25th March 2021

As the planet sprints towards a goal of 'net zero' emissions, what is nature's place in the race?

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Projects that better manage, protect, and restore ecosystems are widely viewed as win-win strategies to address two of the biggest global challenges of this century: climate change and biodiversity loss. Yet the potential contribution of such nature-based solutions (NbS) to mitigating climate change remains controversial.

As the race to net zero gains momentum, decision makers urgently need to know: what is nature's place in the race?

Analyses of nature-based solutions often focus on how much carbon they can remove from the atmosphere. Here, we provide a new perspective by modelling how that carbon removal will impact global *temperatures*—a critical metric as humanity attempts to limit global warming.

Our analysis shows that NbS can have a powerful role in pulling down temperatures in the long term: land use changes will keep on acting long past the time of peak warming, and have an important role to play in planetary cooling in the second half of this century. Before mid-century, NbS can provide real but limited mitigation benefits. Critically, the more ambitious the climate target, the shorter the timeframe for NbS to have an effect on peak warming.

If the greatest value of NbS lies in the long-term, these projects must be properly designed to ensure longevity. This means paying closer attention to the long-term carbon sink benefits of NbS projects, as well as their impacts on biodiversity, equity, and sustainable development goals. It also means continuing to limit global warming through other means, from decarbonization to geological storage of CO_2.

Our model reinforces the conclusion that an ambitious scaling of NbS needs to be implemented quickly and thoughtfully—but not at the expense of other necessary solutions.

Multiple Benefits

The world is currently on a trajectory that will hit 3°C of warming above preindustrial levels by 2100. The Paris Agreement aims to limit global temperature rise this century to *well below* 2°C and to *pursue efforts* to limit the temperature increase to 1.5°C. There isn't a specific date assigned to either temperature goal beyond "end of this century": the metric that matters most is not the speed of temperature stabilization, but the peak temperature itself. Efforts to hit 1.5°C of warming are more aggressive, reaching peak temperature earlier than if the peak is allowed to extend to 2°C of warming.

It is impossible to achieve the needed reduction in peak warming through cuts to greenhouse gas emissions alone, because emissions from some sectors, such as agriculture, air travel and some heavy industry, cannot be driven to zero anytime soon. We will therefore also need to actively remove greenhouse gases from the atmosphere on an unprecedented scale (IPCC, 2018).

There are various options for doing this. Bioenergy with Carbon Capture and Storage (BECCS), for example, involves capturing carbon dioxide emissions from burning vegetation for energy, and sequestering it underground. This requires both time to develop on a large scale, and vast areas of land. Other options involve industrial machines that capture carbon dioxide from the air, though these are currently nascent, expensive technologies.

The subset of nature-based solutions used specifically to limit warming, also called Natural Climate Solutions, aim to reduce atmospheric greenhouse gas concentrations by (i) avoiding emissions, by protecting ecosystems to reduce the release of carbon (eg. avoiding deforestation); (ii) restoring ecosystems to sequester carbon (eg. forest restoration); and (iii) improving the management of timberland, croplands and grazing lands to reduce carbon, methane, and nitrous oxide emissions, as well as sequestering carbon (Figure 2).

Decades of work provide strong evidence that NbS (unlike BECCS) can deliver a multitude of local ecological and socioeconomic benefits (Chausson et al. 2020). Restoring a stream, for example, might reduce flood impacts, improve carbon storage, and support fisheries. NbS can help people adapt to climate change whilst achieving the sustainable development goals, protecting biodiversity, and mitigating climate change (Seddon et al., 2021). As serious climate impacts emerge and rapid declines in global biodiversity are recorded, enthusiasm for the role of nature-based solutions is soaring.

Quantifying Nature's Role

Despite all this, it remains unclear just how much of a role NbS can play in achieving the Paris Agreement goal. There have been robustly-contested claims that tree restoration is the most effective climate change solution at our disposal (Bastin et al., 2019), or, at the other end of the debate, that NbS won't be nearly as fast or effective as often stated (Baldocchi et al., 2019). There is still confusion around how much NbS can contribute to achieving net zero by mid-century, as the results have been estimated over a range of objectives, timeframes, and differing model assumptions (eg. Griscom et al., 2017; Roe et al., 2019, sup info).

