CLARA Missing Pathways to 1.5°C: Supplementary information – methods and data

Part 1: Land rights

A recently published paper from Rights and Resources Initiative[1] reports that collectively-managed land across 64 countries in all forest biomes were found to store at least 293 Gt C in forests and soils. This represents 17% of terrestrial carbon stocks in all assessed countries, and 22% of terrestrial carbon stocks in assessed countries across the tropics.[1]

Part 2: Ecosystem-based restoration

Avoided conversion of ecosystems

Pathway	Biome	Area (Mha/yr)	Flux (Mg C/ha/yr)	Range	Saturation	Gt CO_{2-eq}/yr avoided by 2050	Assumptions
Avoided deforestation and degradation	Tropical	9[2]			>80	4.07[3]†	Deforestation and degradation emissions assumed to halve by 2020, and end by 2030, in line with existing political commitments at global, regional and national scales. Baseline assumption is that if no policy action is taken to prevent forest conversion and degradation, emissions would continue at current or slightly declining rates, resulting in +3-5 Gt CO_2/year in emissions over the course of the century.[4]
Peatland restoration	Temperate /boreal			0.26-0.57[5]	>100[5]	0.42[5]	Avoided emissions from restoring drained peatlands and protecting further degradation of peat based on Leifeld and Menichetti (2015),[5] who find higher current emissions from drained peat than other recent estimates.[3] Base-line assumption that emissions from degraded peat would continue for centuries, but scenario assumption all peatland is protected and restored by 2030.[5]
	Tropical			0.04-2.79[5]	>100[5]	1.48[5]	
Grasslands (avoided conversion)	Temperate /boreal	0.7[6]	0.7[6]	1.13-5.40[6]		0.05[6]	Pathway based on Griscom et al. (2017). Avoiding the conversion of grasslands (including savannas and shrublands) to cropland avoids emissions from soil carbon. The additional sequestration potential of grasslands is also high through changed management practices, but not quantified here for reasons of uncertainty and reversals in soil carbon.
	Tropical / sub-tropical	1[6]	1[6]	1.13-5.40[6]		0.07[6]	

Additional sequestration through changed land-use practices

Pathway	Biome	Area (Mha)	Flux (Mg C/ha/yr)	Range	Saturation	Gt CO_{2-eq}/yr sequestered* by 2050	Assumptions
Forest ecosystem restoration (degraded natural forests restored)	Temperate /boreal	275.5[2]	0.5[7]		100[8,9]	-0.51	In order to ensure half of all forest biomes are protected and allowed to recover to intact forests, we calculated that 25% of 'other natural forests' as classified by the FAO would need to be set aside for restoration. This results in an area of 600 Mha to be 'set-aside', which, along with the current FAO estimate of 1277 Mha of primary forest, would see approximately half of all natural forests left undisturbed. Forests set aside are assumed to be degraded natural forests, with logging or other disturbance not in the recent past (>20 years). Hence mature biome-average above-ground sequestration rates were applied, assuming a
	Tropical/ sub-tropical	335.1[2]	1.1[7]		60[14–16]	-1.35	

