nature climate change

REVIEW ARTICLE
https://doi.org/10.1038/s41558-019-0591-9

Contribution of the land sector to a 1.5 °C world

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The Paris Agreement introduced an ambitious goal of limiting warming to 1.5 °C above pre-industrial levels. Here we combine a review of modelled pathways and literature on mitigation strategies, and 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 and deploying measures in agriculture, forestry, wetlands and bioenergy could feasibly and sustainably contribute about 30%, or 15 billion tonnes of carbon dioxide equivalent ($GtCO_2e$) per year, of the global mitigation needed in 2050 to deliver on the 1.5 °C target, but it will require substantially more effort than the 2 °C target. Risks and barriers must be addressed and incentives will be necessary to scale up mitigation while maximizing sustainable development, food security and environmental co-benefits.

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 $GtCO_2e$ (about 25%) of net anthropogenic greenhouse gas (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]. Although the AFOLU sector generates considerable emissions, the residual terrestrial sink (accumulation of carbon in the terrestrial biosphere excluding land sinks from LULUCF) also currently sequesters about 30% of annual anthropogenic emissions, making land vitally important for generating 'negative emissions' — that is, 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 important 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 globally in 2030[9,10]. Land-based mitigation measures largely fall into four categories: reduced land-use change, CDR 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, yet none mentioned demand-side shifts. As countries submit new or revised NDCs by 2020 and prioritize 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 environmental and social 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).

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 $W\ m^{-2}$)

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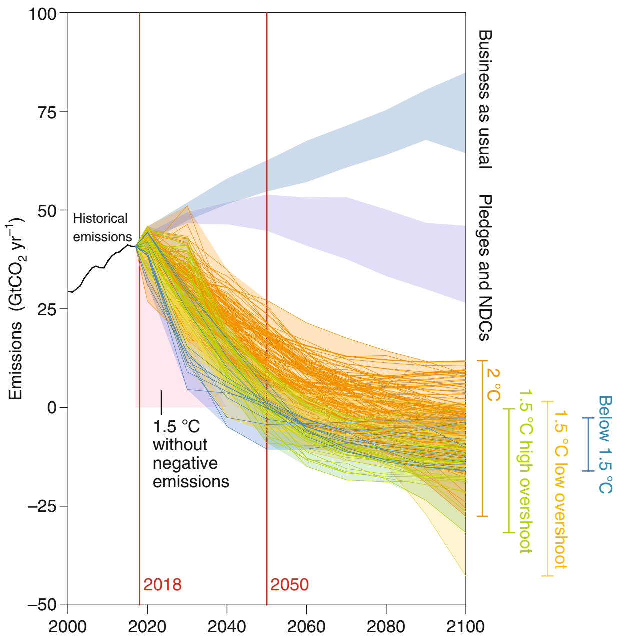


Fig. 1 | Global net anthropogenic CO_2 emission pathways in BAU, 2 °C and 1.5 °C model scenarios. The 2 °C (132 model runs, orange lines), 1.5 °C high overshoot (37 model runs, green lines), 1.5 °C low overshoot (44 model runs, yellow lines) and below 1.5 °C (nine model runs, blue lines) pathways from the 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 Supplementary Information Section 1.1. The scenario of mitigation for 1.5 °C without negative emissions (pink wedge) represents the range of remaining allowable emissions from the carbon budget of 420 $GtCO_2$ from 2018 in the IPCC Special Report on Warming of 1.5 °C (ref. [4]). NDC numbers are adapted from Climate Action Tracker, 2018, removing non-CO_2 emissions (https://climateactiontracker.org). Business as usual numbers represent the range of SSP2 baseline scenarios from the SSP Database[11]. Historical emissions data are from the Global Carbon Project[6].

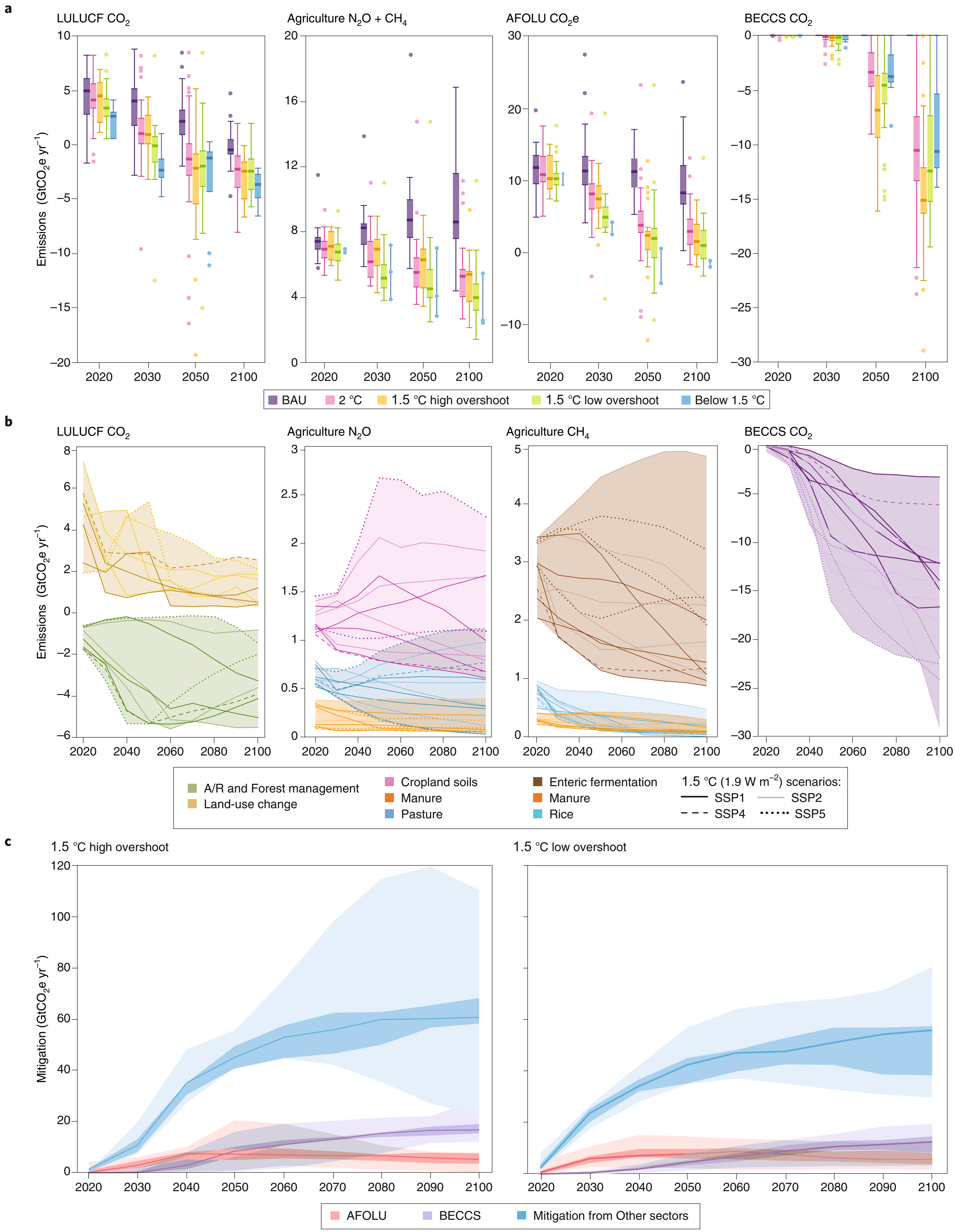
scenarios in the Shared Socioeconomic Pathway (SSP) Database[11] and Integrated Assessment Modeling Consortium (IAMC) Database[22], as well as individual studies of 1.5 °C carbon budgets[2,23–27], agree that aggressive mitigation of total emissions from 2020 until 2050 (approximately 50% reduction per decade, approximately 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 (detailed methods and analysis in Supplementary Information Section 1.1). The 1.5 °C scenarios fall into three categories: 'below 1.5 °C' for the entire twenty-first 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 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 (Fig. 1).

