Title: Contribution of the land sector to a 1.5°C World

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Preface

The Paris Agreement introduced an ambitious goal to limit warming to 1.5°C above pre-industrial levels. Here, we combine modelling and a meta-analysis of mitigation strategies to develop a land sector roadmap of priority measures and regions that can help to achieve the 1.5°C temperature goal. Transforming the land sector (agriculture, forestry, wetlands, bioenergy) towards more sustainable practices could contribute ~30% (15 $GtCO_2e$/yr) of the global mitigation needed in 2050 to deliver on the 1.5°C target, however it will require substantially more ambitious effort than the 2˚C target. Addressing risks, barriers and incentives are necessary to scale up mitigation while maximizing sustainable development, food security, and environmental co-benefits.

Introduction

The Paris Agreement marked the conclusion of many years of negotiations, setting a global temperature target of "well below 2°C" and encouraging efforts to "limit increase to 1.5°C above pre-industrial levels." However, submitted Nationally Determined Contributions (NDCs), countries' pledges to implement emissions reductions, fall short of the goal[1]. Current commitments are more compatible with 2.5°C to 3°C of warming by 2100[2–4]. To limit warming to 1.5°C (and 2°C), countries will need to plan for a more rapid transformation of their national energy, industry, transport, and land-use sectors[1,2,5].

The land sector, commonly referred to as Agriculture, Forestry, and Other Land Uses (AFOLU) is responsible for 10-12 $GtCO_2e$ (~25%) of net anthropogenic GHG emissions, with approximately half from agriculture and half from Land Use, Land Use Change, and Forestry

(LULUCF)[6,7]. LULUCF emissions represent the net balance between emissions from land-use change and carbon sequestration from the regeneration of vegetation and soils[6,7]. While the AFOLU sector generates significant emissions, the residual terrestrial sink (accumulation of carbon in the terrestrial biosphere excluding land sinks from LULUCF) also currently sequesters ~30% of annual anthropogenic emissions, making land vitally important for generating "negative emissions" (or more carbon dioxide removals [CDR] than emissions)[6]. In addition to GHG impacts, land-use generates biophysical impacts that affect the climate by altering water and energy fluxes between the land and the atmosphere[8]. Furthermore, the AFOLU system provides significant ecosystem goods and services such as air and water filtration, nutrient cycling, habitat for biodiversity, and climate resilience[7].

Of the countries that ratified and submitted NDCs, a majority included land sector mitigation providing 10-30% of all planned emissions reductions in 2030[9,10]. Land-based mitigation measures largely fall into four categories: reduced land-use change, carbon removal through enhanced carbon sinks, reduced agricultural emissions, and reduced overall production through demand shifts. Most countries included reduced land-use change, afforestation and forest restoration, a few included soil carbon sequestration and reduced agricultural emissions, and none mentioned demand-side shifts. As countries submit new or revised NDCs by 2020 and prioritise climate strategies and investments, it is helpful to take stock of the scientific and technological advancements in key sectors, particularly in the land sector where there are many opportunities for mitigation-adaptation co-benefits.

Building on existing studies of mitigation pathways[4,11–14] and mitigation potentials[7,15–21] in the land sector, here, we provide a comprehensive assessment of all land-based activities (agriculture, LULUCF, and bioenergy), and their possible contributions to the Paris Agreement temperature target of 1.5°C. We conducted four complementary analyses: 1) review of 1.5°C scenarios across all sectors, 2) comparative analysis of top-down modelled pathways in the land sector, 3) bottom-up assessment and synthesis of land sector mitigation potential, and 4) a geographically explicit roadmap of priority mitigation actions to fulfil the 1.5°C land sector transformation pathway by 2050, informed by the first three analyses (approach described in each section and elaborated in the Supplementary Information (SI)).

Pathways for the Paris Agreement

To put the Paris Agreement in context, we reviewed available 1.5°C scenarios to assess viable emissions pathways and required mitigation across all sectors. Recently released 1.5°C (1.9 W/m^2) scenarios in the Shared Socio-economic Pathway (SSP) Database[11] and Integrated Assessment Modeling Consortium (IAMC) Database[22], as well as individual studies of 1.5°C carbon budgets[2,23–27] agree that aggressive mitigation of total emissions from 2020 until 2050 (~50% reduction per decade, ~90% total reduction) coupled with substantial carbon removals increase the chance (>66% and >90% respectively) of limiting warming to 1.5°C and 2°C by 2100 (SI-section 1). The 1.5°C scenarios fall into three categories: ‘Below 1.5°C’ the entire 21st century; ‘Low overshoot’ in mid-century (50-66% chance of exceeding 1.5°C) before temperatures decrease to below 1.5°C by 2100; and ‘High overshoot’ risk (> 67% chance of overshoot)[4]. Current research thus defines three significant milestones to deliver on the Paris agreement targets: peak emissions around 2020, net zero emissions (balance between sources and sinks) by 2040-2060, and net negative emissions (sinks are greater than sources) thereafter (Figure 1).

Achieving the 1.5°C and 2°C targets requires dramatic transformations of the energy, industry, transportation and land sectors (emission reductions across all sectors), and substantial deployment of CDR (to achieve negative emissions)[4] – with 1.5°C scenarios requiring much earlier and more pronounced action. Net zero emissions for the 1.5°C target must be achieved ~10-40 years before the 2°C scenario, with the earliest mitigation for Below 1.5°C and 1.5°C Low overshoot scenarios (Figure 1). Further, 1.5°C pathways are costlier (median of [USD 2010] \$180/tCO$_2$e in 2030, \$480 in 2050 and \$2400 in 2100) compared to the 2°C pathways (median of \$110/tCO$_2$e in 2030, \$365 in 2050 and \$1505 in 2100) in the IAMC Database. Pathways to 1.5°C also rely on ~40% (median) more CDR annually than 2°C scenarios. Emissions reductions in the next two decades are critical to limiting warming to 1.5°C – the longer mitigation action is delayed, the lower the probability of delivering on the Paris Agreement targets, and the higher the reliance on negative emissions.

In the IPCC-AR5, 87% of the 116 scenarios that limit warming to 2°C with a >66% likelihood relied on CDR, primarily A/R (afforestation and reforestation), CCS (carbon capture and storage) and BECCS (bioenergy with CCS)[20]. Similarly, 17 of the 18 2°C scenarios and all 13 1.5°C scenarios in the SSP Database[11,13], and all 90 scenarios for 1.5°C in the IAMC Database[22] incorporated substantial CDR (range of -1 to -27 GtCO$_2$/yr [95% confidence interval] with a median of -15 GtCO$_2$/yr by 2100)[4]. CDR technologies like CCS of fossil fuels and BECCS, while not yet deployed at scale nor incorporated into any country's NDCs, appear widely in models because of the sizable and speedy emissions reduction needed. Without removing a substantial amount of CO$_2$ from the atmosphere, achieving the 1.5° and 2°C targets is widely considered infeasible due to political and economic inertia[11,28]. For example, a 1.5°C pathway without negative emissions would need to achieve net zero emissions by ~2040 given a post-2018 carbon budget of 420 GtCO$_2$[4] (Figure 1). BECCS is frequently used in models as it provides both energy and negative emissions at relatively low cost[4]. However, given the potential risks associated with CDR technologies like BECCS (unproven at scale, limited effectiveness in overshoot scenarios, unsustainable resource requirements)[17,20,28–31], alternative pathways including reduced reliance on CDR technologies, lower energy demand and sustainable food consumption are being explored[14,32–34].

What the land sector can deliver

Across all top-down 1.5°C models, land-based activities (AFOLU and BECCS) provide 1.6 – 36.6 (median 13.5) GtCO$_2$*e/yr of economic mitigation potential in 2050, ~4 – 40% (median 24%) of the total mitigation required for a 1.5°C pathway (Figure 2c). AFOLU delivers 0.9 – 20.5 (median 7.7) GtCO*$_2$*e/yr of mitigation potential and BECCS delivers 0.7 – 16.1 (median 5.9) GtCO*$_2$*e/yr. In the bottom-up assessment, supply-side AFOLU and BECCS measures provide 2.4 – 48.1 (median 14.6) GtCO*$_2$*e/yr of mitigation potential in 2020-2050. AFOLU provides 2 – 36.8 (median 10.6) GtCO*$_2$*e/yr of mitigation spanning technical and economic potentials, while BECCS provides 0.4 – 11.3 (median 4.0) GtCO*$_2$*e/yr (Figure 4).*

Modelled pathways

To evaluate the contribution of the land sector in 1.5°C and 2°C pathways, we reviewed model assessments of net CO_2, CH_4, and N_2O emissions trajectories in AFOLU and BECCS using the IAMC Database[22]. We then compared the emission pathways of specific mitigation activities in the AFOLU sector as well as land cover changes using the updated SSP Database with 1.5°C scenarios (1.9 W/m^2)[11]. Both databases include model outputs from integrated assessment models (IAMs) which incorporate the coupled energy–land–economy–climate system and quantify pathways of GHG emissions across sectors based on cost optimization.[4]

Of the 2°C and 1.5°C scenarios in the IAMC Database[22], projected emissions reductions in AFOLU (CO_2 reductions in LULUCF and N_2O and CH_4 reductions in agriculture) were similar in the 2°C and 1.5°C High overshoot pathways in the first half of the century, with deeper mitigation and higher BECCS in the 1.5°C High overshoot pathways after 2050 (Figure 2a). Mitigation is earlier and more pronounced in the 1.5°C Low overshoot and Below 1.5°C (no overshoot) scenarios until 2050 in LULUCF, and through 2100 in agriculture. The similarities between the 2°C and 1.5°C pathways in LULUCF after 2050 are mostly due to the relatively low cost of reducing deforestation compared to other land-use activities. Across all the 1.5°C scenarios (high, low and no overshoot), net zero CO_2 emissions in LULUCF were achieved around 2030, with net emissions across all IAMs of -0.6 – -4.7 $GtCO_2$/yr (interquartile range [IQR]) in 2050 compared to 0.9 – 3.2 $GtCO_2$/yr in the business as usual (BAU) scenario. In agriculture, non-CO_2 emissions were 3.9 – 6.8 $GtCO_2$e/yr (IQR) in 2050, down ~40% from BAU (7.7 – 10 $GtCO_2$e/yr). The deployment of CDR from BECCS across all the 1.5°C scenarios is 3.4 – 7.9 $GtCO_2$/yr (IQR) in 2050 compared to ~0 in BAU (Figure 2a), although the Below 1.5°C and Low overshoot scenarios had lower reliance on CDR later in the century because of earlier and deeper mitigation. Across all 1.5˚C scenarios, BECCS provided a majority of all land-based mitigation after 2050 (Figure 2c).

In the 1.5°C scenarios, the largest share of emissions reductions from AFOLU mitigation activities across all SSPs[11] were from forest-related measures. CO_2 emissions from deforestation decreased by ~40% by 2050 (1.6 – 2.9 $GtCO_2$/yr IQR compared to 2.5 – 5.4 $GtCO_2$/yr in BAU) (Figure 2b). Increased A/R and forest management generated an additional carbon sink, producing negative emissions of -0.5 – -5.3 $GtCO_2$/yr (IQR) by 2050 compared to -0.9 – -2.3 $GtCO_2$/yr in BAU. In agriculture, the largest reduction was from CH_4 emissions from enteric fermentation (1.6 – 4.5 $GtCO_2e$/yr (IQR) in 2050 compared to 3.4 – 5.3 $GtCO_2e$/yr in BAU), primarily due to intensification in the livestock sector and related GHG efficiency gains. Additional CH_4 reductions came from changes to irrigation and fertilization practices in rice cultivation with smaller N_2O reductions from cropland soils and pastures. CO_2 and CH_4 decline more rapidly and prominently than N_2O, implying the difficulty in reducing N_2O in agriculture.

The projected GHG mitigation from AFOLU and BECCS yielded 17%-30% (IQR) of the total mitigation required by 2050 to achieve the 1.5°C target, and 23%-32% (IQR) in 2100 (Figure 2c). Despite the currently limited portfolio of land-based mitigation measures in IAMs[4,12], the large share of total mitigation highlights the importance of the land sector in achieving the 1.5°C target. The future inclusion of additional land-based mitigation measures (e.g. wetland conservation and regeneration, soil carbon management, biochar, food and feed substitutes) could further increase the land sector's importance in modelled pathways[4].

Measures taken in the land sector to achieve the 1.5°C target drove vast land-use changes (Figure 3). Across all SSPs in the 1.5°C scenario, pasture and cropland area for food, feed and fibre decreased on average (in 2050: -120 – -450 Mha IQR compared to 2020 in pasture, and -70 Mha – -250 Mha IQR in cropland). On the other hand, natural forests and energy cropland area increased on average (in 2050: -10 – +730 Mha IQR compared to 2020 in natural forests, and +170 – +550 Mha in energy croplands) (Table S1). However, the full range for natural forest change is very large, from ~300 Mha decrease to ~1000 Mha increase in 2050 compared to 2020, primarily due to the inclusion or exclusion of A/R in natural forests by some models (Table S4). The substantial changes and variable ranges in land cover is partially driven by BECCS deployment (and hence land dedicated to energy crops), the scale of which is influenced by the

SSP scenario and differing model assumptions on biomass feedstock, current and future agricultural yields, and conversion efficiencies (Table S3). Moreover, carbon cost-induced shifts of agricultural production between regions, intensification of agricultural production, and changes in consumption preferences away from GHG-intensive ruminant meats and crops also drive land-use change.

The 1.5°C scenarios produce large shifts in land balances as IAMs optimize for cost, despite possible impacts on ecosystems and food security[17,20,30,31]. Currently, few studies explore how BECCS deployment or unsustainable land requirements can be limited in 1.5°C scenarios[14,33,34]. Therefore we conducted a sensitivity analysis for the 1.5˚C scenario using one of the IAMs, the Global Biosphere Management Model (GLOBIOM)[35] to test the effect of carbon price and bioenergy demand on natural ecosystems and food security (SI-section 2). In this scenario, we held biomass demand constant at BAU levels (50 EJ/yr compared to 100 EJ/yr in 2050 in the 1.5˚C scenario) while still applying the increasing carbon prices consistent with the 1.5˚C scenario. Energy crops were reduced by %75 in 2050, and the conversion of ~500 Mha of natural forests, ~100 Mha of grassland, and 20 Mha food and feed crops was avoided (Figure S2). The results of the analysis show that bioenergy deployment had a large impact on natural ecosystems, yet a high carbon price for agricultural emissions was the main driver of food price increases (and food security concerns). While the sensitivity scenario is a departure from the most cost-effective pathway, it demonstrates that alternative paths to 1.5˚C can lower pressure on land. Pathways with reduced bioenergy and CDR from BECCS, however, would need to be counterbalanced by more rapid emission reductions in the short run and additional efforts in potentially more costly sectors such as transportation, industry and non-BECCS CDR such as A/R or DAC [4,14,32].

Bottom-up assessment of mitigation potential

To complement the top-down modelled scenarios and gauge how a larger portfolio of land sector measures could contribute to a 1.5°C pathway, we conducted a bottom-up synthesis of mitigation potential, updating the IPCC-AR5[7] framework with new categories and more recent literature. We assessed the range of technical and economic mitigation potential of 24 land-based activities in both the supply- and demand-side, and developed new estimates of country-level mitigation potential (SI-section 3).

The total mitigation potential of supply side measures from reduced land-use change, carbon sequestration through enhanced carbon sinks, and reduced agricultural emissions amounted to 2 – 36.8 (median 10.6) $GtCO_2e$/yr in 2020-2050 (Figure 4). When BECCS was included, the estimate increased to 2.4 – 48.1 (median 14.6) $GtCO_2e$/yr. Demand-side measures yielded 1.8 – 14.3 (median 6.5) $GtCO_2e$/yr of mitigation potential from reducing food loss and waste, shifting diets, substituting cement and steel with wood products, and switching to cleaner cookstoves. Our upper range from supply-side measures is higher than the IPCC-AR5 economic mitigation potential of 7.18 – 10.60 $GtCO_2e$/yr in 2030, as it reflects technical potential that does not consider cost or feasibility. We also consider a wider scope of AFOLU activities including wetlands and bioenergy, previously unaccounted for ([7,19]). For the same reasons, our estimates are higher than the economic mitigation potential of AFOLU activities in our inter-model analysis (0.9 – 20.5; median 7.2 $GtCO_2e$/yr for all 1.5°C scenarios in 2050). Our estimate is more in line with a recent study (Griscom et al. 2017[18]) of 23.8 $GtCO_2e$/yr in 2030 which represents technical mitigation potential constrained by biodiversity and food security safeguards. About half of their technical mitigation potential (11 $GtCO_2e$/yr) is considered "cost effective" (<\$100/tCO_2e)[18], similar to our median estimate.

Carbon sequestration measures provided the largest land-based mitigation potential. Of the biological solutions, A/R (0.5 – 10.1 $GtCO_2e/yr$) accounted for the highest, followed by soil carbon sequestration (SCS) in croplands (0.3– 6.8 $GtCO_2/yr$), agroforestry (0.1 – 5.7 $GtCO_2e/yr$) and converting biomass into recalcitrant biochar (0.3 – 4.9 $GtCO_2/yr$) (Figure 4). While the restoration of peatlands and coastal wetlands (0.2 – 0.8 $GtCO_2e/yr$ for both) have more moderate potentials, they have among the largest sequestration potentials per unit area[36,37]. The higher range of potentials are largely theoretical, as many estimates do not consider economic and political feasibility, contain uncertainty related to carbon gains and permanence, and require locating available, suitable land that limits food insecurity and biodiversity concerns. Measures such as A/R (particularly, ecosystem restoration) and agroforestry could deliver significant co-benefits if managed sustainably (e.g., enhanced biodiversity, soil fertility, water filtration, and income from agroforestry)[38,39]. As can soil carbon and biochar measures which can increase soil fertility and yields, at lower cost compared to A/R[18,40]. However, below ground carbon potentials have higher uncertainty compared to above ground, specifically on issues of permanence[40,41]. Recent mitigation potential estimates for A/R provide "plausible" figures of 3.04 $GtCO_2/yr$ by 2030 with environmental, social and economic constraints (<\$100/tCO_2)[18], and 3.64 $GtCO_2/yr$ between 2020-2050 based on a conservative scenario of restoration commitments and smaller scale afforestation[42]. Feasible estimates also exist for other activities based on varying economic and socio-political assumptions (indicated as "economic potentials" in Figure 4). In the top-down modelled results, A/R (0 – 3.1 $GtCO_2/yr$ across all SSPs in 2050) are at the lower range of the bottom-up mitigation potential due to higher cost compared with BECCS. The BECCS mitigation potential is 0.4 – 11.3 $GtCO_2e/yr$ (0.4 – 5 $GtCO_2e/yr$ "sustainable potential"), slightly lower compared to the SSP model results (0.7 – 16 $GtCO_2/yr$ in 2050).

Measures that reduce land-use change (reduced deforestation, forest degradation, peatland conversion and coastal wetland conversion), also provided large mitigation potentials: 0.6 – 8.2 $GtCO_2$/yr. Reducing land-use change is an important land-based measure due to its large climate mitigation effect from avoided emissions, continued sequestration[43] and biophysical effects[44], and the many co-benefits from ecosystem services provided by intact forests. Maintaining tropical forests and peatland forests are critical because both store a large fraction of terrestrial carbon per unit area and have high biodiversity[36,43]. The top-down modelled mitigation potential for reduced deforestation (0 – 4.7 $GtCO_2$/yr across all SSPs in 2030 and 0 – 3.8 $GtCO_2$/yr in 2050) is in line with the bottom-up mitigation estimate (0.4 – 5.8 $GtCO_2$/yr) due to low mitigation costs.

