

1 **Title:** Contribution of the land sector to a 1.5°C World
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38 Preface

39 The Paris Agreement introduced an ambitious goal to limit warming to 1.5°C above pre-
40 industrial levels. Here, we combine modelling and a meta-analysis of mitigation strategies to
41 develop a land sector roadmap of priority measures and regions that can help to achieve the
42 1.5°C temperature goal. Transforming the land sector (agriculture, forestry, wetlands, bioenergy)
43 towards more sustainable practices could contribute ~30% (15 GtCO₂e/yr) of the global
44 mitigation needed in 2050 to deliver on the 1.5°C target, however it will require substantially
45 more ambitious effort than the 2°C target. Addressing risks, barriers and incentives are necessary
46 to scale up mitigation while maximizing sustainable development, food security, and
47 environmental co-benefits.

48 Introduction

49 The Paris Agreement marked the conclusion of many years of negotiations, setting a global
50 temperature target of “well below 2°C” and encouraging efforts to “limit increase to 1.5°C above
51 pre-industrial levels.” However, submitted Nationally Determined Contributions (NDCs),
52 countries’ pledges to implement emissions reductions, fall short of the goal¹. Current
53 commitments are more compatible with 2.5°C to 3°C of warming by 2100²⁻⁴. To limit warming
54 to 1.5°C (and 2°C), countries will need to plan for a more rapid transformation of their national
55 energy, industry, transport, and land-use sectors^{1,2,5}.

56

57 The land sector, commonly referred to as Agriculture, Forestry, and Other Land Uses (AFOLU)
58 is responsible for 10-12 GtCO₂e (~25%) of net anthropogenic GHG emissions, with
59 approximately half from agriculture and half from Land Use, Land Use Change, and Forestry

60 (LULUCF)^{6,7}. LULUCF emissions represent the net balance between emissions from land-use
61 change and carbon sequestration from the regeneration of vegetation and soils^{6,7}. While the
62 AFOLU sector generates significant emissions, the residual terrestrial sink (accumulation of
63 carbon in the terrestrial biosphere excluding land sinks from LULUCF) also currently sequesters
64 ~30% of annual anthropogenic emissions, making land vitally important for generating “negative
65 emissions” (or more carbon dioxide removals [CDR] than emissions)⁶. In addition to GHG
66 impacts, land-use generates biophysical impacts that affect the climate by altering water and
67 energy fluxes between the land and the atmosphere⁸. Furthermore, the AFOLU system provides
68 significant ecosystem goods and services such as air and water filtration, nutrient cycling, habitat
69 for biodiversity, and climate resilience⁷.

70

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

81

82 Building on existing studies of mitigation pathways^{4,11–14} and mitigation potentials^{7,15–21} in the
83 land sector, here, we provide a comprehensive assessment of all land-based activities
84 (agriculture, LULUCF, and bioenergy), and their possible contributions to the Paris Agreement

85 temperature target of 1.5°C. We conducted four complementary analyses: 1) review of 1.5°C
86 scenarios across all sectors, 2) comparative analysis of top-down modelled pathways in the land
87 sector, 3) bottom-up assessment and synthesis of land sector mitigation potential, and 4) a
88 geographically explicit roadmap of priority mitigation actions to fulfil the 1.5°C land sector
89 transformation pathway by 2050, informed by the first three analyses (approach described in
90 each section and elaborated in the Supplementary Information (SI)).

91 Pathways for the Paris Agreement

92 To put the Paris Agreement in context, we reviewed available 1.5°C scenarios to assess viable
93 emissions pathways and required mitigation across all sectors. Recently released 1.5°C (1.9
94 W/m²) scenarios in the Shared Socio-economic Pathway (SSP) Database¹¹ and Integrated
95 Assessment Modeling Consortium (IAMC) Database²², as well as individual studies of 1.5°C
96 carbon budgets^{2,23-27} agree that aggressive mitigation of total emissions from 2020 until 2050
97 (~50% reduction per decade, ~90% total reduction) coupled with substantial carbon removals
98 increase the chance (>66% and >90% respectively) of limiting warming to 1.5°C and 2°C by
99 2100 (SI-section 1). The 1.5°C scenarios fall into three categories: ‘Below 1.5°C’ the entire 21st
100 century; ‘Low overshoot’ in mid-century (50-66% chance of exceeding 1.5°C) before
101 temperatures decrease to below 1.5°C by 2100; and ‘High overshoot’ risk (> 67% chance of
102 overshoot)⁴. Current research thus defines three significant milestones to deliver on the Paris
103 agreement targets: peak emissions around 2020, net zero emissions (balance between sources
104 and sinks) by 2040-2060, and net negative emissions (sinks are greater than sources) thereafter
105 (Figure 1).

106

107 Achieving the 1.5°C and 2°C targets requires dramatic transformations of the energy, industry,
108 transportation and land sectors (emission reductions across all sectors), and substantial
109 deployment of CDR (to achieve negative emissions)⁴ – with 1.5°C scenarios requiring much
110 earlier and more pronounced action. Net zero emissions for the 1.5°C target must be achieved
111 ~10-40 years before the 2°C scenario, with the earliest mitigation for Below 1.5°C and 1.5°C
112 Low overshoot scenarios (Figure 1). Further, 1.5°C pathways are costlier (median of [USD
113 2010] \$180/tCO₂e in 2030, \$480 in 2050 and \$2400 in 2100) compared to the 2°C pathways
114 (median of \$110/tCO₂e in 2030, \$365 in 2050 and \$1505 in 2100) in the IAMC Database.
115 Pathways to 1.5°C also rely on ~40% (median) more CDR annually than 2°C scenarios.
116 Emissions reductions in the next two decades are critical to limiting warming to 1.5°C – the
117 longer mitigation action is delayed, the lower the probability of delivering on the Paris
118 Agreement targets, and the higher the reliance on negative emissions.

119
120 In the IPCC-AR5, 87% of the 116 scenarios that limit warming to 2°C with a >66% likelihood
121 relied on CDR, primarily A/R (afforestation and reforestation), CCS (carbon capture and storage)
122 and BECCS (bioenergy with CCS)²⁰. Similarly, 17 of the 18 2°C scenarios and all 13 1.5°C
123 scenarios in the SSP Database^{11,13}, and all 90 scenarios for 1.5°C in the IAMC Database²²
124 incorporated substantial CDR (range of -1 to -27 GtCO₂/yr [95% confidence interval] with a
125 median of -15 GtCO₂/yr by 2100)⁴. CDR technologies like CCS of fossil fuels and BECCS,
126 while not yet deployed at scale nor incorporated into any country’s NDCs, appear widely in
127 models because of the sizable and speedy emissions reduction needed. Without removing a
128 substantial amount of CO₂ from the atmosphere, achieving the 1.5° and 2°C targets is widely
129 considered infeasible due to political and economic inertia^{11,28}. For example, a 1.5°C pathway
130 without negative emissions would need to achieve net zero emissions by ~2040 given a post-
131 2018 carbon budget of 420 GtCO₂⁴ (Figure 1). BECCS is frequently used in models as it

132 provides both energy and negative emissions at relatively low cost⁴. However, given the
133 potential risks associated with CDR technologies like BECCS (unproven at scale, limited
134 effectiveness in overshoot scenarios, unsustainable resource requirements)^{17,20,28–31}, alternative
135 pathways including reduced reliance on CDR technologies, lower energy demand and
136 sustainable food consumption are being explored^{14,32–34}.

