Comment

Supplementary information to:

Nature-based solutions can help cool the planet — if we act now

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Nature-based solutions can help cool the planet — if we act now

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Estimating the annual uptake and avoided emissions from Natural Climate Solutions

Various estimates have been made about how much nature-based solutions (NbS) can contribute to achieving net zero by mid-century. Yet confusion remains, as the results have been estimated over a range of objectives, timeframes, and differing model assumptions (Griscom et al., 2017, 2020; Anderson et al., 2019; Busch et al., 2019; Friedlingstein et al., 2019; Lewis et al., 2019; Roe et al., 2019; Griscom et al., 2020; Suarez et al. 2019; Cook-Patton et al. 2020; Holl & Brancalion 2020; Smith et al., 2020).

To estimate the cost-effective climate mitigation potential of 20 natural pathways on land (≤ \$100 $MgCO2e^{-1}$), we updated the Griscom et al. (2017) global estimate for NbS, with extrapolations from Griscom et al. (2020) (Table S1). We further constrained temperate forest restoration mitigation potential by extrapolating a marginal abatement cost curve for tropical forest restoration (Busch et al., 2019). These are estimated as avoided emissions and enhanced sinks from protection, restoration, and management of terrestrial ecosystems. This is a conservative estimate of NbS, because it excludes avoided emissions of non-CO_2 greenhouse gas mitigation (e.g. N_2O, CH_4) from NbS, estimated to represent 10% of total NbS mitigation potential. For this analysis, we focus on the impact of NbS on CO_2 emissions only and assume this NbS uptake rate is maintained through to 2100.

Reforestation includes the conversion of non-forest lands to forest in areas ecologically appropriate for forests. We exclude afforestation, defined here as conversion of native non-forest cover types (eg. grasslands, savannahs, peatbogs). We exclude reforestation potential in boreal systems due to the albedo effect which means that increased forest cover may lead to net warming (Betts et al., 1997). It is worth noting that Bush et al. (2019) report a higher estimate for avoided deforestation. Here, we use the Griscom et al. (2017), as we were more conservative in constraining our estimates: we only considered deforestation in intact forest, and did not include emissions from avoided deforestation in managed systems. The model includes coastal ecosystems (mangroves, saltmarshes, and seagrass) but exclude marine systems such as coral reefs, phytoplankton, kelp forests, and marine fauna, krill, and teleost fish, for which data remain sparse and estimates uncertain (Howard et al., 2017; Siikamäki et al., 2013). Finally, some biophysical responses of ecosystems to climate change, such as changes in evapotranspiration, or the effects of CO_2 fertilization, are not included in the model. The net effect of these remains unclear, and cannot be quantified in our modelling framework.

For a full description of the design of the model, see the supplementary information of Griscom et al. (2017).

For scenarios limiting warming to 1.5 °C, we estimated a higher Marginal Abatement Cost, to reflect a doubling of BECCs between the 1.5 and 2 °C scenarios in the stylised models. The 1.5 °C-consistent model implements NbS with:

- a ramp up from 0 to 10 Gt CO_2 yr^{-1} globally between 2020 and 2025 at cost-effective levels (≤ $100 Mg CO_2e^{-1});
- a ramp up from 10 to 20 Gt CO_2 yr^{-1} globally between 2025 and 2055 (year of net zero), to consider higher ambition of 1.5 °C scenario, and an increase in carbon prices resulting in an approximate doubling of near-term mitigation needed;
- and an annual uptake and avoided emissions of ca. 10 Gt CO_2 yr^{-1} globally between 2055 and 2100, as biological carbon sinks will begin to saturate, and as direct air capture gets even cheaper.

This results in NbS contributing a removal of 380 Gt CO_2 through 2050, reducing the 750 GtCO_2 emitted through 2050 from other sectors to a 1.5 °C scenario. This trend accounts for two factors: (i) The contribution of NbS is sensitive to the price of carbon, and (ii) Some carbon sinks will saturate over time, for example, as newly planted forests mature.

