$  uncertainties within pathways from each of the four methods options above to  
85 calculate overall inter-pathway uncertainty using IPCC Approach 2: Monte Carlo simulation. Applying the  
86 central limits theorem, we converted 95% confidence intervals to standard errors of the mean (SEM) by  
87 dividing by 1.96. Input parameter SEMs were used to define distributions used in Monte Carlo simulations  
88 ((175), 100,000 iterations). The simulation randomly selected a single value from defined normal  
89 distributions, for each parameter and at each simulation, and passed values into the emissions equation to  
90 calculate uncertainty at the pathway and biome level. The mean of normal distributions for expert elicitation  
91 uncertainty values were not tied to our literature-based estimates of mitigation potential.

### 93 **Assigning cost-constrained mitigation levels**

94 We assumed that a maximum marginal cost of approximately 100 US dollars per Mg of carbon dioxide  
95 equivalent emitted per year ( $\sim 100 \text{ USD MgCO}_2\text{e}^{-1}$ ) in 2030 would be required across all mitigation options  
96 (fossil fuel emissions reductions and NCS) to hold warming below  $2^\circ\text{C}$  (176). To calibrate natural pathway  
97 mitigation levels with a goal of holding warming below  $2^\circ\text{C}$ , we assessed which of three default mitigation  
98 levels – 30%, 60%, or 90% of maximum – captures mitigation costs up to but not more than  $\sim 100 \text{ USD}$   
99  $\text{MgCO}_2\text{e}^{-1}$  (Table S4).

100 This ensures that the marginal (per unit) cost of emissions reductions from NCS does not exceed the  
101 marginal benefit of avoiding carbon emissions. The marginal benefit of emissions reductions is represented  
102 by estimates of the social cost of carbon, which is the value to society of the avoided marginal damage of  
103  $\text{CO}_2$  emissions due to climate change and is obtained through welfare-maximizing emissions pricing models  
104 (177, 178). The social cost of carbon in 2030 is estimated to be 82-260  $\text{USD MgCO}_2\text{e}^{-1}$  to meet the  $1.5\text{-}2^\circ\text{C}$

105 climate target(176). This estimate is based on an updated version of the Dynamic Integrated Climate-  
106 Economy model to allow for endogenous capital and improved models of the damage from climate change.  
107 The exact value depends on the assumptions related to the convexity of the damage function, the discount  
108 rate and climate sensitivity parameter. The model does not allow for adjustments costs and hence is likely to  
109 underestimate the values.

110 100 USD MgCO<sub>2</sub>e<sup>-1</sup> is also in line with the 95<sup>th</sup> percentile of the estimated distribution from the White  
111 House ([https://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-  
112 RIA.pdf](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%  
113 discount rate, the values reported in the White House reports in 2007 USD are 72.8 MgCO<sub>2</sub><sup>-1</sup> and 100  
114 MgCO<sub>2</sub><sup>-1</sup> for 2015 and 2030, respectively. This value represents a conservative estimate, as using a lower  
115 discount rate would result in a larger value. For simplicity and alignment with other parts of the analysis in  
116 this paper, we use the value 100 USD MgCO<sub>2</sub>e<sup>-1</sup> for 2030.

117 We assign low (30%), medium (60%), and high (90%) default cost-constrained mitigation levels, as a  
118 percentage of maximum levels, informed by marginal abatement cost (MAC) curve literature and the 100  
119 USD MgCO<sub>2</sub>e<sup>-1</sup> cost threshold. Our assignment of these default levels reflects that the MAC literature does  
120 not yet enable a precise understanding of the complex and geographically variable range of costs and  
121 benefits associated with our 20 natural pathways (see Table S4 and section below for literature reviewed).  
122 Also, for some pathways we saw a need to adjust levels to consider barriers to implementation beyond costs.  
123 Mitigation level assignments for each pathway are discussed further below.

124 We also assessed the proportion of NCS mitigation towards a <2°C outcome that could be achieved at  
125 low cost. For this we used a marginal cost threshold of ~10 USD MgCO<sub>2</sub>e<sup>-1</sup>, which is consistent with the  
126 current cost of emission reductions efforts underway and current prices on existing carbon markets.

127 We supplemented the authors' knowledge of the literature by searching for MAC curves for each  
128 pathway using Google Scholar, including key words "supply curve" or "marginal abatement cost curve" in  
129 addition to the name of the pathway. In addition, we also searched for the studies citing the studies included  
130 in our database. Where global studies were not available, we searched for regional (e.g., country-specific)



131 studies and assumed a similar percentage of mitigation was available at the USD 100 and USD 10 price  
132 points in related geographies. If multiple curves were presented on a graph, we used the one matching the  
133 year 2030 and the maximum associated with a specific pathway. The list of studies included in our database  
134 is reported in Table S4. We converted all emissions units to TgCO<sub>2e</sub> and the marginal cost estimates to 2015  
135 USD, using US Consumer Price Calculator ((180), available at [https://data.bls.gov/cgi-  
136 bin/cpicalc.pl?cost1=1&year1=199501&year2=200501](https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=1&year1=199501&year2=200501)). Where suitable MAC studies were not available,  
137 we relied on our expert opinion to judge probable costs of mitigation – and compared costs to the most  
138 similar pathways with MAC information.

### 139 140 **Projecting NCS contribution to climate mitigation through 2100**

141 We projected the potential contributions of NCS to overall CO<sub>2e</sub> mitigation action needed for a ‘likely’  
142 (greater than 66%) chance of holding warming below 2°C (181) between 2016 and 2100. We compared this  
143 NCS scenario to a baseline scenario in which NCS are not implemented. In our NCS scenario, we assumed a  
144 linear ramp up period between 2016 and 2025 to our <2°C ambition mitigation levels reported in Tables S1  
145 and S4. During this period, we assumed fossil fuel emissions were also held constant, after which they  
146 would decline. We assumed a maintenance of <2°C ambition NCS mitigation levels through 2060, allowing  
147 for gradual pathway saturation represented as a linear decline of natural pathway mitigation from 2060 to  
148 2090. We consider this a conservative assumption about overall NCS saturation given the time periods we  
149 estimate prior to saturation reported in Table S1. This scenario and the associated action on fossil fuel  
150 emissions reductions needed are represented in Fig. 2 through 2050. Scenario construction builds from  
151 (182), with model parameters derived from Meinshausen et al. (183). The proportion of CO<sub>2</sub> mitigation  
152 provided by NCS according to the scenario described above is adjusted to a proportion of CO<sub>2e</sub> with the  
153 assumption that non-CO<sub>2</sub> greenhouse gases are reduced at the same rate as CO<sub>2</sub> for NCS and other sectors.