Among agriculture measures, the largest potential for non-CO_2 reductions include reduced enteric fermentation from better feed and animal management (CH_4 reduced by 0.1 – 1.2 $GtCO_2e$/yr), improved rice cultivation (CH_4 reduced by 0.1 – 0.9 $GtCO_2e$/yr) and management of cropland nutrients (N_2O reduced by 0.03 – 0.7 $GtCO_2e$/yr). Recent studies suggest "feasible" agricultural non-CO_2 reductions in 2030 from 0.4 $GtCO_2e$/yr[21] at a carbon price of \$20/tCO_2e to 1.0 $GtCO_2e$/yr[16] at \$25/tCO_2e. The modelled economic mitigation potential for agriculture in all 1.5°C pathways is 3.3 – 4.1 $GtCO_2e$/yr in 2050, in line with our bottom-up estimates of 0.3 – 3.4 $GtCO_2e$/yr. Since agriculture accounts for 56% of methane emissions, and 27% of potent short-lived gases, reducing CH_4 emissions from livestock and rice cultivation would reduce global warming effects sooner and may offset delays in reducing emissions[45].

On the demand side, shifting diets and reducing food waste provided large mitigation, contributing 0.7 - 8 $GtCO_2e$/yr (range of "healthy diet" to vegetarian diet) and 0.8 – 4.5 $GtCO_2e$/yr respectively. A recent study finds "plausible" mitigation potential of 2.2 $GtCO_2e$/yr

(0.9 $GtCO_2e$/yr without land-use change impacts) if 50% of the global population adopted diets constrained to ~60g of meat protein per day, and 2.4 $GtCO_2e$/yr (0.9 $GtCO_2e$/yr without land-use change impacts) if food waste is reduced by 50% in 2050[42]. Decreasing meat consumption and reducing food waste reduces overall production, which reduces water use, soil degradation, pressure on forests, land used for feed, and water pollution[46]. Improving woodfuel use by increasing clean cookstoves provides moderate mitigation potential (0.1 – 0.8 $GtCO_2e$/yr), and also delivers high co-benefits of improved air quality and health[47]. The mitigation potential of increasing wood products to replace more energy-intensive building materials like steel and concrete is also moderate (0.3 - 1 $GtCO_2e$/yr), however, wood sourcing would need to be managed sustainably to avoid negative impacts to biodiversity and natural resources.

Brazil, China, Indonesia, the EU, India, Russia, Mexico, the US, Australia and Colombia represent 54% of global AFOLU emissions[48], and are the 10 countries/regions with the highest mitigation potential in the land sector (Figure 5). In tropical countries, the highest mitigation potential is from carbon removals (A/R and forest management) and reduced land-use change (deforestation, peatland and coastal conversion). Brazil and India also have substantial mitigation potential in reducing enteric fermentation. Mitigating emissions from rice cultivation is important in Asian countries. Large emerging countries, China, India, and Russia, as well as developed countries in the EU, the US and Australia have large mitigation potential from A/R and forest management, as well as reduced emissions from enteric fermentation, synthetic fertilizer and manure.

The regional mitigation potentials do not include demand-side potential. However, based on current consumption of beef and food losses and waste (SI-section 3), the highest diet shift potential lies in the US, EU, China, Brazil, Argentina and Russia. The largest food waste potential from consumers is in the US, China and the EU. Southeast Asia and Sub-Saharan Africa have the greatest avoided food loss potential from production. The EU and China also have high potential to reduce the consumption of commodities associated with deforestation (palm oil, soy, beef, leather, timber)[49].

Land sector roadmap for 2050

The land sector transformation characterized in the 1.5°C modelled pathways will require significant investment and action. Given that land interventions have interlinked implications for climate mitigation, adaptation, food security, biodiversity and other ecosystem services, we developed a roadmap of priority activities and geographies through 2050 (Figure 6) to illustrate a potential path of action for achieving climate and non-climate goals. Using the median top down (13.5 $GtCO_2e/yr$) and bottom up (14.6 $GtCO_2e/yr$) estimates, we established a viable mitigation target (sum of emission reductions and removals) for the land sector of ~14 $GtCO_2e/yr$ (15 $GtCO_2e/yr$ with BECCS) in 2050. We then divided the required effort into priority mitigation measures, or “wedges”, first by qualitatively weighing associated risks and trade-offs and prioritizing activities that maximize co-benefits and overlap with Sustainable Development Goals (SDG) and targets in the New York Declaration on Forests (NYDF) (Table S6), and then determining mitigation potentials according to their feasibility and sustainability from the bottom-up mitigation analysis (Table S5). The resulting eight priority wedges maximize emissions reductions from land-use change, and use “sustainable estimates” that are also “cost effective” for carbon sequestration measures, “plausible” estimates for demand-side measures, and conservative economic potentials for agriculture measures (estimates are highlighted in Figure 4). For each wedge, we highlighted important regions and activity types based on bottom-up mitigation potentials, trade-offs, and constrained by a political feasibility analysis (SI-section

4). Finally, we produced GHG reduction trajectories by region consistent with the modelled emissions trajectories pathway.

The 15 $GtCO_2$/yr roadmap mitigation target delivers ~30% of global mitigation, reducing gross emissions by 7.4 $GtCO_2e$/yr (4.6 $GtCO_2e$/yr from reduced land-use change, 1 $GtCO_2e$/yr from agriculture, and 1.8 $GtCO_2e$/yr from diet shifts and reduced food waste) and increasing carbon removals by 7.6 $GtCO_2$/yr (3.6 $GtCO_2$/yr from restored forests, peatlands and coastal wetlands, 1.6 $GtCO_2$/yr from improved plantations and agroforestry, 1.3 $GtCO_2$/yr from enhanced soil carbon sequestration and biochar, and 1.1 $GtCO_2$/yr from the conservative deployment of BECCS) (Figure 6a). Carbon removals of 1.1 $GtCO_2$/yr using BECCS on degraded and marginal lands requires <100 Mha of land[50] and is within the lower range of "sustainable potential"[17]. Each mitigation wedge is associated with a wide portfolio of activities and countries, illustrating that no single strategy or region will be sufficient to deliver on the mitigation target (Figure 6b). Near-term priorities include avoided land-use change in the tropics (deforestation, peatland burning and mangrove conversion), carbon sink enhancement in developed and emerging countries (restoration, forest management, agricultural soils), and reduced food waste in developed countries and China (SI-section 4). The total mitigation effort of 15 $GtCO_2e$/yr would make the AFOLU sector a net carbon sink of 3 $GtCO_2e$/yr by 2050 based on current AFOLU emissions of ~12 $GtCO_2e$/yr.

Our illustrative roadmap diverges with some 1.5°C modelled pathways. Seeking to avoid undesirable impacts from larger-scale deployment of BECCS, our roadmap relies on deeper emissions reductions from lifestyle changes like reducing food waste and shifting diets and higher removals from ecosystem-based sequestration including forest, peatland and coastal mangrove restoration, forest management and agricultural soils. The roadmap will also require additional mitigation effort in the energy sector due to reduced BECCs. Thus, our roadmap may be more expensive than a cost-optimized model pathway. However, the trade-offs illustrated in our roadmap increase the likelihood of limiting warming to 1.5°C (or 2°C) and enhance our ability to deliver on other social and environmental goals, potentially offsetting additional costs not captured in the models.

While mitigation in the land sector is essential for meeting the targets of the Paris Agreement, the land sector is also central to delivering on the SDGs. The roadmap described here reduces deforestation by 95% by 2050, contributing to the NYDF and SDG goals of halving deforestation by 2020 and halting deforestation by 2030. Our restoration wedge (3 $GtCO_2$/yr of reforestation, 0.4 $GtCO_2$/yr of peatland restoration and 0.2 $GtCO_2$/yr of coastal mangrove restoration) would restore forests on >320 Mha of land[20] by 2050– an area consistent with NYDF and SDG targets of 350 Mha by 2030. Our mitigation wedges also contribute to the 2030 SDG goals of sustainably managing forests, conserving biodiversity, reducing water and air pollution, increasing agricultural productivity, and promoting sustainable consumption and production.

Challenges and Opportunities

Our analysis, similar to other studies[2,4,11], shows that delivering on the Paris Agreement's target of 1.5˚C is daunting, yet still within reach if ambitious mitigation is implemented and substantial negative emissions are deployed. Limiting warming to 1.5˚C will require more effort than the 2˚C target and current NDCs. While both targets require steep emission reductions from tropical deforestation, the 1.5˚C goal will require earlier and deeper reductions in agricultural and demand-side emissions, and enhanced carbon removals in the land sector. We show that model results and bottom-up analysis differ on types of mitigation measures included and their relative mitigation contributions, and that additional considerations are needed to account for feasibility and sustainability. In our roadmap, the land sector can deliver 15 $GtCO_2e$/yr (~30% of climate mitigation) by 2050 while contributing to various sustainable development goals. However, top-down and bottom-up mitigation estimates do not reflect biophysical changes nor show how potentials will be affected by future climate change, therefore more research is needed. Furthermore, implementing the roadmap comes with important challenges.

Negative emissions and BECCS

The impacts associated with large-scale deployment of BECCS on natural ecosystems and agricultural land, and the risks from high CDR reliance later in the century is discussed in this review and recent literature[4,14,17,20,29–32]. Better incorporating environmental and social safeguards in IAMs and scenario setting, and emphasizing alternative pathways of early carbon removal and lifestyle changes in climate policy discussions may help address some of these risks. Despite the risks from BECCS, negative emissions will be necessary to limit warming to <2˚C. Counterintuitively, halting the development of carbon removal technologies like CCS and BECCS without a replacement could yield more detrimental effects on land and climate due to the potential for increased use of bioenergy as a cheap energy source without the benefit of sequestration[1,3,4]. Research, development, and investment in negative emissions technologies today could assist their sustainable deployment[20,32] in the future[20,32].

Scaling up action in the land sector

Our 1.5˚C land sector roadmap shows a pathway to reduce emissions and increase carbon removals, which translates to a reduction of gross emissions by ~80% compared to BAU emissions in 2050, and a four-fold increase over BAU of removals in 2050. However, there is a large gap between progress to date and the desired pathway.

Despite efforts to reduce deforestation over the last decade, land-use change emissions have increased modestly due to surging tropical deforestation[51]. More than 8 Mha of tropical forests are lost every year[51], and yet deforestation must decline 70% by 2030 and 95% by 2050 to align with a roadmap to 1.5˚C. Commitments toward ecosystem restoration have been increasing, with a majority of countries (122 of 165 that submitted) including forest restoration pledges in their NDCs. However, only 20% of countries included quantifiable targets, amounting to 43 Mha, and our roadmap suggests >320 Mha of new or restored forests will be needed. Empirical evidence is lacking on progress in addressing emissions in agriculture (non-CO_2 emissions and soil carbon) and demand-side measures.

Major barriers to delivering AFOLU mitigation include political inertia and weak governance. Addressing agricultural emissions is limited by concerns about negative trade-offs, such as food security, economic returns, and adverse impacts on smallholders[21]. Demand-side measures – reducing food waste and shifting diets – have proceeded slowly because of limited awareness and political support, in addition to the difficulties of eliciting behavioural change[52]. Similarly, development of negative emissions technologies is stymied primarily due to low awareness, low prioritisation, and concerns about negative trade-offs.[28] Increased dialogue between scientists and policymakers is important for bridging the knowledge gap in "no-regret" options for mitigation and catalysing political action.[53] Key areas of necessary research include breakthrough technologies and approaches in behavioural science, meat substitutes, livestock production systems including new feed, peatland restoration, improved fertilizer, seed varieties, CCS, and advanced biofuels.

Governance issues related to illegality and a lack of enforcement have been major challenges for addressing land-use change, particularly deforestation and peatland fires in the tropics[54]. Effectively reducing deforestation and scaling up restoration depends on understanding local dynamics at the forest frontier and coordinated action among private and public actors – exemplified by the successes in Brazil[54]. Agricultural intensification combined with forest restoration on spared land holds significant potential when accompanied by stringent land policies and enforcement and demand-side measures (e.g. reduced meat consumption)[55]. Less intensive forestry systems have also shown success in avoiding deforestation if land tenure security is combined with best forest management practices[56].

Efforts to reduce emissions from deforestation and degradation and promote A/R often have higher transaction and implementation costs than expected, and existing finance for forest protection is inadequate[57]. Climate finance for forests accounts for 1% ($2.3 billion) of global public climate funding ($167 billion), and 0.3% of total public and private land sector funding in countries with high levels of deforestation ($777 billion)[58]. A lack of finance, high transition costs and low expected returns from changed practices are the main challenges for farmers[21,59,60]. A significant shift from traditional investments in the land sector (e.g., intensified commodities with no environmental benefits) to financing that promotes sustainable land-use and capacity building at the farm level will be needed to scale up action.

In addition to addressing barriers, there is opportunity adopt a larger portfolio of land-sector mitigation in the next round of NDCs and accompanying UNFCCC negotiations. This includes increasing ambition in avoided deforestation and ecosystem restoration and reducing agricultural emissions, and actively addressing demand-side measures and negative emissions with concrete commitments and investment plans.

Methods

Detailed methods, including data used and produced with associated references are available in the Supplementary Information.

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Author contributions

S.R. led the study design and the writing of the paper with significant contributions from D.L., C.S., M.O., and S.F. S.R. and Z.H. conducted the synthesis of 1.5C pathways, S.R. and S.F. the model assessment land sector pathways, S.R. and B.G. the bottom-up mitigation potential, and S.R. and C.S. the land sector mitigation wedges. M.O., S.F., P.H., and M.G. developed the land sector pathways and sensitivity analysis in GLOBIOM. B.G., L.D., O.F., N.H., T.H., Z.H., P.H., J.H., G.N., A.P., M-J.S., J.S., P.S., and E.S. provided data and/or analysis and drafting of the paper.

Competing financial interests

The authors declare no competing financial interests.

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Figures and Tables

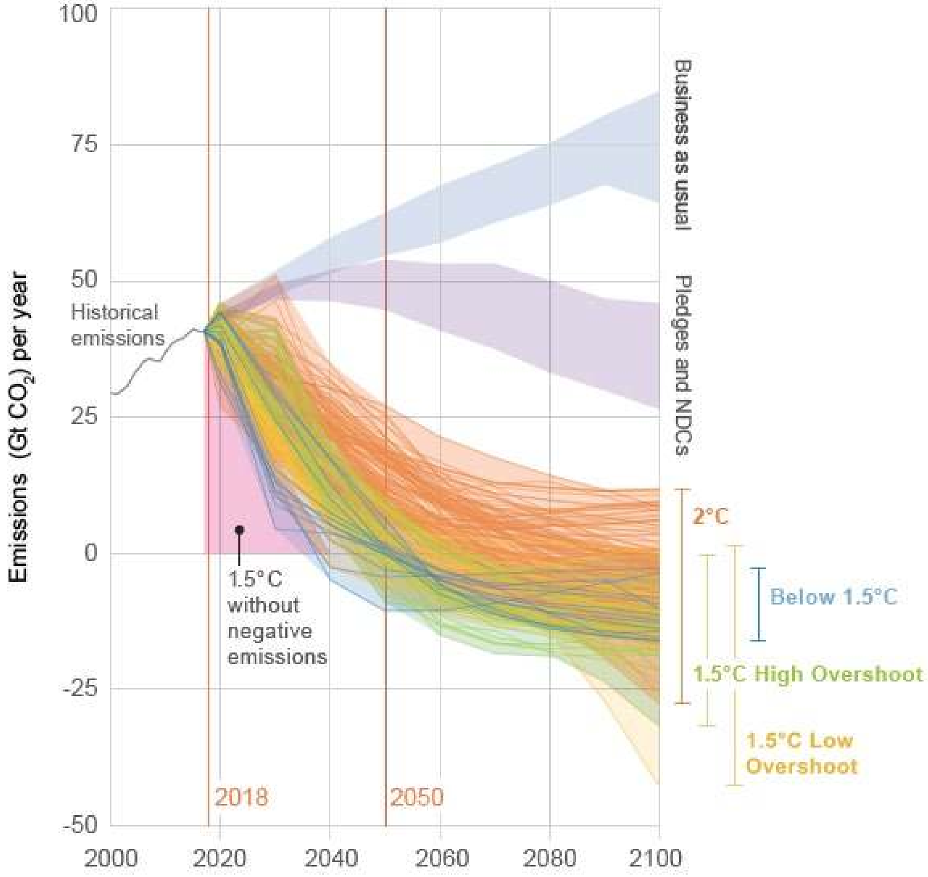


Figure 1. Synthesis of global net anthropogenic CO_2 emissions trajectories of 2°C, 1.5°C high overshoot, 1.5°C low overshoot and below 1.5°C scenarios, in $GtCO_2$ /year. The 2°C (132 model runs, orange lines), 1.5°C high overshoot (37 model runs, green lines), 1.5°C low overshoot (44 model runs, yellow lines) and Below 1.5°C (9 model runs, blue lines) pathways from the recently released Integrated Assessment Modeling Consortium (IAMC) 1.5°C Database[22], present values at a >66% probability threshold (2°C and 1.5°C high overshoot) and 50-66% probability threshold (1.5°C low overshoot and below 1.5°C scenarios)[4]. More details on these emission trajectories, comparisons with other carbon budgets in the literature, and a variant of the figure including all greenhouse gases in CO_2e can be found in SI-section 1. The Mitigation for 1.5°C without negative emissions scenario (pink wedge) represents the range of remaining allowable emissions from the IPCC Special Report on 1.5°C carbon budgets of 420 $GtCO_2$ from 2018 (see SI-section 1). NDC numbers are adapted from Climate Action Tracker, 2018, removing non-CO2 emissions. Business as usual numbers represent the range of SSP2 baseline scenarios for 1.9 W/m^2 from the SSP Database[11]. *Historical emissions data is from the Global Carbon Project* [6]