							forest already recovered from logging was able to shift to an older age-class, and continue to accumulate carbon stocks. Above-ground carbon (MgC/ha/yr) biome average sequestration rates are taken from Pan et al. (2011),[7] and are slightly conservative compared to other values in the literature that estimate carbon sequestration potential from previously logged forests representative of a range of environmental domains and logging histories.[8,10,11] The resulting sequestration would represent an additional sink, if further anthropogenic disturbance of these forests were to cease. The on-going sink in primary / mature forests after saturation is not included, to avoid double-counting with residual land sink.
Natural forest expansion	Temperate	50[2]	2.6[17]	0.56-7.05[17]	100[8,9]	-0.48	Forest expansion occurs through either natural regeneration or tree-planting (reforestation) on recently deforested land (implying a land-use change from non-forest to forest). We assume that natural regeneration is assumed to be by far the most effective intervention for both biodiversity and climate mitigation, hence we employ this intervention to meet all 350 Mha of the Bonn Challenge (despite that current pledges use a mix of natural regeneration and plantations).[18] 80% of regeneration assumed to be met in the tropics, in line with current Bonn Challenge pledges.[18] Boreal forests are excluded from large-scale forest expansion (but not forest restoration) due to albedo effect.[12] The 350 Mha of regeneration is assumed to be regeneration for conservation purposes, which creates an on-going sink. Carbon uptake continues for decades before declining as forests mature - large trees can take well over a century to mature fully.[19,14,20] IPCC biome average sequestration rates for regrowth forests are used here, which are comparable to estimates in the literature for temperate forests[10,21–23] and for tropical forests.[14, 7,24,12,16]
	Tropical / sub-tropical	300[2]	3.1[17]	0.42-8.46[17]	60[14–16]	-3.41	
Responsible use of natural forests	Temperate /boreal	74[2]	0.4[10]	+	100[8,9]	-1.09	For temperate and boreal regions, responsible use of natural forests means reduced wood harvest. Based on assumptions of reducing harvest, extending rotation times and reducing disturbance, carbon stock in production forests could as much as double[10,21] Wood harvest is reduced, meaning reduced income for landowners if appropriate incentives/subsidies not in place.[22,23] HWP not included, which could add 0.43-1 GtCO2/year,[10,12] but mitigation value of HWP disputed.[22,26] Substitution effects excluded.[21] In tropical forests, reduced harvest and sustainable management practices have not been shown to increase carbon stocks or biodiversity,[27] hence responsible forest use in the tropics is characterised by withdrawing industrial logging and other extractive activities. Shifting cultivation, identified as a significant contributor to degradation emissions in tropical forests[3,25] is assumed to halve in this scenario, with any ongoing disturbance from shifting cultivation or swidden agriculture offset by regrowth in abandoned fallows, lengthened fallow times and/or improved swidden practices.[28–30]
	Tropical / sub-tropical	419[2]	1.19[12]	+	60[14–16]	-1.83	
Part 3: Agriculture							
Pathway	**Region**	**Area**	**Flux**		**Saturation**	**Gt CO_{2-eq}/yr sequestered* by 2050**	**Assumptions**
Agroforestry	Temperate /boreal	100[2]	0.65[31–33]		50[34]	-0.24	Zomer et al. (2016) identify a baseline uptake for agroforestry of 0.03 MgC/ha/yr in temperate and boreal biomes, and 0.14 MgC/ha/yr in tropical biomes, attributed mostly to additional trees in agricultural landscapes.[31] We calculate an average sequestration rate from the literature for above-ground carbon uptake due to a broad range of agroforestry practices as 0.67 MgC/ha/yr for temperate and boreal biomes and 1.23 MgC/ha/yr for tropical biomes.[31–35] We subtract Zomer's baseline rate from these figures to
	Tropical / sub-tropical	200[2]	1.09[31,3435]		50[34]	-0.8	

							achieve an additional MgC/ha/yr uptake, and assume the resulting sequestration rate could be sustained for 50 years[34] across a wide area of agricultural land (300 Mha of permanent cropland), given positive incentives to increase tree cover.[35] This area estimate is considered conservative as +40% of agricultural land identified suitable for agroforestry.[31,34] Sequestration values are conservative, as they concentrate on above-ground carbon increases in agroforestry, which also delivers significant increases in soil carbon.*
	Region	2050 agriculture sector baseline scenario: 11 Gt CO_2eq/yr				**Gt $CO_{2\text{-}eq}$/yr avoided by 2050**	
Reduced use of synthetic fertilizer	Global					0.69[36]	More efficient fertilisation and increased use of biologically-derived nitrogen inputs like manure and crop residues could reduce field losses by 58 Tg Nr (0.69 Gt CO_2eq). This is not included in total avoided emissions by 2050 reported here due to potential overlap with reduced use of synthetic fertilisers in the following three reduced production and consumption pathways, which result in less cropland area.
Ecological livestock production	Global					4.5[37]	Reducing animal product production and consumption by 50% by 2050, in line with healthy diet recommendations[38], represents a reduction of 64% over baseline emissions in 2050[37] (reducing emissions from a baseline estimate of 11 Gt CO_2eq/yr in 2050 to 6.5 Gt CO_2eq/yr).[38] This would require reducing meat production to 155 million tonnes per year by 2050, limiting meat consumption to 300 g per capita per week and dairy consumption to 630 g per capita per week meaning some regions would reduce consumption by more than 50%, while others increased consumption, for an equitable outcome.
Healthy diets	Global					2.5[38]	Limiting overall consumption to healthy calorie levels in line with dietary guidelines, would further reduce emissions from 6.5 to 4 Gt CO_2eq/year globally by 2050[38], while in regions where food insecurity and hunger are high, consumption may need to increase, particularly in certain food groups to ensure adequate nutrition.
Reducing food waste	Global					0.5[38]	Reducing food waste by 50% would reduce emissions still further, to a rate of 3.5 Gt CO2eq/year by 2050[38]
		2050 mitigation scenario: 3.5 Gt CO_2/yr					