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157 **Characterizing Activities and Co-Benefits**

158 We identified mitigation activities and non-carbon ecosystem services associated with each of the 20  
159 natural pathways (Tables S5 and S7). We used a taxonomy of conservation actions developed by the  
160 International Union for Conservation of Nature (IUCN) and the Conservation Measure Partnership (168) to  
161 link pathways with a known set of conservation activities. The IUCN taxonomy does not identify activities  
162 that are specific to many of our pathways, so we list examples of more specific activities associated with  
163 each pathway (Table S7). Activities represent specific conservation, restoration, and improved land  
164 management actions that practitioners may take to avoid emissions and/or enhance sequestration.

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

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

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183 The following are pathway-specific methods:

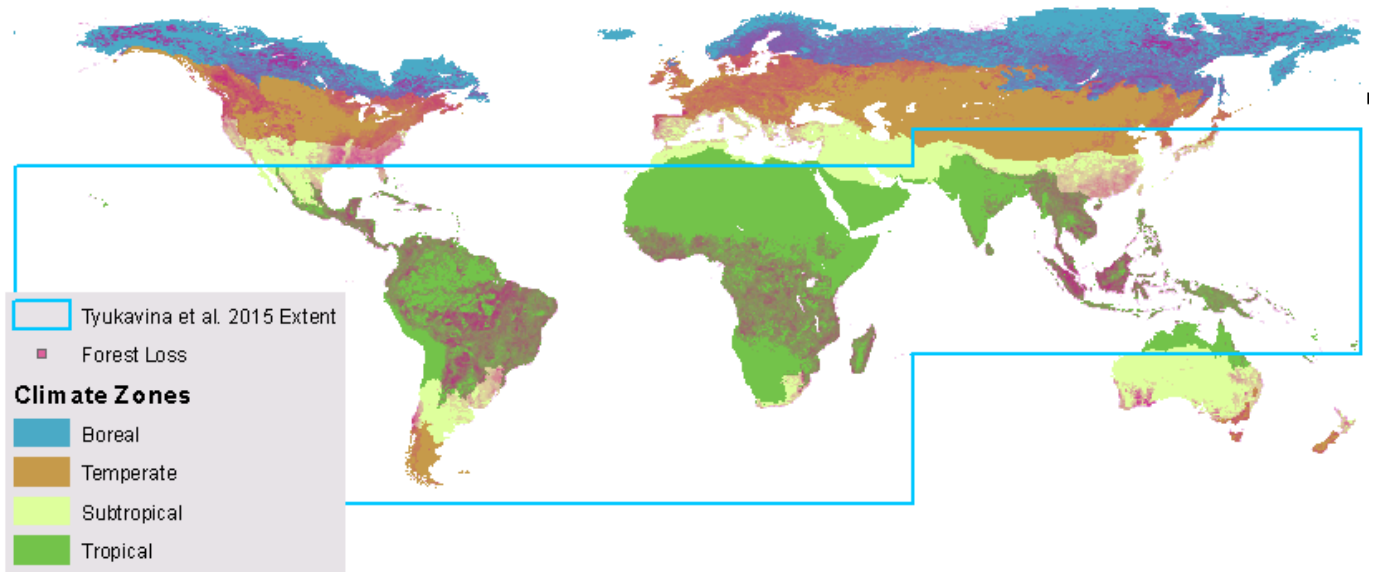
#### 184 **Avoided Forest Conversion**

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

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

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**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).

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To calculate the area of avoided loss we assume a constant rate of forest loss through 2030, based on an historical baseline of  $5.9 \text{ Mha yr}^{-1}$  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).

228 To calculate forest loss emissions, we adjust UMD's gross above- and below-ground natural forest loss  
229 emissions estimate ( $750 \text{ Tg yr}^{-1}$ ) by accounting for elemental charcoal carbon and wood product carbon  
230 retention, overlap with forested wetlands, and soil emissions. We assume that – in conjunction with the  
231 deforestation process – 2.0% of initial biomass is stored in long-term charcoal, and 2.4% is stored in long  
232 term wood products (2). To prevent double counting with the avoided wetland loss pathway, we further  
233 deduct historic mangrove and forested peatland loss from UMD's area and carbon loss estimates (65, 73,  
234 207, 208). We take a committed emissions approach (209) to assume 100% loss of carbon from the  
235 remaining “slash” biomass pool, a reasonable assumption for tropical forests given a 20 year time horizon,  
236 since even a conservative  $0.3 \text{ yr}^{-1}$  decay constant results in >99% decay within 15 years (2, 210). We  
237 assume 54% of natural forest lost is converted to commercial agriculture (4), resulting in an additional 13  
238  $\text{Mg ha}^{-1}$  of soil carbon emissions from tilling (3). This is a conservative estimate compared to other meta-  
239 analyses (211).

240 We estimate that an additional 314 TgC are emitted every year as a result of subsistence agriculture in  
241 the tropics, based on UMD's estimates of the loss of managed forest (1), and an assessment of the  
242 proportion of this loss attributable to subsistence agriculture (4). Using data from Hansen et al. (6) and a  
243 stratified random sample of 3000 loss pixels, UMD calculate  $5.3 \text{ Mha yr}^{-1}$  of managed forest loss, including  
244 plantation forestry and subsistence agriculture. A pan-tropical assessment of deforestation drivers (4)  
245 estimates that 32% of deforestation is a result of subsistence agriculture, translating to 26% of all forest loss  
246 ( $3.0 \text{ Mha}$ ), given that the authors do not account for plantation forestry in their definition of deforestation.  
247 UMD calculates  $553 \text{ Tg yr}^{-1}$  of carbon emissions resulting from managed forest loss, or  $105 \text{ Mg ha}^{-1}$ .  
248 Applying a 2% deduction for charcoal storage after burning (2), the total historic flux from subsistence  
249 agriculture is  $314 \text{ TgC yr}^{-1}$  or  $103 \text{ MgC ha}^{-1}$ .

250 Recent research suggests that standing forests provide an additional sequestration benefit between 1.3  
251 and  $2.6 \text{ PgC yr}^{-1}$  not accounted for in traditional avoided forest loss estimates (192, 212–214). There is  
252 disagreement about the nature and magnitude of this carbon sink, and how it will respond to future changes  
253 in atmospheric  $\text{CO}_2$  levels, water availability, seasonality, weather, and pests/pathogens (215–221). Based

254 on our estimated natural forest loss conversion rate, this carbon sink could provide an additional 3.4 – 8.8  
255 TgC yr<sup>-1</sup>, but we exclude this from our maximum mitigation estimate until more conclusive evidence is  
256 available, such as from NASA’s Orbiting Carbon Observatory-2 (222), available at <http://oco.jpl.nasa.gov/>.

### 257 *Mapping Country-Level Mitigation*

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

### 262 *Uncertainty*

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

271 To check this uncertainty estimate against the literature, we compared UMD’s reported pan-tropical  
272 above- and below-ground forest carbon loss ( $3.7 \text{ PgCO}_2 \text{ yr}^{-1}$ ) to four recent estimates from the literature  
273 (Table S8). All estimates are within 18% of the mean, providing further justification for our combined area-  
274 flux uncertainty estimate of 17%.