137 What the land sector can deliver

138 *Across all top-down 1.5°C models, land-based activities (AFOLU and BECCS) provide 1.6 –*
139 *36.6 (median 13.5) GtCO₂e/yr of economic mitigation potential in 2050, ~4 – 40% (median*
140 *24%) of the total mitigation required for a 1.5°C pathway (Figure 2c). AFOLU delivers 0.9 –*
141 *20.5 (median 7.7) GtCO₂e/yr of mitigation potential and BECCS delivers 0.7 – 16.1 (median 5.9)*
142 *GtCO₂e/yr. In the bottom-up assessment, supply-side AFOLU and BECCS measures provide 2.4*
143 *– 48.1 (median 14.6) GtCO₂e/yr of mitigation potential in 2020–2050. AFOLU provides 2 – 36.8*
144 *(median 10.6) GtCO₂e/yr of mitigation spanning technical and economic potentials, while*
145 *BECCS provides 0.4 – 11.3 (median 4.0) GtCO₂e/yr (Figure 4).*

146

147 Modelled pathways

148 To evaluate the contribution of the land sector in 1.5°C and 2°C pathways, we reviewed model
149 assessments of net CO₂, CH₄, and N₂O emissions trajectories in AFOLU and BECCS using the
150 IAMC Database²². We then compared the emission pathways of specific mitigation activities in
151 the AFOLU sector as well as land cover changes using the updated SSP Database with 1.5°C
152 scenarios (1.9 W/m²)¹¹. Both databases include model outputs from integrated assessment
153 models (IAMs) which incorporate the coupled energy–land–economy–climate system and
154 quantify pathways of GHG emissions across sectors based on cost optimization.⁴

155

156 Of the 2°C and 1.5°C scenarios in the IAMC Database²², projected emissions reductions in
157 AFOLU (CO₂ reductions in LULUCF and N₂O and CH₄ reductions in agriculture) were similar
158 in the 2°C and 1.5°C High overshoot pathways in the first half of the century, with deeper
159 mitigation and higher BECCS in the 1.5°C High overshoot pathways after 2050 (Figure 2a).
160 Mitigation is earlier and more pronounced in the 1.5°C Low overshoot and Below 1.5°C (no
161 overshoot) scenarios until 2050 in LULUCF, and through 2100 in agriculture. The similarities
162 between the 2°C and 1.5°C pathways in LULUCF after 2050 are mostly due to the relatively low
163 cost of reducing deforestation compared to other land-use activities. Across all the 1.5°C
164 scenarios (high, low and no overshoot), net zero CO₂ emissions in LULUCF were achieved
165 around 2030, with net emissions across all IAMs of -0.6 – -4.7 GtCO₂/yr (interquartile range
166 [IQR]) in 2050 compared to 0.9 – 3.2 GtCO₂/yr in the business as usual (BAU) scenario. In
167 agriculture, non-CO₂ emissions were 3.9 – 6.8 GtCO₂e/yr (IQR) in 2050, down ~40% from BAU
168 (7.7 – 10 GtCO₂e/yr). The deployment of CDR from BECCS across all the 1.5°C scenarios is 3.4
169 – 7.9 GtCO₂/yr (IQR) in 2050 compared to ~0 in BAU (Figure 2a), although the Below 1.5°C
170 and Low overshoot scenarios had lower reliance on CDR later in the century because of earlier
171 and deeper mitigation. Across all 1.5°C scenarios, BECCS provided a majority of all land-based
172 mitigation after 2050 (Figure 2c).

173

174 In the 1.5°C scenarios, the largest share of emissions reductions from AFOLU mitigation
175 activities across all SSPs¹¹ were from forest-related measures. CO₂ emissions from deforestation
176 decreased by ~40% by 2050 (1.6 – 2.9 GtCO₂/yr IQR compared to 2.5 – 5.4 GtCO₂/yr in BAU)
177 (Figure 2b). Increased A/R and forest management generated an additional carbon sink,
178 producing negative emissions of -0.5 – -5.3 GtCO₂/yr (IQR) by 2050 compared to -0.9 – -2.3
179 GtCO₂/yr in BAU. In agriculture, the largest reduction was from CH₄ emissions from enteric

180 fermentation (1.6 – 4.5 GtCO₂e/yr (IQR) in 2050 compared to 3.4 – 5.3 GtCO₂e/yr in BAU),
181 primarily due to intensification in the livestock sector and related GHG efficiency gains.
182 Additional CH₄ reductions came from changes to irrigation and fertilization practices in rice
183 cultivation with smaller N₂O reductions from cropland soils and pastures. CO₂ and CH₄ decline
184 more rapidly and prominently than N₂O, implying the difficulty in reducing N₂O in agriculture.
185

186 The projected GHG mitigation from AFOLU and BECCS yielded 17%-30% (IQR) of the total
187 mitigation required by 2050 to achieve the 1.5°C target, and 23%-32% (IQR) in 2100 (Figure
188 2c). Despite the currently limited portfolio of land-based mitigation measures in IAMs^{4,12}, the
189 large share of total mitigation highlights the importance of the land sector in achieving the 1.5°C
190 target. The future inclusion of additional land-based mitigation measures (e.g. wetland
191 conservation and regeneration, soil carbon management, biochar, food and feed substitutes)
192 could further increase the land sector's importance in modelled pathways⁴.

193
194 Measures taken in the land sector to achieve the 1.5°C target drove vast land-use changes (Figure
195 3). Across all SSPs in the 1.5°C scenario, pasture and cropland area for food, feed and fibre
196 decreased on average (in 2050: -120 – -450 Mha IQR compared to 2020 in pasture, and -70 Mha
197 – -250 Mha IQR in cropland). On the other hand, natural forests and energy cropland area
198 increased on average (in 2050: -10 – +730 Mha IQR compared to 2020 in natural forests, and
199 +170 – +550 Mha in energy croplands) (Table S1). However, the full range for natural forest
200 change is very large, from ~300 Mha decrease to ~1000 Mha increase in 2050 compared to 2020,
201 primarily due to the inclusion or exclusion of A/R in natural forests by some models (Table S4).
202 The substantial changes and variable ranges in land cover is partially driven by BECCS
203 deployment (and hence land dedicated to energy crops), the scale of which is influenced by the

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

209

210 The 1.5°C scenarios produce large shifts in land balances as IAMs optimize for cost, despite
211 possible impacts on ecosystems and food security^{17,20,30,31}. Currently, few studies explore how
212 BECCS deployment or unsustainable land requirements can be limited in 1.5°C scenarios^{14,33,34}.
213 Therefore we conducted a sensitivity analysis for the 1.5°C scenario using one of the IAMs, the
214 Global Biosphere Management Model (GLOBIOM)³⁵ to test the effect of carbon price and
215 bioenergy demand on natural ecosystems and food security (SI-section 2). In this scenario, we
216 held biomass demand constant at BAU levels (50 EJ/yr compared to 100 EJ/yr in 2050 in the
217 1.5°C scenario) while still applying the increasing carbon prices consistent with the 1.5°C
218 scenario. Energy crops were reduced by %75 in 2050, and the conversion of ~500 Mha of natural
219 forests, ~100 Mha of grassland, and 20 Mha food and feed crops was avoided (Figure S2). The
220 results of the analysis show that bioenergy deployment had a large impact on natural ecosystems,
221 yet a high carbon price for agricultural emissions was the main driver of food price increases
222 (and food security concerns). While the sensitivity scenario is a departure from the most cost-
223 effective pathway, it demonstrates that alternative paths to 1.5°C can lower pressure on land.
224 Pathways with reduced bioenergy and CDR from BECCS, however, would need to be
225 counterbalanced by more rapid emission reductions in the short run and additional efforts in
226 potentially more costly sectors such as transportation, industry and non-BECCS CDR such as
227 A/R or DAC^{4,14,32}.

228

229 Bottom-up assessment of mitigation potential

230 To complement the top-down modelled scenarios and gauge how a larger portfolio of land sector
231 measures could contribute to a 1.5°C pathway, we conducted a bottom-up synthesis of mitigation
232 potential, updating the IPCC-AR5⁷ framework with new categories and more recent literature.
233 We assessed the range of technical and economic mitigation potential of 24 land-based activities
234 in both the supply- and demand-side, and developed new estimates of country-level mitigation
235 potential (SI-section 3).

236

237 The total mitigation potential of supply side measures from reduced land-use change, carbon
238 sequestration through enhanced carbon sinks, and reduced agricultural emissions amounted to 2
239 – 36.8 (median 10.6) GtCO₂e/yr in 2020-2050 (Figure 4). When BECCS was included, the
240 estimate increased to 2.4 – 48.1 (median 14.6) GtCO₂e/yr. Demand-side measures yielded 1.8 –
241 14.3 (median 6.5) GtCO₂e/yr of mitigation potential from reducing food loss and waste, shifting
242 diets, substituting cement and steel with wood products, and switching to cleaner cookstoves.
243 Our upper range from supply-side measures is higher than the IPCC-AR5 economic mitigation
244 potential of 7.18 – 10.60 GtCO₂e/yr in 2030, as it reflects technical potential that does not
245 consider cost or feasibility. We also consider a wider scope of AFOLU activities including
246 wetlands and bioenergy, previously unaccounted for (^{7,19}). For the same reasons, our estimates
247 are higher than the economic mitigation potential of AFOLU activities in our inter-model
248 analysis (0.9 – 20.5; median 7.2 GtCO₂e/yr for all 1.5°C scenarios in 2050). Our estimate is more
249 in line with a recent study (Griscom et al. 2017¹⁸) of 23.8 GtCO₂e/yr in 2030 which represents
250 technical mitigation potential constrained by biodiversity and food security safeguards. About
251 half of their technical mitigation potential (11 GtCO₂e/yr) is considered “cost effective”
252 (<\$100/tCO₂e)¹⁸, similar to our median estimate.