Achieving the 1.5 °C and 2 °C targets requires huge 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 about 10–40 years before those for the 2 °C scenario, with the earliest mitigation for below 1.5 °C and 1.5 °C low overshoot scenarios (Fig. 1). The early action contributes to making 1.5 °C pathways costlier, with a median of (in 2010 prices) US\$480 per tCO_2e in 2050 and US\$2,400 in 2100, compared with the 2 °C pathways (median of US\$365 per tCO_2e in 2050 and US\$1,505 in 2100)[22]. Pathways to 1.5 °C also rely on about 40% (median) more CDR annually than 2 °C scenarios, primarily from bioenergy with carbon capture and storage (BECCS), but also afforestation and reforestation (A/R), and CCS of fossil fuels[20]. Substantial CDR was incorporated in 17 of the 18 2 °C scenarios and all 13 of the 1.5 °C scenarios in the SSP Database[11,13], and all 90 scenarios for 1.5 °C in the IAMC Database[22] (range of −1 to −27 $GtCO_2\ yr^{-1}$ (95% confidence interval) with a median of −15 $GtCO_2\ yr^{-1}$ by 2100)[4], because of the sizable and speedy emissions reduction needed. A 1.5 °C pathway without negative emissions would need to achieve net zero emissions by about 2040, given a post-2018 median carbon budget of 420 $GtCO_2$ (ref. [4]) (Fig. 1). Emissions reductions in the next two decades are therefore critical to limiting warming to 1.5 °C. The longer mitigation is delayed, the lower the probability of delivering on the Paris Agreement targets, and the higher the reliance on negative emissions.

What the land sector can deliver

- Across top-down 1.5 °C models, land-based activities (AFOLU and BECCS) provide 0.9–36.6 (median 13.8) $GtCO_2e\ yr^{-1}$ of economic mitigation potential in 2050, about 4–40% (median 25%) of the total mitigation required for a 1.5 °C pathway (Fig. 2c). AFOLU delivers 0.9–20.5 (median 9.1) $GtCO_2e\ yr^{-1}$ of mitigation potential and BECCS delivers 0–16.1 (median 4.7) $GtCO_2e\ yr^{-1}$.
- In the bottom-up assessment, supply-side AFOLU and BECCS measures provide 2.4–48.1 (median 14.6) $GtCO_2e\ yr^{-1}$ of mitigation potential in 2020–2050. AFOLU provides 2–36.8 (median 10.6) $GtCO_2e\ yr^{-1}$ of mitigation spanning technical and economic potentials, while BECCS provides 0.4–11.3 (median 4.0) $GtCO_2e\ yr^{-1}$ (Fig. 4).

Fig. 2 | GHG emission pathways in the land sector across model scenarios. a, Emission pathways in LULUCF, Agriculture, AFOLU (LULUCF + Agriculture) and BECCS in 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 fewer than five data points (below 1.5 °C in agriculture and AFOLU), only the minimum–maximum range and single data points are shown. Data are 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 activity. Single pathways are lines, styled according to the SSP scenario in the key. **c**, Total mitigation of AFOLU, BECCS and Other sectors (total global mitigation minus AFOLU and BECCS) in 1.5 °C high and low overshoot scenarios. Below 1.5 °C scenarios are not illustrated as there are 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 are from the IAMC Database[22]. The GHG flux of bioenergy plantations is accounted for in the land sector until harvest (that is, 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'.


a
LULUCF CO$_2$
Agriculture N$_2$O + CH$_4$
AFOLU CO$_2$e
BECCS CO$_2$
Emissions (GtCO$_2$e yr^{-1})
10
5
0
−5
−10
−15
−20
20
16
12
8
4
0
30
20
10
0
−10
0
−5
−10
−15
−20
−25
−30
2020
2030
2050
2100
BAU
2 °C
1.5 °C high overshoot
1.5 °C low overshoot
Below 1.5 °C
b
LULUCF CO$_2$
Agriculture N$_2$O
Agriculture CH$_4$
BECCS CO$_2$
Emissions (GtCO$_2$e yr^{-1})
8
6
4
2
0
−2
−4
−6
3
2.5
2
1.5
1
0.5
0
5
4
3
2
1
0
0
−5
−10
−15
−20
−25
−30
2020
2040
2060
2080
2100
A/R and Forest management
Land-use change
Cropland soils
Manure
Pasture
Enteric fermentation
Manure
Rice
1.5 °C (1.9 W m^{-2}) scenarios:
SSP1
SSP2
SSP4
SSP5
c
1.5 °C high overshoot
1.5 °C low overshoot
Mitigation (GtCO$_2$e yr^{-1})
120
100
80
60
40
20
0
2020
2030
2040
2050
2060
2070
2080
2090
2100
AFOLU
BECCS
Mitigation from Other sectors