In particular, this scenario accounts for a decline in NbS price due to improving land sector technology on both the demand and supply side, while safeguarding food security, and acknowledging that the price of direct air capture will create a ceiling for the price of carbon (Allen et al., 2009). Limiting warming to 1.5 °C would require bigger investments overall, and we can anticipate those delivered in all sectors - including NbS. Hence our willingness to pay for NbS would increase, as the price of CO_2e has been estimated to increase up to $ 700-1500 Mg CO_2e under such high-ambition scenarios (Huppmann et al., 2018). This would lead to an increase in NbS until we reach peak warming. However, the actual cost of carbon is unlikely to rise above that of free air capture, currently estimated at $ 200 Mg CO_2, suggesting some high carbon cost scenarios may not continue through the century. Hence, we constrain the contribution of NbS to 10 Gt CO_2 yr^{-1} after 2050, to account for a fall of the price of carbon and carbon sequestration saturation in some systems.

It is worth noting that the increased scaling up of NbS up to 2050 did not change the contribution of NbS to peak warming by much, compared to estimates from using 10 Gt CO_2 yr^{-1} globally from 2025 to 2100.

For scenarios consistent with limiting warming to 2 °C (1.3 - 2.7 °C) and 3 °C (1.6 - 3.6 °C), we use an estimated uptake and avoided emissions of ca. 10 Gt CO_2 yr^{-1} globally between 2025 and 2100 at cost-effective levels (≤ $100 Mg CO_2e^{-1}). Thus, NbS contributes an additional removal of 280 Gt CO_2 through 2050, reducing the 1050 Gt CO_2 (2 °C scenario) and 1270 Gt CO_2 (3 °C scenario) contributed by other sectors through 2050.

These estimates must come well caveated. Adding NbS implementation on top of a standard 1.5 °C scenario is asking NbS to achieve more than our highest ambition target, hence it is not possible to compare the contribution of NbS here to other sectors. Here, we need to clarify that both scenarios are considered 1.5 °C -consistent. However, in one sense our estimate of NbS is conservative because our scenarios ask it to contribute a more time-constrained outcome of achieving 1.4 °C, or further improving the likelihood of achieving 1.5 °C outcome. On the other hand, we may be overestimating the contribution of NbS in a 1.5 °C scenario (averaging between 10 and 20 Gt CO_2 yr^{-1} between 2020 and 2100). Several interventions implemented in the standard scenario will depend on the same land availability (particularly bioenergy crops with carbon capture and storage, BECCS). While our NbS scenario has the advantage of being transparent, an ideal modelling study would include all pathways within an Integrated Assessment Model (IAM), to avoid double-counting. Finally, we have not considered the huge potential for rapid technological advances in land use change to release land for ecosystem restoration, such as technological advances in cultured meat, which could rapidly increase the potential contribution of NbS to reducing peak warming (Tuomisto et al., 2011).

Further, whereas we may overestimate the potential from ecosystem restoration pathways, our estimates of the cost-effective climate mitigation potential of NbS on land remain very conservative. Indeed, whereas carbon sequestration rates from ecosystem restoration will slow down from 2050 (as the rate of growth of forests slows down), NbS from avoided deforestation can be extrapolated to 2100, and we likely underestimate the NbS potential from improvements in land management. It is reasonable to assume that we will achieve this level of emissions reductions from deforestation up to 2100, as there is sufficient remaining forest area to estimate that deforestation at business-as-usual rates would result in that level of emissions. The rate of deforestation is estimated compared to annual deforestation rates at a decadal level: whereas the rate of deforestation fluctuates from year to year, it is relatively consistent at a decadal level (Griscom et al., 2017). Further, land management pathways can be implemented most rapidly. Management pathways are essentially an improvement of land that is currently used for agricultural practices. For example, technologies to intensify agriculture, and technologies such as cultured meet will free up land for ecosystems restoration on a large scale and on short timescales. However, we do not consider climate feedback processes by which climate change affects ecosystem carbon cycling properties.

Table S1: Cost-effective climate mitigation potential of 20 natural pathways on land (≤ \$100 $MgCO_2e^{-1}$), presented as Avoided emissions and Enhanced sinks from protection, restoration, and management of terrestrial ecosystems. Adjustments from Griscom et al. 2017 are presented in italics.