253

254 Carbon sequestration measures provided the largest land-based mitigation potential. Of the
255 biological solutions, A/R (0.5 – 10.1 GtCO₂e/yr) accounted for the highest, followed by soil
256 carbon sequestration (SCS) in croplands (0.3– 6.8 GtCO₂/yr), agroforestry (0.1 – 5.7 GtCO₂e/yr)
257 and converting biomass into recalcitrant biochar (0.3 – 4.9 GtCO₂/yr) (Figure 4). While the
258 restoration of peatlands and coastal wetlands (0.2 – 0.8 GtCO₂e/yr for both) have more moderate
259 potentials, they have among the largest sequestration potentials per unit area^{36,37}. The higher
260 range of potentials are largely theoretical, as many estimates do not consider economic and
261 political feasibility, contain uncertainty related to carbon gains and permanence, and require
262 locating available, suitable land that limits food insecurity and biodiversity concerns. Measures
263 such as A/R (particularly, ecosystem restoration) and agroforestry could deliver significant co-
264 benefits if managed sustainably (e.g., enhanced biodiversity, soil fertility, water filtration, and
265 income from agroforestry)^{38,39}. As can soil carbon and biochar measures which can increase soil
266 fertility and yields, at lower cost compared to A/R^{18,40}. However, below ground carbon potentials
267 have higher uncertainty compared to above ground, specifically on issues of permanence^{40,41}.
268 Recent mitigation potential estimates for A/R provide “plausible” figures of 3.04 GtCO₂/yr by
269 2030 with environmental, social and economic constraints (<\$100/tCO₂)¹⁸, and 3.64 GtCO₂/yr
270 between 2020-2050 based on a conservative scenario of restoration commitments and smaller
271 scale afforestation⁴². Feasible estimates also exist for other activities based on varying economic
272 and socio-political assumptions (indicated as “economic potentials” in Figure 4). In the top-down
273 modelled results, A/R (0 – 3.1 GtCO₂/yr across all SSPs in 2050) are at the lower range of the
274 bottom-up mitigation potential due to higher cost compared with BECCS. The BECCS
275 mitigation potential is 0.4 – 11.3 GtCO₂e/yr (0.4 – 5 GtCO₂e/yr “sustainable potential”), slightly
276 lower compared to the SSP model results (0.7 – 16 GtCO₂/yr in 2050).

277

278 Measures that reduce land-use change (reduced deforestation, forest degradation, peatland
279 conversion and coastal wetland conversion), also provided large mitigation potentials: 0.6 – 8.2
280 GtCO₂/yr. Reducing land-use change is an important land-based measure due to its large climate
281 mitigation effect from avoided emissions, continued sequestration⁴³ and biophysical effects⁴⁴,
282 and the many co-benefits from ecosystem services provided by intact forests. Maintaining
283 tropical forests and peatland forests are critical because both store a large fraction of terrestrial
284 carbon per unit area and have high biodiversity^{36,43}. The top-down modelled mitigation potential
285 for reduced deforestation (0 – 4.7 GtCO₂/yr across all SSPs in 2030 and 0 – 3.8 GtCO₂/yr in
286 2050) is in line with the bottom-up mitigation estimate (0.4 – 5.8 GtCO₂/yr) due to low
287 mitigation costs.

288

289 Among agriculture measures, the largest potential for non-CO₂ reductions include reduced
290 enteric fermentation from better feed and animal management (CH₄ reduced by 0.1 – 1.2
291 GtCO₂e/yr), improved rice cultivation (CH₄ reduced by 0.1 – 0.9 GtCO₂e/yr) and management of
292 cropland nutrients (N₂O reduced by 0.03 – 0.7 GtCO₂e/yr). Recent studies suggest “feasible”
293 agricultural non-CO₂ reductions in 2030 from 0.4 GtCO₂e/yr²¹ at a carbon price of \$20/tCO₂e to
294 1.0 GtCO₂e/yr¹⁶ at \$25/tCO₂e. The modelled economic mitigation potential for agriculture in all
295 1.5°C pathways is 3.3 – 4.1 GtCO₂e/yr in 2050, in line with our bottom-up estimates of 0.3 – 3.4
296 GtCO₂e/yr. Since agriculture accounts for 56% of methane emissions, and 27% of potent short-
297 lived gases, reducing CH₄ emissions from livestock and rice cultivation would reduce global
298 warming effects sooner and may offset delays in reducing emissions⁴⁵.

299

300 On the demand side, shifting diets and reducing food waste provided large mitigation,
301 contributing 0.7 - 8 GtCO₂e/yr (range of “healthy diet” to vegetarian diet) and 0.8 – 4.5
302 GtCO₂e/yr respectively. A recent study finds “plausible” mitigation potential of 2.2 GtCO₂e/yr

303 (0.9 GtCO₂e/yr without land-use change impacts) if 50% of the global population adopted diets
304 constrained to ~60g of meat protein per day, and 2.4 GtCO₂e/yr (0.9 GtCO₂e/yr without land-use
305 change impacts) if food waste is reduced by 50% in 2050⁴². Decreasing meat consumption and
306 reducing food waste reduces overall production, which reduces water use, soil degradation,
307 pressure on forests, land used for feed, and water pollution⁴⁶. Improving woodfuel use by
308 increasing clean cookstoves provides moderate mitigation potential (0.1 – 0.8 GtCO₂e/yr), and
309 also delivers high co-benefits of improved air quality and health⁴⁷. The mitigation potential of
310 increasing wood products to replace more energy-intensive building materials like steel and
311 concrete is also moderate (0.3 - 1 GtCO₂e/yr), however, wood sourcing would need to be
312 managed sustainably to avoid negative impacts to biodiversity and natural resources.

313

314 Brazil, China, Indonesia, the EU, India, Russia, Mexico, the US, Australia and Colombia
315 represent 54% of global AFOLU emissions⁴⁸, and are the 10 countries/regions with the highest
316 mitigation potential in the land sector (Figure 5). In tropical countries, the highest mitigation
317 potential is from carbon removals (A/R and forest management) and reduced land-use change
318 (deforestation, peatland and coastal conversion). Brazil and India also have substantial mitigation
319 potential in reducing enteric fermentation. Mitigating emissions from rice cultivation is
320 important in Asian countries. Large emerging countries, China, India, and Russia, as well as
321 developed countries in the EU, the US and Australia have large mitigation potential from A/R
322 and forest management, as well as reduced emissions from enteric fermentation, synthetic
323 fertilizer and manure.

324

325 The regional mitigation potentials do not include demand-side potential. However, based on
326 current consumption of beef and food losses and waste (SI-section 3), the highest diet shift
327 potential lies in the US, EU, China, Brazil, Argentina and Russia. The largest food waste

328 potential from consumers is in the US, China and the EU. Southeast Asia and Sub-Saharan
329 Africa have the greatest avoided food loss potential from production. The EU and China also
330 have high potential to reduce the consumption of commodities associated with deforestation
331 (palm oil, soy, beef, leather, timber)⁴⁹.

332 Land sector roadmap for 2050

333 The land sector transformation characterized in the 1.5°C modelled pathways will require
334 significant investment and action. Given that land interventions have interlinked implications for
335 climate mitigation, adaptation, food security, biodiversity and other ecosystem services, we
336 developed a roadmap of priority activities and geographies through 2050 (Figure 6) to illustrate a
337 potential path of action for achieving climate and non-climate goals. Using the median top down
338 (13.5 GtCO₂e/yr) and bottom up (14.6 GtCO₂e/yr) estimates, we established a viable mitigation
339 target (sum of emission reductions and removals) for the land sector of ~14 GtCO₂e/yr (15
340 GtCO₂e/yr with BECCS) in 2050. We then divided the required effort into priority mitigation
341 measures, or “wedges”, first by qualitatively weighing associated risks and trade-offs and
342 prioritizing activities that maximize co-benefits and overlap with Sustainable Development
343 Goals (SDG) and targets in the New York Declaration on Forests (NYDF) (Table S6), and then
344 determining mitigation potentials according to their feasibility and sustainability from the
345 bottom-up mitigation analysis (Table S5). The resulting eight priority wedges maximize
346 emissions reductions from land-use change, and use “sustainable estimates” that are also “cost
347 effective” for carbon sequestration measures, “plausible” estimates for demand-side measures,
348 and conservative economic potentials for agriculture measures (estimates are highlighted in
349 Figure 4). For each wedge, we highlighted important regions and activity types based on bottom-
350 up mitigation potentials, trade-offs, and constrained by a political feasibility analysis (SI-section