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

Study	Gross Deforestation Emissions (PgCO <sub>2e</sub> yr <sup>-1</sup> )
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%)

282

283 *Mitigation Targets*

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

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

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

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

299

## 300 **Reforestation**

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

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

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

- 322 • Deductions to avoid double-counting with forest management pathways: To adjust the  
323 estimated restoration opportunity area to our definition of reforestation opportunities (where  
324 non-forests can be converted to forests >25% tree cover), we removed (i) areas identified by  
325 FLRO based on Olson ecoregions (231) as having potential forest cover with <25% tree canopy



326 cover, and (ii) Hansen pixels (6) identifying existing forest cover >25% tree canopy cover. This  
327 modification avoids double-counting between reforestation and other forest restoration  
328 pathways (e.g. natural forest management), and reduces the substantial remote sensing error  
329 associated with more subtle changes in vegetation in forests remaining forests and non-forests  
330 remaining non-forests (240).

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

343 We also applied a non-spatial deduction to eliminate double counting: we deducted the unmapped area  
344 of forested peatlands and mangrove forests (66, 73, 76, 77) (see wetland restoration methods below). We  
345 note that our definition of agroforestry in this analysis (use of trees in cropping systems where tree cover  
346 <25%), excludes agroforestry interventions as defined here from the reforestation pathway, thereby  
347 eliminating double-counting. We assumed that potential reforestation areas do not compete with future areas  
348 of cropland expansion, as croplands were already excluded from the FLRO map, and we assume that the  
349 current extent of agricultural land can effectively feed projected future populations ((191) “yield growth”  
350 scenario).

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

355 **Table S9.** Summary of maximum potential extent and sequestration rates for reforestation pathway. We  
 356 used current plantation extent (11) to estimate the proportion of future reforestation allocated to plantations.  
 357 Growth rates include aboveground biomass (sources listed), belowground biomass (9), and soil organic  
 358 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 <sup>-1</sup> yr <sup>-1</sup> )	Plantation Forest Growth Rate (MgC ha <sup>-1</sup> yr <sup>-1</sup> )	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%	

359 We eliminate double-counting of mitigation potential with grazing pathways as follows. We calculate  
 360 the proportion of lands with mitigation potential from improved grazing and sowing legumes (56) that  
 361 overlap our reforestation map (13% and 15%, respectively). We deduct the corresponding mitigation  
 362 potential from our reforestation maximum (158 TgCO<sub>2e</sub>), representing a 1.5 % deduction.

363 We assessed the requirements for reforestation to deliver additional global wood yield in order to make  
 364 up for lack of wood yield from natural forests under maximum implementation of the natural forest  
 365 pathway. We estimate 2.2 billion m<sup>3</sup> of wood (woodfuel and industrial roundwood) provided by natural  
 366 production forests would need to be generated instead from new forests associated with the reforestation  
 367 pathway. This could be generated if 144 million hectares of the maximum reforestation area (= 21% of 678  
 368 M ha) was in the form of plantations with the mean growth rate of 6.1 MgC ha<sup>-1</sup> yr<sup>-1</sup> (see Table S9 for  
 369 sources). Given mean harvest rotation length of 45 years for commercial plantations, the additional  
 370 sequestration in new plantations would saturate after about two decades (see Table S1). The saturation

371 period would be much longer for the majority of reforestation from which commercial timber harvest would  
372 not be necessary.

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

### 382 *Mapping Country-Level Mitigation*

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

### 388 *Uncertainty*

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

### 391 *Mitigation Targets*

392 We set the <2C° target at 30%, or 1.2 PgC yr<sup>-1</sup>. This corresponds to approximately 200 Mha of  
393 implementation area. This level of mitigation exceeds 100 USD MgCO<sub>2</sub><sup>-1</sup> according to an analysis of the  
394 marginal abatement cost of reforestation with commercial plantations (115). However, we assigned a 30%  
395 mitigation level considering that large extents of reforestation could be achieved at lower costs by halting

396 intentional burning of marginal grazing lands in places like the Amazon basin to allow natural forest  
397 regeneration (245).

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

405

#### 406 **Natural Forest Management**

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

418 The FAO GFRA are the only global datasets on native forest production forest areas. The total area  
419 under consideration is 1,914 Mha as of 2015, of which 545 million ha occurs in tropical and sub-tropical  
420 climate domains, and 1,369 Mha occurs in temperate and boreal climate domains (11, 83). This naturally

421 regenerating production forest area is assumed to be constant between now and our reference baseline year  
422 of 2030.

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

433 This rate is derived assuming that forests subject to logging maintain ~50% of stock levels of old-  
434 growth forest, and that old-growth stock levels require several hundred years to recover (12–14). Global  
435 temperate average initial above- and belowground stocks in natural production forests are estimated to be  
436  $49.4 \text{ MgC ha}^{-1}$  (11, 83), and global average “fully recovered” stocks are assumed to be  $98.8 \text{ MgC ha}^{-1}$ .

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

446 growth rate of forests older than 30 to 50 years, we believe it is best assumed that global natural production  
447 forest area is growing at slow rates typical of stands approaching mature, uneven-aged conditions.

#### 448 *Mapping Country-Level Mitigation*

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

#### 454 *Uncertainty*

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

#### 459 *Mitigation Targets*

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

465

#### 466 **Improved Plantations**

467 This pathway involves extending harvest rotation lengths on intensively managed production forests  
468 (i.e. plantations) subject to even-aged stand management. Unlike the Natural Forest Management pathway,  
469 we constrain the Improved Plantations to increases in carbon stocks associated with maximizing wood  
470 volume yields. We assume baseline rotation lengths are at the economic optimum, which is generally  
471 shorter than the optimum rotation for wood yield (biological optimum). In contrast to the biological

472 optimum based simply on the optimization of the tree species growth function, the economic optimum  
473 balances discounted costs with discounted stream of revenues from timber production, given a tree species  
474 growth function (84). In our modeling exercise, we set the target extended rotation length based on the  
475 biological optimum, i.e. the point that maximizes the Mean Annual Increment (MAI) for timber. Shifting  
476 rotations from an economic to a biological optimum will increase timber volumes harvested from stands in  
477 the long run, as the biological optimum rotation length yields the highest mean annual productivity.

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

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

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

493

494

495

496

497

498 **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

499  
 500 We calculated the ratio of biological optimum rotation age: economic optimum rotation age to be 1.45. This  
 501 was calculated using a generalized Chapman Richards form yield curve and assuming a global average  
 502 discount rate of 8% (85).