Part of the reason for the debate and confusion is that while there are many well-known examples of papers discussing the annual carbon uptake possibilities of NbS, they fail to discuss the cooling impact year on year of these NbS efforts. Since the Paris Agreement is framed in terms of temperature, we argue that this is a critical flaw: we need to know how NbS will affect global temperature.

To model this, we consider an ambitious but realistic scenario of NbS, an update to the estimates by one of our co-authors (Griscom et al., 2017, 2020, Busch et al., 2019). This scenario only considers NbS projects constrained by many factors: they are cost effective (<100USD $MgCO_2e^{-1}$), they ensure adequate global food production, fibre production, biodiversity conservation, and they are aligned with respect of land tenure rights (see sup info). In these estimates, NbS ramps up quickly (by 2025) to avoid emissions and absorb carbon at a rate of 10 Gt CO_2 yr^{-1} (or 20 Gt CO_2 yr^{-1} in the most ambitious scenario, where we assume a higher price of carbon). For comparison, 10 Gt CO_2 yr^{-1} is more than the emissions from the entire global transportation sector.

Achieving 10 Gt CO_2 yr^{-1} of mitigation from NbS would involve stopping vast amounts of deforestation worldwide (around 1,840 million hectares); restoring 678 million ha of ecosystems (more than twice the size of India); and improving the management of around 4.1 billion ha of land (Griscom et al., 2017). This is ambitious, but it is important to note that the bulk of land required (85%) involves improving management on existing agricultural, grazing, and production forest lands without displacing food, fibre, and fuel yields (Figure 2).

These estimates come with caveats (see sup info). The role of NbS could be larger if one considers, for example, the impacts of NbS on other greenhouse gases besides CO_2. This could represent an additional ~1-3 CO_2e yr^{-1} of climate mitigation. Even larger numbers for mitigation can be achieved by including more expensive interventions. On the other hand, the role for NbS might be smaller in the long term if the carbon drawdown from land-based NbS decreases over time as the carbon pools in these natural sinks saturate due to climate impacts, such as forest fires, that are not included in our estimates.

We then modelled how this level of NbS would impact global temperature (Figure 1, sup info). We looked at illustrative IPCC pathways where the world's peak warming is constrained to 1.5°C or 2°C, and ran these scenarios with the added contribution of NbS as described above. These pathways already include BECCS and a small amount of land use change, but not an extensive amount of NbS.

Taking the Temperature

Our analysis shows that implementing this level of NbS would reduce the peak warming by an additional 0.1°C under a 1.5°C-consistent scenario (by 2055); 0.3°C under a 2°C-consistent scenario (by 2085); and 0.3°C under a 3°C-by-2100 scenario (Figure 1).

The most significant contribution NbS can make to mitigating the peak temperature is in the 2°C scenario. In a more ambitious 1.5°C scenario, there isn't enough time for NbS to have as large an impact on peak warming. In the 3°C scenario there are a number of issues that constrain the impact of NbS, including the limited ability of ecosystems to absorb carbon in a warmer world, and the low price on carbon in a world that isn't prioritizing limited warming.

Overall, the mitigation potential of NbS remains a minority contribution compared to what can be achieved through the decarbonisation of our economy. But it is also true that--assuming a concurrent commitment to reducing emissions--NbS can account for a large chunk of the warming suppression (see sup info).

Critically, NbS acts to cool the planet long *after* the peak temperature is reached. In the 1.5°C scenario, NbS produces a total of 0.4°C of warming suppression by 2100—four times the suppression to the peak temperature in 2055 (Table S2).

Achieving these significant long-term benefits requires several things. It requires that good quality NbS be scaled rapidly, but not at the expense of other robust strategies. Long-term geological storage of CO_2, for example, is also needed, and will need to be ramped up significantly in the coming decade as technologies mature and prices come down. The long-term benefits of NbS also depend upon warming being held in check. Warming and associated phenomena, such as increased frequency and intensity of wildfires, can undermine the health of ecosystems and their capacity to draw down and store carbon or provide any other benefits to society.

Protected and carefully managed ecosystems -such as intact peatlands and old-growth tropical rainforests- are very likely to continue to store carbon for thousands of years and are more resilient in the face of climate extremes and pathogens than damaged ecosystems.