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

353

354 The 15 GtCO₂/yr roadmap mitigation target delivers ~30% of global mitigation, reducing gross
355 emissions by 7.4 GtCO₂e/yr (4.6 GtCO₂e/yr from reduced land-use change, 1 GtCO₂e/yr from
356 agriculture, and 1.8 GtCO₂e/yr from diet shifts and reduced food waste) and increasing carbon
357 removals by 7.6 GtCO₂/yr (3.6 GtCO₂/yr from restored forests, peatlands and coastal wetlands,
358 1.6 GtCO₂/yr from improved plantations and agroforestry, 1.3 GtCO₂/yr from enhanced soil
359 carbon sequestration and biochar, and 1.1 GtCO₂/yr from the conservative deployment of
360 BECCS) (Figure 6a). Carbon removals of 1.1 GtCO₂/yr using BECCS on degraded and marginal
361 lands requires <100 Mha of land⁵⁰ and is within the lower range of “sustainable potential”¹⁷.
362 Each mitigation wedge is associated with a wide portfolio of activities and countries, illustrating
363 that no single strategy or region will be sufficient to deliver on the mitigation target (Figure 6b).
364 Near-term priorities include avoided land-use change in the tropics (deforestation, peatland
365 burning and mangrove conversion), carbon sink enhancement in developed and emerging
366 countries (restoration, forest management, agricultural soils), and reduced food waste in
367 developed countries and China (SI-section 4). The total mitigation effort of 15 GtCO₂e/yr would
368 make the AFOLU sector a net carbon sink of 3 GtCO₂e/yr by 2050 based on current AFOLU
369 emissions of ~12 GtCO₂e/yr.

370

371 Our illustrative roadmap diverges with some 1.5°C modelled pathways. Seeking to avoid
372 undesirable impacts from larger-scale deployment of BECCS, our roadmap relies on deeper
373 emissions reductions from lifestyle changes like reducing food waste and shifting diets and
374 higher removals from ecosystem-based sequestration including forest, peatland and coastal
375 mangrove restoration, forest management and agricultural soils. The roadmap will also require

376 additional mitigation effort in the energy sector due to reduced BECCs. Thus, our roadmap may
377 be more expensive than a cost-optimized model pathway. However, the trade-offs illustrated in
378 our roadmap increase the likelihood of limiting warming to 1.5°C (or 2°C) and enhance our
379 ability to deliver on other social and environmental goals, potentially offsetting additional costs
380 not captured in the models.

381

382 While mitigation in the land sector is essential for meeting the targets of the Paris Agreement,
383 the land sector is also central to delivering on the SDGs. The roadmap described here reduces
384 deforestation by 95% by 2050, contributing to the NYDF and SDG goals of halving
385 deforestation by 2020 and halting deforestation by 2030. Our restoration wedge (3 GtCO₂/yr of
386 reforestation, 0.4 GtCO₂/yr of peatland restoration and 0.2 GtCO₂/yr of coastal mangrove
387 restoration) would restore forests on >320 Mha of land²⁰ by 2050— an area consistent with NYDF
388 and SDG targets of 350 Mha by 2030. Our mitigation wedges also contribute to the 2030 SDG
389 goals of sustainably managing forests, conserving biodiversity, reducing water and air pollution,
390 increasing agricultural productivity, and promoting sustainable consumption and production.

391 Challenges and Opportunities

392 Our analysis, similar to other studies^{2,4,11}, shows that delivering on the Paris Agreement’s target
393 of 1.5°C is daunting, yet still within reach if ambitious mitigation is implemented and substantial
394 negative emissions are deployed. Limiting warming to 1.5°C will require more effort than the
395 2°C target and current NDCs. While both targets require steep emission reductions from tropical
396 deforestation, the 1.5°C goal will require earlier and deeper reductions in agricultural and
397 demand-side emissions, and enhanced carbon removals in the land sector. We show that model
398 results and bottom-up analysis differ on types of mitigation measures included and their relative

399 mitigation contributions, and that additional considerations are needed to account for feasibility
400 and sustainability. In our roadmap, the land sector can deliver 15 GtCO₂e/yr (~30% of climate
401 mitigation) by 2050 while contributing to various sustainable development goals. However, top-
402 down and bottom-up mitigation estimates do not reflect biophysical changes nor show how
403 potentials will be affected by future climate change, therefore more research is needed.
404 Furthermore, implementing the roadmap comes with important challenges.

405

406 **Negative emissions and BECCS**

407 The impacts associated with large-scale deployment of BECCS on natural ecosystems and
408 agricultural land, and the risks from high CDR reliance later in the century is discussed in this
409 review and recent literature^{4,14,17,20,29–32}. Better incorporating environmental and social
410 safeguards in IAMs and scenario setting, and emphasizing alternative pathways of early carbon
411 removal and lifestyle changes in climate policy discussions may help address some of these
412 risks. Despite the risks from BECCS, negative emissions will be necessary to limit warming to
413 <2°C. Counterintuitively, halting the development of carbon removal technologies like CCS and
414 BECCS without a replacement could yield more detrimental effects on land and climate due to
415 the potential for increased use of bioenergy as a cheap energy source without the benefit of
416 sequestration^{1,3,4}. Research, development, and investment in negative emissions technologies
417 today could assist their sustainable deployment^{20,32} in the future^{20,32}.

418

419 **Scaling up action in the land sector**

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

424

425 Despite efforts to reduce deforestation over the last decade, land-use change emissions have
426 increased modestly due to surging tropical deforestation⁵¹. More than 8 Mha of tropical forests
427 are lost every year⁵¹, and yet deforestation must decline 70% by 2030 and 95% by 2050 to align
428 with a roadmap to 1.5°C. Commitments toward ecosystem restoration have been increasing, with
429 a majority of countries (122 of 165 that submitted) including forest restoration pledges in their
430 NDCs. However, only 20% of countries included quantifiable targets, amounting to 43 Mha, and
431 our roadmap suggests >320 Mha of new or restored forests will be needed. Empirical evidence is
432 lacking on progress in addressing emissions in agriculture (non-CO₂ emissions and soil carbon)
433 and demand-side measures.

434

435 Major barriers to delivering AFOLU mitigation include political inertia and weak governance.
436 Addressing agricultural emissions is limited by concerns about negative trade-offs, such as food
437 security, economic returns, and adverse impacts on smallholders²¹. Demand-side measures –
438 reducing food waste and shifting diets – have proceeded slowly because of limited awareness
439 and political support, in addition to the difficulties of eliciting behavioural change⁵². Similarly,
440 development of negative emissions technologies is stymied primarily due to low awareness, low
441 prioritisation, and concerns about negative trade-offs.²⁸ Increased dialogue between scientists
442 and policymakers is important for bridging the knowledge gap in “no-regret” options for
443 mitigation and catalysing political action.⁵³ Key areas of necessary research include
444 breakthrough technologies and approaches in behavioural science, meat substitutes, livestock
445 production systems including new feed, peatland restoration, improved fertilizer, seed varieties,
446 CCS, and advanced biofuels.

447

448 Governance issues related to illegality and a lack of enforcement have been major challenges for
449 addressing land-use change, particularly deforestation and peatland fires in the tropics⁵⁴.

450 Effectively reducing deforestation and scaling up restoration depends on understanding local
451 dynamics at the forest frontier and coordinated action among private and public actors –
452 exemplified by the successes in Brazil⁵⁴. Agricultural intensification combined with forest
453 restoration on spared land holds significant potential when accompanied by stringent land
454 policies and enforcement and demand-side measures (e.g. reduced meat consumption)⁵⁵. Less
455 intensive forestry systems have also shown success in avoiding deforestation if land tenure
456 security is combined with best forest management practices⁵⁶.

457

458 Efforts to reduce emissions from deforestation and degradation and promote A/R often have
459 higher transaction and implementation costs than expected, and existing finance for forest
460 protection is inadequate⁵⁷. Climate finance for forests accounts for 1% (\$2.3 billion) of global
461 public climate funding (\$167 billion), and 0.3% of total public and private land sector funding in
462 countries with high levels of deforestation (\$777 billion)⁵⁸. A lack of finance, high transition
463 costs and low expected returns from changed practices are the main challenges for farmers^{21,59,60}.

464 A significant shift from traditional investments in the land sector (e.g., intensified commodities
465 with no environmental benefits) to financing that promotes sustainable land-use and capacity
466 building at the farm level will be needed to scale up action.