503 All existing rotations were increased by a factor of 1.45, to produce the new (extended) rotation regime  
 504 scenarios. In both business-as-usual and extended rotation scenarios, the total long-term average stock of  
 505 above- and belowground biomass carbon in MgCO<sub>2e</sub> was calculated for each rotation length class as:

506 
$$\text{Area (ha)} * \text{MAI (m}^3 \text{ ha}^{-1} \text{ yr}^{-1}) * \text{midpoint of rotation length (yrs)} * \text{BCEF (Mg AGBm}^{-3}) * 0.47$$
  
 507 
$$\text{(carbon fraction)} * (44/12) * (1+ \text{R:S ratio})$$

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



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

524 Using these methods, we estimate that the potential benefit of extended rotations globally is 27.0  
525 PgCO<sub>2e</sub>, which is the estimated difference in long-term average stocks between the two scenarios assessed.  
526 To interpret this value as a rate, we assume that the time to transition the global landscape to the new long-  
527 term average stocking state is equal to the length of the new (extended rotation) in years, for each rotation  
528 length class. This is the shortest possible timeframe to transition all age cohorts across a landscape. For the  
529 2030-2045 assessment timeframe, we estimate an unconstrained maximum biophysical potential benefit of  
530 extended rotations of 0.443 PgCO<sub>2e</sub> per year, sequestered as additional long-term average stocks in  
531 plantation forests worldwide.

### 532 *Mapping Country-Level Mitigation*

533 We mapped improved plantations maximum mitigation by multiplying FAO estimates of intensively  
534 managed plantation forest extent at continental scales (251) times the sequestration rate of 0.47 MgC ha<sup>-1</sup> yr<sup>-1</sup>  
535 reported above.

### 536 *Uncertainty*

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

### 541 *Mitigation Targets*

542 We assigned the same mitigation target for <2°C ambition as the natural forest management pathway,  
543 while noting that the marginal abatement curve sources (60, 116) are less directly applicable. We assigned  
544 0% low cost mitigation opportunities, anticipating that low cost mitigation opportunities for improved  
545 plantations will be more limited than for natural forest management, given that additional mitigation  
546 requires a shift away from economic optimum harvest rotations.

547

## 548 **Fire Management**

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

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

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

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

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

#### 574 *Uncertainty*

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

#### 580 *Mitigation Targets*

581 We are unaware of available literature on marginal abatement cost curves applicable to this pathway.  
582 We assumed this is a relatively expensive pathway in the context of other forest pathways and based on  
583 conversations with practitioners. We assigned 30% mitigation at  $\sim 100$  USD MgCO<sub>2</sub><sup>-1</sup> and 0% mitigation at  
584  $\sim 10$  USD MgCO<sub>2</sub><sup>-1</sup>.

585

#### 586 **Avoided Woodfuel Harvest**

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

594 *Uncertainty*

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

598 *Mitigation Targets*

599 We are unaware of available literature on marginal abatement cost curves applicable to this pathway.  
600 We assumed this is a relatively expensive pathway in the context of other forest pathways and based on  
601 conversations with practitioners and assigned a 30% mitigation at ~100 USD MgCO<sub>2</sub><sup>-1</sup> and 0% mitigation at  
602 ~10 USD MgCO<sub>2</sub><sup>-1</sup>.

603

#### 604 **Avoided Grassland Conversion**

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

613 **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 <sup>-1</sup>	MgC ha <sup>-1</sup> (0-30cm depth)	%	MgC ha <sup>-1</sup>	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

614

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

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

#### 624 *Uncertainty*

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

#### 629 *Mitigation Targets*

630 In the absence of available MAC curves applicable to this pathway, we assumed a 30% mitigation level for  
631 <2°C ambition. The ongoing demand for arable land, and the relatively small emissions per ha compared  
632 with forest and wetland biomes, suggests a relatively high cost per Mg of avoided CO<sub>2</sub> emissions.

633

#### 634 **Biochar**

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

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

644 We assume the average carbon content of residues is 45% (29) and the amount of carbon retained in  
645 biochar is 50% (32, 33). 97% of biochar carbon represents the recalcitrant fraction, with a long but highly  
646 uncertain mean residence time of 556 years in soils (32, 33). 79.6% of char carbon is estimated to persist on  
647 a timescale of >100 years. As such, we estimate “long-term” mitigation at 0.18 MgCe per Mg dm of dry  
648 feedstock. We do not assume that the pyrolysis process is used to offset fossil fuel use. We also do not  
649 include any second order effects of biochar on soil organic matter or emissions of N<sub>2</sub>O or CH<sub>4</sub>, based on  
650 recent meta-analyses showing these effects to be neutral or weakly beneficial on average (91, 92).

651 We estimate total mitigation potential as:

$$652 \quad 1,670 \text{ Tg dm yr}^{-1} * 0.18 \text{ MgCe (Mg dm)}^{-1} = 300 \text{ TgCe yr}^{-1}$$

653 Our new maximum estimate of potential carbon sequestration, derived from independent data for available  
654 crop residues and experimental measurements of the fraction of biomass carbon that becomes recalcitrant to  
655 decomposition, is 70-87% lower than those of Woolf et al. (90), largely owing to our exclusion of energy  
656 crops and estimated mitigation from energy generation and reductions in non-CO<sub>2</sub> GHGs.

### 657 *Uncertainty*

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

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

$$664 \quad M = F_C * Y_C * f_R * F_{100}$$

665 Where  $M$  is mitigation per unit biomass,  $F_C$  is carbon content of residue feedstocks,  $Y_C$  is “carbon  
666 yield” (% of feedstock carbon retained in char during pyrolysis),  $f_R$  is the fraction of char carbon that is

667 recalcitrant, and  $F_{100}$  is the fraction of recalcitrant carbon remaining after 100 years.  $f_R$  and  $F_{100}$  are drawn  
668 directly from a recent meta-analysis of 121 data points (92). We used option 3 to generate confidence  
669 intervals for  $F_C$  and  $Y_C$  based on studies of residue feedstocks (29, 264–267) and pyrolysis (264, 265, 267,  
670 268). We used IPCC Uncertainty Approach 1 to combine these into a single figure, with a final 95%  
671 confidence interval range of 16.7-20.6%.

### 672 *Mitigation Targets*

673 In the absence of available global MAC curves applicable to this pathway, we assumed relatively high  
674 costs per Mg of avoided CO<sub>2</sub> emissions, given the labor and technical requirements of implementing biochar  
675 across extensive and often remote agricultural landscapes. Our assignments are consistent with a MAC  
676 curve for biochar in Germany (269).