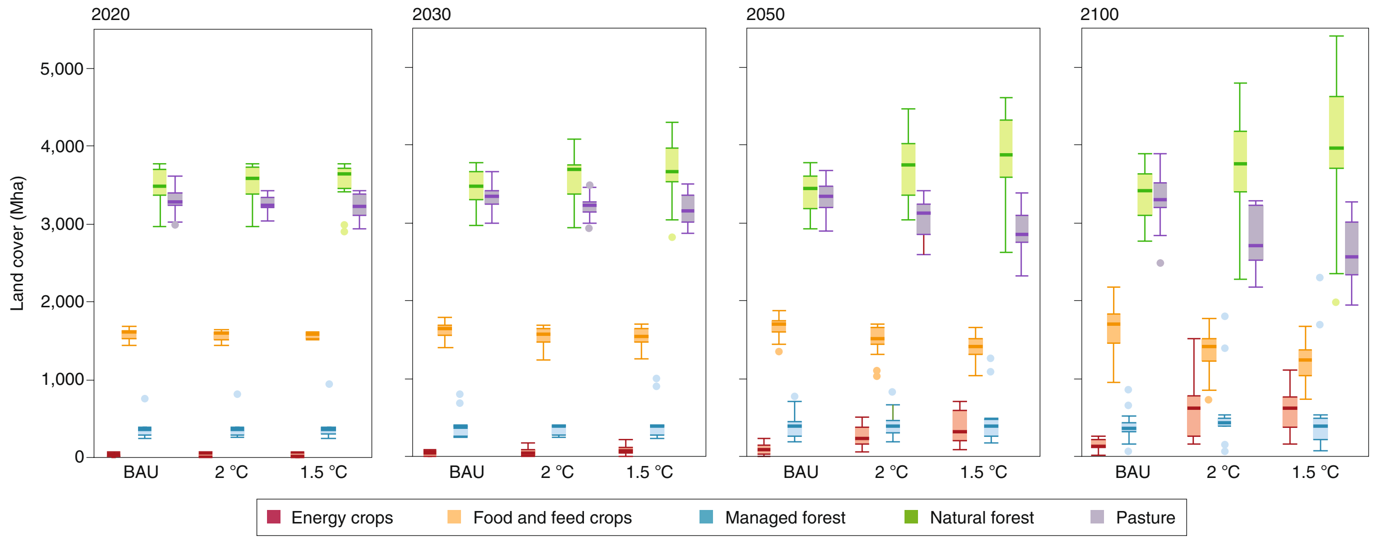


Fig. 3 | Land-cover balance in million hectares (Mha) in BAU, 2 °C and 1.5 °C model scenarios. Natural forests (unmanaged forests) are primary, secondary and protected forests with no planned timber production and tree felling either for wood extraction or for silvicultural purposes such as pre-commercial 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 (the treatment of A/R in each of six models is outlined in Supplementary Table 2 and detailed in Supplementary Information Section 1.2). Managed forests are forests that are managed 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. Data from the SSP Database. Boxplots show the median, interquartile range and minimum–maximum range.

Top-down 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] (Supplementary Information Section 1.2). We then compared the emission pathways of specific mitigation activities in the AFOLU sector and land cover changes using the updated SSP Database with 1.5 °C scenarios (1.9 W m^{-2})[11]. Both databases include outputs from integrated assessment models (IAMs) which incorporate the coupled energy–land–economy–climate system and quantify GHG emissions pathways 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 before 2050, with deeper mitigation and higher BECCS in the 1.5 °C high overshoot pathways after 2050 (Fig. 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 due to the lower cost of reducing deforestation compared with other land-use activities. Across all 1.5 °C scenarios (high, low and no overshoot), net zero CO_2 emissions in LULUCF were achieved around 2030, with net emissions of −0.6 to −4.7 GtCO$_2$ yr^{-1} (interquartile range, IQR) in 2050 compared with 0.9–3.2 GtCO$_2$ yr^{-1} in the business as usual (BAU) scenario. In agriculture, non-CO_2 emissions were 3.9–6.8 GtCO$_2$e yr^{-1} (IQR) in 2050, down about 40% from BAU (7.7–10 GtCO$_2$e yr^{-1} IQR). The deployment of CDR from BECCS across all 1.5 °C scenarios is 3.4–7.9 GtCO$_2$ yr^{-1} (IQR) in 2050 compared with about 0 in BAU (Fig. 2a), although the below 1.5 °C scenarios had approximately 50% lower CDR because of earlier and deeper mitigation. Although there were a few pathways in which BECCS was not deployed at all[14,28,29], BECCS provided a majority of land-based mitigation after 2050 across the 1.5 °C scenarios (Fig. 2c). From all 1.5 °C scenarios in the SSP Database[11], the largest share of emissions reductions from AFOLU was from forest-related measures. CO_2 emissions from deforestation decreased by about 40% by 2050 (1.6–2.9 GtCO$_2$ yr^{-1} IQR compared with 2.5–5.4 GtCO$_2$ yr^{-1} in BAU) (Fig. 2b). Increased A/R and forest management produced negative emissions of −0.5 to −5.3 GtCO$_2$ yr^{-1} (IQR) by 2050 compared with −0.9 to −2.3 GtCO$_2$ yr^{-1} in BAU. In agriculture, the largest reduction was from CH_4 emissions from enteric fermentation (1.6–4.5 GtCO$_2$e yr^{-1} (IQR) in 2050 compared with 3.4–5.3 GtCO$_2$e yr^{-1} in BAU), primarily owing to intensification in the livestock sector and related GHG efficiency gains. Additional CH_4 reductions came from changing 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[4].

AFOLU and BECCS yielded 21–30% (IQR) of the total mitigation required by 2050 to achieve the 1.5 °C target, and 23–32% (IQR) in 2100 (Fig. 2c). Despite the 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 inclusion of additional land-based mitigation measures (for example, wetland conservation and regeneration, soil carbon management, biochar, food and feed substitutes) may increase the land sector's importance in modelled pathways[4].

Measures taken to achieve the 1.5 °C target drove vast land-use changes (Fig. 3). Across SSPs in the 1.5 °C scenario, average pasture and cropland area for food, feed and fibre decreased (in 2050: −120 to −450 Mha IQR compared with 2020 in pasture, and −70 Mha to −250 Mha IQR in cropland). Simultaneously, average natural forests and energy cropland area increased (in 2050: −10 to +730 Mha IQR compared with 2020 in natural forests, and +170 to +550 Mha in energy croplands) (Supplementary Table 1). However, the full range for natural forest change is large, from about 300 Mha decrease to about 1,000 Mha increase in 2050 compared with 2020, primarily due to the inclusion or exclusion of A/R in natural forests by some models (Supplementary Table 2). The substantial land-use changes were largely driven by BECCS deployment, the scale of which is influenced by the SSP scenario and model assumptions on biomass feedstock (trees, energy crops or residues), agricultural yields and conversion efficiencies[4,12]. Land-use changes were also driven by carbon-price-induced shifts in agricultural systems and consumption of GHG-intensive ruminant meats and crops.

CDR and BECCS in modelled pathways. CDR is deployed widely in models because, owing to political and economic inertia, achieving the 1.5 °C and 2 °C targets is generally considered infeasible without removing large amounts of CO_2 from the atmosphere[5,11]. However, models make implicit assumptions about CDR availability in the future, with some using an amount of CDR comparable to the remaining carbon budget[4,5]. IAMs also optimize for least cost and often make idealized assumptions about a global carbon price and effective land governance which promote measures such as BECCS as the predominant CDR technology used (as energy and negative emissions are produced at relatively low cost)[4].