467

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

473

474 **Methods**

475 Detailed methods, including data used and produced with associated references are available in
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477

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493

494 **Author contributions**

495 S.R. led the study design and the writing of the paper with significant contributions from D.L.,
496 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

497 model assessment land sector pathways, S.R. and B.G. the bottom-up mitigation potential, and
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500 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
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502

503 **Competing financial interests**

504 The authors declare no competing financial interests.

505

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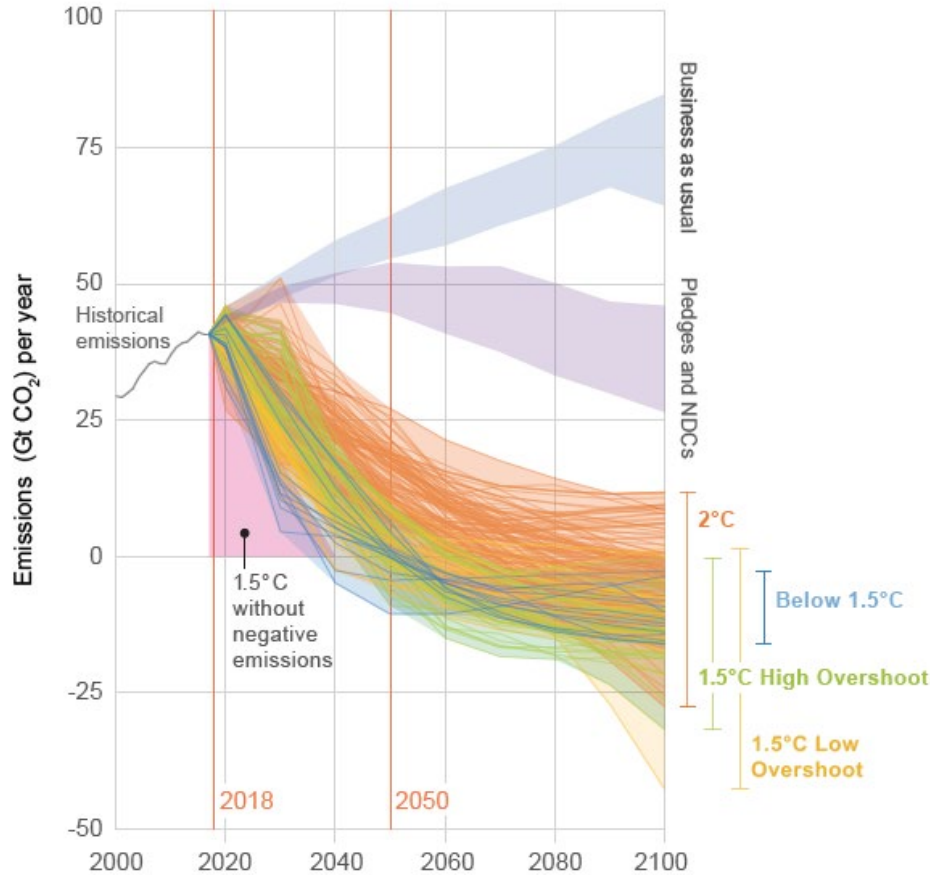
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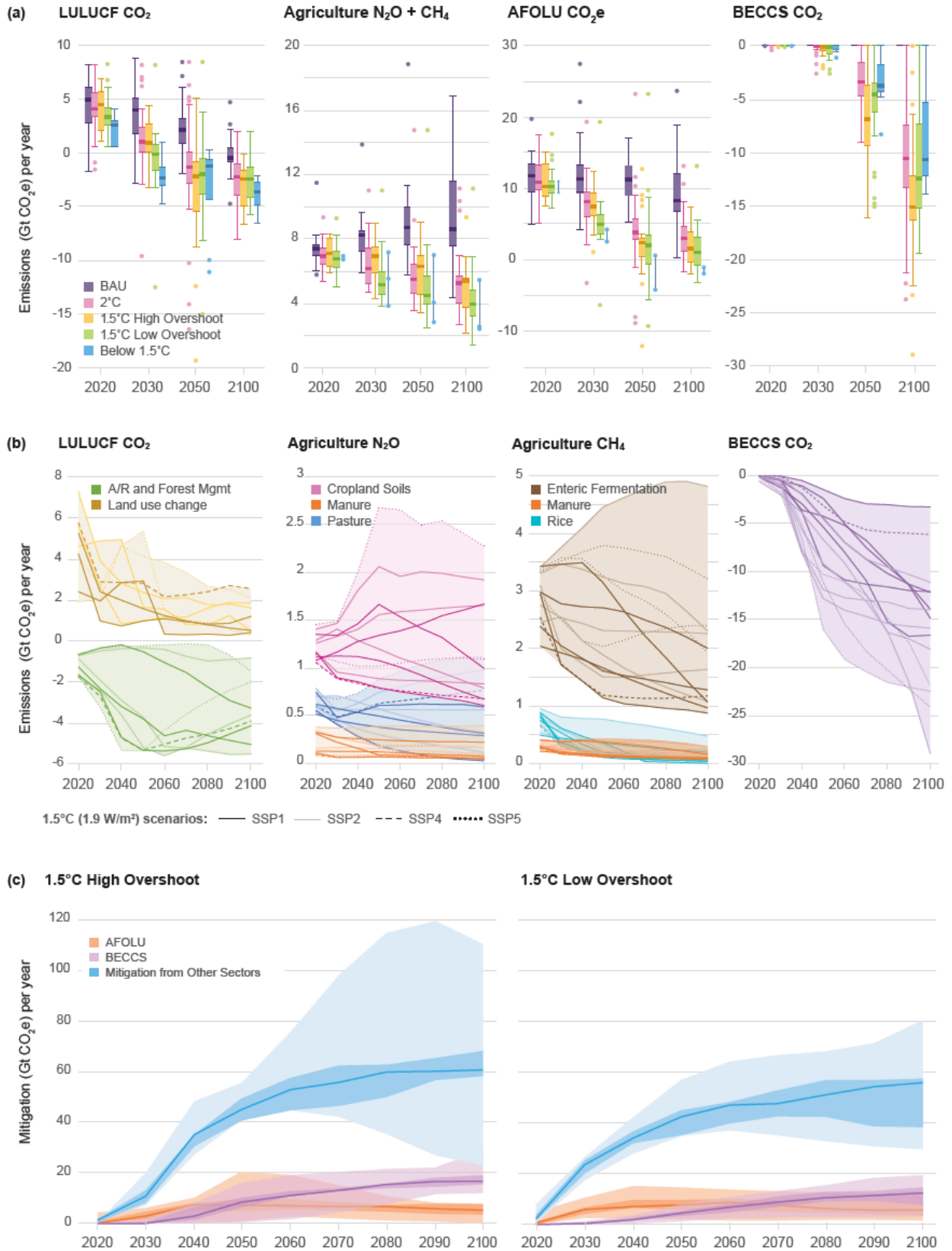
721 Figures and Tables

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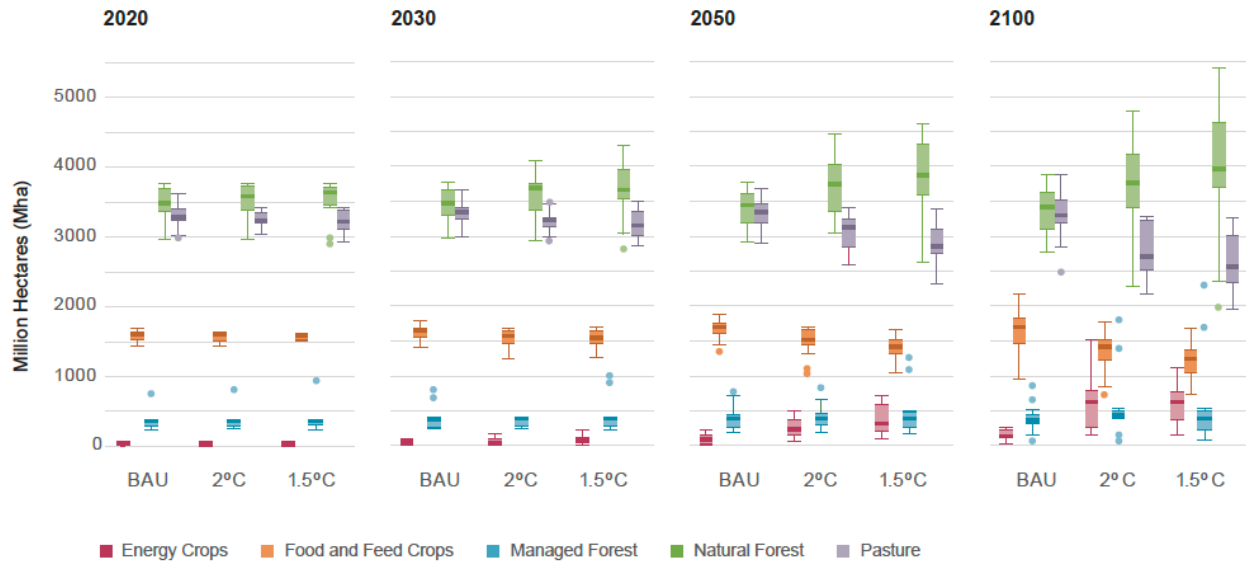
724 Figure 1. Synthesis of global net anthropogenic CO₂ emissions trajectories of 2°C, 1.5°C high overshoot, 1.5°C low
 725 overshoot and below 1.5°C scenarios, in GtCO₂/year. The 2°C (132 model runs, orange lines), 1.5°C high overshoot (37
 726 model runs, green lines), 1.5°C low overshoot (44 model runs, yellow lines) and Below 1.5°C (9 model runs, blue lines)
 727 pathways from the recently released Integrated Assessment Modeling Consortium (IAMC) 1.5°C Database²², present values
 728 at a >66% probability threshold (2°C and 1.5°C high overshoot) and 50-66% probability threshold (1.5°C low overshoot and
 729 below 1.5°C scenarios)⁴. More details on these emission trajectories, comparisons with other carbon budgets in the
 730 literature, and a variant of the figure including all greenhouse gases in CO₂e can be found in SI-section 1. The Mitigation for
 731 1.5°C without negative emissions scenario (pink wedge) represents the range of remaining allowable emissions from the
 732 IPCC Special Report on 1.5°C carbon budgets of 420 GtCO₂ from 2018 (see SI-section 1). NDC numbers are adapted from
 733 Climate Action Tracker, 2018, removing non-CO₂ emissions. Business as usual numbers represent the range of SSP2
 734 baseline scenarios for 1.9 W/m² from the SSP Database¹¹. Historical emissions data is from the Global Carbon Project⁶