677

### 678 **Cropland Nutrient Management**

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

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

692 Translating into business as usual (BAU) N<sub>2</sub>O emissions, we follow Davidson (37) in using an  
693 emissions factor of 2.54% for fertilizer N and 2.03% for manure N, or 11.9 and 9.5 MgCO<sub>2e</sub> per MgN  
694 applied. This is slightly higher than IPCC emissions factors (2% direct + indirect), but consistent with range  
695 of estimates reviewed by Snyder et al. (38) of 2-5%. Total N<sub>2</sub>O emissions from fertilizer and manure are  
696 therefore 2,054 TgCO<sub>2e</sub> yr<sup>-1</sup>.

697 Finally, we acknowledge that fertilizer production itself is a significant source of greenhouse gas  
698 emissions, both through CO<sub>2</sub> emitted during ammonia production and excess nitrous oxide during nitric acid  
699 production. Snyder et al. (38), reviewing a range of estimates, report an overall upstream emissions factor of  
700 about 4 kgCO<sub>2e</sub> kgN<sup>-1</sup> averaged over the mix of different fertilizers used in North America. Assuming no  
701 major technology change under a business as usual scenario to 2030, this adds 34% to in-field emissions  
702 from synthetic fertilizer, bringing the business as usual total in 2030 to 2,612 TgCO<sub>2e</sub> yr<sup>-1</sup>.

703 *Saving in N<sub>2</sub>O emissions under max mitigation: 706 TgCO<sub>2e</sub> yr<sup>-1</sup>*

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

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

713 Assuming again that humanity approaches this maximum linearly towards 2050, SNUPE would reach  
714 65% globally in 2030, which is 5% higher than the current European average. The amount of fertilizer used  
715 would decrease by 32% (compared to the BAU) to 95 TgN yr<sup>-1</sup>, leading to total emissions of 1,906 TgCO<sub>2e</sub>  
716 yr<sup>-1</sup> and a saving of 706 TgCO<sub>2e</sub> yr<sup>-1</sup> (= 192.6 TgCe yr<sup>-1</sup>). Note that this assumes no change in the emissions  
717 per Tg from fertilizer production.



718 *Uncertainty*

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

721 
$$Potential = F * x * (EF_{N2O} + EF_{CO2})$$

722 Where  $F$  is total nitrogen in synthetic fertilizer use in 2030,  $x$  is the percentage by which we are  
723 technically able to reduce synthetic fertilizer use through better fertilizer and manure management,  $EF_{N2O}$  is  
724 the  $N_2O$  released  $Mg^{-1}$  of nitrogen in fertilizer used and  $EF_{CO2}$  is the  $CO_2$  released  $Mg^{-1}$  of nitrogen in  
725 fertilizer produced. We follow option 3 approaches for each term using figures drawn or calculated from  
726 other sources that best reflect the suite of efficiency measures captured by this pathway.

727 To capture measurement uncertainties rather than uncertainties in assumptions of future fertilizer use,  
728 we construct a distribution out of six estimates for the year 2000 (270–272) and apply the resulting relative  
729 uncertainty of 7.2% to our assumed 2030 estimate of 139.5 Tg  $yr^{-1}$ . We construct similar confidence  
730 intervals for  $x$  (35, 36, 273–275),  $EF_{N2O}$  (37, 38) and  $EF_{CO2}$  (38) from literature estimates. IPCC Approach 1  
731 uncertainty calculations were used to generate confidence intervals for total avoided N use  $F * x$  (32.6-58.0  
732 TgN  $yr^{-1}$ ) and overall emissions flux per ha  $EF_{N2O} + EF_{CO2}$  (10.5-19.5 MgCO<sub>2</sub>e MgN<sup>-1</sup>) for Monte Carlo  
733 propagation.

734 *Mitigation Targets*

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

743

744 **Conservation Agriculture**

745 Changing agricultural practices and cropping systems can have widely varying effects on soil carbon  
746 (95, 276). However, among the practices with the most consistent positive recorded effects on carbon  
747 sequestration is the cultivation of additional cover crops in fallow periods between main crops (39).

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

755 In our baseline/BAU case, we assume the area planted with cover crops remains roughly constant at  
756 2000 levels. Poepflau & Don (39) cite several regional studies from 2007-2013 reporting low uptake of cover  
757 crops, qualitatively supporting this assumption.

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

765 *No-till agriculture not included in our estimate*

766 A second often-cited driver of soil carbon gains in agricultural soils is a shift to reduced-tillage or zero-  
767 tillage systems. Originally developed to reduce soil erosion, no-till has been promoted widely as a carbon  
768 sequestration practice (277–281). However, several more recent expert reviews of the evidence base have  
769 concluded that the evidence behind consistent carbon sequestration through practicing reduced or zero-

770 tillage is weak or inconclusive (96), and that most reports of strong positive effects on soil carbon levels  
771 were at least partly due to inherent biases in soil sampling technique (94, 95, 97, 98).

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

777 In addition, no-till may result in an increase in N<sub>2</sub>O emissions, eliminating any net greenhouse gas  
778 mitigation benefit (282, 283). Specifically, N<sub>2</sub>O emissions tend to increase, compared to conventional  
779 tillage, in the first ten years of no-till, but then tend to be reduced compared to conventional tillage.  
780 However, no-till is often not implemented continuously for longer than ten years. For fields where no-till  
781 has been implemented, the average time in no-till before tillage in the corn belt is less than three years. Less  
782 than 14% of no-till fields have been in continuous no till for at least 6 years (284).

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

#### 787 *Uncertainty*

788 We use a global estimate of SOC sequestration and associated uncertainty of  $0.12 \pm 0.03$  PgC yr<sup>-1</sup> (39).

#### 789 *Mitigation Targets*

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

## 796 **Trees in Croplands**

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

### 803 *Windbreaks*

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

813 Our review of the literature found an average of 0.175 MgC ha<sup>-1</sup> yr<sup>-1</sup> additional sequestration in  
814 biomass and soils (42–46). These numbers reflect the fact that windbreaks only cover ~5% of the cropland  
815 (i.e. the sequestration rates just on the portion of the field with the windbreak would be 20 times higher;  
816 (100)).

### 817 *Alley Cropping*

818 Alley cropping refers to planting trees in rows with crops in between. Udawatta and Jose (41) estimate  
819 that 22% of cropland in the USA is suitable for alley cropping. We applied this to the area of 635 Mha of  
820 treeless, annual cropland, outside of Africa, calculated for the maximum area for windbreaks. This yields a  
821 140 Mha maximum area of implementation for alley cropping.

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

#### 824 *Farmer Managed Natural Regeneration (FMNR)*

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

833 We assume an average sequestration of 0.4 MgC ha<sup>-1</sup> yr<sup>-1</sup> in biomass and soils based on a review of  
834 agroforestry parklands by Luedeling et al. (55).