Various studies, however, question the feasibility and sustainability of large-scale BECCS deployment. Feasibility concerns include: (1) bioenergy crop yields and available land in IAMs are higher compared with ecological studies[30–33]; and (2) the technical, economic and political requirements of establishing adequate BECCS plants and storage basins may not materialize[5,17,31–35]. Sustainability concerns include: (1) the extensive amount of land (31–58 Mha per $GtCO_2e$ (ref. [20])), water (60 km^3 per $GtCO_2e$ (ref. [20])) and fertilizer required by BECCS could cause deforestation, biodiversity loss and GHG emissions, and risk food security[17,20,30–32,34–37]; and (2) the emissions from production and potential deforestation, biophysical changes to surface energy fluxes, and high yield assumptions that may not materialize could make BECCS less effective in removing CO_2 (refs. [30–32,34,36]). Although some models are developing sustainable development pathways that limit the negative effects of BECCS and/or CDR deployment[11,14,28,29,38], social and environmental safeguards are typically not addressed by IAMs, resulting in some undesirable scenarios such as large-scale conversion of forests and croplands into BECCS plantations. The sustainable pathways include increased emission reductions, increased energy and material efficiency, and reduced pressure on land through dietary change, lower population growth, and alternative CDR such as using algae for BECCS.

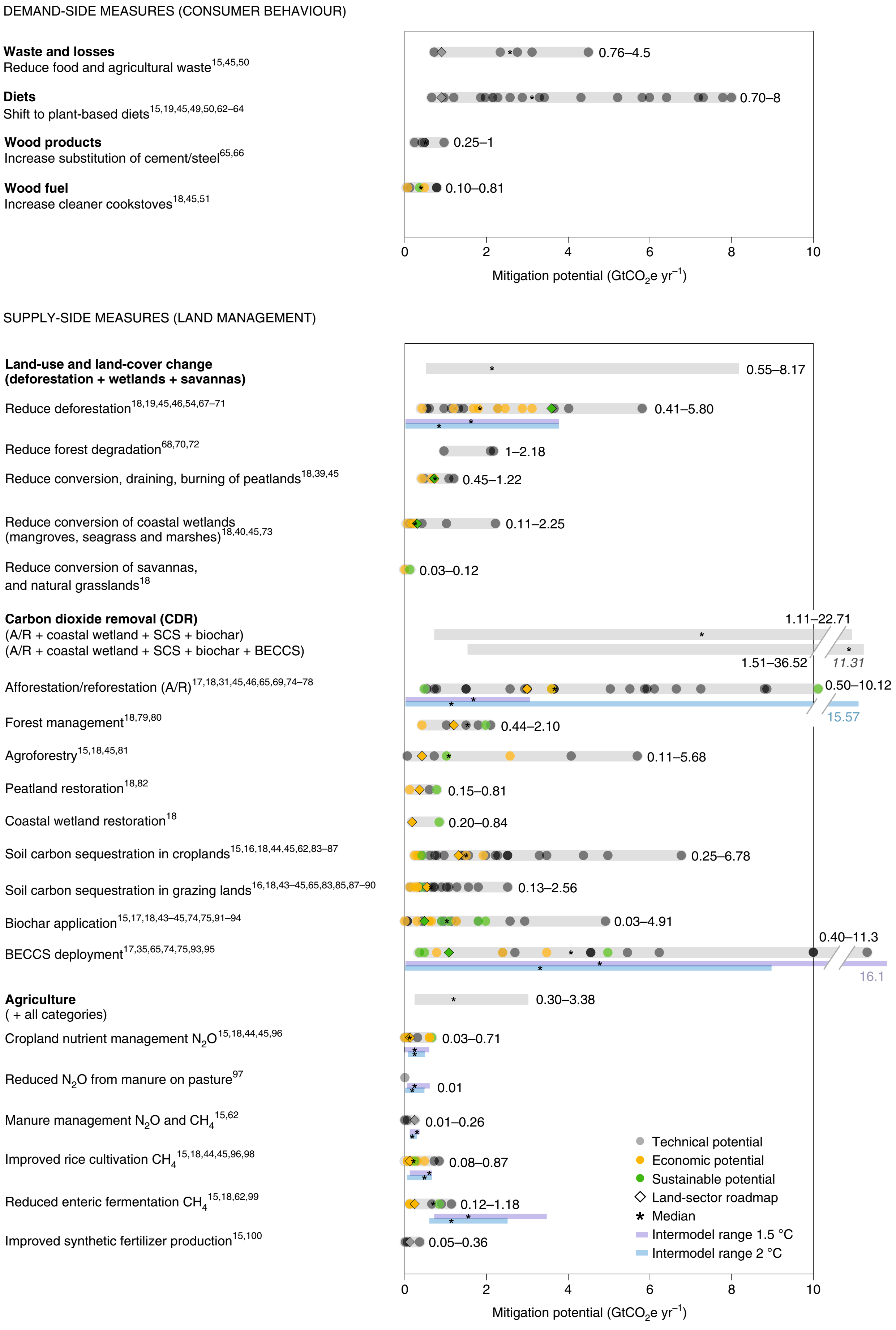
Bottom-up assessment of mitigation potential

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 (methods and additional analysis of land-sector measures in Supplementary Information Section 1.3). We assessed the range of technical, economic and sustainable mitigation potential of 24 land-based activities on both the supply- and demand-side, and developed new estimates of country-level mitigation potential.

The total mitigation potential of supply-side measures from reduced land-use change, CDR through enhanced carbon sinks, and reduced agricultural emissions amounted to 2–36.8 (median 10.6) $GtCO_2e\ yr^{-1}$ in 2020–2050 (Fig. 4). When BECCS was included, the estimate increased to 2.4–48.1 (median 14.6) $GtCO_2e\ yr^{-1}$. Demand-side measures yielded 1.8–14.3 (median 6.5) $GtCO_2e\ yr^{-1}$ 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 $GtCO_2e\ yr^{-1}$ in 2030, as it reflects technical potential that does not consider cost or feasibility. We also consider a wider scope of previously unaccounted for AFOLU activities including wetlands and bioenergy[7,19]. For the same reasons, our estimates are higher than the economic mitigation potential of AFOLU activities in our intermodel analysis (0.9–20.5 $GtCO_2e\ yr^{-1}$ (median 9.1) across 1.5 °C scenarios in 2050). Our estimate is more consistent with a recent study (by Griscom et al.[18]) of 23.8 $GtCO_2e\ yr^{-1}$ in 2030 which represents technical mitigation potential constrained by biodiversity and food security safeguards. About half of their technical mitigation potential (11 $GtCO_2e\ yr^{-1}$) is considered 'cost-effective' (<US$100 per tCO_2e)[18], similar to our median estimate.