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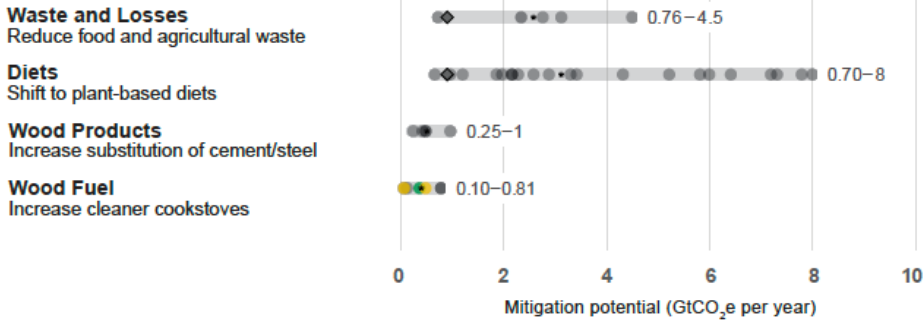
Figure 2. (a) Range of land sector emissions pathways in LULUCF, Agriculture, AFOLU (LULUCF +Agriculture) and BECCS in business as usual (BAU), 2°C, 1.5°C high overshoot, 1.5°C low overshoot and below 1.5°C scenarios. Boxplots show the median, interquartile range, and minimum-maximum range of pathways. 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 Database²² (b) 1.5°C Mitigation pathways of land-based activities in LULUCF, agriculture and BECCS from the SSP

741 Database^{11,13}. Shaded areas show the minimum-maximum range across the SSPs per activity. Single pathways are lines,
 742 styled according to the SSP scenario in the legend. (c) Total mitigation of AFOLU, BECCS and Other sectors (total global
 743 mitigation minus AFOLU and BECCS) in the 1.5°C high overshoot and 1.5°C low overshoot scenarios. Below 1.5°C
 744 scenarios are not illustrated due to too few data points. Total mitigation is calculated as the reference scenario minus 1.5°C
 745 for each model and scenario, then summed for AFOLU, BECCS and Other sectors. Shaded areas show the minimum-
 746 maximum range (light shading), interquartile range (dark shading) and median (dark line). Data is from the IAMC
 747 Database²². The GHG flux of bioenergy plantations is accounted for in the land sector until harvest (i.e. these are included
 748 as part of the AFOLU flux), then bioenergy, processing, use and carbon removal through CCS is accounted for in the energy
 749 sector (BECCS). Additional energy and industry sector mitigation falls under all Other sectors.
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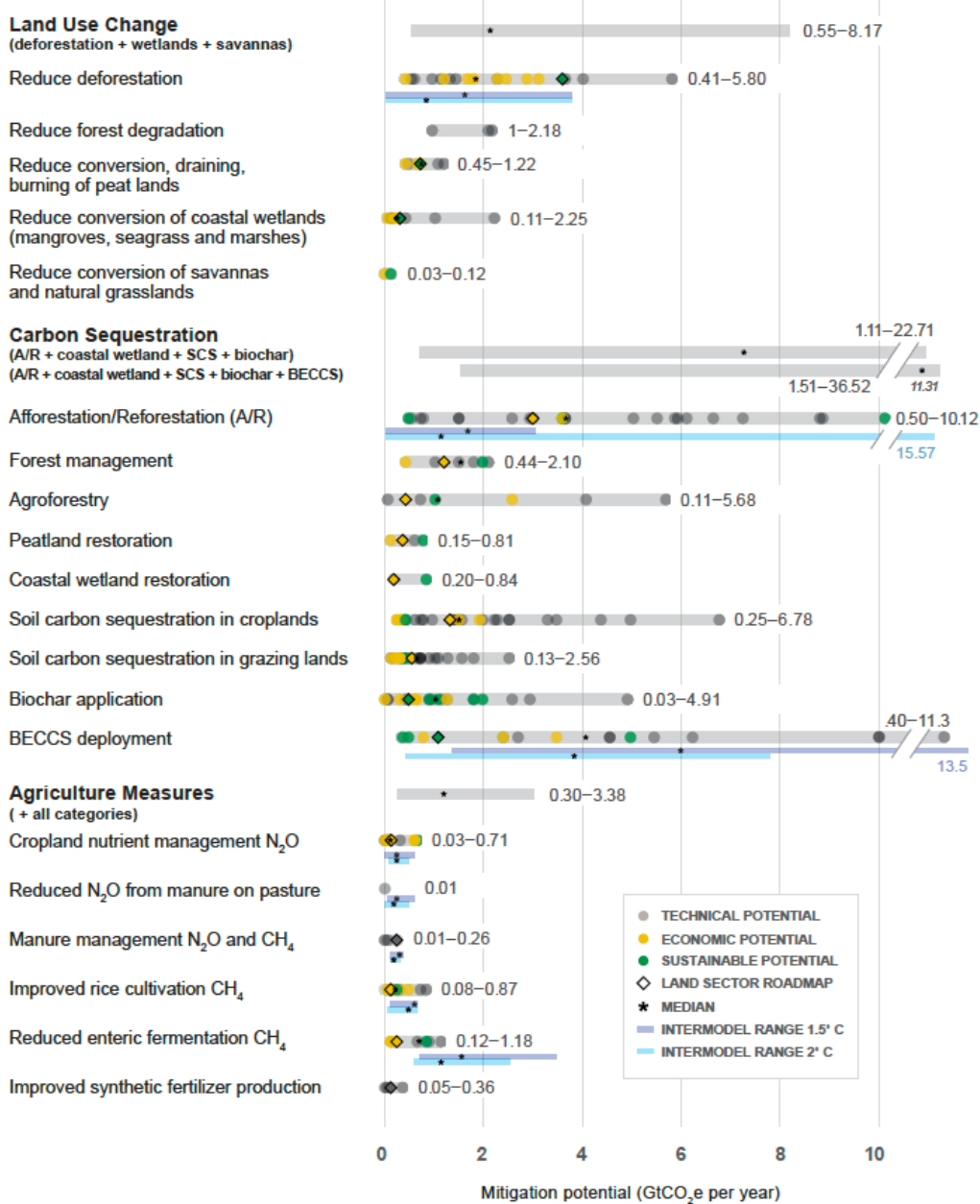


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 758 **Figure 3. Land cover balance in million hectares (Mha) in BAU, 2°C and 1.5°C scenarios from the SSP Database¹¹. Natural**
 759 **forests (unmanaged forests) are primary, secondary, and protected forests with no planned timber production and tree**
 760 **felling either for wood extraction or for silvicultural purposes such as pre-commercial thinnings. Some models account for**
 761 **afforestation and reforestation (A/R) under natural forests, which is why natural forests increase over time in certain models**
 762 **and scenarios (SI-section 3). Managed forests are forests which are managed either for timber production and/or carbon**
 763 **sequestration, in some models, including BECCS. Energy Crops are short rotation plantations and other feedstocks for**
 764 **bioenergy including BECCS.**
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DEMAND SIDE MEASURES