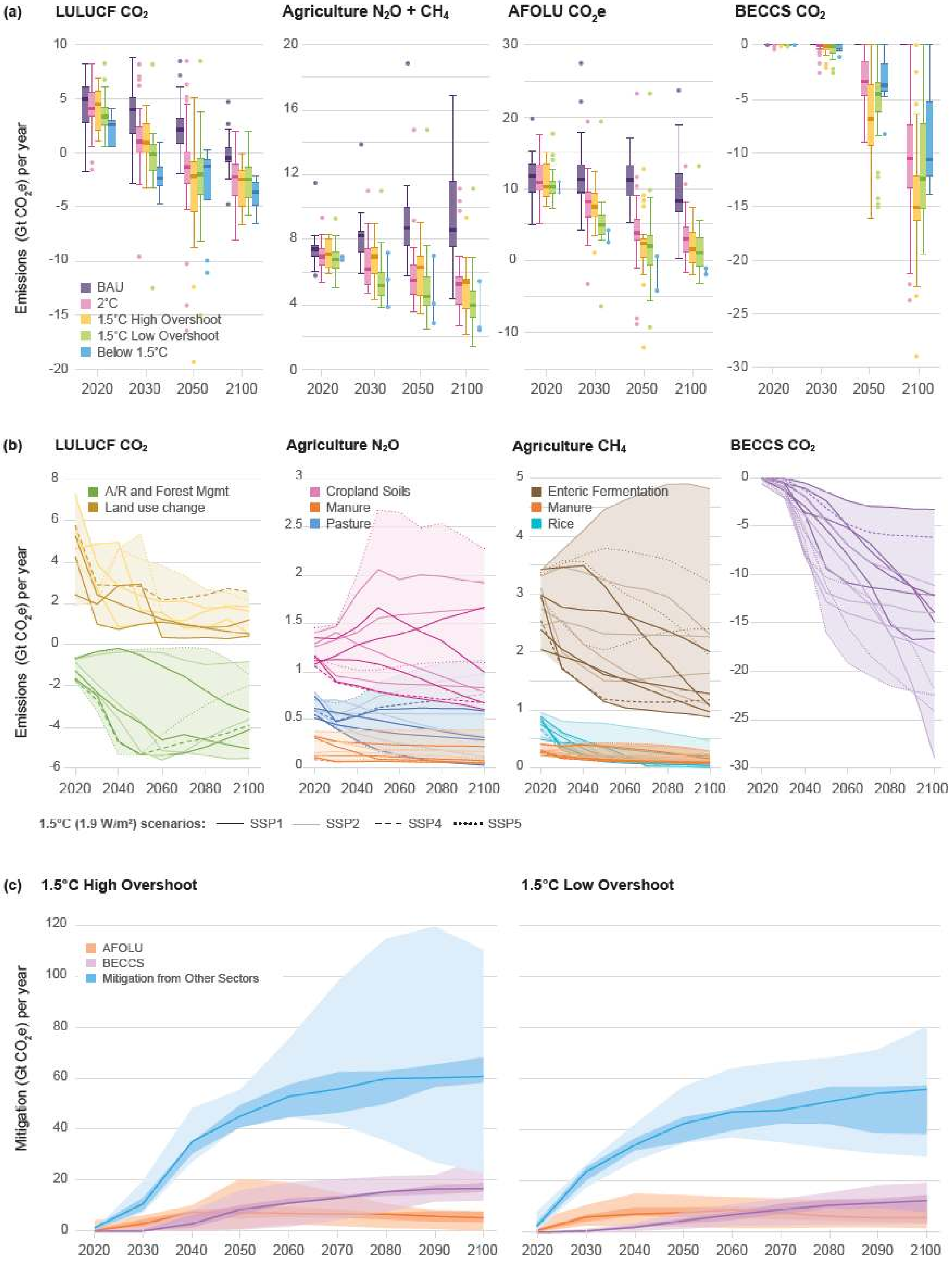


Figure 2. (a) Range of land sector emissions pathways in LULUCF, Agriculture, AFOLU (LULUCF +Agriculture) and BECCS in business as usual (BAU), 2°C, 1.5°C high overshoot, 1.5°C low overshoot and below 1.5°C scenarios. Boxplots show the median, interquartile range, and minimum-maximum range of pathways. In scenarios with <5 data points (below 1.5°C in agriculture and AFOLU), only the minimum-maximum range and single data points are shown. Data is from the IAMC Database[22] *(b) 1.5°C Mitigation pathways of land-based activities in LULUCF, agriculture and BECCS from the* SSP

Database[11,13]. *Shaded areas show the minimum-maximum range across the SSPs per activitiy. Single pathways are lines, styled according to the SSP scenario in the legend. (c) Total mitigation of AFOLU, BECCS and Other sectors (total global mitigation minus AFOLU and BECCS) in the 1.5°C high overshoot and 1.5°C low overshoot scenarios. Below 1.5°C scenarios are not illustrated due to too few data points. Total mitigation is calculated as the reference scenario minus 1.5°C for each model and scenario, then summed for AFOLU, BECCS and Other sectors. Shaded areas show the minimum-maximum range (light shading), interquartile range (dark shading) and median (dark line). Data is from the IAMC Database*[22]*. The GHG flux of bioenergy plantations is accounted for in the land sector until harvest (i.e. these are included as part of the AFOLU flux), then bioenergy, processing, use and carbon removal through CCS is accounted for in the energy sector (BECCS). Additional energy and industry sector mitigation falls under all Other sectors.*

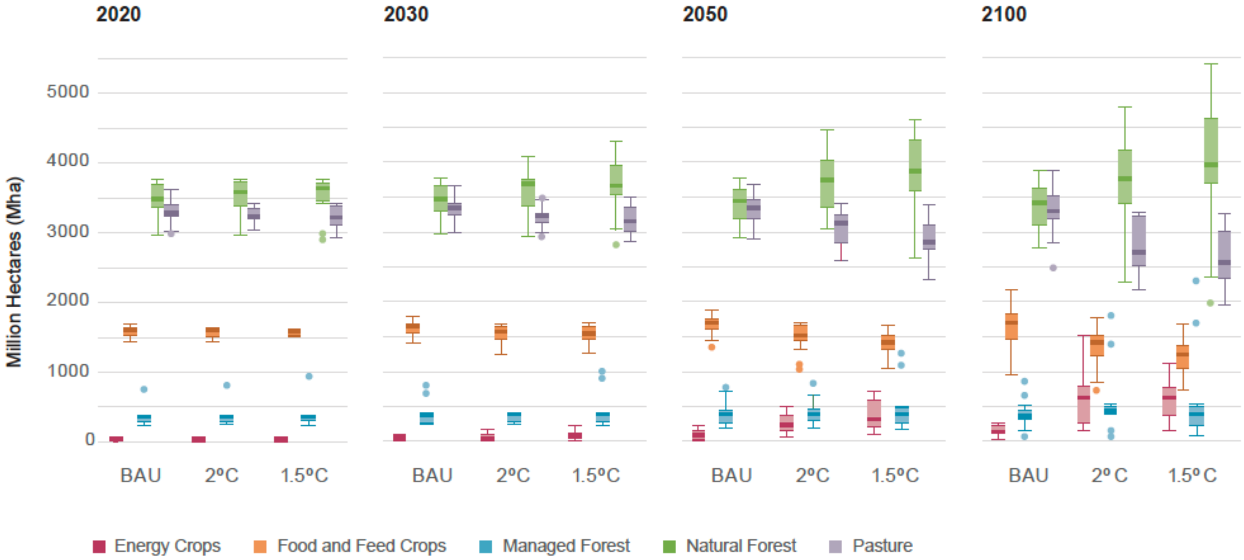


Figure 3. Land cover balance in million hectares (Mha) in BAU, 2°C and 1.5°C scenarios from the SSP Database[11]. *Natural forests (unmanaged forests) are primary, secondary, and protected forests with no planned timber production and tree felling either for wood extraction or for silvicultural purposes such as pre-commercial thinnings. Some models account for afforestation and reforestation (A/R) under natural forests, which is why natural forests increase over time in certain models and scenarios (SI-section 3). Managed forests are forests which are managed either for timber production and/or carbon sequestration, in some models, including BECCS. Energy Crops are short rotation plantations and other feedstocks for bioenergy including BECCS.*

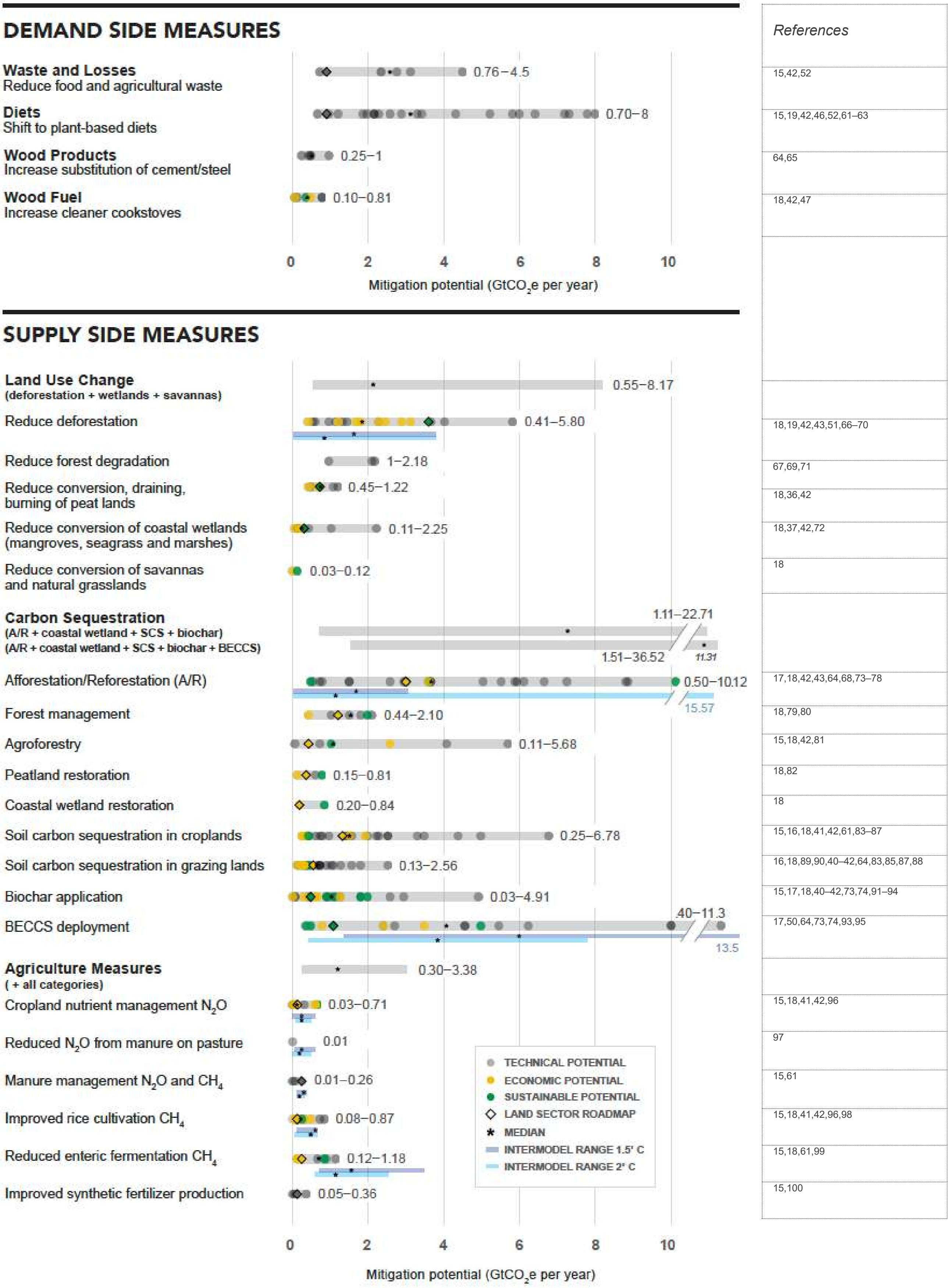

DEMAND SIDE MEASURES
References
Waste and Losses
Reduce food and agricultural waste
0.76–4.5
15,42,52
Diets
Shift to plant-based diets
0.70–8
15,19,42,46,52,61–63
Wood Products
Increase substitution of cement/steel
0.25–1
64,65
Wood Fuel
Increase cleaner cookstoves
0.10–0.81
18,42,47
0
2
4
6
8
10
Mitigation potential (GtCO$_2$e per year)
SUPPLY SIDE MEASURES
Land Use Change
(deforestation + wetlands + savannas)
0.55–8.17
Reduce deforestation
0.41–5.80
18,19,42,43,51,66–70
Reduce forest degradation
1–2.18
67,69,71
Reduce conversion, draining, burning of peat lands
0.45–1.22
18,36,42
Reduce conversion of coastal wetlands (mangroves, seagrass and marshes)
0.11–2.25
18,37,42,72
Reduce conversion of savannas and natural grasslands
0.03–0.12
18
Carbon Sequestration
(A/R + coastal wetland + SCS + biochar)
(A/R + coastal wetland + SCS + biochar + BECCS)
1.11–22.71
1.51–36.52
11.31
Afforestation/Reforestation (A/R)
0.50–10.12
15.57
17,18,42,43,64,68,73–78
Forest management
0.44–2.10
18,79,80
Agroforestry
0.11–5.68
15,18,42,81
Peatland restoration
0.15–0.81
18,82
Coastal wetland restoration
0.20–0.84
18
Soil carbon sequestration in croplands
0.25–6.78
15,16,18,41,42,61,83–87
Soil carbon sequestration in grazing lands
0.13–2.56
16,18,89,90,40–42,64,83,85,87,88
Biochar application
0.03–4.91
15,17,18,40–42,73,74,91–94
BECCS deployment
.40–11.3
13.5
17,50,64,73,74,93,95
Agriculture Measures
(+ all categories)
0.30–3.38
Cropland nutrient management N$_2$O
0.03–0.71
15,18,41,42,96
Reduced N$_2$O from manure on pasture
0.01
97
Manure management N$_2$O and CH$_4$
0.01–0.26
15,61
Improved rice cultivation CH$_4$
0.08–0.87
15,18,41,42,96,98
Reduced enteric fermentation CH$_4$
0.12–1.18
15,18,61,99
Improved synthetic fertilizer production
0.05–0.36
15,100
● TECHNICAL POTENTIAL
● ECONOMIC POTENTIAL
● SUSTAINABLE POTENTIAL
◇ LAND SECTOR ROADMAP
★ MEDIAN
▬ INTERMODEL RANGE 1.5° C
▬ INTERMODEL RANGE 2° C
0
2
4
6
8
10
Mitigation potential (GtCO$_2$e per year)

Figure 4. Land-based mitigation potential in 2020-2050 by activity type, measured in $GtCO_2e$/yr. Mitigation potentials reflect the full range of low to high estimates from studies published after 2010, and are differentiated according to technical (possible with current technologies), economic (possible given economic constraints) and sustainable potential (technical or economic potential constrained by sustainability considerations). Medians are calculated across all potentials in categories with >4 data points. We only include references that provide global mitigation potential estimates in CO2e/yr (or similar derivative) by 2050. Supply-side and demand-side measures are treated separately as these two categories are not additive. Supply-side measures are activities that require a change in land-use and/or management. Demand-side measures are activities that require a change in consumer behaviour. The analysis was designed to avoid potential double-counting of emissions reductions – the summed categories are highlighted in the supply-side measures (e.g. total land use change "deforestation+wetlands+savannas" excludes forest degradation and peatlands as these categories are included in many estimates). More information on the methods and description of activities are in SI-section 3. To compare with bottom-up potentials, top-down intermodel ranges and medians are included in available categories from the 2°C and 1.5°C scenarios in the SSP Database. The models reflect land management changes, yet in some instances, can also reflect demand-side effects from carbon prices, so may not be defined exclusively as "supply-side." Estimates used for the Land Sector Roapmap are given more context in Figure 6.

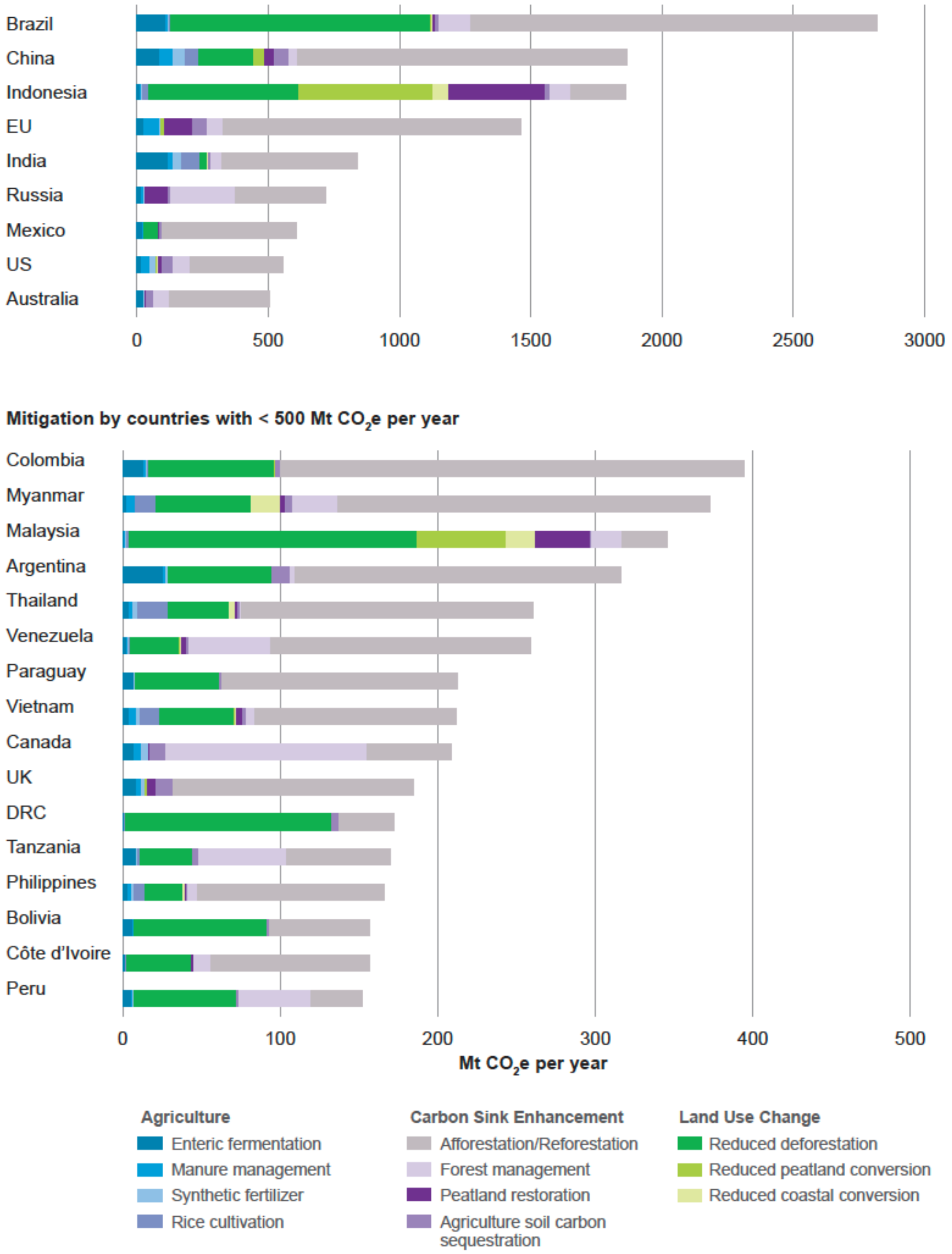
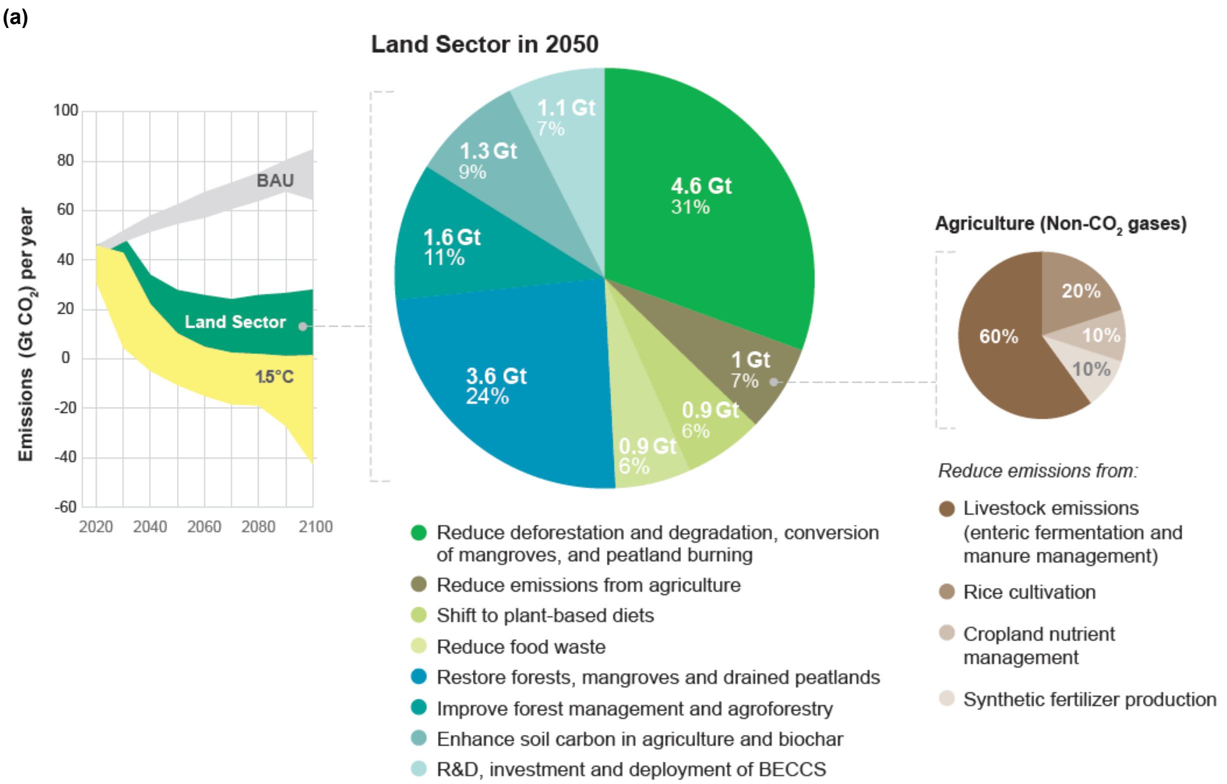