#### 835 *Uncertainty*

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

#### 840 *Mitigation Targets*

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

845

846

847

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

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

858 Non-soil carbon improvements in management can also reduce emissions. We include reductions in  
859 emissions from improved feed digestibility and animal management (292). Improved feed management  
860 represents "inclusion of energy-dense feeds (e.g. cereal grains) in the ration, with the greatest potential in  
861 production systems that utilize little or no grain to feed animals, which are common in many parts of the  
862 world." (292). While this reduces methane emissions from enteric fermentation, more importantly this  
863 allows a reduction in total animal numbers needed to supply the same level of meat and milk demand (103).  
864 Improved animal management includes use of improved livestock breeds, and increased reproductive  
865 performance, health, and liveweight gain. Both Improved Feed and Animal Management pathways assume  
866 that demand for livestock products is relatively inelastic, such that improved efficiency of production  
867 reduces livestock numbers and emissions. We do not include changes in manure management or feed  
868 additives. The costs of reducing emissions via manure management have been estimated at 200 USD  
869 MgCO<sub>2</sub>e<sup>-1</sup> (107) and the total potential is below 100 TgCO<sub>2</sub>e yr<sup>-1</sup> (292). Feed additives have uncertain long-  
870 term effects on emissions due to adaptation of rumen microbial systems, potential environmental and health  
871 impacts have not yet been adequately studied, and public acceptance is uncertain.

872 *Mapping Country-Level Mitigation*

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

#### 876 *Uncertainty*

877 Uncertainty for animal management and grazing optimization are drawn from Herrero et al. (292).  
878 Uncertainty for improved feed was calculated using option three (see above) using estimates from Havlik et  
879 al (108), Herrero et al. (292) and Gerber et al (106). Uncertainty for the legumes in pastures pathway was  
880 obtained via expert elicitation (N=3 experts). The mean estimate for the climate mitigation potential for  
881 sowing legumes in planted pastures is conservative (and toward the lower end of stated confidence  
882 intervals) because Henderson et al. (56) quantified soil C sequestration potential only in areas where sowing  
883 legumes would lead to net greenhouse gas benefits (i.e., soil C sequestration exceeded increased CO<sub>2</sub>e due  
884 to greater N<sub>2</sub>O emissions).

#### 885 *Mitigation Targets*

886 Target assignments for optimal intensity, legumes, and improved feed are based on global model MAC  
887 curves (293). Our target assignments for animal management were informed by IPCC and EPA studies  
888 (117, 119) while noting that sources did not fully match our grazing animal management pathway  
889 definition.

890

#### 891 **Improved Rice Cultivation**

892 Much of the world's rice is typically grown in standing water, generating anaerobic conditions in the  
893 soil, which causes methane and N<sub>2</sub>O emissions, comprising 10-14% of anthropogenic methane emissions  
894 (152, 294). Water management techniques such as alternate wetting and drying (AWD) and midseason  
895 drainage (MSD) limit the time rice paddies spend in an anaerobic state thereby reduce annual methane  
896 emissions while at the same time saving water (152). Additional management techniques applied to upland  
897 rice such as fertilizer applications, residue and tillage management practices reduce the amounts of nitrogen  
898 and carbon emissions (295).

899 Projected total global emissions associated with rice cultivation in 2030 are estimated to be 755  
900 TgCO<sub>2</sub>e yr<sup>-1</sup> (59). This includes 473 TgCO<sub>2</sub>e yr<sup>-1</sup> methane and 341 TgCO<sub>2</sub>e yr<sup>-1</sup> nitrous oxide offset by soil  
901 carbon sequestration of 16 TgC<sub>e</sub> yr<sup>-1</sup>. Using twenty-six mitigation scenarios produced from the  
902 Denitrification-Decomposition (DNDC) model for both dryland and flooded rice the US EPA 2013 study  
903 reports a 35% reduction in combined Ce emissions from improved cultivation techniques. We apply the  
904 EPA's 35% mitigation potential value to the EPA's estimated total global emissions from rice production in  
905 2030 (755 TgCO<sub>2</sub>e yr<sup>-1</sup>) to arrive at a maximum mitigation potential of 265 TgCO<sub>2</sub>e yr<sup>-1</sup> from improving  
906 rice cultivation (59). Compared to an IPCC, 2006 study (296) that reports a 40% reduction in methane from  
907 midseason drainage, this EPA-derived estimate is conservative while being more inclusive, since it includes  
908 nitrous oxide and carbon flux in stated mitigation potential.

#### 909 *Uncertainty*

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

#### 913 *Mitigation Targets*

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

916

#### 917 **Avoided Coastal Wetland Impacts**

918 We define coastal wetland conversion as the anthropogenic loss of organic carbon stocks in  
919 mangroves, saltmarshes, and seagrass ecosystems. For mangroves, we calculate the extent of conversion  
920 based on best estimates of current extent (13.8 ±1.24 Mha, (77)), and recently reported loss rates loss rate  
921 (0.7% (66)). We estimated mangrove carbon stocks by combining the mean of seven above and below-  
922 ground vegetation biomass estimates from the literature (194 ±76 MgC ha<sup>-1</sup>, (65–69, 71, 299)), with the  
923 most recent and comprehensive global estimate of soil organic carbon (SOC) density in the top meter (369



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

926 For all three coastal wetland ecosystems, flux is the sum of vegetation biomass emissions (assuming  
927 100% committed emissions within a 20-year time horizon), and SOC emissions – calculated as the product  
928 of SOC stocks and percent carbon stock released into the atmosphere post disturbance ( $63\% \pm 25\%$  (65, 66,  
929 300)), and percent committed emissions released in the first 20 years post-disturbance. Like all our avoided  
930 loss pathways (avoided forest conversion, avoided woodfuel harvest, avoided peatland conversion, and  
931 avoided grassland loss), avoided coastal wetland conversion is calculated based on 20 year “committed  
932 emissions” accounting approach (209). Given that coastal wetland soil organic carbon pools are lost over a  
933 long time frame, the 20 year accounting window captures  $86\% \pm 11\%$  of SOC emissions based on estimated  
934 half-life of 7.5 years (65). Therefore, 54% of carbon in coastal wetlands is lost within in 20 years.

### 935 *Mapping Country-Level Mitigation*

936 Only the mangroves component of this pathway was mapped. We mapped our mangrove maximum  
937 mitigation potential using the annual proportion of mangroves lost in each country per year reported in  
938 (301).

### 939 *Uncertainty*

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

### 943 *Mitigation Targets*

944 Our coastal wetland mitigation targets are informed by a recent study (62) reporting that a large  
945 percentage of mangrove conversion is possible at costs  $<10 \text{ USD MgCO}_2^{-1}$ . In the absence of cost curve  
946 literature for other pathway elements (salt marsh, sea grass) we assumed similar cost-effectiveness as  
947 mangrove systems.