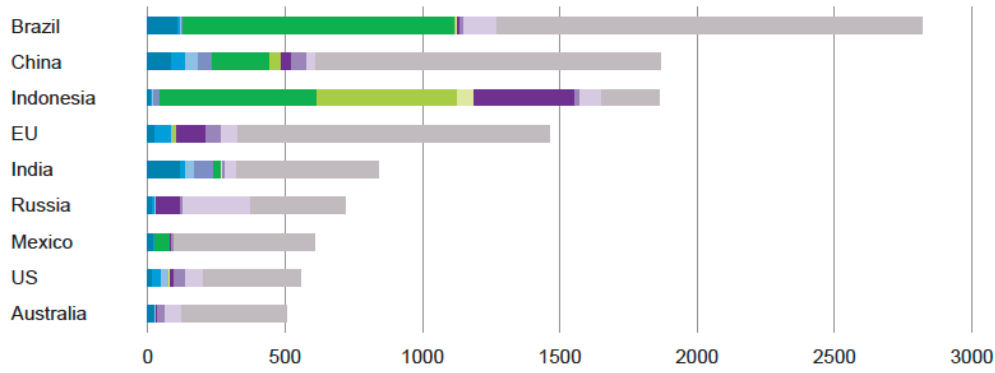
SUPPLY SIDE MEASURES



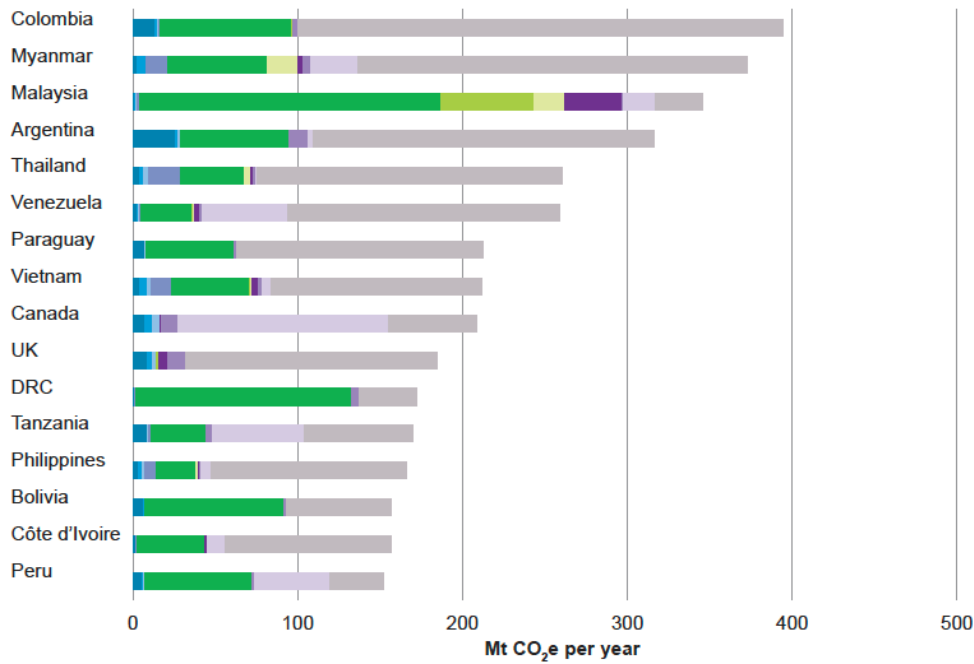
References

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771 *Figure 4. Land-based mitigation potential in 2020-2050 by activity type, measured in GtCO₂e/yr. Mitigation potentials reflect*
772 *the full range of low to high estimates from studies published after 2010, and are differentiated according to technical*
773 *(possible with current technologies), economic (possible given economic constraints) and sustainable potential (technical or*
774 *economic potential constrained by sustainability considerations). Medians are calculated across all potentials in categories*
775 *with >4 data points. We only include references that provide global mitigation potential estimates in CO₂e/yr (or similar*
776 *derivative) by 2050. Supply-side and demand-side measures are treated separately as these two categories are not*
777 *additive. Supply-side measures are activities that require a change in land-use and/or management. Demand-side measures*
778 *are activities that require a change in consumer behaviour. The analysis was designed to avoid potential double-counting of*
779 *emissions reductions – the summed categories are highlighted in the supply-side measures (e.g. total land use change*
780 *“deforestation+wetlands+savannas” excludes forest degradation and peatlands as these categories are included in many*
781 *estimates). More information on the methods and description of activities are in SI-section 3. To compare with bottom-up*
782 *potentials, top-down intermodel ranges and medians are included in available categories from the 2°C and 1.5°C scenarios*
783 *in the SSP Database. The models reflect land management changes, yet in some instances, can also reflect demand-side*
784 *effects from carbon prices, so may not be defined exclusively as “supply-side.” Estimates used for the Land Sector*
785 *Roapmap are given more context in Figure 6.*
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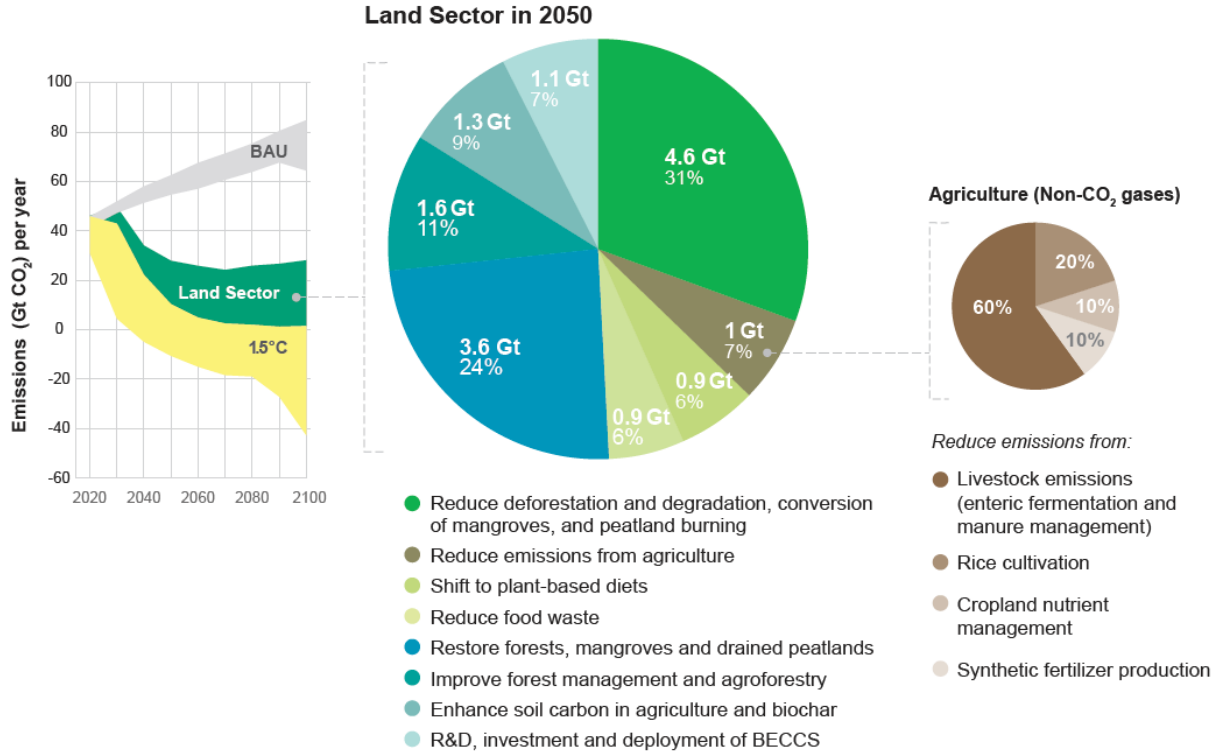
Mitigation by countries with < 500 Mt CO₂e per year



- | | | |
|------------------------|---|-------------------------------|
| Agriculture | Carbon Sink Enhancement | Land Use Change |
| ■ Enteric fermentation | ■ Afforestation/Reforestation | ■ Reduced deforestation |
| ■ Manure management | ■ Forest management | ■ Reduced peatland conversion |
| ■ Synthetic fertilizer | ■ Peatland restoration | ■ Reduced coastal conversion |
| ■ Rice cultivation | ■ Agriculture soil carbon sequestration | |

787
 788 *Figure 5. Land sector mitigation potential by country/region measured in Mt CO₂e per year. The top 25 countries with the*
 789 *highest mitigation potential are presented, nine with over 500 Mt CO₂e per year and 16 with 100 to 400 Mt CO₂e per year.*
 790 *Numbers are compiled from country mitigation potentials in Griscom et al. (2017) (Rice cultivation, Forest management,*
 791 *Peatland restoration, A/R, Reduced deforestation, Reduced peatland conversion, and Reduced coastal conversion), as well*
 792 *as percentages of FAOSTAT emissions data calculated for this study (Enteric fermentation, Manure Management, Synthetic*
 793 *Fertilizer and Agriculture soil carbon enhancement (Table S4 in SI-section 3)*
 794