Figure 5. Land sector mitigation potential by country/region measured in Mt CO2e per year. The top 25 countries with the highest mitigation potential are presented, nine with over 500 Mt CO2e per year and 16 with 100 to 400 Mt CO2e per year. Numbers are compiled from country mitigation potentials in Griscom et al. (2017) (Rice cultivation, Forest management, Peatland restoration, A/R, Reduced deforestation, Reduced peatland conversion, and Reduced coastal conversion), as well as percentages of FAOSTAT emissions data calculated for this study (Enteric fermentation, Manure Management, Synthetic Fertilizer and Agriculture soil carbon enhancement (Table S4 in SI-section 3)



(b)			Implementation trajectory: % reduction (green) or cumulative increase in removals GtCO₂ (blue)			
Wedge	**Priority regions for mitigation**	**Activity types**	**2020**	**2030**	**2040**	**2050**
Reduce emissions from deforestation and degradation, conversion of coastal wetlands, and peatland burning[18] (95% emissions reduction by 2050 compared to 2018)	Tropical countries, particularly countries with high overall loss: Brazil, Indonesia, DRC, Myanmar, Bolivia, Malaysia, Paraguay, Colombia, Peru and Madagascar	Conservation policies, establishment of protected areas, law enforcement, improved land tenure, REDD+, sustainable commodity production, improved supply chain transparency, procurement policies, commodity certification, cleaner cookstoves	25%	70%	90%	95%
Reduce emissions from agriculture[16,21] (25% emissions reduction by 2050 compared to 2018)	Developed and emerging countries (China, India, Brazil, EU, US, Australia, Russia)	Reduce CH_4 and N_2O emissions from enteric fermentation, nutrient management, synthetic fertilizer production, manure management	0	0	15%	25%
	Asia (India, China, Indonesia, Thailand, Bangladesh, Vietnam, Philippines)	Reduce CH_4 emissions by improving water and residue management of rice fields, and manure management				
	Latin America (Brazil, Argentina, Mexico, Colombia, Paraguay, Bolivia)	Reduce CH_4 emissions from enteric fermentation and manure management				
Shift to plant-based diets[42] (50% adoption in global population by 2050)	Developed and emerging countries (US, EU, China, Brazil, Argentina, Russia, Australia)	Reduce production of GHG intensive foods through public health policies, consumer campaigns, development of novel foods	5%	20%	35%	50%
Reduce food waste[42] (50% reduction in total food waste by 2050 compared)	China, Europe, North America, Latin America	Reduce food waste: consumer campaigns, private sector policies, supply chain technology, improved food labelling, waste to biogas	20%	30%	45%	50%
	Southeast Asia, Sub-Saharan Africa	Reduce food loss: improve handling & storage practices through training, investment and technology	10%	30%	45%	50%
Restore forests, coastal wetlands and drained peatlands[18]	Brazil, Indonesia, China, EU, India, Mexico, Australia, US, Russia, Colombia, Malaysia	Invest in restoration, national and local policies, payment for ecosystem services	0	9	45	90
Improve forest management and agroforestry[18]	Russia, Canada, Brazil, Indonesia, US, EU, Australia, Tropical countries	Optimizing rotation lengths and biomass stocks, reduced-impact logging, improved plantations, forest fire management, certification; integration of agroforestry into agricultural and grazing lands	0	4	20	40

Enhance soil carbon sequestration in agriculture and apply biochar[17,42]	China, EU, USA, Australia, Brazil, Argentina, India, Indonesia, Mexico, Sub-Saharan Africa	Erosion control, use of larger root plants, reduced tillage, cover cropping, restoration of degraded soils, biochar amendments	**0**	**3**	**16**	**32**
Deploy BECCS[17,50]	USA, Russia, China, Canada[50]	BECCS R&D, investment and deployment	**0**	**0**	**11**	**22**

Figure 6. Land sector roadmap for 2050. (a) Land-based mitigation wedges to deliver total mitigation of ~15 $GtCO_2e$/yr by 2050. The land sector makes up ~30% of total needed mitigation in 2050 (left panel, data from Fig 1 and 2c) which is delivered by eight priority wedges (middle panel). The green and brown wedges represent emissions reduction measures (7.4 GtCO2e/yr), and the blue wedges represent carbon removal measures (7.6 $GtCO_2$/yr). (b) Priority regions and activity types for each wedge, and their implementation trajectories in percent for emission reduction activities and cumulative GtCO2e for carbon removal activities starting in 2020. The overall number in 2050 for the implementation trajectories are based on the source used for each wedge, cited in the first column and detailed in Table S5. The 2020-2050 trajectories are based on an expert assessment weighing co-benefits, risks, and feasibility, with the cumulative carbon removal trajectories using 25% of mitigation potential per year for 2020-2030, and full mitigation potential per year after 2030 for biological measures and after 2040 for BECCS. The wedges are measures which are individually accounted for with the intent of avoiding double counting of emissions reductions (SI-section 4). Mitigation potentials for the wedges in $GtCO_2e$/yr are highlighted in Figure 4 "Land sector roadmap." Priority regions for mitigation are detailed in SI-section 4 and 5. The related risks, co-benefits, and alignment to international policies and commitments of the various wedges are detailed in Table S6.

SUPPLEMENTARY INFORMATION

Contribution of the land sector to a 1.5°C World

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Methods

To provide a comprehensive assessment of the entire land sector (agriculture, LULUCF, and bioenergy), and its potential contributions to the Paris Agreement temperature target of 1.5°C, we conducted four separate, yet complementary analyses: 1) Review and synthesis of published, economy-wide 1.5°C pathways, 2) top-down comparative analysis of integrated assessment modelling of 1.5°C pathways in the land sector, 3) review and bottom-up assessment of land sector mitigation potential, updating the IPCC AR5 Ch11 findings, and 4) a geographically explicit roadmap of priority mitigation measures or "wedges" and regions to fulfil the 1.5°C land sector transformation pathway, informed by a triangulation of the first three analyses.

The detailed methods and some resulting data are outlined below, structured in four sections according to the four analyses.

SECTION 1. Review of 1.5°C pathways

We assess the pathways to 1.5°C and 2°C by compiling and analysing published, publicly available modelled data for emissions reductions to 2100. We chose studies that modelled emissions pathways for 1.5°C and 2°C scenarios, including scenarios that exceeded one or both of the temperature targets but met the target by the end of the 21st century. The studies were examined on a decade by decade basis, and we explored the assumptions regarding reductions in land versus non- land sectors, negative emissions deployment, total carbon budgets until 2100, and forecast trajectories of emissions reductions.

We examined both 2.6 w/m^2 (2°C forcing target) and 1.9 w/m^2 (1.5°C forcing target) Integrated Assessment Model (IAM) runs from the Shared Socioeconomic Pathways (SSP) Database[1,2] published in Rogelj et al. (2018)[2], the Integrated Assessment Modeling Consortium (IAMC) Database[3] that accompanied the IPCC special report on 1.5C, as well as individual estimates from Rockstrom et al. (2017)[4], Millar et al. (2017)[5], Walsh et al. (2017)[6], Goodwin et al. (2018)[7], and Tokarska and Gillett (2018)[8]. Rogelj et al. (2015)[9] was also reviewed but excluded in the analysis given its overlap with the new Rogelj et al. (2018) which assessed the same underlying IAMs with small version differences. The 2.6 w/m^2 model runs suggest that emissions reductions of between 70% and 90% are needed between 2020 and 2060, with net-negative emissions in most models starting between 2060 and 2080 in order to meet a 66% probability threshold keeping emissions below 2°C by 2100. 1.9 w/m^2 models require still steeper reductions, with emissions dropping to zero in all models between 2040 and 2060 and net-negative thereafter for the same probability threshold of 66%.

The total carbon budget available in the SSP Database 2.6 w/m^2 models between 2018 and 2100 ranges from 436 $GtCO_2$ to 1159 $GtCO_2$, with a median estimate of 964 $GtCO_2$. Models limiting 2100 radiative forcing to 1.9 w/m^2 (and 2100 temperatures to below 1.5°C) show correspondingly smaller carbon budgets from 2018-2100, ranging from requiring net-negative emissions of -174 $GtCO_2$ to allowing up to 402 $GtCO_2$, with a median estimate of 237 $GtCO_2$. Much of the difference in the budgets results from the treatment of non-CO_2 GHGs and aerosols in different IAMs[2,9], though the duration of net-negative emissions can also affect the results as it tends to deviate from the linear relationship between cumulative CO_2 and warming during periods of positive emissions[10].

The IAMC Database[3] models also include a wide range of 2018-2100 carbon budgets. Excluding those model runs also found in the SSP Database, the IAMC 2C runs have a budget ranging from 135 $GtCO_2$ to 1887 $GtCO_2$ with a median estimate of 951 $GtCO_2$. IAM 1.5C runs have a correspondingly lower cumulative carbon budget, ranging from -182 $GtCO_2$ to 745 $GtCO_2$ with a median of 144 $GtCO_2$.

Individual studies (Rockstrom et al. (2017), Walsh et al. (2017), and our own estimates) of the available carbon budget to limit 2100 warming to below 1.5°C provide results comparable to the range of SSP and IAMC Database IAMs for both 2°C and 1.5°C targets. Rockstrom et al. combined published model findings with expert judgment to prescribe a 50% reduction in CO_2 emissions per decade (88% total) between 2020 and 2050 until net zero emissions are reached in order to meet a 66% probability threshold for 2°C and a 50% probability threshold for 1.5°C, with an available 2018-2100 carbon budget of 132 $GtCO_2$. Walsh et al. derive emissions and temperature change from the FeliX integrated assessment model to find CO_2 emissions must peak in or slightly before 2020 and achieve net zero by about 2040 for 1.5°C, equating to 5% annual emissions reductions, and net zero by 2050 for 2°C, equating to 3% annual emissions reductions – or 100% and 97% by 2050, respectively. Their available 2018-2100 carbon budget is 371 $GtCO_2$ for 2°C and -489 $GtCO_2$ for 1.5°C, respectively, and is a bit below the range of values for IAM models. Our own model suggests 2018-2100 budgets of 979 $GtCO_2$ for 2°C and 268 $GtCO_2$ for 1.5°C, close to the median of SSP Database models.

The SSP and individual IAM studies represent avoidance budgets that target limiting warming in 2100 below 1.5°C by limiting end-of-century forcings to around 1.9 w/m^2. Millar et al. (2017), Goodwin et al. (2018), and Tokarska and Gillett (2018) use observational warming and cumulative emissions to-date to observationally constrain CMIP5 Earth System Model (ESM) results, and suggest significantly higher remaining 1.5°C carbon budgets than IAM-based approaches. Remaining 2018-2100 carbon budgets in Millar et al. are 625 $GtCO_2$ to 695 $GtCO_2$ for a 66% to 50% chance of preventing warming from exceeding 1.5°C, respectively. Goodwin et al. find a similar range from 693 $GtCO_2$ to 766 $GtCO_2$, while Tokarska and Gillett find somewhat lower values (395 $GtCO_2$ and 681 $GtCO_2$) for a 66% and 50% chance. These papers calculate exceedance rather than avoidance budgets, looking at how long emissions can continue increasing by 1% per year until temperatures exceed 1.5°C.

As Rogelj et al. (2018) point out, observation and ESM-based exceedance budgets that increase CO2 by 1% per year until temperatures exceed 1.5°C and IAM-based avoidance budgets that limit radiative forcing to 1.9 w/m^2 (and temperatures to below 1.5°C) in 2100 are not easily comparable. ESM-based approaches use the 50th and 66th percentiles of CMIP5 models, while IAMs use a proscribed climate sensitivity probability density function. This leads to somewhat more conservative outcomes among IAM-based approaches. While exceedance budgets using ESMs that have a 66% chance of avoiding 1.5°C still show maximum warming of around 1.45°C, IAMs with a 66% chance of avoiding 1.5°C have much lower 2100 warming, reaching only 1.3°C to 1.4°C above pre-industrial levels (though most IAMs exceed 1.5°C mid-century before reducing temperatures through the large-scale application of negative emissions).

Because the maximum warming lags emissions of carbons by about a decade, exceedance budgets do not fully account for emissions over the final decade before the 1.5°C threshold is exceeded. IAMs, on the other hand, are somewhat penalised because the cooling from negative emissions in the last decade before 2100 is not fully accounted for[2]. Additionally, many observationally-constrained ESM budgets use global surface temperature records that are not globally complete and use slower-warming ocean surface temperatures rather than the surface air temperatures over oceans[11,12].

These combine to make IAM-based avoidance carbon budgets relatively low compared to combined observation/ESM exceedance budgets. Rogelj et al. (2018) recalculated the Millar et al. carbon budget and found that a comparable globally-representative 2018-2100 avoidance budget would be somewhere between 25 $GtCO_2$ and 375 $GtCO_2$, overlapping with the majority of SSP Database IAM 1.9 w/m^2 budgets. Thus, we suggest that these recent exceedance budget studies are not necessarily at odds with the 1.5°C budgets used in this paper. Similarly, while the IPCC SR15 provides a best-estimate remaining 1.5C carbon budget of 420 $GtCO_2$, this value is not inconsistent with IAM-derived 2018-2100 cumulative budgets due to the differences in exceedance and avoidance calculations.

The IAM studies show a dramatic transformation of the energy and land sectors. Energy system transformation is generally characterized by a fossil fuel phase out, energy efficiency improvement, more rapid decarbonization of electricity compared to industry, buildings and transport, and extensive use of CO_2 capture and storage (CCS)[9]. The land sector transformation includes a dramatic decline in deforestation, a significant increase in afforestation and reforestation (A/R) and forest management, and reduced agricultural emissions after 2030-2040, facilitated by improved crop production efficiencies and yields[13,14]. These broad transformations are in line with those observed in the main IPCC AR5 RCP 2.6 scenario.

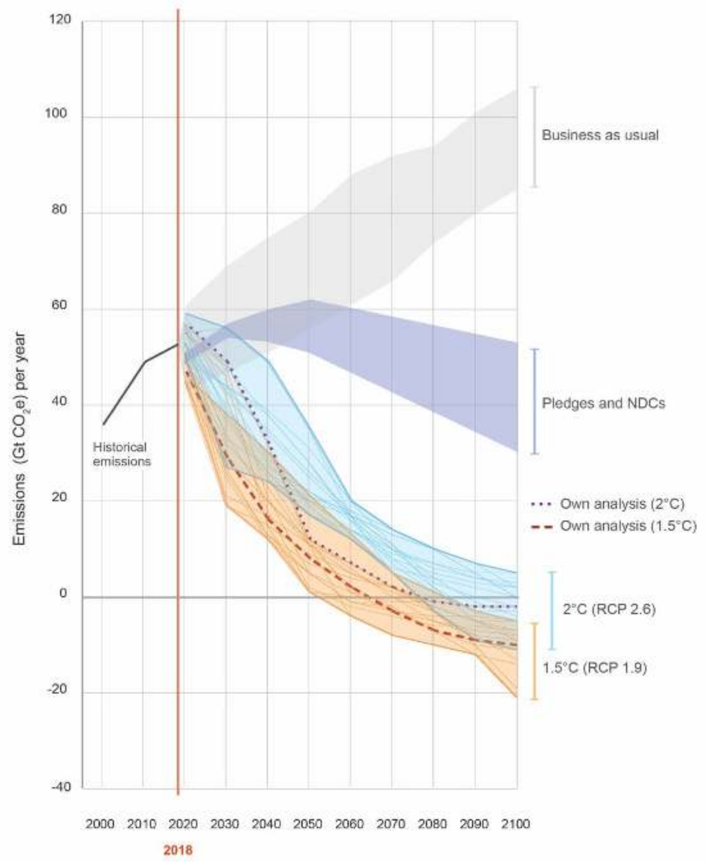

Figure S1. Greenhouse gas emission trajectories (in $GtCO_2e$ per year using 100-year global warming potential values) of 2°C and 1.5°C scenarios. This figure includes major anthropogenic greenhouse gas emissions (CO_2, CH_4, N_2O, and various halocarbons) and is a variant of the main text Figure 1 (which only includes CO_2). The 2°C (18 model runs in blue lines) and 1.5°C (13 model runs in orange lines) scenarios, from the recently updated SSP Database of Integrated Assessment Model runs, present values at a >66% probability threshold[1,2]. NDC numbers are adapted from Climate Action Tracker, 2018. Business as usual numbers represent the range of SSP2 baseline scenarios. Historical emissions data is from EDGAR 4.3.2.

SECTION 2. Review of 1.5°C pathways in the land sector

To gauge the contribution of the land sector in 1.5°C and 2°C pathways, we conducted a comparative assessment of model outputs from the Integrated Assessment Modeling Consortium (IAMC) Database[3] and Shared Socioeconomic Pathways (SSP) Database[1,2]. We reviewed emission pathways and land cover balances of the various pathways. We also conducted a sensitivity analysis to test the effect of reducing BECCS.

Emission pathways

We used the IAMC Database[3] (Version 1.0) to assess net CO_2, CH_4, and N_2O emissions trajectories to 2100 in 1.5°C (1.9 w/m^2), 2°C (2.6 w/m^2), and Reference (BAU) scenarios in LULUCF, Agriculture and BECCS (Figure 2a). We combined the LULUCF and Agriculture categories to derive trajectories for AFOLU. We calculated the mitigation potential for the land sector in the 1.5°C scenarios by summing mitigation potentials from AFOLU and BECCS (Figure 2c). Mitigation potential for all other sectors represents global mitigation minus land sector mitigation. Mitigation potential is the difference between the reference scenario and the 1.5°C scenario for each model and scenario, summed for AFOLU, BECCS and Other sectors. The Database represents 19 models and 90 model scenarios. More detailed information is provided in the IPCC Special Report on 1.5°C Chapter 2[15] and the IAMC Database website[3].