Pathway Type	Pathway	Cost-Effective Mitigation Potential ($PgCO_2$ yr^{-1})	Avoided Emissions ($PgCO_2$ yr^{-1})	Enhanced Sinks ($PgCO_2$ yr^{-1})	Percentage of total
Protect	Avoided Forest Conversion	2.90	2.90		
Protect	Avoided Grassland Conversion	0.04	0.04		
Protect	Avoided Peatland Impacts	0.68	0.68		
Protect	Avoided Coastal Wetland Impact	0.27	0.27		
Manage	Natural Forest Management	*0.93*	0.465	0.465	
Manage	Improved Plantations	0.27		0.27	
Manage	Avoided Woodfuel Harvest	0.13	0.13		
Manage	Fire Management	*0.14*	0.14		
Manage	Biochar	0.33		0.33	
Manage	Trees in Agricultural Lands	*1.86*		1.86	
Manage	Cropland Nutrient Management	non CO_2			

Manage	Grazing - Improved Feed	non CO_2			
Manage	Conservation Agriculture	0.37		0.37	
Manage	Improved Rice Cultivation	non CO_2			
Manage	Grazing - Animal Management	non CO_2			
Manage	Grazing - Optimal Intensity	0.09		0.09	
Manage	Grazing - Legumes in Pastures	0.13		0.13	
Restore	Reforestation	*1.48*		1.48	
Restore	Coastal Wetland Restoration	*0.08*		0.08	
Restore	Peatland Restoration	0.39	0.39		
Total		**10.08**	**5.01**	**5.07**	
Total Protect		3.89			39%
Total Manage		4.24			42%
Total Restore		1.95			19%

Estimate the potential effect of NbS in terms of peak warming

Peak warming is the most useful target to consider, as many ecological and societal impacts of climate change are broadly correlated with maximum temperature change (SR1.5, 2018).
To estimate the potential effect of NbS in terms of peak warming, we apply a time-constrained estimate of potential cost-effective sequestration rate on land alone (≤ \$100 $MgCO_2e^{-1}$). We demonstrate the impact on global mean surface temperature (GMST) using a stylized modelling

framework (Myhre et al., 2013; Millar et al., 2017) that reproduces the behaviour of much more complex models (Jenkins et al., 2018) and represents key properties and timescales of the climate response (Geoffroy et al., 2013).

Figure S1 (the complete version of figure 1 in the main text) follows the design of figure 1 (SPM.1) in the Summary for Policymakers document of the IPCC's Special Report on the Global Warming of 1.5°C (IPCC, 2018). SPM.1 uses the FaIRv1.0 (Millar et al., 2017; Jenkins et al., 2018) simple climate model to determine a plume of likely warming responses to 3 stylized emissions and radiative forcing scenarios. These depict a range of plausible pathways to 1.5°C and show the trade-offs between mitigation of CO_2 and non-CO_2 pollutants.

Two scenarios are shown in Figure S1: a grey scenario which is described as being 1.5°C-consistent and a purple one which is described as 2.0°C-consistent. The grey scenario (solid line, panels a, b, d) is lifted directly from SPM.1; with CO_2 emissions declining in a straight line from 2020 to net-zero in 2055, and non-CO_2 radiative forcing (RF) following a peak and decline pathway consistent with ambitious mitigation (see description of SPM.1 in SR15 Chapter 1 supplementary material). Similarly, the purple scenario (solid lines panels a, b, d) has CO_2 emissions declining in a straight line from 2020 to reach net-zero in 2100, and non-CO_2 RF held fixed after peaking in 2030 (panel d).

Both grey scenarios are considered 1.5°C-consistent. The 1.5°C+NbS scenario (grey dashed line) has best-estimate peak warming of 1.4°C, with the peak temperature distribution covering the range 1.1 - 1.8°C (17th to 83rd percentiles). To put this in context, the standard 1.5°C scenario has a peak warming of 1.5°C (without NbS, grey solid line), with a range of 1.1 - 1.9°C. The 1.5°C + NbS scenario is slightly more likely to achieve a 1.5°C world, although by how much exactly is up for discussion. Both scenarios are well within the uncertainty of a 1.5°C-consistent scenario.

In the 2°C scenario, NbS accounts for about 25% of the total warming suppression achieved by 2085. However, this estimate is too conservative because what we actually modelled is how much NbS draws down temperature below 2°C, which is asking each tonne of NbS to achieve more than each tonne of fossil fuel emissions reductions, as there are diminished temperature returns from each marginal tonne removed.

Of course, our final result could be rescaled according to the input estimates of annual carbon uptake with NbS (i.e. if we exchange estimates from Griscom et al. 2017, 2020 and replace with others), but the result on the relative benefit of NbS to peak warming in the warming scenarios considered here remains the same.