Notes:

* Sequestration potential values are for above-ground carbon only. Soil carbon stocks are extensive, representing 3 times the carbon in the atmosphere, and twice that contained in forests. Hence, the exclusion of below-ground carbon does not diminish the importance of this carbon pool, but rather the large range in estimates and uncertainties. Average shoot:root ratios would see the mitigation potential in most pathways increase by approximately 20 - 40% if below-ground carbon estimates were included. Including median assumptions in the literature for below-ground sequestration from activities such as agroforestry would provide very large sequestration potentials, which come with equally large uncertainties. Estimates of future mitigation potential from the land sector should be conservative rather than optimistic given the great uncertainties, governance challenges and risks posed by climate change itself, to realizing these potentials. Avoided emissions from peatlands and grasslands includes avoided soil carbon loss.

** The above pathways would result in cumulative carbon-dioxide removal of 448 Gt CO_2eq by 2100. This is due to the time taken for natural sinks to scale in to full sequestration capacity, and then scaling out as sinks saturate. While old-growth forests continue to sequester carbon, this is accounted for already as the residual carbon sink, therefore we are only counting here the additional emissions of creating new carbon sinks and protecting those sinks to maturity. Ongoing sequestration in mature primary forests is not counted. 448 Gt CO_2eq (122 Gt C) is close to the historical land-use debt, which has been estimated between 119-187 Gt C.[25,3,39]

References

1. Rights and Resources Initiative. *A Global Baseline of Carbon Storage in Collective Lands: Indigenous and local community contributions to climate action*. (Rights and Resources Initiative, 2018).
2. FAO. *FAOSTAT*. (2015).
3. Houghton, R. A. & Nassikas, A. A. Global and regional fluxes of carbon from land use and land cover change 1850-2015: Carbon Emissions From Land Use. *Glob. Biogeochem. Cycles* **31,** 456–472 (2017).
4. Gullison, R. E. *et al.* ENVIRONMENT: Tropical Forests and Climate Policy. *Science* **316,** 985–986 (2007).
5. Leifeld, J. & Menichetti, L. The underappreciated potential of peatlands in global climate change mitigation strategies. *Nat. Commun.* **9,** (2018).
6. Griscom, B. W. *et al.* Natural climate solutions. *Proc. Natl. Acad. Sci.* **114,** 11645–11650 (2017).
7. Pan, Y. *et al.* A Large and Persistent Carbon Sink in the World's Forests. *Science* **333,** 988–993 (2011).
8. Roxburgh, S. H., Wood, S. W., Mackey, B. G., Woldendorp, G. & Gibbons, P. Assessing the carbon sequestration potential of managed forests: a case study from temperate Australia: Carbon sequestration potential. *J. Appl. Ecol.* **43,** 1149–1159 (2006).
9. Luyssaert, S. *et al.* Old-growth forests as global carbon sinks. *Nature* **455,** 213–215 (2008).
10. Nabuurs, G.-J. *et al.* By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry. *Forests* **8,** 484 (2017).
11. Houghton, R. A., Byers, B. & Nassikas, A. A. A role for tropical forests in stabilizing atmospheric CO2. *Nat. Clim. Change* **5,** 1022–1023 (2015).
12. Houghton, R. A. & Nassikas, A. A. Negative emissions from stopping deforestation and forest degradation, globally. *Glob. Change Biol.* **24,** 350–359 (2018).
13. Rutishauser, E. *et al.* Rapid tree carbon stock recovery in managed Amazonian forests. *Curr. Biol.* **25,** R787–R788 (2015).
14. Poorter, L. *et al.* Biomass resilience of Neotropical secondary forests. *Nature* **530,** 211–214 (2016).
15. Asner, G. P. *et al.* Mapped aboveground carbon stocks to advance forest conservation and recovery in Malaysian Borneo. *Biol. Conserv.* **217,** 289–310 (2018).
16. Grace, J., Mitchard, E. & Gloor, E. Perturbations in the carbon budget of the tropics. *Glob. Change Biol.* **20,** 3238–3255 (2014).
17. IPCC. Chapter4: Forest Land. in *2006 IPCC Guidelines for National Greenhouse Gas Inventories* **Volume 4: Agriculture, Forestry and Other Land Use,** (2006).
18. Wheeler, C., Mitchard, E., Koch, A. & Lewis, S. L. The mitigation potential of large-scale tropical forest restoration: assessing the promise of the Bonn Challenge. *Rev.*
19. Keith, H., Mackey, B. G. & Lindenmayer, D. B. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. *Proc. Natl. Acad. Sci.* **106,** 11635–11640 (2009).
20. Lutz, J. A. *et al.* Global importance of large-diameter trees. *Glob. Ecol. Biogeogr.* **27,** 849–864 (2018).
21. Böttcher, H., Hennenberg, K. & Winger, C. *Forest Vision Germany*. 77 (Oko Institut, 2018).
22. Law, B. E. *et al.* Land use strategies to mitigate climate change in carbon dense temperate forests. *Proc. Natl. Acad. Sci.* **115,** 3663–3668 (2018).
23. Pingoud, K., Ekholm, T., Sievänen, R., Huuskonen, S. & Hynynen, J. Trade-offs between forest carbon stocks and harvests in a steady state – A multi-criteria analysis. *J. Environ. Manage.* **210,** 96–103 (2018).
24. Bonner, M. T. L., Schmidt, S. & Shoo, L. P. A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations. *For. Ecol. Manag.* **291,** 73–86 (2013).
25. Arneth, A. *et al.* Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed. *Nat. Geosci.* **10,** 79–84 (2017).
26. Keith, H., Lindenmayer, D., Macintosh, A. & Mackey, B. Under What Circumstances Do Wood Products from Native Forests Benefit Climate Change Mitigation? *PLOS ONE* **10,** e0139640 (2015).