The IAMC Database does not have data for specific activities in agriculture, therefore, we used the updated SSP Database (Version 2.0)[1,2] to assess the N2O emission pathways for Cropland Soils, Manure, and Pastures, the CH4 emission pathways from Enteric Fermentation, Manure, and Rice, and CO2 emission pathways for Land-use change, A/R and Forest Management, and BECCS in a 1.5°C scenario (1.9 W/m^2) (Figure 2b). We also calculated the mitigation potentials for the mentioned activities (Difference between BAU and 1.5°C for each model scenario) to compare with the bottom-up assessment of literature (Figure 4). The SSP Database represents five Shared Socio-economic Pathways (SSPs – described in Box S1) and includes six integrated assessment models (AIM, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND-MAgPIE, and WITCH-GLOBIOM). Popp et al. (2017)[13] provide a comparative assessment of emission pathways, land use changes, prices and consequences for the agricultural system across the SSPs in the BAU, 2°C (2.6 w/m^2), and 4°C (4.6 w/m^2) scenarios – but not for 1.5°C (1.9 W/m^2). More detailed information on the SSPs and the six models in the SSP Database, including their underlying assumptions for the energy sector (energy demand, supply and conversion technologies) and the land sector is provided in Riahi et al. (2017)[1] and the Supplementary Information of the same study.

Box S1. Representative Concentration Pathways (RCP) and Shared Socioeconomic Pathways (SSP)

Developed by the scientific community for the IPCC, four RCPs have been developed to provide climate modelers a consistent framework of possible development trajectories for the main forcing agents of climate change (van Vuuren et al., 2011). RCPs can be used in General Circulation Models (more complex, full Earth System Models) and in Integrated Assessment Models (simpler models that use socio-economic development pathways) to project temperature increases and related impacts. Other concentration pathways have been developed, including one with radiative forcing of 1.9 W/m^2 which is consistent with 1.5°C of warming. The four RCPs include:

- RCP 2.6: Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2e) and then decline to 2.6 W/m^2 by 2100

- RCP 4.5: Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2e) at stabilization after 2100
- RCP 6: Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2e) at stabilization after 2100
- RCP 8.5: Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2e) by 2100

Five Shared Socioeconomic Pathways (SSP1-SSP5) have been developed by the climate modelling community to facilitate comparable integrated assessments of future climates. The SSPs are based on different socio-economic development narratives, including:

- SSP1: Sustainable Development;
- SSP2: Middle-of-the-road development (business as usual);
- SSP3: Regional rivalry;
- SSP4: Inequality;
- SSP5: Fossil-fueled development.

References: [1,13]

Land cover balance

To assess projected land cover changes, we used the updated SSP Database (Version 2.0)[1,2] to compare land cover (Mha) trajectories in 1.5°C (1.9 w/m^2), 2°C (2.6 w/m^2), and BAU scenarios until 2100. We used the SSP Database instead of the IAMC Database as there are more land cover categories (e.g. managed vs unmanaged forests). Two land cover change calculations were assessed: the change in 2050 and 2100 compared to 2020, and compared to BAU for each model and scenario (Table S1).

Natural forests (unmanaged forests) are primary, secondary, and protected forests with no planned timber production and tree felling either for wood extraction or for silvicultural purposes such as pre-commercial thinnings. Managed forests are forests which are managed either for timber production and/or carbon sequestration which could include BECCS. Energy Crops are short rotation plantations and other feedstocks for bioenergy including BECCS. The definitions for natural and managed forests are not fully harmonized across models. Two models account for A/R (e.g. newer forests) in natural forests – making it possible for natural forests to increase over time, another three models have a separate A/R forest category, and one model did not include A/R (Table S2). The different methodologies makes the distinction between natural and managed forests difficult to disentangle and natural forest loss difficult to evaluate. However, instead of including all forests under one category, we think it is helpful to distinguish in our study to shed a light on these issues.

As mentioned in our paper, BECCS deployment (and hence land dedicated to energy crops) is one of the main reasons for land-use change. The scale of BECCS deployment is influenced by the SSP and radiative forcing scenario, and differing model assumptions. To elucidate some of these assumptions, we compare model methodologies on biomass feedstock, current and future agricultural yields, and conversion efficiencies (Table S3).

Table S1. Land cover changes in Mha in 1.5°C scenarios across all SSPs, compared to 2020 and BAU levels. The change in land cover balance is calculated as the difference in Mha between the two scenarios being compared for each model scenario, then aggregated into quartiles (positive numbers indicate increase in land cover, negative numbers indicate decrease).

Energy crops	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	647	1051	Min	649	757

	Q1	554	705	Q1	494	589
	Median	287	594	Median	204	299
	Q3	168	371	Q3	113	175
	Max	91	152	Max	48	-24
Food (and feed and fibre) crops	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	50	66	Min	-40	41
	Q1	-69	-206	Q1	-205	-284
	Median	-159	-334	Median	-294	-393
	Q3	-254	-517	Q3	-327	-423
	Max	-470	-775	Max	-423	-616
Pasture	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	-40	-107	Min	-11	-14
	Q1	-123	-242	Q1	-49	-49
	Median	-386	-583	Median	-359	-520
	Q3	-456	-730	Q3	-496	-709
	Max	-632	-1155	Max	-625	-1474
Managed forest	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	313	1348	Min	545	1431
	Q1	127	165	Q1	58	72
	Median	43	42	Median	22	27
	Q3	-66	-134	Q3	-12	-3
	Max	-116	-225	Max	-48	-36
Natural (unmanaged) Forests	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	1014	1809	Min	972	1534
	Q1	734	932	Q1	846	801
	Median	182	364	Median	303	446
	Q3	-9	4	Q3	76	60
	Max	-294	-929	Max	-313	-1070

Table S2. Treatment of A/R across the six models in the SSP Database

AIM/CGE 2.0	A/R is included in natural forests
GCAM4 4.2	A/R is included in natural forests
IMAGE 3.0.1	A/R (forests afforested or reforested after 2020) is reported in a separate A/R category, the vegetation type is natural, secondary forest after natural regrowth and succession dynamics
MESSAGE-GLOBIOM 1.0	A/R (forests afforested or reforested after 2000) is accounted for in a separate A/R category, there is also an increase in managed forests which come from a decrease in natural forests
REMIND-MAgPIE 1.5	There is no A/R in the SSP runs. All forest area increases are related to regrowth of natural vegetation on abandoned agricultural land
WITCH-GLOBIOM	Relies on GLOBIOM assumptions

Table S3. Assumptions and methodologies relevant for bioenergy and BECCS deployment in the six models in the SSP Database

	AIM/CGE 2.0	**GCAM 4.2**	**IMAGE 3.0.1**	**MESSAGE-GLOBIOM 1.0**	**REMIND-MAgPIE 1.5**	**WITCH-GLOBIOM**
Feedstocks used for BECCS	Dedicated 2nd generation bioenergy crops such as miscanthus and switchgrass, as well as residues	A variety of BECCS feedstocks, including grassy crops (e.g., switchgrass), woody crops (e.g., willow), and residues are used. In practice, most of the bioenergy pool comes from grassy crops and residues – not a lot of woody bioenergy	Dedicated bioenergy crops (sugar cane, miscanthus, short-rotation forestry) and crop residues	Short rotation tree plantations such as poplar, willow or eucalyptus as biomass feedstock, and forest biomass feedstocks. Grassy crops such as Miscanthus or switchgrass are not represented in GLOBIOM due to a lack of information on spatially explicit productivities and costs at global scale	Residues as well as dedicated 2nd generation bioenergy crops such as Miscanthus and Poplar	Energy crops and residues for BECCS
Average yield of bioenergy feedstock	Average yields varies across scenarios and time. Energy-crop yield is estimated using a process-based biogeochemical model, VISIT (Ito et al. 2012)[16] and data from the H08 model (Hanasaki et al. 2018)[17].	Average yields vary depending on feedstock, region, year, and scenario.	Yields differ through time - described in detail in Daioglou et al. (2019)[18]	Yields change over time and across SSP scenario following the GLOBIOM assumptions on different SSPs – described in detail in in Fricko et al. (2017)[19]	Average yields vary across time, scenario and region - described in detail in Kriegler et al (2017)[20] and Popp et al (2014)[21] (compares bioenergy yields for IMAGE, MAgPIE and GCAM)	Same as GLOBIOM
Conversion efficiency of BECCS EJ/yr to CO2/yr captured	The conversion efficiency is 75 MtCO2/EJ. As CO2 emissions associated with life cycle is considered in an input-output table structure in the CGE model, this number represents direct emissions only, but the emissions associated with life cycle is considered in our calculation. Energy loss rate is 30%.	Two different types of BECCS power plants and four different types of BECCS refineries are included. These differ in their energy conversion efficiency (EJ of bioenergy input divided by EJ of electricity/liquids output) and their capture rates (what % of the CO2 is captured post-combustion/conversion). We calculate the potential emissions from combustion (for electricity) or conversion (for liquids). For BECCS plants, we then remove some fraction (~90% for electricity, 25-90% for liquids) of the CO2 and put it underground instead of in the atmosphere.	Varies significantly according to scenario - described in Daioglou et al. (2018)[18]	MESSAGE includes four BECCS technology types: Hydrogen production via biomass gasification; Fischer-Tropsch biomass-to-liquids; Ethanol synthesis via biomass gasification; and biomass IGCC power plant. Capture rates for non-liquefaction processes with BECCS vary from around 86%-90%. Ethanol production from biomass with BECCS have a capture rate of around 65-67%. Detailed are described online and in Chapter 13 of the GEA[22].	Differ according to scenario - described in Kriegler et al. (2017)[20]	In WITCH, conversion efficiency of BECCS plant is 90% - described in Vinca et al. (2018)[23]

Main land cover changes in 1.5C scenario and rationale	Bioenergy crops are allocated on abandoned cropland and natural grasslands	Where bioenergy is actually grown depends on the relative profitability, which in turn depends on the yield & price of bioenergy and the yield & price of alternative land uses. The exact distribution of bioenergy is very scenario dependent, with assumptions about trade and land policy strongly influencing where it is grown.	Bioenergy crops are preferably allocated on abandoned cropland and natural grasslands - with large variations based on location.	Bioenergy crops largely replace pasture lands, and managed forests replace natural forests. In the 1.5°C scenario, intensity of forest resource use (share of total harvest volumes in total forest increment) increased significantly by 2100.	Bioenergy crops primarily replace pastures. Land cover changes detailed in Popp et al. (2017)[13] and Rogelj et al. (2018)[2]	Same reference as REMIND

Sensitivity analysis using GLOBIOM

We explored the effect of limiting bioenergy demand on land cover balance, and the impact on natural ecosystems and food security using one of the models in the SSP Database, MESSAGE-GLOBIOM[24]. In the 1.5°C scenario for MESSAGE-GLOBIOM, a significant amount of unmanaged (natural) forests were converted into managed forests to meet additional demand for bioenergy for BECCS. By optimizing for cost-efficiency, the model increased the intensity of forest resource use (share of total harvest volumes in total forest increment) and harvested large areas instead of enhancing harvest in smaller areas. Therefore, in a sensitivity analysis using SSP 2, "middle of the road", we disentangled bioenergy demand from the carbon price by setting a bioenergy threshold at baseline levels (53 EJ/yr and 59 EJ/yr in 2050 and 2100 respectively compared to 109 EJ/yr and 220EJ/yr in the 1.5°C scenario) while still applying the same carbon price trajectories from the 1.5°C and 2°C scenarios. The results are illustrated in Figure S2. In this sensitivity scenario, lower bioenergy demand, and thus mitigation would need to be counterbalanced by additional, more costly efforts in energy (e.g., CCS), negative emissions (potentially technologies like direct air capture), and agriculture. The carbon price would need to increase in the shorter and mid-term to drive these efforts. If agriculture emissions will need to be reduced further, food prices may likely increase in this scenario, and thus potentially affect food security. However, the sensitivity analysis does not represent a fully consistent 1.5˚C scenario across all sectors, hence it was not possible to show this effect.

GLOBIOM is a partial equilibrium model of the global agricultural and forestry sectors. The model is spatially explicit at a high resolution of 5x5 minutes of arc, and depict different production and management systems, differences in natural resource and climatic conditions as well as differences in cost structures and input use. The model explicitly represents technical mitigation options for the agricultural and forestry sectors. For the agriculture sector, mitigation is based on the EPA database on mitigation options[25], structural adjustments in the crop- and livestock sector i.e. through transition in management systems or reallocation of production within and across regions[24], and consumers' response to model endogenous price signals[26]. For the forestry sector the model considers the reduction of deforestation area, increase of afforestation area, and change in forest management activities such as rotation length, thinnings, harvest intensity etc. The carbon price is implemented in the objective function of the model as a tax on GHG emissions, consequently mitigation options get adopted if the carbon price exceeds the marginal cost of a mitigation practice. More information on the mitigation options in the model is provided in Frank et al. (2018)[27] and Gusti and Kindermann (2011)[28]. More detailed information on GLOBIOM is available in Havlík et al. (2014)[24].

GLOBIOM is coupled with the MESSAGE[29] energy model which calculates carbon prices, as well as biomass demand for energy use, compatible with the respective climate stabilization scenarios. Biomass demand in GLOBIOM can be satisfied from multiple sources: managed forests, short rotation tree plantations and forest industry residues. Bioenergy plantations are accounted for in the land sector (under forest management) until harvest, then bioenergy, processing, use and carbon removal through CCS is accounted for in the energy sector. In the event of conversion of natural forests into managed forests for BECCS, the deforested biomass is used for BECCS. The MESSAGE energy model and its methodologies and assumptions on future energy demand and use of fossil fuels, nuclear, renewables, and biomass for energy are outlined in Fricko et al. (2017)[19].

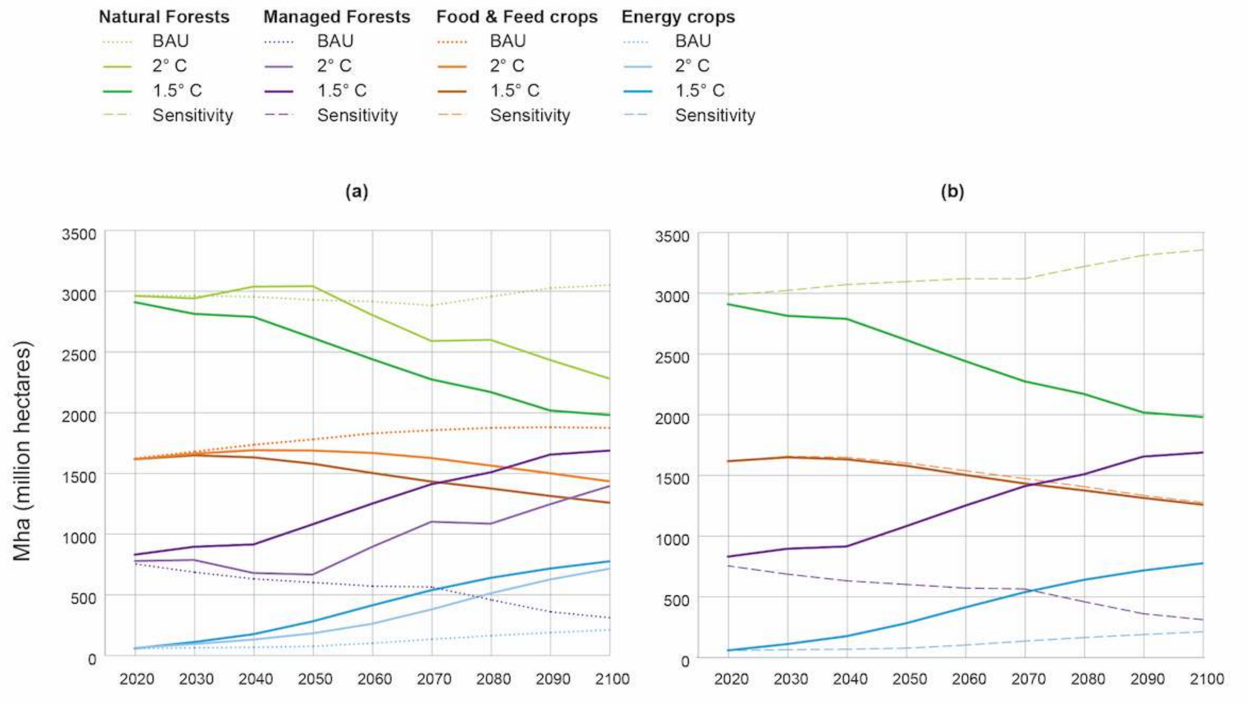

Figure S2. (a) Land cover balance in million hectares (Mha) in BAU, 2°C and 1.5°C scenarios, (b) Land cover balance in Mha in the 1.5°C and sensitivity (bioenergy threshold) scenarios. Unmanaged forests (natural forests) are defined as primary, secondary, and protected forests with no planned timber production and tree felling either for wood extraction or for silvicultural purposes such as pre-commercial thinnings. Managed forests are forests which are managed either for timber production and/or carbon sequestration, including BECCS. Energy Crops are short rotation plantations for bioenergy including BECCS, and consist of willow, poplar, eucalyptus or other fast-growing species.

SECTION 3. Bottom-up assessment of mitigation potential in the land sector

To gauge what activities will be the most effective in meeting the 1.5°C temperature target, we assessed the full range of technical and economic mitigation potential by synthesizing published literature and data for the following main categories: land-use change, carbon sequestration, and agriculture on the supply-side, and food waste and losses, diets, wood fuel, and wood products on the demand side. Technical mitigation potential is the amount of additional emissions reductions and carbon sequestration possible with current technologies without economic and political constraints. Economic mitigation potential is the amount of emissions reductions and carbon sequestration possible given cost constraints, usually a carbon price at $/tCO$_2$. We also identified "Sustainable mitigation potential" when it was explicitly specified by studies, defined as technical or economic mitigation potential constrained by food security and environmental considerations. We adopted the framework and data from the IPCC AR5 AFOLU Chapter 11[30] and updated with more categories and newer data from recently published literature. We include all mitigation potential estimates that provide a CO2e/yr (or similar derivative) figure by 2050, from studies published on or after 2010 (after IPCC AR5). Given that we combine estimates from multiple studies and sources, there are a range of methodologies reflected that may not be directly comparable or additive. Some of the studies use biophysical estimates, and others combine biophysical and economic mitigation potential. Insofar as it was possible, elements of the analysis were designed to avoid potential double-counting of mitigation opportunities (each of the categories and what was considered and calculated is detailed below). Some of the estimates are imprecise due to limited data, uncertainties in emissions, and variable mitigation interventions, and some do not include time-bound pathways.

For the regional estimates, we used the country-level mitigation potential estimates of Reduced deforestation, Afforestation/Reforestation, Forest Management (Natural Forest Management + Improved Plantations + Forest Fire Management), Rice cultivation, Pasture management (Optimal intensity of grazing + Legumes), Peatland Restoration, Reduced peatland conversion, and Reduced coastal conversion from Griscom et al. (2017)[31]. We disaggregated the global mitigation potential of avoided forest conversion as reported in Griscom et al. (2017), to country level using proportional historic forest loss emissions as derived through Global Forest Watch using datasets from Hansen et al. (2015)[32] and Zarin et al. (2016)[33]. We also produced country mitigation potential estimates of enteric fermentation, manure management and synthetic fertilizer by using percentages of FAOSTAT emissions averaged between 2010-2015 (40% reduction of enteric fermentation in countries with extensive cattle production and 10% reduction in countries with intensive cattle production, 70% reduction of manure emissions, and 30% reduction of synthetic fertilizer emissions). The percentages are based on technical feasibility ranges presented in literature ([34–38]) to generate a rough technical mitigation potential by country. EU emissions were derived by summing the mitigation potential of all EU countries by category. Categories and numbers are presented in Table S4.