Carbon dioxide removal. CDR measures provided the largest land-based mitigation potential. Of the biological solutions, A/R (0.5–10.1 $GtCO_2\ yr^{-1}$) accounted for the highest, followed by soil carbon sequestration (SCS) in croplands (0.3–6.8 $GtCO_2\ yr^{-1}$), agroforestry (0.1–5.7 $GtCO_2\ yr^{-1}$) and converting biomass into recalcitrant biochar (0.3–4.9 $GtCO_2\ yr^{-1}$) (Fig. 4). Although the restoration of peatlands and coastal wetlands (0.2–0.8 $GtCO_2e\ yr^{-1}$ for both) has more moderate potentials, they have among the largest sequestration potentials per unit area[39,40]. 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 considerable co-benefits if managed sustainably (for example, enhanced biodiversity, soil fertility, water filtration and income from agroforestry)[41,42]. Soil carbon and biochar measures can increase soil fertility and yields at lower cost than A/R[18,43]. However, below-ground carbon potentials have higher uncertainty compared with above-ground, specifically on issues of permanence[43,44]. Recent mitigation potential estimates for A/R provide 'plausible' figures of 3.04 $GtCO_2\ yr^{-1}$ by 2030 with environmental, social and economic constraints (<US$100 per tCO_2)[18], and 3.64 $GtCO_2\ yr^{-1}$ between 2020 and 2050, based on a conservative scenario of restoration commitments and smaller-scale afforestation[45]. Feasible estimates also exist for other activities based on varying economic and sociopolitical assumptions (indicated as 'economic potential' in Fig. 4). In the top-down modelled results, A/R (0–3.1 $GtCO_2\ yr^{-1}$ across all

Fig. 4 | Global land-based mitigation potential in 2020–2050 by activity type from bottom-up literature review. 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 more than four data points. We only include references (cited after each category title; refs. [62–100], plus references cited in the text) that provide global mitigation potential estimates in $CO_2e\ yr^{-1}$ (or similar derivative) by 2050. Supply-side measures (activities that require a change in land management) and demand-side measures (activities that require a change in consumer behaviour) are treated separately, as these two categories are not additive. The analysis was designed to avoid potential double-counting of emissions reductions. The summed categories are highlighted in the supply-side measures (for example, total land-use change 'deforestation + wetlands + savannas' excludes forest degradation and peatlands as these categories are included in many estimates). For Agriculture, all categories are summed ('+ all categories'). More information on the methods and description of activities are in Supplementary Information Section 1.3. 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, and in the IAMC Database for BECCS. 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 roadmap are given more context in Fig. 6.


DEMAND-SIDE MEASURES (CONSUMER BEHAVIOUR)
Waste and losses
Reduce food and agricultural waste[15,45,50]
0.76–4.5
Diets
Shift to plant-based diets[15,19,45,49,50,62–64]
0.70–8
Wood products
Increase substitution of cement/steel[65,66]
0.25–1
Wood fuel
Increase cleaner cookstoves[18,45,51]
0.10–0.81
0
2
4
6
8
10
Mitigation potential ($GtCO_2e\ yr^{-1}$)
SUPPLY-SIDE MEASURES (LAND MANAGEMENT)
Land-use and land-cover change
(deforestation + wetlands + savannas)
0.55–8.17
Reduce deforestation[18,19,45,46,54,67–71]
0.41–5.80
Reduce forest degradation[68,70,72]
1–2.18
Reduce conversion, draining, burning of peatlands[18,39,45]
0.45–1.22
Reduce conversion of coastal wetlands (mangroves, seagrass and marshes)[18,40,45,73]
0.11–2.25
Reduce conversion of savannas, and natural grasslands[18]
0.03–0.12
Carbon dioxide removal (CDR)
(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)[17,18,31,45,46,65,69,74–78]
0.50–10.12
15.57
Forest management[18,79,80]
0.44–2.10
Agroforestry[15,18,45,81]
0.11–5.68
Peatland restoration[18,82]
0.15–0.81
Coastal wetland restoration[18]
0.20–0.84
Soil carbon sequestration in croplands[15,16,18,44,45,62,83–87]
0.25–6.78
Soil carbon sequestration in grazing lands[16,18,43–45,65,83,85,87–90]
0.13–2.56
Biochar application[15,17,18,43–45,74,75,91–94]
0.03–4.91
BECCS deployment[17,35,65,74,75,93,95]
0.40–11.3
16.1
Agriculture
(+ all categories)
0.30–3.38
Cropland nutrient management N_2O[15,18,44,45,96]
0.03–0.71
Reduced N_2O from manure on pasture[97]
0.01
Manure management N_2O and CH_4[15,62]
0.01–0.26
Improved rice cultivation CH_4[15,18,44,45,96,98]
0.08–0.87
Reduced enteric fermentation CH_4[15,18,62,99]
0.12–1.18
Improved synthetic fertilizer production[15,100]
0.05–0.36
● 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 ($GtCO_2e\ yr^{-1}$)

SSPs in 2050) are at the lower range of the bottom-up mitigation potential, owing to higher cost compared with BECCS. The BECCS mitigation potential is 0.4–11.3 $GtCO_2$ yr^{-1} (0.4–5 $GtCO_2$ yr^{-1} 'sustainable potential'), lower than in the IAMC model results (0–16.1 $GtCO_2$ yr^{-1} in 2050). The feasibility and sustainability of BECCS is discussed in 'Modelled pathways'.

Land-use change. 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^{-1}. Reducing the conversion and degradation of natural ecosystems is an important land-based measure because of its large climate mitigation effect from avoided emissions, continued sequestration[46] and biophysical effects[47], and the many co-benefits from ecosystem services provided by intact forests. Maintaining tropical and peatland forests is particularly critical because both store a large fraction of terrestrial carbon per unit area and have high biodiversity[39,46]. The top-down modelled mitigation potential for reduced deforestation (0–4.7 $GtCO_2$ yr^{-1} across all SSPs in 2030 and 0–3.8 $GtCO_2$ yr^{-1} in 2050) is in line with the bottom-up mitigation estimate (0.4–5.8 $GtCO_2$ yr^{-1}) due to low mitigation costs.