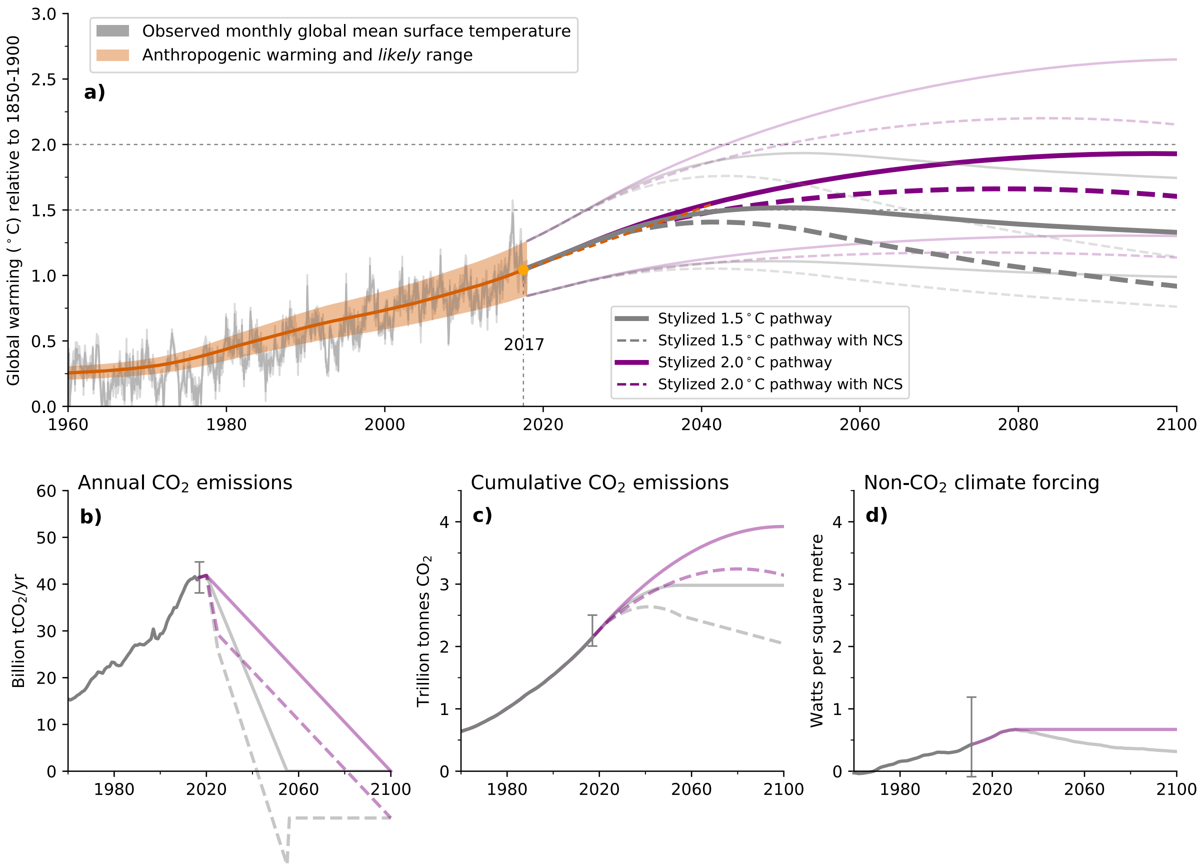

Figure S1: This is a complete version of figure 1 in the main text. This figure follows the design of figure 1 in the Summary for Policymakers document of the IPCC's Special Report on the Global Warming of 1.5°C. (a) An ambitious implementation of nature-based solutions can pull down the 1.5ºC target world to 1.4ºC, and a 2ºC target world to 1.7ºC. Temperatures continue to be drawn down until 2100 and beyond. Additional panels describe the inputs of the model: annual CO_2 emissions (b) and cumulative emissions (c) up to 2100 for each scenario, and the pathway set for of non-CO_2 radiative forcing (d).

Table S2. The contributions of NbS to warming reductions in 1.5, 2, and 3 °C -consistent scenarios. All values in degrees C above pre-industrial (1850-1900).