NbS require a significant investment now, but, when properly managed, will remain beneficial for people for generations to come.

The Right Metrics

Restoration of forest cover is widely considered the most viable near-term opportunities for carbon removal. Unfortunately, some of this enthusiasm has been used to promote plantation forestry, with trees of a limited variety of ages and species (eg. monoculture plantations), which does not have the same carbon benefits as an intact forest ecosystem (Lewis et al., 2019).

There is a serious problem that some nature-based solutions, as currently implemented, have unintended and unwanted consequences. For example, an area of 34,007 ha of intact forest ecosystem in Cambodia was replaced by a plantation of Acacia monoculture between 2000 and 2014, as Cambodia's first large scale reforestation project funded in the context of climate change mitigation. This unethical and ecologically devastating project resulted in 1900 families being displaced (Scheidel & Work, 2018).

Similarly, Chilean government subsidies for new exotic tree plantations (pine, eucalyptus) have resulted in plantation expansion by 1.3 Mha since 1986, with an associated carbon sequestration of about 3.4 Mt C. However, regulations stating that expansion cannot happen at the expense of native biodiverse forests were not enforced, resulting in large scale reductions in native forest cover. The clearing of the original forest led to a net impact of an increase in carbon *emissions* (not sequestration) of approximately 0.05 Mt C since 1986 (Heilmayr et al. 2020).

These examples show how a singular focus on rapid carbon sequestration as the metric of success for land-based climate mitigation can result in perverse outcomes. Activities should be evaluated and monitored with the right metrics to be held accountable for the multitude of benefits they provide in the long term.

In order to ensure long-term resilience, NbS projects should adhere to four high-level principles (nbsguidelines.info): NbS are not an alternative to rapid decarbonisation; involve a wide range of ecosystems; are led by local people; and support biodiversity (from the level of the gene to the ecosystem). In addition, the Oxford principles (Allen et al., 2020) for high quality offsets call for safe and durable CO_2 removal and storage for every tonne of CO_2 emitted. Metrics of success should include measures of carbon dynamics, biodiversity across multiple trophic levels, and socioeconomic factors like women empowerment and youth employment.

There are many examples of good-practice projects (naturebasedsolutionsinitiative.org). For example, mangrove forests in eastern India that have been protected from deforestation since 1985 have been shown to protect coastal regions from the negative impacts of cyclones far better than artificial defenses, while also soaking up carbon (Badola et al., 2005). In Sierra Leone's tropical rainforest, cocoa agroforestry (where cocoa is planted with trees for shade, alongside pineapples, chillies and maize as an additional source of food and income) has been shown to produce cocoa sustainably while diminishing additional forest clearance. One agroforestry project in the Gola rainforest national park, initiated 30 years ago, has increased profitability of crops and biodiversity, while saving an estimated 500 000 tonnes of carbon each year through sequestration and avoided deforestation (golarainforest.org).

The Path Forwards

This much is clear: we urgently need to increase the flow of investment to high quality nature-based solutions. NbS has a significant contribution to make to global emissions reductions, yet remains dramatically under-invested, receiving <3% of existing climate mitigation financing (Buchner et al., 2015). This low investment does not reflect their potential for immediate and cost-effective climate mitigation and adaptation.

Carbon markets are increasingly considered as mechanisms for financing NbS. However, carbon offsets on the voluntary market present a number of problems if poorly implemented. Carbon offset projects need to consider additionality, permanence, and social/ecological safeguards. Even offsets that adhere to standards can allow organisations to purchase the rights to continue emitting greenhouse gases, providing an avenue to delay decarbonization if permits to emit are not ratcheted down over time.

NbS activities need to be supported by a diversity of funding options, including blending philanthropy with profit-making, or incorporating NbS activities in company supply chains to build social and ecological resilience (ie. insetting).

The United Nations Framework Convention on Climate Change (UNFCCC) needs to provide clear guidelines on national level accounting for NbS, as this will guide the national targets set in the Paris Agreement's Nationally Determined Contributions (NDCs), and the Monitoring, Reporting, and Verification (MRV) methodologies required to comply to these targets.