Agriculture. Among agricultural 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^{-1}), improved rice cultivation (CH_4 reduced by 0.1–0.9 $GtCO_2e$ yr^{-1}) and management of cropland nutrients (N_2O reduced by 0.03–0.7 $GtCO_2e$ yr^{-1}). Recent studies suggest 'feasible' agricultural non-CO_2 reductions in 2030 from 0.4 $GtCO_2e$ yr^{-1} (ref. [21]) at a carbon price of US$20 per tCO_2e to 1.0 $GtCO_2e$ yr^{-1} (ref. [16]) at US$25 per tCO_2e. The modelled economic mitigation potential for agriculture in all 1.5 °C pathways is 3.3–4.1 $GtCO_2e$ yr^{-1} in 2050, consistent with our bottom-up estimates of 0.3–3.4 $GtCO_2e$ yr^{-1}. 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[48].

Consumer behaviour. On the demand-side, shifting diets and reducing food waste have potential to mitigate 0.7–8 $GtCO_2e$ yr^{-1} (range of 'healthy diet' to vegetarian diet) and 0.8–4.5 $GtCO_2e$ yr^{-1} respectively. A recent study finds 'plausible' mitigation potential of 2.2 $GtCO_2e$ yr^{-1} (0.9 $GtCO_2e$ yr^{-1} excluding emissions from land-use change) if 50% of the global population adopted diets restricted to 60 g of meat protein per day, and 2.4 $GtCO_2e$ yr^{-1} (0.9 $GtCO_2e$ yr^{-1} excluding emissions from land-use change) if food waste is reduced by 50% in 2050[45]. Decreasing meat consumption and food waste reduces land used for feed, water use and soil degradation, thereby increasing resources for improved food security[49,50]. Improving woodfuel use by increasing clean cookstoves provides moderate mitigation potential (0.1–0.8 $GtCO_2e$ yr^{-1}), and also delivers high co-benefits of improved air quality and health[51]. The mitigation potential of increasing wood products to replace energy-intensive building materials such as steel and concrete is moderate (0.3–1 $GtCO_2e$ yr^{-1}), and wood sourcing would need to be managed sustainably to avoid negative impacts to biodiversity and natural resources.

Regional mitigation potential. Brazil, China, Indonesia, the European Union, India, Russia, Mexico, the United States, Australia and Colombia represent 54% of global AFOLU emissions[52], and are the 10 countries/regions with the highest mitigation potential in the land sector (Fig. 5). In tropical countries, the highest mitigation potential is from carbon removals (A/R and forest management) and reduced land-use change. 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 European Union, the United States 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 (Supplementary Information Section 1.3), the highest potential for diet shift lies in the United States, European Union, China, Brazil, Argentina and Russia. The largest food waste potential from consumers is in the United States, China and the European Union. Southeast Asia and Sub-Saharan Africa have the greatest potential for avoided food loss from production. The European Union and China also have high potential to reduce the consumption of commodities associated with deforestation (palm oil, soy, beef, timber)[53].

Land-sector roadmap for 2050

The land-sector transformation characterized in the 1.5 °C modelled pathways will require considerable 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 (Fig. 6) to illustrate a potential path of action for achieving climate and non-climate goals. Reconciling the median top-down (13.8 $GtCO_2e$ yr^{-1}) and bottom-up (14.6 $GtCO_2e$ yr^{-1}) estimates of mitigation potential, we established a viable mitigation target (sum of emission reductions and removals) for the land sector of approximately 14 $GtCO_2e$ yr^{-1} (15 $GtCO_2e$ yr^{-1} with BECCS) in 2050. We then divided the required effort into priority mitigation measures, or 'wedges', by determining mitigation potentials according to their feasibility and sustainability from the bottom-up mitigation analysis (Supplementary Table 5), qualitatively weighing associated risks and trade-offs, and prioritizing activities that maximize co-benefits (Supplementary Table 6). The resulting eight priority wedges incorporate the 24 activity types from the bottom-up assessment, maximizing emissions reductions from land-use change, and using 'sustainable estimates' that are also 'cost-effective' for carbon removal measures, 'plausible' estimates for demand-side measures and conservative economic potentials for agriculture measures (estimates are highlighted in Fig. 4 and detailed in Supplementary Table 5). For each wedge, we highlighted important regions and activity types based on bottom-up mitigation potentials and a political feasibility analysis. Finally, we produced GHG reduction trajectories by region consistent with the modelled emissions trajectories pathway (full analysis and methods in Supplementary Information Section 1.4).

The 15 $GtCO_2e$ yr^{-1} mitigation target in the roadmap delivers about 30% of global mitigation, reducing gross emissions by 7.4 $GtCO_2e$ yr^{-1} (4.6 $GtCO_2e$ yr^{-1} from reduced land-use change, 1 $GtCO_2e$ yr^{-1} from agriculture and 1.8 $GtCO_2e$ yr^{-1} from diet shifts and reduced food waste) and increasing carbon removals by 7.6 $GtCO_2e$ yr^{-1} (3.6 $GtCO_2e$ yr^{-1} from restored forests, peatlands and coastal wetlands, 1.6 $GtCO_2$ yr^{-1} from improved plantations and agroforestry, 1.3 $GtCO_2$ yr^{-1} from enhanced soil carbon sequestration and biochar, and 1.1 $GtCO_2$ yr^{-1} from the conservative deployment of BECCS) (Fig. 6b). Carbon removal of 1.1 $GtCO_2$ yr^{-1} through BECCS requires 34–180 Mha of land[20,35] 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 (Fig. 6c). Near-term priorities include avoidance of deforestation, of peatland burning and of mangrove conversion in the tropics, CDR in developed and emerging countries (restoration, forest management, agricultural soils), and reduced