Best estimate (50th percentile)									
	1.5C	**1.5C + NbS**	**difference**	**2.0C**	**2.0C + NbS**	**difference**	**3.0C**	**3.0C + NbS**	**difference**
2050	1.52	1.37	0.15	1.67	1.56	0.11	1.75	1.64	0.11
2080	1.39	1.06	0.33	1.90	1.66	0.24	2.24	2.02	0.22
2100	1.33	0.92	0.41	1.93	1.60	0.33	2.55	2.26	0.29
Peak	1.52	1.41	0.11	1.93	1.66	0.27	2.55	2.26	0.29
lower bound (17th percentile)									
	1.5C	**1.5C + NbS**	**difference**	**2.0C**	**2.0C + NbS**	**difference**	**3.0C**	**3.0C + NbS**	**difference**
2050	1.11	1.03	0.08	1.19	1.14	0.05	1.23	1.18	0.05
2080	1.03	0.85	0.18	1.30	1.17	0.13	1.47	1.36	0.11
2100	0.99	0.76	0.23	1.30	1.14	0.16	1.61	1.47	0.14
Peak	1.11	1.05	0.06	1.30	1.18	0.12	1.61	1.47	0.14
Upper bound (83rd percentile)									
	1.5C	**1.5C + NbS**	**difference**	**2.0C**	**2.0C + NbS**	**difference**	**3.0C**	**3.0C + NbS**	**difference**
2050	1.93	1.73	0.20	2.15	2.00	0.15	2.26	2.11	0.15
2080	1.81	1.33	0.48	2.55	2.20	0.35	3.07	2.73	0.34
2100	1.74	1.14	0.60	2.65	2.15	0.50	3.58	3.14	0.44
Peak	1.93	1.76	0.17	2.65	2.20	0.45	3.58	3.14	0.44

*All values in °C above pre-industrial (1850-1900)

The 3°C scenario is made by driving the simple model with constant CO_2 emissions from 2020 to 2100 with the emissions level in 2020 (~42 $GtCO_2\ yr^{-1}$), along with the purple stabilised non-CO_2 RF pathway. We should note that the peak warming numbers for the 3°C scenario are only valid till 2100, as warming is expected to continue rising after 2100 in the 3°C case because emissions have not reached net-zero.

Temperature responses to these three input scenarios are calculated in an identical way to those in the original SPM.1 figure; a range of physical climate response parameters (including TCR, ECS, thermal response timescales) are covaried to find a best estimate and likely range of temperature responses. The carbon cycle parameters in FaIRv1.0 are fit so best estimate and likely range present day CO_2 RF estimates from IPCC's AR5 correspond to best estimate present day annual CO_2 emissions estimates. Input non-CO_2 RFs are scaled by component to sample the likely range in IPCC's AR5 Chapter 8, and the aerosol RF is rescaled so the FaIRv1.0 derived warming at present day matches the attributable warming likely range at present day. For a full description of the design of SPM.1 see the supplementary information of the IPCC's SR15 Chapter 1 text.

Consistent estimates of the potential impact of NBS can also be obtained from the ratio between CO_2-induced warming and cumulative CO_2 emissions, estimated by the IPCC 5th Assessment Report to be 0.45±0.23°C per 1000 PgCO_2. This Transient Climate Response to Cumulative Emissions (TCRE) remains relatively constant over the timescale we consider for the present analysis.

All of the 1.5°C-consistent scenarios assessed by SR1.5 already contain some of these NbS measures, so adding on this maximal estimate of NbS CO_2-removal may exaggerate the potential contribution of NbS to reducing peak warming to below 1.5°C. Furthermore, other decarbonisation measures might compromise these NbS measures (e.g. bioenergy with carbon capture and storage (BECCS) competing with NbS for land), so all of these estimates of NbS potential should be regarded as upper bounds.

That said, the majority of 1.5°C-consistent scenarios display faster emission reductions over the 2020-2030 period than this stylized scenario even without specifically invoking rapid NbS scaling up, so this stylized approach is not inconsistent with the alternative of exploring NbS within an Integrated Assessment Model, and is substantially more transparent.

Successful scaling up of NbS also brings forward the date of peak warming under such an ambitious mitigation scenario such that, when added to a scenario of linearly declining emissions from 2020 to 2055 (SR1.5), NbS reduces best-estimate peak warming by 0.1 °C (see Figure S1).

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