27. Martin, P. A., Newton, A. C., Pfeifer, M., Khoo, M. & Bullock, J. M. Impacts of tropical selective logging on carbon storage and tree species richness: A meta-analysis. *For. Ecol. Manag.* **356,** 224–233 (2015).
28. Ziegler, A. D. *et al.* Carbon outcomes of major land-cover transitions in SE Asia: great uncertainties and REDD+ policy implications. *Glob. Change Biol.* **18,** 3087–3099 (2012).
29. Mackey, B. *et al. Options and Implementation for Ecosystem-based Adaptation, Tanna Island, Vanuatu*. (Griffith University, 2018).
30. van Vliet, N. *et al.* Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: A global assessment. *Glob. Environ. Change* **22,** 418–429 (2012).
31. Zomer, R. J. *et al.* Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Sci. Rep.* **6,** (2016).
32. Cardinael, R. *et al.* Increased soil organic carbon stocks under agroforestry: A survey of six different sites in France. *Agric. Ecosyst. Environ.* **236,** 243–255 (2017).
33. Ramachandran Nair, P. K., Mohan Kumar, B. & Nair, V. D. Agroforestry as a strategy for carbon sequestration. *J. Plant Nutr. Soil Sci.* **172,** 10–23 (2009).
34. Dixon, K., Winjum, K., Andrasko, J., Lee, J. & Schroeder, E. Integrated land-use systems: Assessment of promising agroforest and alternative land-use practices to enhance carbon conservation and sequestration. 22 (1994).
35. Watson, B., Noble, L., Bolin, B. & et. al.,. *Summary for policymakers: land use, land-use change, and forestry : a special report of the Intergovernmental Panel on Climate Change.* (Intergovernmental Panel on Climate Change, 2000).
36. Bodirsky, B. L. *et al.* Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nat. Commun.* **5,** (2014).
37. Tirado, R., Thompson, K. ., Miller & Johnston, P. Less is More: Reducing Meat and Dairy for a Healthier Life and Planet Scientific Background. (2018).
38. Röös, E. *et al.* Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. *Glob. Environ. Change* **47,** 1–12 (2017).
39. Mackey, B. *et al.* Untangling the confusion around land carbon science and climate change mitigation policy. *Nat. Clim. Change* **3,** 552–557 (2013).