Table S4. Country/regional level mitigation potential in MtCO₂e/yr in the top 25 countries, from Griscom et al., 2017 and calculations from FAOSTAT 2017. The categories used for country-level mitigation potential in Figure 5 are highlighted in grey. Estimates of mitigation potential for enteric fermentation, manure management, and synthetic fertilizer were calculated from country-level FAOSTAT emissions data. We derived mitigation potential by multiplying acceptable % emissions reductions from the literature with the emissions data. For enteric fermentation, 40% emissions reductions are for extensive pasture-based systems in developing and emerging countries and 10% are for more intensive systems in developed countries.

FAOSTAT					**Griscom et al., 2017**											**FAOSTAT croplands + Griscom pasture mgmt**
	30%	40% /10%	70%	30%												
	Cropland mgmt	Enteric fermentation	Manure mgmt	Synthetic fertilizer	Reduced deforestation	Avoided wood fuel	A/R	Forest mgmt	Grazing-Optimal Intensity	Grazing-Legumes	Pasture mgmt (optimal intensity + legumes)	Rice cultivation	Peatland restoration	Reduced conversion of peatlands	Reduced coastal conversion	Agriculture soil carbon sequestration
Brazil	6.55	105.63	7.66	7.81	990.23	25.12	1549.72	121.39	10.52	0.23	10.75	4.38	8.74	1.75	3.79	17.3
China	12.19	80.46	51.93	46.5	208.05	65.2	1256.71	35.27	25.04	19.4	44.44	51.42	36.32	42.47	0.05	56.63
Indonesia	12.28	7.95	4.88	5.56	570.24	27.42	212.02	80.25	0.24	8.58	8.82	21.56	363.85	514.24	60.2	21.11
EU	25.3	22.07	59.41	4.01	0	0	1140.28	60.75	14.19	15.37	29.56	1.9	104.94	13.86	0	54.86
India	8.8	113.72	19.93	32.66	28.55	53.88	519.47	42.58	0.93	0	0.93	69.66	1.46	0.29	2.18	9.74
Russia	6.77	14.45	7.77	2.32	0	0	351.33	245.05	0.78	0	0.78	0.33	89	2.07	0	7.55
Mexico	1.02	18.01	2.41	2.37	53.25	4.8	516.96	0	5.23	1.46	6.69	0.26	2.91	0.58	2.33	7.72
USA	12.91	12.32	30.07	23.62	0	0	357.98	65.72	13.73	13.79	27.52	2.35	17.58	3.54	3.8	40.43
Australia	17.11	19.84	3.59	2.26	0	0	385.67	60.35	8.95	2.43	11.38	0.28	2.5	0.21	0.77	28.49
Colombia	0.43	12.79	1.02	1.14	80.09	1.8	295.04	0	1.84	0.77	2.61	0.71	0.09	0.1	0.16	3.04
Myanmar	1.66	2.01	4.82	0.23	60.33	6.24	237.27	28.89	0.2	2.51	2.71	13.03	2.91	0.58	18.4	4.37
Malaysia	1.36	0.43	0.62	0.89	182.86	0.9	29.38	19.14	0	0	0	1.1	34.93	57.01	17.94	1.36
Argentina	2.72	25.16	1.32	1.51	65.68	2.13	207.41	3.08	8.27	0.77	9.04	0.34	0.07	0.05	0	11.76
Thailand	1.28	2.99	2.31	3.03	38.57	5.67	186.18	0.8	0	0.05	0.05	19.7	1.57	0.25	3.74	1.33
Venezuela	0.37	1.99	0.75	0.55	30.92	0.67	165.53	52.04	0.94	0.37	1.31	0.48	2.62	1.11	0.97	1.68
Paraguay	0.44	6.31	0.32	0.2	53.96	2.07	150.16	0	1.01	0.03	1.04	0.07	0.06	0.01	0	1.47
Vietnam	1.4	3.67	4.29	2.44	47.66	6.76	128.2	5.4	0.21	0.63	0.84	12.16	3.81	0.76	0.65	2.24

Canada	4.23	6.4	4.26	4.95	0	0	54.58	127.86	0	5.32	5.32	0	0.99	0.2	0	9.55
UK	1.14	7.96	3.44	2.03	0	0	153.05	0	1.31	8.53	9.84	0	5.76	1.15	0	10.98
DRC	4.75	0.41	0.15	0.01	130.92	0.9	35.64	0.1	0.1	0	0.1	0.34	0.01	0.01	0.05	4.85
Tanzania	2.97	7.69	0.56	0.12	33.14	8.94	66.73	55.26	0.95	0.01	0.96	1.72	0.26	0.11	0.16	3.93
Philippines	0.65	2.69	2.4	0.97	24.06	3.29	118.84	6.47	0.09	0	0.09	7.08	0.23	0.05	2.03	0.74
Bolivia	0.48	5.46	0.58	0.04	84.32	0.41	64.37	0.03	0.89	0.26	1.15	0.38	0.04	0.01	0	1.63
Cote d'Ivoire	0.46	0.58	0.1	0.06	41.07	2.95	101.23	10.72	0.26	0	0.26	0.8	0.87	0.47	0.05	0.72
Peru	0.18	4.97	0.6	0.5	64.52	1.2	32.88	45.61	0.86	0.5	1.36	0.62	0.29	0.06	0	1.54

Supply-side Measures

Reduce land use change

The overall mitigation potential for the land use change category include deforestation + coastal wetlands + savannas and natural grasslands. We do not include the estimates for degradation and reduced conversion and burning of peatlands as some deforestation estimates include degradation and peatlands.

Land conversion is the single largest source of land sector emissions, with estimates ranging between 2.3 – 5.8 Gt CO_2/yr for deforestation and 2.1 – 3.67 GtCO_2/yr for degradation[32,33,39–44]. Agriculture drives 50-80% of tropical deforestation, primarily from commodity-driven agribusiness[45]. Peatland conversion (fires and peat decomposition from drainage) account for 0.6 – 1.2 GtCO_2e/yr[46,47]. Globally, the drainage of peatlands generates 32% of cropland emissions yet only produce 1.1% of total crop calories[47]. While only 10% of peatlands are located in the tropics, they account for more than 80% of peatland soil emissions, primarily in Indonesia (~60%) and Malaysia (~10%)[46,48]. Wetlands (mangroves, tidal marshes, and seagrasses) have also been converted, with over 25-50% of wetlands lost in the last 50-100 years due to aquaculture, agriculture, industrial use, upstream dams, dredging, eutrophication of overlying waters, and urban development[49–51]. Limiting warming to 1.5°C will require a near halt of all gross deforestation and conversion by 2040.

Land can be spared and conserved through direct activities (e.g., REDD+, land planning policies, and supply chain interventions), and indirect activities (agricultural intensification to increase yields and reduce conversion pressure, reduce food waste to increase yields, and shift diets to reduce demand for commodities that cause deforestation.

Countries with the highest area of deforested lands include Brazil, Indonesia and the Democratic Republic of Congo (DRC), while countries with the highest deforestation rates include West African and Southeast Asian countries, as well as Paraguay in South America (Figure S3 - S4). Tropical peatland forests have a deforestation rate of 4% per year, significantly higher than the average rate for tropical forests at 0.5%[44,52].

The potential for reducing emissions from reducing and/or halting deforestation range between 0.4 – 5.8 Gt CO_2/yr, with the higher figure representing a complete halting of land use conversion in forests and peatlands and accounting for biomass and soil carbon[31,33,35,42,53–58]. Reducing annual emissions from peatland conversion, draining and burning would mitigate 0.45 – 1.22Gt CO_2e/yr[31,46,53], while reducing the conversion of coastal wetlands (mangroves, seagrass and marshes) would realize mitigation of 0.11 – 2.25 Gt CO_2e/yr of emissions[31,49,53,59]. These estimates represent biophysical and technical potential (higher ranges) and economic and feasible mitigation potential (lower ranges). The upper estimates reflect the theoretical avoidance of all land-use change emissions. Differences in estimates also stem from varying land cover definitions, time periods assessed, and carbon pools included (most lower estimates only include aboveground biomass, and most higher estimates include all five IPCC carbon pools: aboveground, belowground, dead wood, litter, soil, and peat).

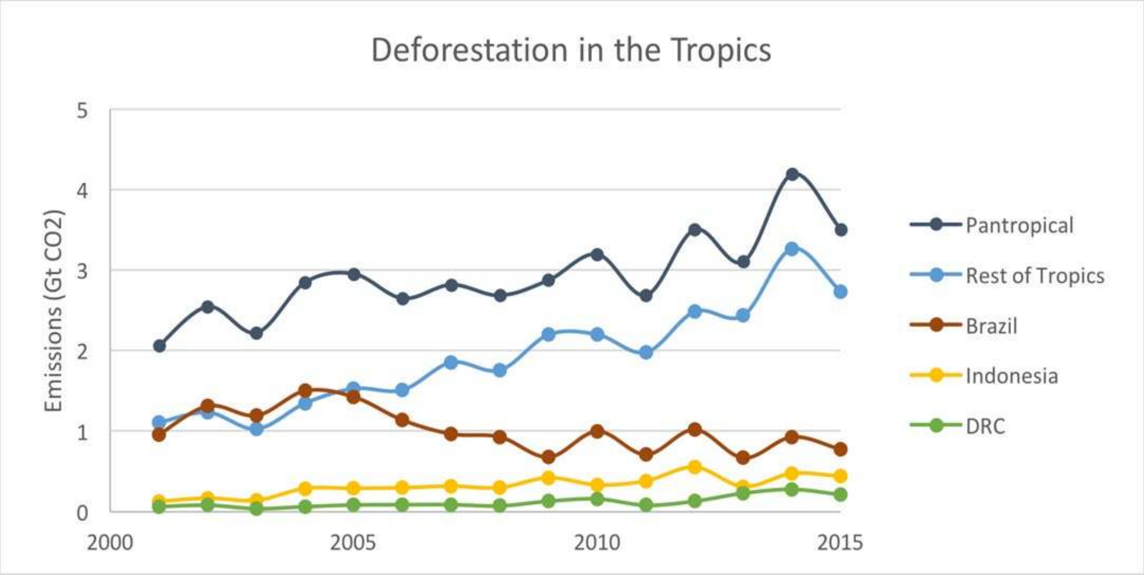

Figure S3. Trends in tree cover loss in the tropics from 2000-2015. Data source: Global Forest Watch, 2017

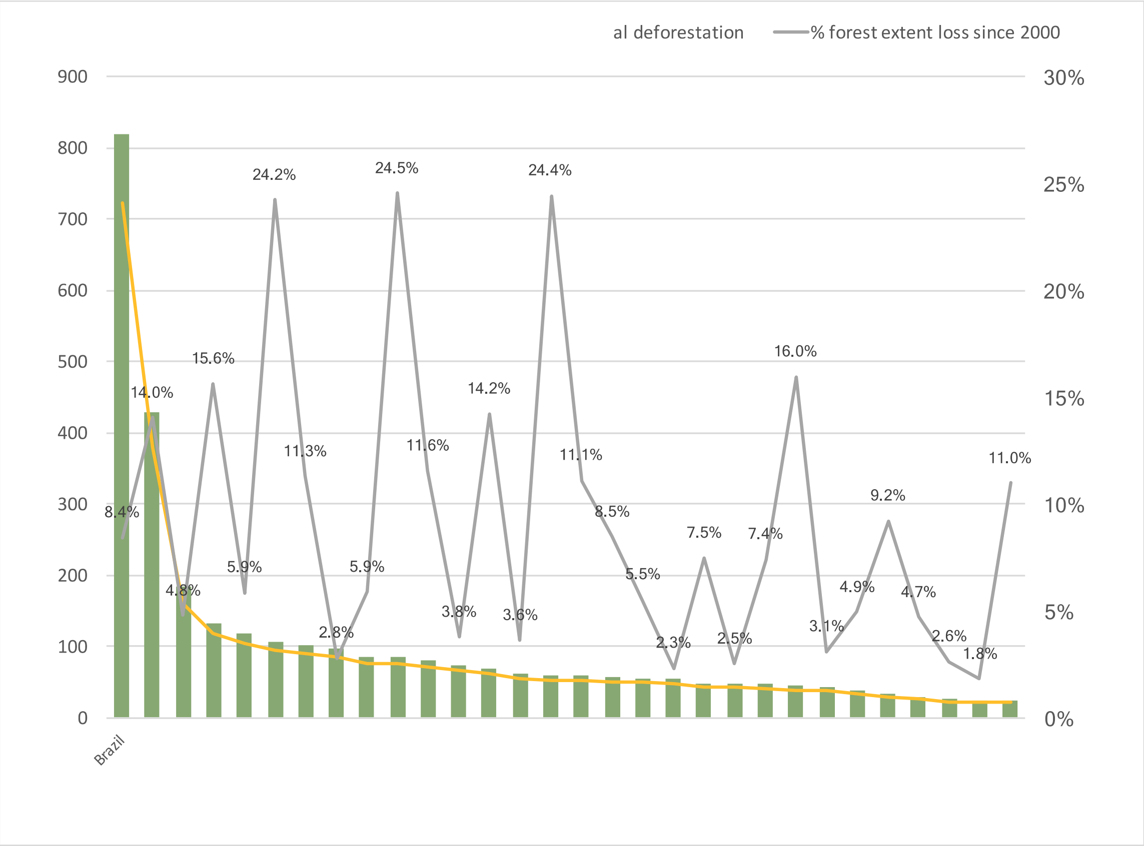

Figure S4. Land use change emissions (deforestation) in MtCO$_2$e/yr by country, in green bars, using a five-year average (2011-2015). The yellow line represents the share of total tropical deforestation by each country – it is not continuous data. The grey line represents the percent of forest extent lost in each country since 2000 – it is not continuous data. Data source: Global Forest Watch, 2017

Enhance carbon sequestration

The overall mitigation potential for the carbon sink enhancement category includes afforestation / reforestation (converting non-forest land into forests, and reforesting and restoring forests) + restoration of coastal wetlands (mangroves and marshes) + agricultural soil carbon enhancement (soil carbon sequestration in croplands and grazing lands) + biochar application. We do not include forest management (natural forest management, improved plantations, forest fire management), agroforestry and peatland restoration due to some estimate overlaps with A/R.

Increasing sequestration of vegetation and soil carbon in natural and managed systems can remove a significant amount of carbon emissions in the atmosphere. Currently, the terrestrial carbon sink removes 30% of anthropogenic emissions[60]. Land-based activities that could sequester additional carbon include A/R, forest management, agroforestry, peatland restoration, coastal wetland restoration, agricultural soil carbon enhancement, biochar, harvested wood products and bioenergy with carbon capture and storage (BECCS).

Afforestation, the conversion of non-forested land into forests, and reforestation, restoring and replanting deforested or degraded forests, can increase carbon sequestration in both vegetation and soils by 0.5 – 10.12 Gt CO_2/yr[31,53,54,56,61–68]. The lower estimate represents the lowest range from an earth system model[66] and of sustainable global negative emissions potential[63], and the higher estimate[31] reforests all areas where forests are the native cover type, constrained by food security and biodiversity considerations. Recent mitigation potential estimates for A/R provide "plausible" figures of 3.04 $GtCO_2$/yr by 2030 with environmental, social and economic constraints (<\$100/tCO_2)[31], and 3.64 $GtCO_2$/yr between 2020-2050 based on a conservative scenario of restoration commitments and smaller scale afforestation[53]. The annual reforestation in 2015 was reported at 27 Mha, and countries have committed to restore another 161 Mha of forests by 2030 led by China, Brazil, India and the US[69,70].

Improving forest management includes extending rotation cycles between harvests, reducing damage to remaining trees when harvesting, reducing logging waste, implementing soil conservation practices, fertilization, and using wood more efficiently. Forest management could potentially mitigate 0.44 – 2.1 Gt CO_2/yr[31,71,72], where the low estimate is the "low cost" (<\$10/tCO_2) implementation of natural forest management and improving plantations[31] and the upper estimate represents switching from conventional logging to reduced-impact logging practices[72]. A new study asserts that Climate Smart Forestry, a technique addressing the ecosystem, wood products and the energy supply chain in Europe, could double the forest management climate mitigation potential by 2050[73].

Agroforestry is a land management system that combines woody biomass (e.g., trees or shrubs) with crops and/or livestock, and can include fruit or timber trees for harvest, windbreaks, riparian buffers, and silvopasture. Agroforestry systems have a long tradition in temperate regions around the world and have also been developed as a land management practice in many developing countries, particularly for smallholder systems. The mitigation potential ranges between 0.11 – 5.68 Gt CO_2/yr[31,36,53,74], where the low estimate represents a conservative adoption of agroforestry practices in mixed crop-livestock systems in humid and tropical highland areas of the developing world, and the high estimate represents the "optimum" implementation scenario of "silvopasture" + "tree intercropping" + "multistrata agroforesty" + "tropical staple trees."[53]

Wetland and peatland restoration includes rewetting peat soils and replanting peatland and mangrove vegetation. Approximately 0.6 Gt CO_2/yr can be mitigated if 30% of the 65 Mha of drained peatlands were rewetted to stop continued emissions from carbon oxidation, and about 3.2 Gt CO_2/yr if all ongoing CO_2 emissions from continued peat oxidation were ceased[75,76]. The mitigation potential range is between 0.15 – 0.81 Gt CO_2/yr from studies since 2010[31,75], where the lower estimate represents "low cost" (<\$10/tCO_2) restoration[31] and the higher estimate represents biophysical potential constrained by food security and environmental considerations[31]. Mangrove restoration can mitigate the release of 0.20 Gt CO_2/yr through "cost effective" (<\$100/tCO_2) restoration[31] and 0.84 Gt CO_2/yr from biomass and soil enhancement[31]. Peatland restoration, as well as agroforestry and forest management mitigation potential are included in some of the A/R estimates and are therefore not added to the total terrestrial carbon enhancement mitigation potential.

Sequestering carbon in agricultural systems through regenerative and conservation agriculture practices (including use of perennials or deeper rooted cultivars, reduced tillage, crop residue management, organic amendment and fire management), and grazingland management (including managing stocking rates, timing and rotation of livestock, higher productivity grass species or legumes, and nutrient management) have considerable mitigation potential. Soil carbon sequestration (SCS) in croplands have a potential range of 0.25 – 6.78 Gt CO_2/yr[14,31,36,38,53,77–82], where the low estimate is the "low cost" (<\$10/tCO_2) implementation of conservation agriculture[31], and the high estimate is the increase of soil organic carbon in 0-30 cm of all cropland soils from 0.27% to 0.54%[83]. The SCS potential in grazing lands is 0.13 – 2.56 CO_2/yr[14,31,53,61,77,78,80,82–86], where the low estimate is the "low cost" (<\$10/tCO_2) implementation of "grazing - optimal intensity" + "grazing - legumes in pasture" and "fire management in savannas" [31], and the high estimate is a maximum biophysical potential[80]. Storing carbon by converting biomass into recalcitrant biochar to use for soil amendment also has the potential to mitigate 0.030 – 6.6 Gt CO_2/yr[31,36,53,62,63,68,77,84,87–90]. The higher end of the estimate assumes bioenergy crops can be used to make biochar and includes syn-gas production as offsetting fossil fuel usage[90], while the lower estimate uses a fraction of available residues only (no purpose grown crops)[53]. While soil carbon and biochar have large mitigation potential, there continues to be a great deal of uncertainty in the science of soil carbon, specifically on issues of storage capacity and permanence[77,84]. Levels of carbon in the soil, as well as biomass, trend towards a new equilibrium level, meaning that sequestration rates steadily drop to negligible levels over the course of several decades for most soils[91]. In the future, that carbon can also be released back into the atmosphere depending on the crop management practice and climatic conditions. Additionally, there is great inconsistency in observed carbon sequestration rates from different management practices (particularly on tillage), primarily due to variety of environmental factors including soil type, moisture, temperature, microbial and fungi composition, nutrient availability[92], and the particulars of how the management is actually applied.