948

949

950 **Avoided Peatland Impacts**

951 We estimated emissions from conversion of peatlands in three climate zones: boreal, temperate, and  
 952 tropical. For each type, we calculated annual loss rates and annual emission rates to determine the total  
 953 emissions upon conversion using a 20-year time horizon. To determine the recent annual conversion rate of  
 954 freshwater peatlands we used The International Mire Conservation Group Global Peatland Database (73,  
 955 111, 112). We aggregated the reported peatland area by climate zone to determine the change in intact  
 956 tropical, temperate, and boreal peatland during the 18 year period between 1990 and 2008 (73). We  
 957 calculated the rate of decrease of intact (versus degraded) peatlands between 1990 and 2008. We also used  
 958 the peatland database for information on the extent of forested peatlands and country level CO<sub>2</sub> emissions  
 959 (Table S12).

960 **Table S12.** Carbon stocks and conversion rates for global peatlands

	Conversion	Carbon Stocks		
	Rate Mha yr <sup>-1</sup>	Biomass MgC ha <sup>-1</sup>	Soil MgC ha <sup>-1</sup>	Total MgC ha <sup>-1</sup>
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

961

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

968 We calculated a per area annual emission rate for each country using country-level data on area of  
 969 degraded (drained and deforested) peatlands and emissions in 2008 (73). We calculated a per area annual

970 emission rate for each climate zone based on the weighted average of these country-level emissions. Using  
971 this rate, we calculated the 'committed emissions' over a 20-year time horizon by multiplying the annual rate  
972 by twenty (Table S12). Although Joosten (73) does not include emissions from tropical peatland fires, the  
973 loss of carbon stocks resulting from fire is likely to be similar to carbon losses from decomposition over our  
974 20 year time-horizon.

#### 975 *Mapping Country-Level Mitigation*

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

#### 978 *Uncertainty*

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

#### 983 *Mitigation Targets*

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

986

### 987 **Coastal Wetland Restoration and Peatland Restoration**

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

991 We estimate potential extent of wetland restoration based on the extent of “degraded” wetlands. For  
992 peatlands, this is derived from Joosten (73), a review of country-level peatland statistics. We use peatland  
993 area estimates for 2008, representing a snapshot of peatlands in various states of degradation. For  
994 mangroves and saltmarshes, we calculate the total historic area lost by combining estimates of global extent

995 (described in coastal wetlands avoided conversion pathway methods above) and percent of original extent  
996 disturbed (76).

997 To calculate the rate of soil carbon sequestration in restored coastal wetlands, we use published carbon  
998 burial rates (76) and mangrove vegetation sequestration rates (78), assuming negligible vegetation  
999 sequestration in saltmarshes and seagrass. Due to controversy in the literature about the timing and net  
1000 atmospheric effect of methane emissions in restored peatlands, we choose to omit a sequestration benefit  
1001 from peatland restoration in our calculations (79–81). This conservative assumption has a small impact on  
1002 the overall estimate of biophysical mitigation potential, as total sequestration is heavily outweighed by  
1003 avoided loss. Wetland vegetation biomass growth rates for mangroves and peatlands were added to soil  
1004 carbon sequestration based on available estimates in the literature (7, 10, 78).

1005 The majority of wetland restoration mitigation is avoided emissions from re-wetting (peatlands) and  
1006 revegetation (coastal wetlands). To calculate these avoided emissions, we assume degraded wetlands have  
1007 already lost 50% of their original carbon stocks, based on the reasoning that the global aggregate of  
1008 degraded wetlands represents a balanced chronosequence of all phases of carbon depletion. This assumption  
1009 avoids the problematic application of an average rate of global wetland carbon loss, which has very high  
1010 uncertainty (302–304). Therefore, our wetlands restoration avoided emissions flux factors are 50% of  
1011 avoided wetlands conversion flux for corresponding ecosystems.

1012 Carbon accounting for the coastal wetland restoration pathways contains both a sequestration  
1013 component, and an avoided emissions component. Therefore, the maximum potential mitigation expressed  
1014 here is a mixture of two accounting methods: (i) an annual rate of carbon sequestration per unit area (coastal  
1015 wetlands only), and (ii) total avoided loss of carbon per unit area (all wetlands). Therefore, to combine (i)  
1016 and (ii), we divide the SOC avoided emissions by 20 years (our committed emissions time horizon), to  
1017 achieve our avoided emissions flux rate.

1018 Saturation of annual mitigation potential occurs after about 20 years, at which point we assume the rate  
1019 of avoided SOC emissions ( $4.79 \text{ MgCe ha}^{-1}\text{yr}^{-1}$ ) decline, because SOC stocks held in drained peatlands  
1020 would be mostly oxidized after two decades in the absence of re-wetting.

1021 *Mapping Country-Level Mitigation*

1022 Like avoided peatland impacts, we mapped peatland restoration using the country-level estimates of the  
1023 extent of degraded peatlands (73) and the avoidable flux reported in Table S11. The coastal wetland  
1024 restoration pathway was not mapped.

1025 *Uncertainty*

1026 We used an option 1 approach to calculate uncertainty of coastal wetland restoration – similar to  
1027 coastal wetland avoided conversion uncertainty described above. We applied literature-based uncertainties  
1028 to certain variables (e.g. carbon burial (76)) and inter-study variance to others (e.g. seagrass loss rate).

1029 Available published data did not permit options 1-3 for empirical estimation of uncertainty of the  
1030 global area of degraded peatlands, so we employed expert elicitation for this component of uncertainty (N =  
1031 3 experts elicited). Results of expert elicitation for avoided peatland impacts also informed our estimate of  
1032 peatland restoration mitigation potential uncertainty.

1033 *Mitigation Targets*

1034 In the absence of prior studies reporting marginal abatement cost (MAC) curves to assign mitigation  
1035 targets, we constructed them using a comprehensive project database (120), available at  
1036 [https://www.researchgate.net/publication/284714306\\_Restoration\\_database](https://www.researchgate.net/publication/284714306_Restoration_database). This database contains  
1037 separate data for saltmarsh, seagrass, and mangrove restoration projects from the published and gray  
1038 literature. The costs included are the technical costs of restoration (capital and operating costs), but no  
1039 opportunity or transaction costs, and, hence, they are likely underestimates of the true restoration costs. We  
1040 retained only the observations with non-missing values for both the area of the project and the cost per ha.

1041 The emissions reductions from a project were calculated using the total project area from the database  
1042 and a CO<sub>2</sub> sequestration rate per year per ha based on our database. The restoration costs per MgCO<sub>2</sub> were  
1043 calculated by dividing the per ha sequestration rate by the per ha restoration cost. Since all costs had been  
1044 converted to 2010 values, we used a conversion factor of 1.09 based on CPI to get them to 2015 values.