The next UNFCCC meeting, COP26, due to be held in Glasgow this November, provides an opportunity to lay the foundations for robust national reporting systems: ensuring that NbS projects make a real, long-term contribution to carbon removal, setting metrics that ensure high-biodiversity and maximise human wellbeing. One pressing issue for COP26 is Article 6 of the Paris Agreement, which establishes a new "mechanism to contribute to the mitigation of greenhouse gas emissions and support sustainable development". A tightly regulated compliance market defined in Article 6 of the Paris Agreement will provide the grounding for a tightly regulated voluntary offsetting market.

COP26 also presents an opportunity to harmonise the goals of the UNFCCC and those of the Convention on Biological Diversity. For example, NbS projects will likely be required to adhere to the principle of Free Prior Informed Consent of local people: local communities need to be involved at all stages of project planning and management. Similarly, NbS projects should be required to protect and enhance biodiversity. This work can build on existing social and biodiversity standards.

The race to net zero is uncompromisingly about decarbonising our economy at unprecedented rates to achieve net zero by mid-century, including removing carbon from the atmosphere to counter hard to eliminate emissions, via NbS and other means. At the core of this are transformative changes to shift social and economic systems to deliver societal resilience in the face of ongoing climate impacts. This can only be achieved by investing in ecologically sound, socially equitable, net zero aligned NbS activities. This is nature-based solutions' place in the race.

To achieve this, we need to re-assess the way investors measure the success of NbS activities, ensuring high quality NbS aligned with the mitigation hierarchy framework (avoid, minimise, reduce emissions along the supply chain before offsetting); using offsetting of remaining emissions with NbS activities that meet the Oxford principles for net zero aligned carbon offsetting (Allen et al., 2021; safe and durable CO_2 removal and storage for every tonne of CO_2 emitted), and the four high-level principles of NbS (nbsguidelines.info); recognising the need to increase geological storage; and recognising the need to establish to new finance mechanisms for NbS.

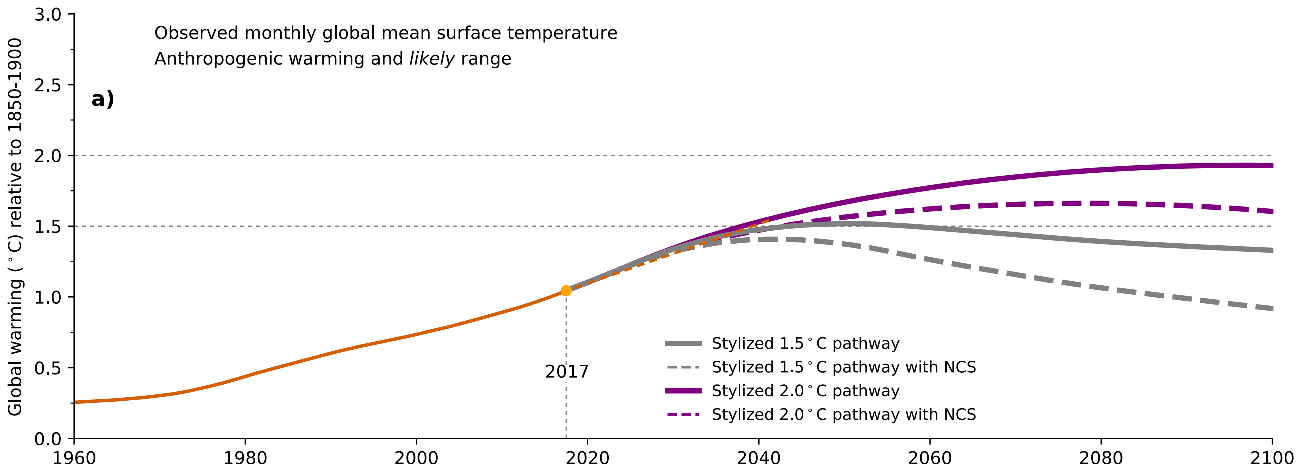

Figure 1: This figure follows the design of figure 1 (SPM.1) in the Summary for Policymakers document of the IPCC's Special Report on the Global Warming of 1.5°C (IPCC, 2018). The grey scenario is the same as the one presented in SPM.1 (1.5°C-consistent). The purple scenario is consistent with global peak in warming at 2.0°C. An ambitious implementation of nature-based solutions can pull down the 1.5°C target world to 1.4°C, and a 2°C target world to 1.7°C. With nature-based solutions, temperatures continue to be drawn down until 2100 and beyond.