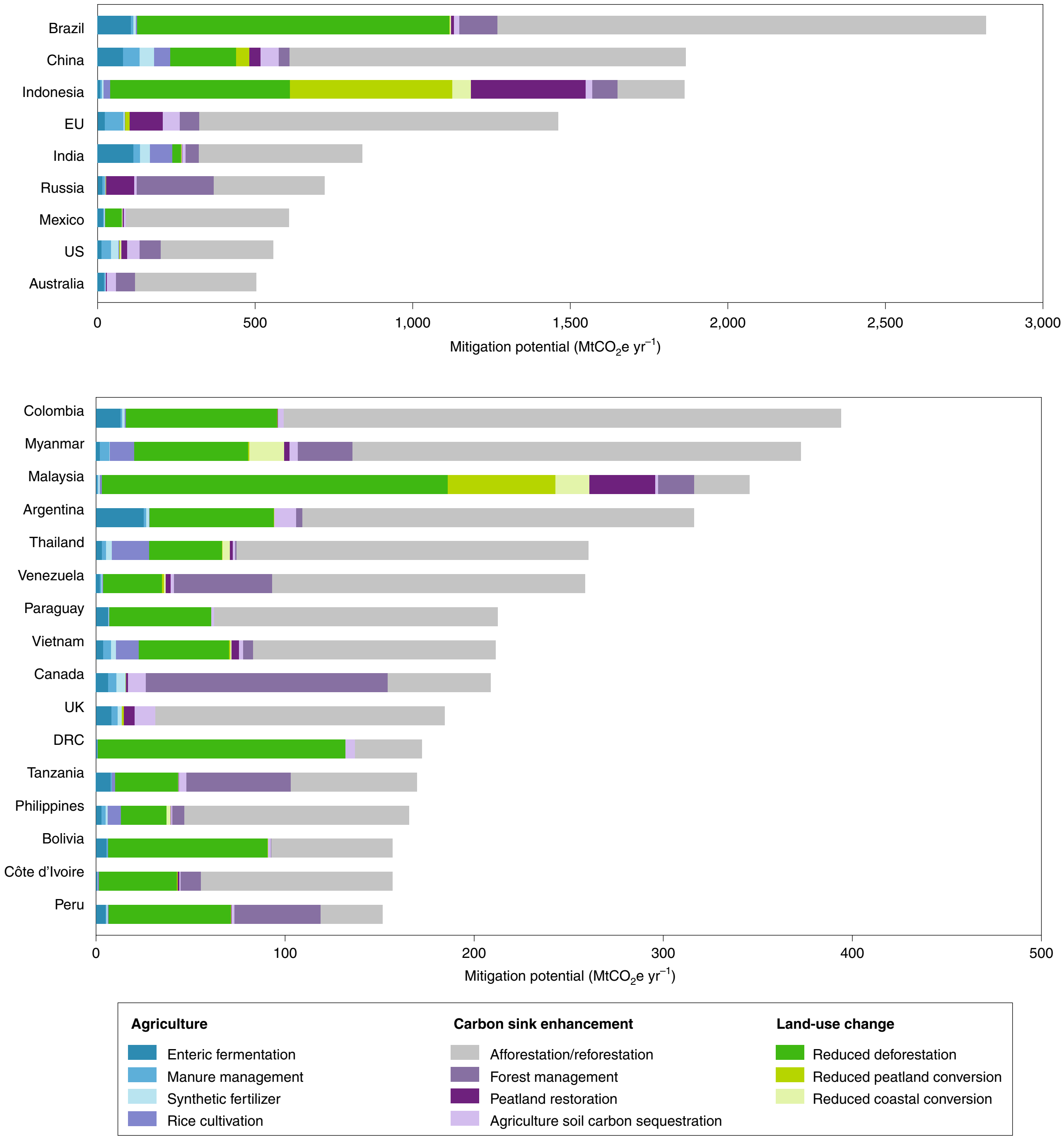
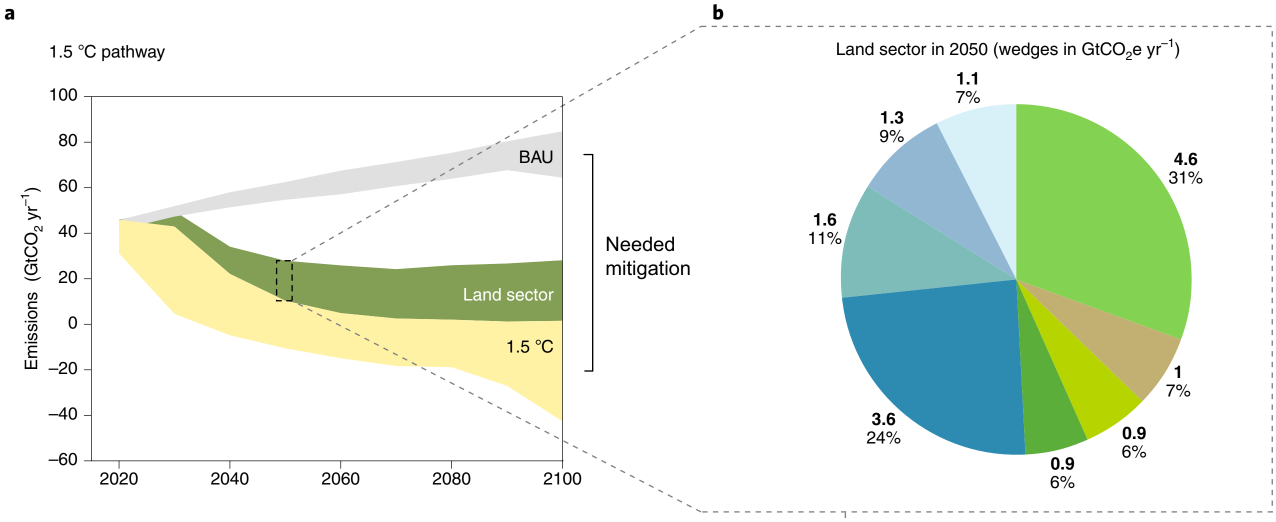


Fig. 5 | Land-based mitigation potential in 2020–2050 by region. The top 25 countries or regions with the highest mitigation potential are presented, nine with over 500 MtCO$_2$e yr^{-1} (top panel) and 16 with 100–400 MtCO$_2$e yr^{-1} (bottom panel). Numbers are compiled from country mitigation potentials in ref. [18] (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). Additional detail and data available in Supplementary Information section 1.3 and Supplementary Table 4.

food waste and a shift in diets in developed countries and China. The roadmap translates to a needed reduction of land-based emissions by about 50% per decade (85% decrease by 2050) compared to BAU, and about a tenfold increase in carbon removals over two decades 2030–2050 (cumulative 184 GtCO$_2$e by 2050) to make the land sector net zero emissions by 2040 and a net carbon sink of approximately 3 GtCO$_2$e yr^{-1} by 2050.

Our illustrative roadmap diverges from some 1.5 °C modelled pathways. Seeking to avoid undesirable impacts from larger-scale deployment of BECCS (detailed in 'Modelled pathways'), our roadmap relies on deeper emissions reductions from lifestyle changes such as reducing food waste and shifting diets, which have various economic, environmental and health co-benefits[49,50], and on higher removals from ecosystem-based sequestration including forest, peatland and coastal mangrove restoration, forest management and agricultural soils, which enhance vital ecosystem services[41,42] (Supplementary Information Sections 1.3 and 1.4). The roadmap, similar to other sustainable pathways that limit BECCS and improve



c

Implementation roadmap to 2050 (% emissions reductions [green] or cumulative GtCO$_2$ increase in carbon removals [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 BAU)	Developed and emerging countries (China, India, Brazil, EU, US, Australia, Russia)	Reduce CH$_4$ and N$_2$O 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[45] (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 new foods	5%	20%	35%	50%
●	Reduce food waste[45] (50% reduction in total food waste by 2050 compared to BAU)	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 and 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[17,45]	China, EU, US, 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[17,35]	USA, Russia, China, Canada[35]	BECCS R&D, investment and deployment	0	0	11	22