Carbon can also be removed through technologies that use land such as bioenergy with carbon capture and storage (BECCS). Biomass used for BECCS (trees, energy crops and residues) sequester carbon as they grow, the biomass is then processed in plants to produce energy, and finally the CO_2 is stored in geological reservoirs to produce net negative emissions. The mitigation potential is estimated to be approximately 0.4 – 11.3 Gt CO_2/yr in 2050[61–63,68,89,93,94]. The low estimate only uses available residues[93] and the high estimate is the upper range from a modelling study[89]. BECCS is included in our mitigation potential estimate, however, it is important to note that BECCS deployment is still in the development, exploration, and piloting stages.

Reduce direct agricultural emissions

The overall mitigation potential for the agriculture category includes all direct CH_4 and N_2O emissions: CH_4 and N_2O from manure management, N_2O emissions from cropland nutrient management and manure on pasture, CH_4 emissions from rice cultivation and enteric fermentation, and all emissions from synthetic fertilizer production. We do not include cropland and pastureland management as they are accounted for in the soil carbon enhancement category.

Sustainable intensification reduces the emissions intensity of agriculture by using inputs more efficiently or adding new inputs that address limiting factors of production. These practices are typically based on changes or increases in the use of direct inputs, such as improved varieties/breeds, nutrient and organic amendments, water and mechanization. In addition, a variety of farming practices can be adopted that optimize density, rotations and precision of inputs.

Reducing emissions intensity from agriculture: cropland nutrient managagement, enteric fermentation, manure management, rice cultivation and fertilizer production has a total mitigation potential of 0.30 – 3.38 Gt CO_2/yr (Figure 4). The mitigation potential of cropland nutrient management (fertilizer application) 0.03 – 0.71 Gt CO_2/yr[25,31,36,53,77], and manure on pasture is 0.01 Gt CO_2/yr[37].

Enteric fermentation is responsible for over 40% of direct agricultural emissions with beef and dairy cattle accounting for approximately 65%[38]. The three main measures to reduce enteric fermentation include improved diets (higher quality, more digestible livestock feed), supplements and additives (reduce methane by changing the microbiology of the rumen), and animal management and breeding (improve husbandry practices and genetics)[36]. Applying these measures can mitigate 0.12 – 1.18 Gt CO_2/yr[31,34,36,38]. Most livestock production systems in highly developed countries (e.g., the U.S., E.U., Australia, and Canada) have intensified systems and thus have lower mitigation potential per unit compared to developing countries with large livestock herds managed at low productivity levels, suboptimal diets, nutrition and herd structure (e.g., India, Latin America and Sub-Saharan Africa). These developing countries have higher mitigation potential gains from sustainable intensification.

Manure from livestock cause both nitrous oxide and methane emissions, and account for roughly one quarter of direct agricultural GHG emissions[36]. Although stored manure accounts for a relatively small amount of direct agricultural emissions, it is technically possible to mitigate a high percentage of these emissions (as much as 70% for most systems)[34,36]. The mitigation potential ranges from 0.01 – 0.26 Gt CO2/yr[36,38]. The highest manure management emissions come from China, India, the US and the EU (Figure S6). Measures to manage manure include anaerobic digestion for energy use, composting as a nutrient source, reducing storage time, and changing livestock diets. Improved manure management practices have important co-benefits including reducing water and air pollution, and increased yields and income from nutrient and energy inputs produced.

Rice production contributes about 11% of emissions from agriculture and 90% of this is from Asia[95]. The top rice producing countries—China, India, Indonesia, Thailand, Philippines, Vietnam Bangladesh, and Myanmar—account for more than 85% of global rice emissions (Figure S5). Reducing emissions from rice production through improved water management (periodic draining of flooded fields to reduce methane emissions from anaerobic decomposition), and straw residue management (apply in dry conditions instead of on flooded fields, avoid burning to reduce methane and nitrous oxide emissions) has the potential to mitigate up to 60% of emissions[96] or 0.08 – 0.87 Gt CO_2/yr[25,31,36,53,77,96]. While well managed rice fields can increase yields and reduce water needs, correct management of water levels requires precise control of irrigated systems and high technical capacity that may present barriers to adoption[36].

Synthetic fertilizer production is a major source of GHG emissions and air pollution as it requires a large amount of energy to produce and uses fossil fuels (natural gas or coal) as feedstocks. China has the largest emissions from synthetic fertilizer production as they have older, less efficient plants and use coal feedstocks[36]. Improvements in industrial efficiency are typically cost effective, would improve the productivity of the sector, reduce pollution, and have the potential to mitigate 0.05 to 0.36 Gt CO_2e/yr in China (there are no global estimates)[36,97].

Efficiency improvements from sustainable intensification generally produce productivity gains and improve farmers' livelihoods, especially smallholders. If managed well, intensification can also spare land/avoid land conversion because greater agricultural production occurs on the same area of land. However, efficiency improvements also carry the risk of environmental and social trade-offs that need to be managed. Intensification will likely produce an increase in fertilizer use and other agrochemicals which may increase emissions and pollution. Further, more efficient production methods can reduce costs and increase yields, and therefore, may encourage farmers to further increase production and expand land use (deforest)[98]. Sustainable intensification will need to go hand in hand with improved land-use planning, environmental safeguards and standards, and law enforcement to avoid these negative impacts.

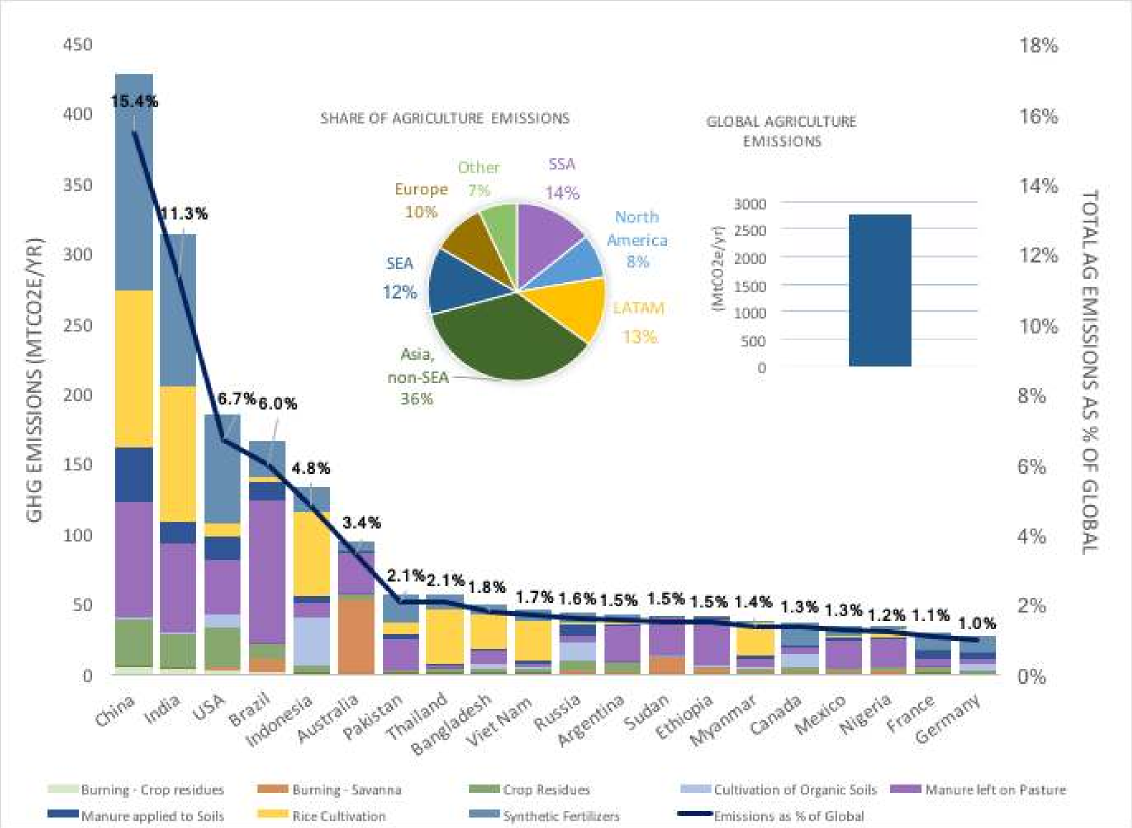

Figure S5. Agriculture emissions (crops and soils) in $MtCO_2e$/yr by country and region, using a five-year average (2010-2014). The blue line represents share of global emissions by country – data is not continuous. Data source: FAOSTAT, 2015

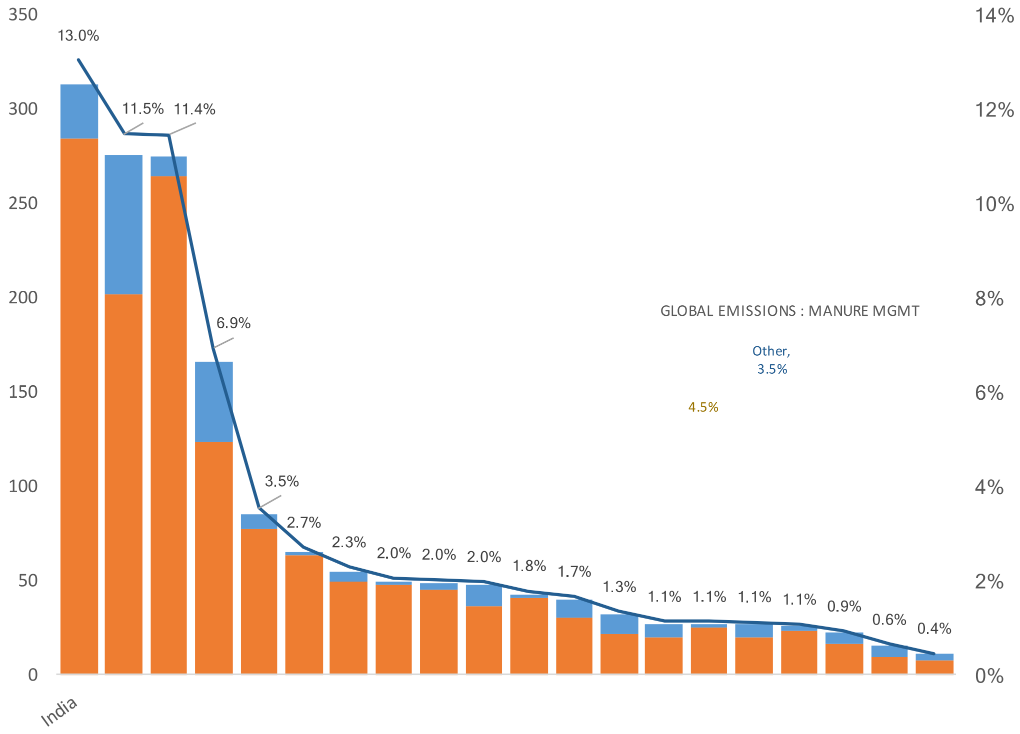

Figure S6. Livestock emissions (enteric fermentation in orange and manure management in blue) in MtCO$_2$e/yr by country and region, using a five-year average (2010-2014). The blue line represents share of global emissions by country – data is not continuous. Data source: FAOSTAT, 2015

Demand-side Measures

The overall mitigation potential for the demand-side measures includes diet shifts + food waste + demand for wood products + demand for wood fuel. We provide separate estimates for total supply-side and demand-side measures as these two categories are not additive.

Demand-side measures reduce GHG emissions by cutting down the overall level of production and increasing the efficiency of high emission intensity products, thus sparing land and decreasing direct agriculture emissions. Most of the impacts from demand-side interventions are therefore generally positive as they reduce competition and pressure on land, water and other inputs in contrast to supply-side measures that require more land and/or more inputs[35].

The discussion on food security and agriculture mitigation over the last two decades has almost exclusively focused on ways to increase productivity and reduce net GHGs emissions from production – i.e., the supply side. However, as the global population grows and incomes rise, the demand-side of the equation will become more important, including which products are consumed, how much is consumed, and how much food is wasted. Demand-side measures have the potential to significantly mitigate emissions of 1.81 – 14.31 Gt CO$_2$e/yr from reductions in food loss and waste (food wastage), changes in diets, the substitution of wood for cement and steel in construction, and the use of cleaner cookstoves. Approximately 55% of the upper bound of this estimate comes from changes in diet, and another 30% comes from reductions in food wastage.

Shifting away from emissions-intensive foods like beef delivers a substantial mitigation potential of 0.7 – 8 Gt CO_2e/yr[35,36,38,53,99–102], with the high estimate representing a vegan diet[99]. The production of beef produces the highest GHG, water, land, and energy footprint of all proteins – approximately 10 times higher in GHG emissions than any other animal protein (dairy cattle, pigs, chicken)[36,45,100]. Countries with the highest overall and projected beef consumption include predominantly developed and emerging countries: US, EU, China, Brazil, Argentina, Russia (Figure S7). A recent study finds "plausible" mitigation potential of 2.2 GtCO_2e/yr (0.9 GtCO_2e/yr without land-use change impacts) if 50% of the global population adopted "plant-based diets" constrained to 2500 kilocalories/ person/day and 57g of meat protein per day[53]. In addition to reduced emissions, shifting diets has the potential to deliver additional environmental, health and economic co-benefits. Decreasing meat consumption, primarily of ruminants, reduces water use, soil degradation, pressure on forests, and manure and pollution into water systems[36]. Reducing the amount of land and grains used for livestock could also increase food supply by 50% by freeing available resources[103]. Given the established links between diet-related diseases and high levels of meat consumption, keeping global average per capita meat consumption at healthy levels will also have important health benefits (reduced risks of cardiovascular diseases, cancer, stoke and diabetes)[99].

Reducing food losses and waste increases the overall efficiency of food value chains, reduces land pressure, and could contribute to reducing 0.76 – 4.5 of CO2e/year[36,53,101]. A recent study finds "plausible" mitigation potential of 2.4 GtCO_2e/yr (0.9 GtCO_2e/yr without land-use change impacts) if food waste is reduced by 50% in 2050[53]. In the developing world, losses mainly occur postharvest as a result of financial and technical limitations in production techniques, storage and transport[104] (Figure S8). In contrast, losses in the developed world are mostly incurred by end consumers[104]. The highest overall food waste occurs in China, the US and the EU, while the highest food losses occur primarily in Southeast Asia and Sub-Saharan Africa. When considering per capita waste and losses however, the US is almost double that of the EU and China. Strategies to reduce food loss and waste include improving harvesting, handling and storage techniques for the downstream losses, and consumer awareness campaigns and policies for the upstream food waste. Cutting current food loss and waste levels in half has the potential to close the 70% gap of food needed to meet 2050 demand by roughly 22%, potentially making the reduction of food wastage a leading strategy in achieving global food security[104]. As food wastage is a by-product of inefficiency, the negative trade-offs are limited and there are vast opportunities for savings along the entire supply chain.

Increasing demand of wood products in construction to substitute more GHG intensive materials like cement and steel could also present an opportunity for emissions reductions. Pathways to reduce emissions include increasing carbon storage in harvested wood products (HWP) and avoiding emissions from the production of concrete and steel[105,106]. Various studies have calculated the displacement factor, or the substitution benefit in CO_2, when wood is used instead of another material – with a range of -2.3 to 15 tC of emission reduction per tC in wood product and a mode range of 1.0 to 3.0 tC[105]. Displacement factors, as well as calculations of carbon storage from HWPs have been used to calculate mitigation potential of wood substitution in various countries including Canada[106], the EU[107], Japan[108] and the US[109]. However, there are limited estimates of global mitigation potential from increasing the demand of timber products to replace construction materials, as well as their potential risks and co-benefits. The range of 0.25

– 1.0 $GtCO_2$ of mitigation potential[61,110] is relatively small compared to other demand-side measures. There is concern that increased demand for wood products may reduce forest stocks and have other environmental risks, however studies have shown that increased wood demand led to higher wood prices and investments in forest management in some parts of Europe, China and New Zealand[19,73,111]. Additional studies are needed to better understand the global dynamics (GHG emissions, trade, deforestation impacts) of increasing wood products in construction.

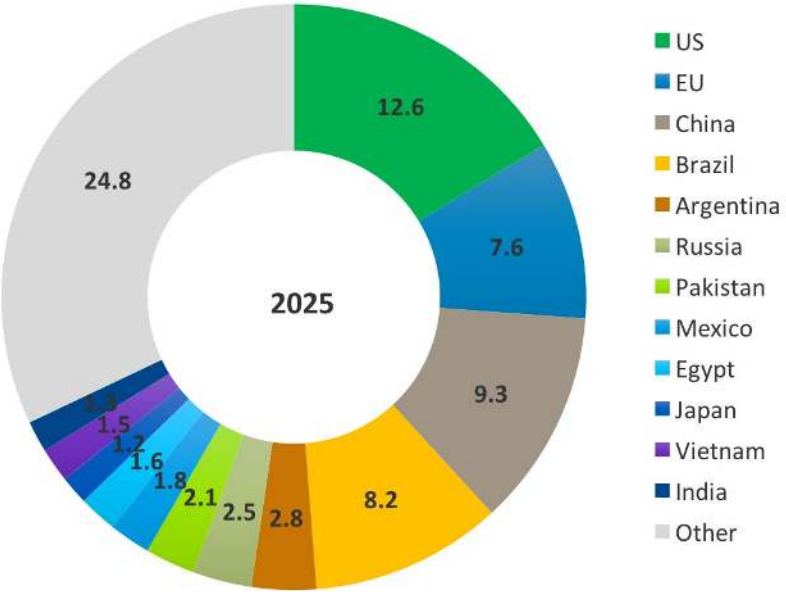

Figure S7. Beef consumption projected by 2025 in total tons of kcal by country. Data source: FAOSTAT, 2015

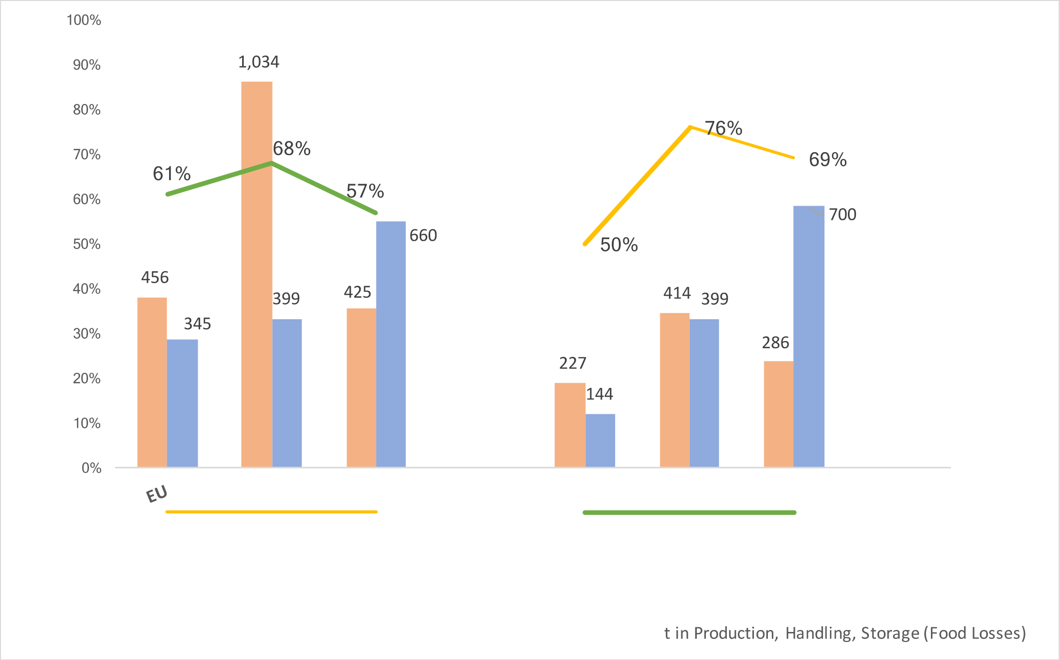

Figure S8. Food loss and food waste in Kcal/capita/day by region. Data source: World Resources Institute, 2014

SECTION 4. Roadmap of priority mitigation wedges for the land sector to 2050

We developed a roadmap of priority activities and geographies to deliver on the 1.5°C temperature goal, drawing upon our modelled pathways and the bottom-up mitigation potential assessment. Drawing upon the median top down modelling (13.5 $GtCO_2e/yr$) and bottom up literature review (14.6 $GtCO_2e/yr$) estimates, we established a viable mitigation target (sum of emission reductions and removals) for the land sector of ~14 $GtCO_2e/yr$ (15 $GtCO_2e/yr$ with BECCS) in 2050. We then divided the mitigation effort into eight priority mitigation measures, or "wedges"[112]. The wedges incorporate activity types from all four main mitigation categories: reduced land-use change, reduced agricultural emissions, reduced overall production through demand shifts, and carbon removal through enhanced carbon sinks. The amount of mitigation for the individual wedges were determined by first qualitatively weighing associated risks and co-benefits (Table S6), and then identifying feasible estimates (plausible, cost effective, sustainable, desirable) in the bottom-up assessment of the literature (Table S5). Given the strong interaction effects of land-based mitigation activities on each other (e.g. land competition, prices, yields), on ecosystem services (e.g. water, air and biodiversity) and on biophysical impacts (e.g. radiative cooling/warming and albedo), we prioritized measures that minimize risks, maximize co-benefits and overlap with Sustainable Development Goals, the New York Declaration on Forests (NYDF) and United Nations Convention on Biological Diversity (UNCBD), Aichi Targets (Table S6). The wedges are measures which are individually accounted for with the intent of avoiding double counting of emissions reductions so that the measures are additive (Table S5, described in activity types and source).