Figure 2: The partitioning of cost-effective climate mitigation potential of natural path

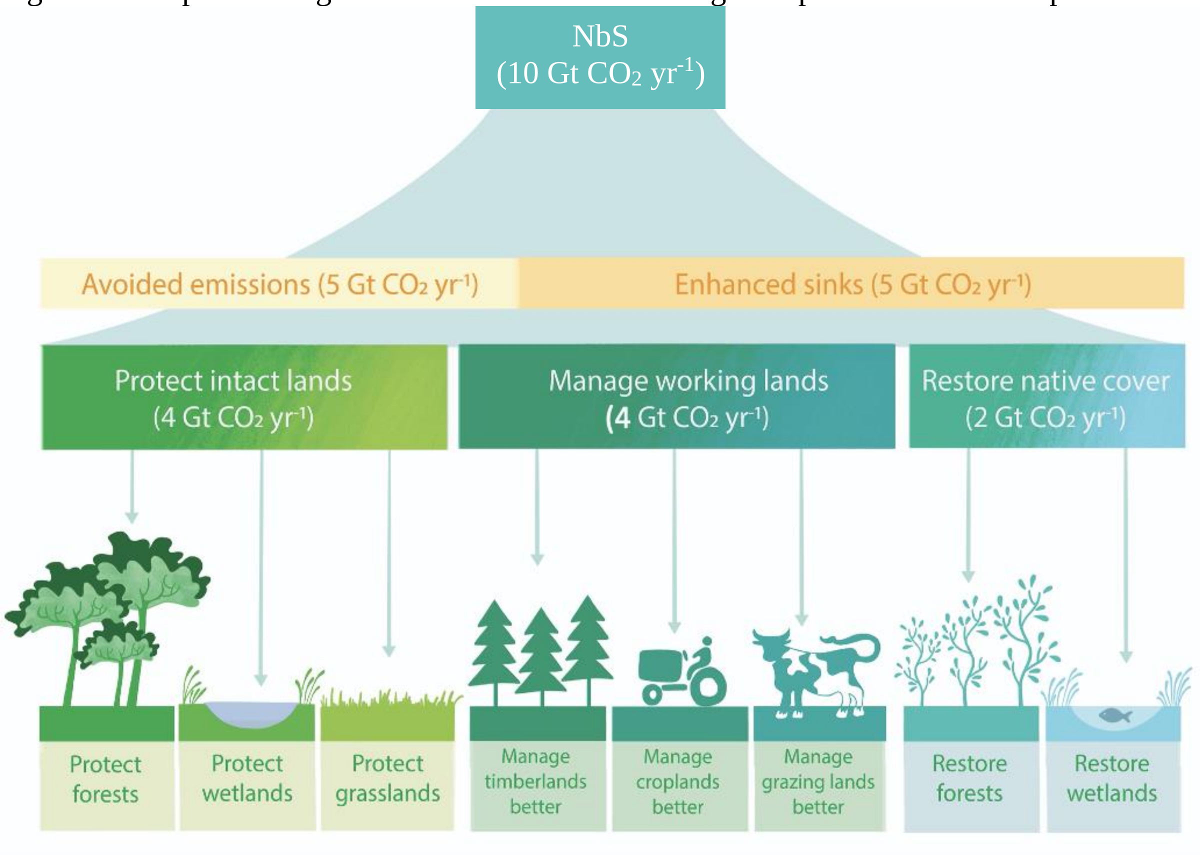

Figure 2: NbS mitigation pathways on land (≤ \$100 $MgCO_2e^{-1}$), presented as avoided emissions and enhanced sinks from protecting intact lands, managing working lands, and restoring native cover. Data provided in Table S1. Figure based on Jenkins M. (2018).