Fig. 6 | Land-sector roadmap for 2050. a, The land sector makes up 21–30% interquartile range (median 25%, approximately 14 GtCO$_2$e yr^{-1}) of the total mitigation in 2050 in modelled 1.5 °C pathways (data from Fig. 2c). In the bottom-up assessment, the median mitigation potential of the land sector is about 15 GtCO$_2$e yr^{-1} in 2020–2050, or about 30% of total mitigation needed. **b**, The needed mitigation is translated into eight priority land-based measures (wedges), combining the 24 land-based activities from the bottom-up assessment, and based on an analysis of co-benefits and risks, feasibility and sustainability to deliver mitigation of about 15 GtCO$_2$e yr^{-1} by 2050 (detailed in Supplementary Tables 5 and 6). The green wedges represent emission reduction measures (7.4 GtCO$_2$e yr^{-1}), and the blue wedges represent carbon removal measures (7.6 GtCO$_2$e yr^{-1}). Each wedge is individually accounted for with the intent of avoiding double-counting (Supplementary Information Section 1.4). **c**, The implementation roadmap to 2050 details each wedge and related priority regions, activity types and implementation trajectories in per cent for emission reduction activities and cumulative GtCO$_2$e for carbon removal activities starting in 2020. The baseline and trajectory numbers in 2050 are based on the source used for each wedge (Supplementary Table 5). The 2020–2050 trajectories were developed through a political feasibility assessment combined with an expert assessment weighing trade-offs. Additional details on priority regions and trajectories are provided in Supplementary Information Sections 1.3 and 1.4.

food consumption[14,28,38], will require additional efforts in the energy sector (for example, lower energy demand and more aggressive emissions reductions). Thus, our roadmap may be more expensive than a cost-optimized model pathway. However, the trade-offs illustrated in our roadmap (Supplementary Tables 5 and 6) increase the likelihood of limiting warming to 1.5 °C (or 2 °C) and improve our ability to deliver on other social and environmental goals, potentially offsetting additional costs (damages from climate change and adaptation costs) not captured in the models.

The roadmap described here was designed to meet the targets of the Paris Agreement, enhance co-benefits (biodiversity, water, air, soil, resilience, food security and livelihoods) and also deliver on other international commitments and policies including the Sustainable Development Goals (SDG) 2, 6, 12, 14 and 15, the New York Declaration on Forests (NYDF) goals 1 and 5, and the United Nations Convention on Biological Diversity (UNCBD) Aichi Targets 5 and 15 (Supplementary Table 6). The roadmap reduces deforestation by 95% by 2050, contributing to the NYDF, SDG and Aichi Targets of halving deforestation by 2020 and halting deforestation by 2030. Our restoration wedge (3 $GtCO_2$ yr^{-1} of reforestation, 0.4 $GtCO_2e$ yr^{-1} of peatland restoration and 0.2 $GtCO_2e$ yr^{-1} of coastal mangrove restoration) would restore forests on more than 320 Mha of land[20] by 2050 — an area consistent with the NYDF and Bonn Challenge 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. Although 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^{-1} (about 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, so 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, are discussed in this Review and recent literature[4,5,17,20,30–38]. 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 to 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 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 in the future[20,38].

Scaling up action in the land sector. Our 1.5 °C land-sector roadmap shows a pathway to reduce emissions by about 85% by 2050 and increase carbon removals, tenfold between 2030–2050. However, there is a large gap between progress so far and the desired pathway.

Despite efforts to reduce deforestation over the past decade, emissions from land-use change have increased because of surging tropical deforestation[54,55]. Between 2014 and 2018, more than 26 Mha of forests were lost every year, a 43% increase since 2001–2013[55], yet deforestation must decline 70% by 2030 and 95% by 2050 to align with the 1.5 °C roadmap. 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 that more than 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, weak governance, and lack of finance. 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[50]. Similarly, development of negative emissions technologies is stymied primarily because of low awareness, low prioritization and concerns about negative trade-offs[17]. Increased dialogue between scientists and policymakers is important for bridging the knowledge gap in 'no-regret' options for mitigation and catalysing political action. 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[56,55]. Effectively reducing deforestation and scaling up restoration depends on understanding local dynamics at the forest frontier and on coordinated action among private and public actors — exemplified by the successes in Brazil from the mid 2000s until 2015, and in Indonesia from 2016[56,55]. Agricultural intensification combined with forest restoration on spared land holds considerable potential when accompanied by stringent land policies and enforcement and demand-side measures (for example, reduced meat consumption)[57]. Less-intensive forestry systems have also shown success in avoiding deforestation if land tenure security is combined with best forest management practices[58].

Efforts to reduce emissions from deforestation and degradation and to promote A/R often have higher transaction and implementation costs than expected, and existing finance for forest protection is inadequate[59]. Climate finance for forests accounts for 1.5% (US$3.2 billion) of global public climate funding (US$256 billion), and 0.1% of total public and private land-sector funding in countries with high levels of deforestation (US$1,495 billion)[55]. A lack of finance, high transition costs and low expected returns from changed practices are the main challenges for farmers[21,60,61]. A large shift from traditional investments in the land sector (for example, 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 to 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, in ecosystem restoration and in reducing agricultural emissions, and actively addressing demand-side and CDR measures with concrete commitments and investment plans.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of code and data availability and associated accession codes are available at https://doi.org/10.1038/s41558-019-0591-9.

Received: 31 October 2017; Accepted: 3 September 2019;

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Acknowledgements

The design of and analysis in this study was guided by the feedback and recommendations of expert consultations (January and May 2017 workshops in London) and interviews, and we thank all those who contributed: J. Atkins, J. Busch, P. Ellis, J. Funk, T. Gopalakrishna, A. Kroeger, B. Lee, D. Lee, S. Lewis, G. Lomax, D. Mitchell, R. Rajão, J. Rogelj, C.-F. Schleussner, P. West, G. Wynne, A. Yang and D. Zarin. We thank E. Chak and M.-J. Valentino for helping to design the figures. This work was supported by the Children's Investment Fund Foundation and the authors' institutions and funding sources.

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 1.5 °C 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.-J.N., A.P., M.J.S.S., J.S., P.S. and E.S. provided data and/or analysis and drafting of the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-019-0591-9.

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Peer review information *Nature Climate Change* thanks Felix Creutzig and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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Methods

Detailed methods, including additional figures and tables, are available in the Supplementary Information.

Data availability

The modelled data used for this study are available in the IAMC 1.5 °C Scenario Explorer and Data hosted by IIASA. The rest of the data that support the findings of this study are available in the Supplementary Information files and from the corresponding author upon request.