To assess for relative cost, we compared our priority wedges and mitigation trajectories to our modelled results. For each wedge, we then disaggregated action into geographies, prioritizing countries/regions according to their mitigation potential (Section 3 above, Table S4, Figures S7 and S8), and constrained by our political feasibility assessment as outlined in the next section.

Table S5. Priority mitigation measures ("wedges) in 2050 Land Sector Roadmap. Includes activity types, GHG mitigation potential, and related source and rationale for mitigation estimate.

	Mitigation wedge	Activity types	Mitigation potential	Source
Land-use change	Reduce deforestation and degradation, conversion of coastal wetlands, and peatland burning	Conservation policies, establishment of protected areas, law enforcement, improved land tenure, REDD+, sustainable commodity production, improved supply chain transparency, procurement policies, commodity certification, cleaner cookstoves	4.6 GtCO$_2$e/yr: 3.6 from deforestation 0.7 from conversion of peatlands 0.3 from coastal wetlands	"Maximum additional" mitigation potential by 2030 from Griscom et al. (2017)[31]. Estimate is constrained to be consistent with meeting human needs for food and fiber,
Agriculture	Agriculture	Reduce CH4 and N2O emissions from enteric fermentation, fertilizer management, synthetic fertilizer production, water and residue management of rice fields, and manure management	1.0 GtCO$_2$e/yr	"Needed mitigation" from Wollenberg et al. (2017)[113] and "feasible mitigation at \$25/tCO$_2$e" from Frank et al. (2017)[14]
Demand shifts	Shift to plant-based diets	Reduce production of high GHG intensive foods through public health policies, consumer campaigns, development of novel foods	0.9 GtCO$_2$e/yr	"Plausible scenario" from Hawken (2017)[53] where 50% of the global population will adopt a plant-rich diet by 2050 (criteria: 2500 kilocalories/ person/day; Meat constrained to 57 grams per day; Purchasing locally produced food when possible) by 2050. Estimate only reflects emissions reductions from diverted agricultural production, and not from avoided land use change.
	Reduce food waste	Reduce food waste: consumer campaigns, private sector policies, supply chain technology, improved food labelling, waste to biogas Reduce food loss: improve handling & storage practices through training, investment and technology	0.9 GtCO$_2$e/yr	"Plausible scenario" from Hawken (2017)[53] where 50% reduction in total global food loss and wastage is achieved by 2050. Estimate only reflects emissions reductions from diverted agricultural production, and not from avoided land use change.
Carbon enhancement	Restore forests, coastal wetlands and drained peatlands	Investment in restoration, national and local policies, payment for ecosystem services, integration of agroforestry into agricultural and grazing lands	3.6 GtCO$_2$/yr: 3.0 from reforestation 0.4 from peatland restoration 0.2 from coastal wetland restoration	"Cost effective" mitigation at <\$100/tCO$_2$ in 2030 from Griscom et al. (2017)[31]. Estimate is constrained to be consistent with meeting human needs for food and fiber, and avoiding negative impacts to biodiversity (no establishment of forests where they are not the native cover type),
	Improve forest management and agroforestry	Optimizing rotation lengths and biomass stocks, reduced-impact logging, improved plantations, forest fire management, certification, integration of agroforestry into agricultural and grazing lands	1.6 GtCO$_2$/yr: 0.9 from natural forest management 0.3 from improved plantations 0.4 from trees in croplands	"Cost effective" mitigation at <\$100/tCO$_2$ in 2030 from Griscom et al. (2017)[31]. Estimate is constrained to be consistent with meeting human needs for food and fiber, and avoiding negative impacts to biodiversity.
	Enhance soil carbon sequestration in agriculture and apply biochar	Erosion control, use of larger root plants, reduced tillage, cover cropping, restoration of degraded soils, biochar amendments	1.3 GtCO$_2$/yr: 0.8 from agriculture soil carbon enhancement 0.5 from biochar	"Plausible scenario" from Hawken (2017)[53] adopting regenerative agriculture practices on 407Mha by 2050 to sequester carbon. To be conservative, mitigation potential of other SCS activities from Hawken (2017) is excluded. "Sustainable global NET potential" of biochar from Fuss (2018)[63]. Lowest estimate in the range of 0.5-2 GtCO$_2$/yr
	Deploy BECCS	R&D, investment and deployment	1.1 GtCO$_2$/yr	Mitigation potential of "sustainably harvestable" biomass for BECCS on "marginal land" overlapping CO$_2$ storage basins, from Turner et al. (2018)[93]

Table S6. 2050 Land Sector Roadmap priority mitigation measures (“wedges) and their related risks, co-benefits, and alignment to international policies and commitments.

			Co-benefits[31,36,63,114]						**International policies and commitments**		
	Mitigation wedge	**Risks** [36,63,114]	Biodiversity	Water (filtration, flood control, reduced pollution)	Soil (fertility, water retention, reduced erosion)	Air (filtration, reduced pollution)	Food security (increased yields, available land)	Livelihoods (incomes, jobs)	Sustainable Development Goals (SDGs)[115]	New York Declaration on Forests (NYDF)	United Nations Convention on Biological Diversity (UNCBD), Aichi Targets
Land-use change	Reduce deforestation and degradation, conversion of coastal wetlands, and peatland burning	Potentially impact farming practices and development	✓	✓	✓	✓	✓	✓	Goal 14.5 By 2020, conserve at least 10 per cent of coastal and marine areas... Goal 15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands... Goal 15.2 By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally	Goal 1: "…halve rate of loss of natural forests globally by 2020…end natural forest loss by 2030"	Target 5: "By 2020, rate of loss of all natural habitats… is at least halved…and degradation and fragmentation is significantly reduced"
Agriculture	Agriculture	Technology and capacity needs for farmers; Potential to reduce yields depending on mgmt; Interventions can be costly		✓	✓	✓	✓	✓	Goal 2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change... and that progressively improve land and soil quality Goal 14.1 By 2025, prevent and significantly reduce marine pollution...in particular from land-based activities, including...nutrient pollution		

Demand shifts	Shift to plant-based diets	Shift to unsustainable fisheries; Potentially reduce farmer incomes	✓	✓	✓	✓	✓		Goal 12. Ensure sustainable consumption and production patterns Goal 12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature Goal 2.4 (see above)		
	Reduce food waste	Short-term profit shortfalls for retailers	✓	✓	✓	✓	✓	✓	Goal 12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses		
Carbon enhancement	Restore forests, coastal wetlands and drained peatlands	Land requirements; Net-positive warming effect from albedo in high latitudes; Permanence; Possible nutrient and water requirements	✓	✓	✓	✓	✓	✓	Goal 6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes Goal 15.1 (see above) Goal 15.2 (see above)	Goal 5: "Restore 150 million hectares of degraded landscapes and forestlands by 2020…an additional 200 million hectares by 2030"	Target 15: "By 2020… restoration of at least 15% of degraded ecosystems"
	Improve forest management and agroforestry	Land requirements; Net-positive warming effect from albedo in high latitudes; Permanence; Possible nutrient and water requirements	✓	✓		✓		✓	Goal 15.2 (see above)		
	Enhance soil carbon sequestration in agriculture and apply biochar	Permanence; Competition for biomass resources in biochar	✓	✓	✓	✓	✓	✓	Goal 2.4 (see above)		
	Deploy BECCS	Land competition; Natural ecosystem conversion; Biodiversity losses; Nutrient and water requirements; Reduce mitigation ambition						✓	Goal 15.2 (see above)		

__Political feasibility assessment__

We conducted a political feasibility assessment based on two main criteria: 1) The political will to realize mitigation potentials and 2) The ability to implement mitigation policies. As a proxy (indicator) for political will, we analysed the land-sector goals included by countries in their NDCs (Nationally Determined Contributions) submitted to the UNFCCC secretariat. We assessed NDCs according to the following categories:

a. Specified activities, policies and measures for the land-use sector (2 points);
b. Specified land-use targets that are quantifiable in terms of emissions reductions (4 points);
c. Specified economy-wide targets that include land use and are quantifiable in terms of emissions reductions (6 points).

Countries were assigned scores according to the category they fall into (Figure S9). NDCs that achieved the highest score contained quantifiable measures that were economy-wide. Countries with specified and quantifiable targets for the land-use sector scored slightly lower, while lowest scores were assigned to NDCs that communicate non-quantifiable activities or measures. Subtractions were made if emissions reductions targets were made relative to projected business-as-usual scenarios (-2 points) or if made contingent upon the provision of international climate finance (-1 point).

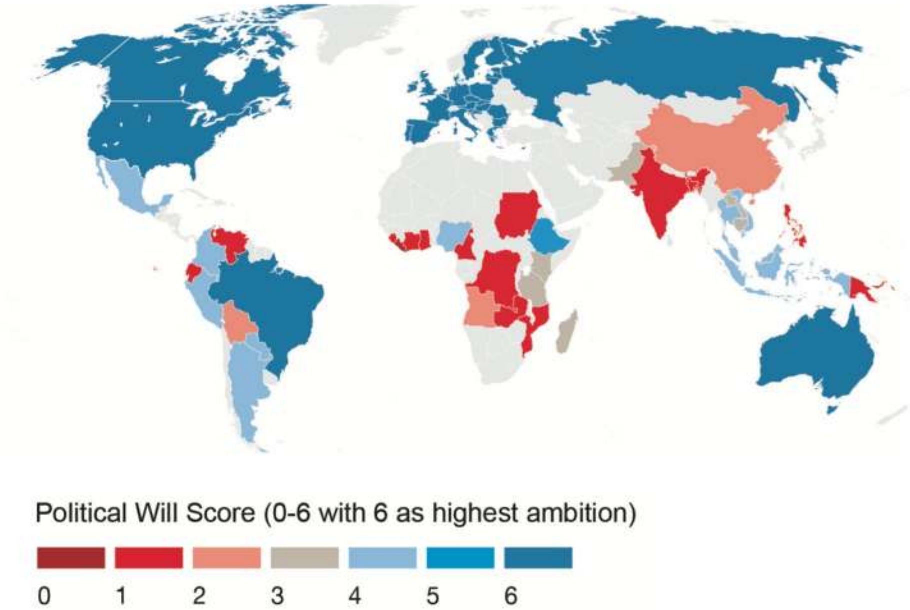

Figure S9. Political will of top 40 emitting countries including the European Union which submitted a regional NDC. Scores are based on current NDCs and not political declarations or elections. Data source: UNFCCC submissions

To gauge the ability of countries to implement mitigation policies, we used (a) governance indicators; and (b) access to finance as indicators. For governance, we used six of the World Bank governance indicators (government effectiveness, regulatory quality, rule of law, political stability, control of corruption, and voice and accountability), and averaged the rankings to create a governance score for each country (Figure S10). For access to finance, we used GDP per capita of a country to serve as proxy (indicator), differentiating countries along four World Bank income categories: low income, lower middle, upper middle, and high income (Figure S11).

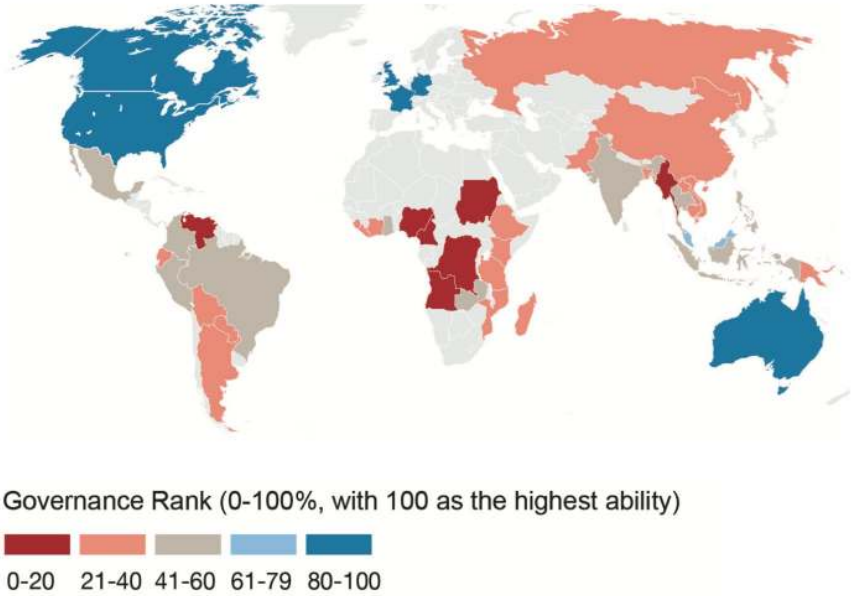

Figure 10. Governance rank of top 40 emitting countries. Data source: World Bank governance indicators, 2014 (government effectiveness, regulatory quality, rule of law, political stability, control of corruption, and voice and accountability)

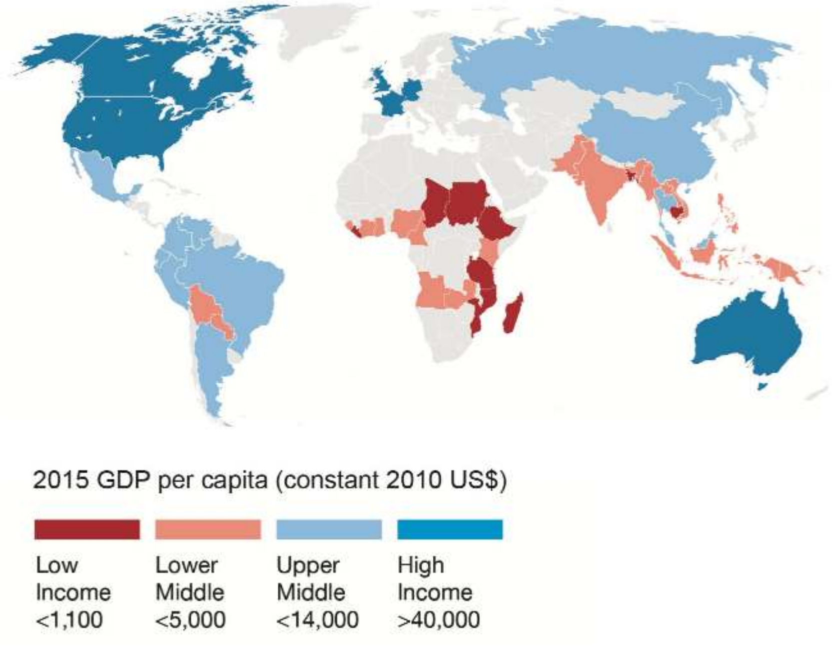

Figure S11. GDP per capita of top 40 emitting countries. Data source: World Bank, 2014

Geographic priorities

Considering the technical mitigation potential as well as feasibility of action, countries can be grouped according to their impact, ability to act, and need for support and assistance. The countries below are listed according to their technical potential.

- High-income and capacity countries with large mitigation potential (210-1500 $MtCO_2e/yr$) that need early aggressive action: the EU, the US, Australia, and Canada. Main areas of action include A/R and restoration, forest management, diet shifts, reduced food waste, reduced enteric fermentation, and improved crop-land management and soil carbon restoration, fertilizer use, and synthetic fertilizer production.
- Upper-middle-income countries that have high mitigation potential (700-1800 $MtCO_2e/yr$) also need early and aggressive action: Brazil, China and Russia. Main areas of action include A/R, and restoration, forest management, diet shifts, reduced food waste, reduced enteric fermentation, and improved crop-land management and soil carbon restoration, fertilizer use, and synthetic fertilizer production. Deforestation emissions in Brazil, peatland restoration in Russia and rice paddy emissions in China are also of priority.
- Lower-middle income countries with less financial and governance capacity (will require high levels of assistance) and have high mitigation potential (800-1800 $MtCO_2e/yr$) need to act by 2025-2030: Indonesia and India. Reduced deforestation, peatland and coastal wetland conversion, A/R and restoration, forest management, food loss and soil carbon enhancement are important actions in Indonesia, while A/R and restoration, enteric fermentation, food loss, synthetic fertilizer production, manure management and rice paddy emissions are priorities for India.
- Other upper-middle-income countries that have important mitigation potential (150-600 $MtCO_2e/yr$) need to act by 2020-2025: Mexico Colombia, Malaysia, Argentina, Thailand, Venezuela, and Peru. Main areas of action include A/R and restoration, reduced deforestation, peatland and coastal wetland conversion, forest management, food loss and soil carbon enhancement. Enteric fermentation is important in Latin American countries, and rice paddy emissions are important in Asian countries.
- Other low and lower-middle income countries requiring high levels of assistance with important mitigation potential (150-380 $MtCO_2e/yr$) need to act by 2030: Myanmar, Paraguay, Vietnam, the Democratic Republic of Congo, Tanzania, Philippines, Bolivia, Cote d'Ivoire. Main activities are the same as the previous bullet.

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