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Supplementary Material

Estimating the annual uptake and avoided emissions from Natural Climate Solutions

Various estimates have been made about how much 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 ^oC, we estimated a higher Marginal Abatement Cost, to reflect a doubling of BECCs between the 1.5 and 2 ^oC scenarios in the stylised models. The 1.5 ^oC-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 ^oC 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 ^oC 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 ^oC (1.3 - 2.7 ^oC) and 3 ^oC (1.6 - 3.6 ^oC), 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 ^oC scenario) and 1270 Gt CO_2 (3 ^oC 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.

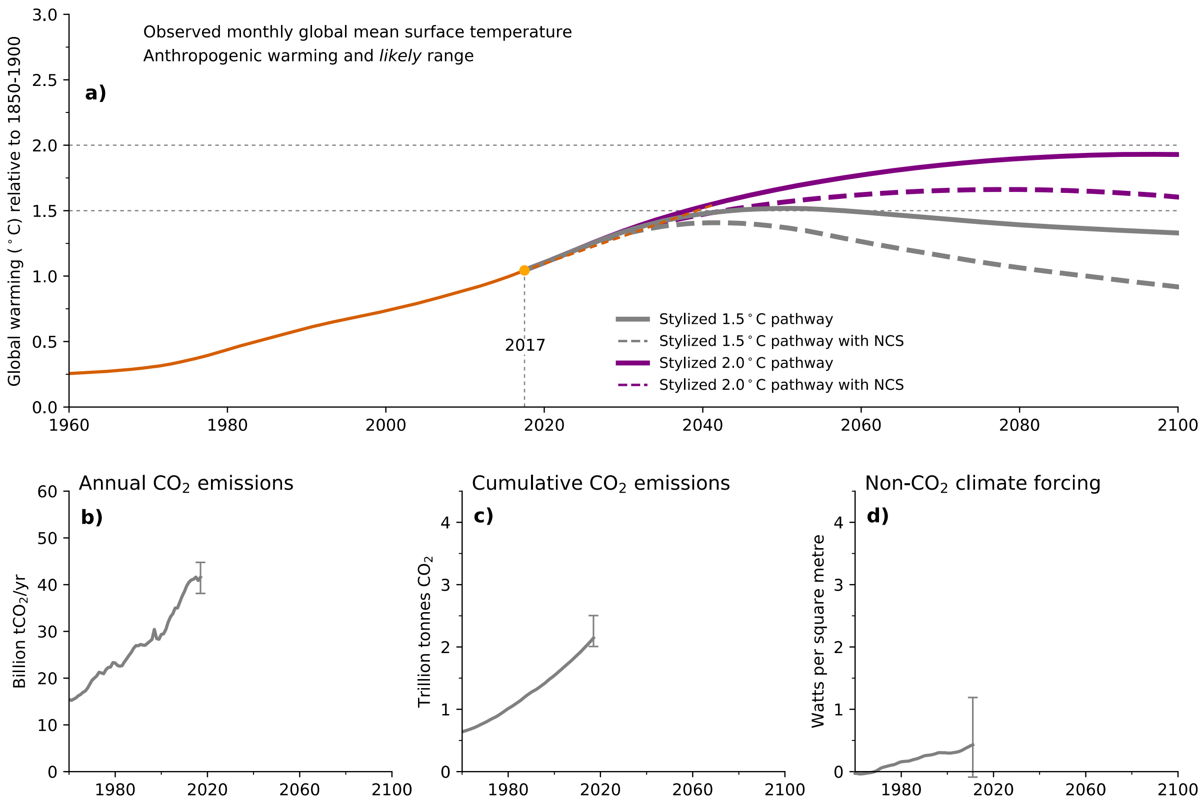

Figure S1: This is a complete version of figure 1 in the main text. This figure follows the design of figure 1 in the Summary for Policymakers document of the IPCC's Special Report on the Global Warming of 1.5°C. (a) An ambitious implementation of nature-based solutions can pull down the 1.5°C target world to 1.4°C, and a 2°C target world to 1.7°C. 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 + NCS**	**difference**	**2.0C**	**2.0C + NCS**	**difference**	**3.0C**	**3.0C + NCS**	**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 + NCS**	**difference**	**2.0C**	**2.0C + NCS**	**difference**	**3.0C**	**3.0C + NCS**	**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 + NCS**	**difference**	**2.0C**	**2.0C + NCS**	**difference**	**3.0C**	**3.0C + NCS**	**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

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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