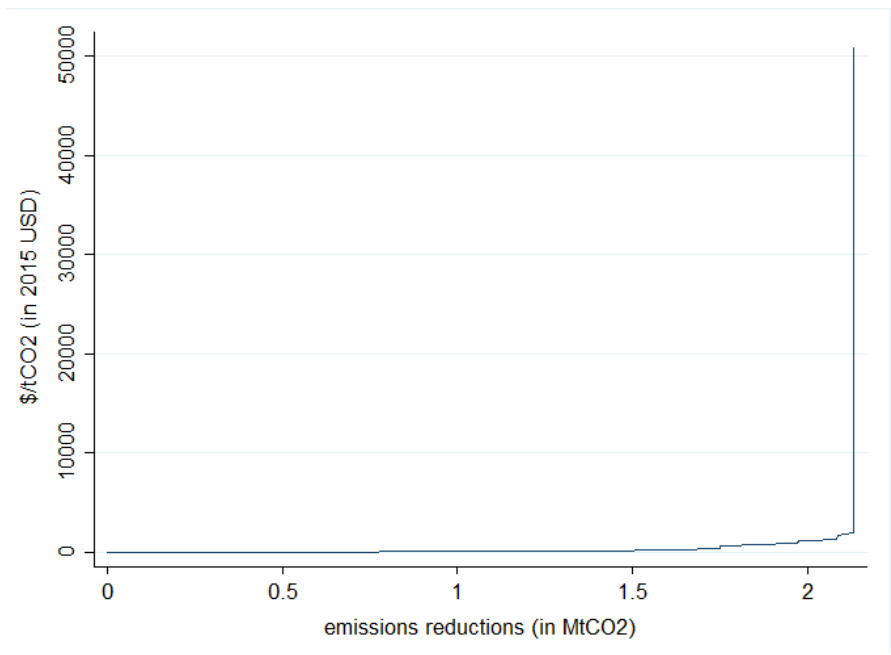
1045 We used 55 mangrove studies from both developed and developing countries (American Samoa,  
1046 Australia, Bangladesh, China, Colombia, Ecuador, Hong Kong, India, Indonesia, Malaysia, Philippines,

1047 Puerto Rico, Thailand, USA, Venezuela, and Vietnam). We used the sum of emissions abated from all  
1048 projects to determine the maximum abatement (Fig. S6).

1049 We constructed a saltmarsh cost curve with 51 observations (Fig. S7). In contrast to the mangrove  
1050 restoration studies, projects were all based in developed countries (UK, US, Australia) and, hence, are likely  
1051 to overestimate global restoration costs.

1052 The seagrass constructed cost curve (Fig. S8) is based on 35 observations from developed countries  
1053 only (UK, US, Australia) and is therefore likely to overestimate the global restoration costs. However,  
1054 seagrass restoration projects tend to be much more expensive than other types of restoration projects (e.g.,  
1055 mangroves) (120). Our assignment of individual mitigation targets based on these constructed cost curves  
1056 for mangroves, saltmarshes, and seagrass are reported in Table S4.

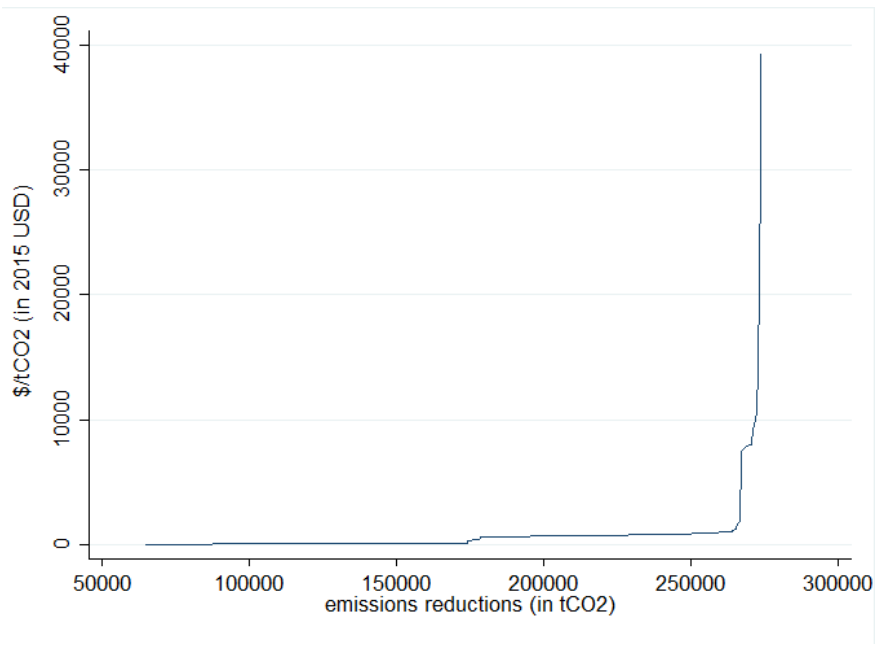
1057



1058

1059 **Fig. S6.** Cost curve for mangrove restoration.

1060

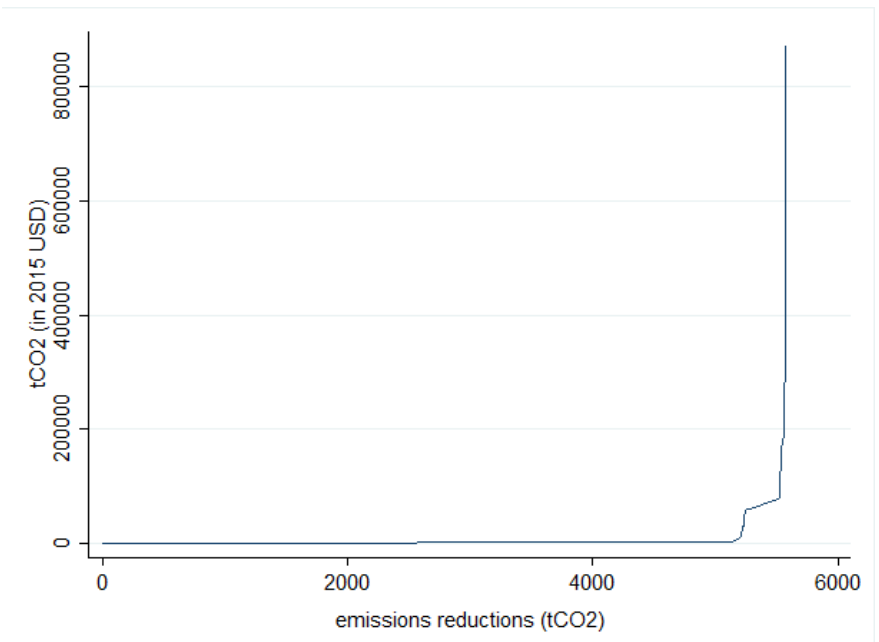


1061

1062 **Fig. S7.** Cost curve for salt marsh restoration. Two observations with very high values excluded from the  
 1063 graph, but not the calculations.

1064

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1066

1067 **Fig. S8.** Cost curve for seagrass restoration.

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