795 (a)



796

Wedge	Priority regions for mitigation	Activity types	Implementation trajectory: % reduction (green) or cumulative increase in removals GtCO ₂ (blue)			
			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 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 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

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Figure 6. Land sector roadmap for 2050. (a) Land-based mitigation wedges to deliver total mitigation of ~15 GtCO₂e/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 GtCO₂e/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 GtCO₂e/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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37 Methods

38
39 To provide a comprehensive assessment of the entire land sector (agriculture, LULUCF, and
40 bioenergy), and its potential contributions to the Paris Agreement temperature target of 1.5°C,
41 we conducted four separate, yet complementary analyses: 1) Review and synthesis of published,
42 economy-wide 1.5°C pathways, 2) top-down comparative analysis of integrated assessment
43 modelling of 1.5°C pathways in the land sector, 3) review and bottom-up assessment of land
44 sector mitigation potential, updating the IPCC AR5 Ch11 findings, and 4) a geographically
45 explicit roadmap of priority mitigation measures or “wedges” and regions to fulfil the 1.5°C land
46 sector transformation pathway, informed by a triangulation of the first three analyses.

47
48 The detailed methods and some resulting data are outlined below, structured in four sections
49 according to the four analyses.

52 SECTION 1. Review of 1.5°C pathways

53
54 We assess the pathways to 1.5°C and 2°C by compiling and analysing published, publicly
55 available modelled data for emissions reductions to 2100. We chose studies that modelled
56 emissions pathways for 1.5°C and 2°C scenarios, including scenarios that exceeded one or both
57 of the temperature targets but met the target by the end of the 21st century. The studies were
58 examined on a decade by decade basis, and we explored the assumptions regarding reductions in
59 land versus non- land sectors, negative emissions deployment, total carbon budgets until 2100,
60 and forecast trajectories of emissions reductions.

61
62 We examined both 2.6 w/m² (2°C forcing target) and 1.9 w/m² (1.5°C forcing target) Integrated
63 Assessment Model (IAM) runs from the Shared Socioeconomic Pathways (SSP) Database^{1,2}
64 published in Rogelj et al. (2018)², the Integrated Assessment Modeling Consortium (IAMC)
65 Database³ that accompanied the IPCC special report on 1.5C, as well as individual estimates
66 from Rockstrom et al. (2017)⁴, Millar et al. (2017)⁵, Walsh et al. (2017)⁶, Goodwin et al. (2018)⁷,
67 and Tokarska and Gillett (2018)⁸. Rogelj et al. (2015)⁹ was also reviewed but excluded in the
68 analysis given its overlap with the new Rogelj et al. (2018) which assessed the same underlying
69 IAMs with small version differences. The 2.6 w/m² model runs suggest that emissions reductions
70 of between 70% and 90% are needed between 2020 and 2060, with net-negative emissions in
71 most models starting between 2060 and 2080 in order to meet a 66% probability threshold
72 keeping emissions below 2°C by 2100. 1.9 w/m² models require still steeper reductions, with
73 emissions dropping to zero in all models between 2040 and 2060 and net-negative thereafter for
74 the same probability threshold of 66%.

75
76 The total carbon budget available in the SSP Database 2.6 w/m² models between 2018 and 2100
77 ranges from 436 GtCO₂ to 1159 GtCO₂, with a median estimate of 964 GtCO₂. Models limiting
78 2100 radiative forcing to 1.9 w/m² (and 2100 temperatures to below 1.5°C) show
79 correspondingly smaller carbon budgets from 2018-2100, ranging from requiring net-negative
80 emissions of -174 GtCO₂ to allowing up to 402 GtCO₂, with a median estimate of 237 GtCO₂.
81 Much of the difference in the budgets results from the treatment of non-CO₂ GHGs and aerosols
82 in different IAMs^{2,9}, though the duration of net-negative emissions can also affect the results as it

83 tends to deviate from the linear relationship between cumulative CO₂ and warming during
84 periods of positive emissions¹⁰.

85
86 The IAMC Database³ models also include a wide range of 2018-2100 carbon budgets. Excluding
87 those model runs also found in the SSP Database, the IAMC 2C runs have a budget ranging from
88 135 GtCO₂ to 1887 GtCO₂ with a median estimate of 951 GtCO₂. IAM 1.5C runs have a
89 correspondingly lower cumulative carbon budget, ranging from -182 GtCO₂ to 745 GtCO₂ with a
90 median of 144 GtCO₂.

91
92 Individual studies (Rockstrom et al. (2017), Walsh et al. (2017), and our own estimates) of the
93 available carbon budget to limit 2100 warming to below 1.5°C provide results comparable to the
94 range of SSP and IAMC Database IAMs for both 2°C and 1.5°C targets. Rockstrom et al.
95 combined published model findings with expert judgment to prescribe a 50% reduction in CO₂
96 emissions per decade (88% total) between 2020 and 2050 until net zero emissions are reached in
97 order to meet a 66% probability threshold for 2°C and a 50% probability threshold for 1.5°C,
98 with an available 2018-2100 carbon budget of 132 GtCO₂. Walsh et al. derive emissions and
99 temperature change from the FeliX integrated assessment model to find CO₂ emissions must
100 peak in or slightly before 2020 and achieve net zero by about 2040 for 1.5°C, equating to 5%
101 annual emissions reductions, and net zero by 2050 for 2°C, equating to 3% annual emissions
102 reductions – or 100% and 97% by 2050, respectively. Their available 2018-2100 carbon budget
103 is 371 GtCO₂ for 2°C and -489 GtCO₂ for 1.5°C, respectively, and is a bit below the range of
104 values for IAM models. Our own model suggests 2018-2100 budgets of 979 GtCO₂ for 2°C and
105 268 GtCO₂ for 1.5°C, close to the median of SSP Database models.

106
107 The SSP and individual IAM studies represent avoidance budgets that target limiting warming in
108 2100 below 1.5°C by limiting end-of-century forcings to around 1.9 w/m². Millar et al. (2017),
109 Goodwin et al. (2018), and Tokarska and Gillett (2018) use observational warming and
110 cumulative emissions to-date to observationally constrain CMIP5 Earth System Model (ESM)
111 results, and suggest significantly higher remaining 1.5°C carbon budgets than IAM-based
112 approaches. Remaining 2018-2100 carbon budgets in Millar et al. are 625 GtCO₂ to 695 GtCO₂
113 for a 66% to 50% chance of preventing warming from exceeding 1.5°C, respectively. Goodwin
114 et al. find a similar range from 693 GtCO₂ to 766 GtCO₂, while Tokarska and Gillett find
115 somewhat lower values (395 GtCO₂ and 681 GtCO₂) for a 66% and 50% chance. These papers
116 calculate exceedance rather than avoidance budgets, looking at how long emissions can continue
117 increasing by 1% per year until temperatures exceed 1.5°C.

118
119 As Rogelj et al. (2018) point out, observation and ESM-based exceedance budgets that increase
120 CO₂ by 1% per year until temperatures exceed 1.5°C and IAM-based avoidance budgets that
121 limit radiative forcing to 1.9 w/m² (and temperatures to below 1.5°C) in 2100 are not easily
122 comparable. ESM-based approaches use the 50th and 66th percentiles of CMIP5 models, while
123 IAMs use a proscribed climate sensitivity probability density function. This leads to somewhat
124 more conservative outcomes among IAM-based approaches. While exceedance budgets using
125 ESMs that have a 66% chance of avoiding 1.5°C still show maximum warming of around
126 1.45°C, IAMs with a 66% chance of avoiding 1.5°C have much lower 2100 warming, reaching
127 only 1.3°C to 1.4°C above pre-industrial levels (though most IAMs exceed 1.5°C mid-century
128 before reducing temperatures through the large-scale application of negative emissions).

129
130 Because the maximum warming lags emissions of carbons by about a decade, exceedance
131 budgets do not fully account for emissions over the final decade before the 1.5°C threshold is

132 exceeded. IAMs, on the other hand, are somewhat penalised because the cooling from negative
 133 emissions in the last decade before 2100 is not fully accounted for². Additionally, many
 134 observationally-constrained ESM budgets use global surface temperature records that are not
 135 globally complete and use slower-warming ocean surface temperatures rather than the surface air
 136 temperatures over oceans^{11,12}.

137
 138 These combine to make IAM-based avoidance carbon budgets relatively low compared to
 139 combined observation/ESM exceedance budgets. Rogelj et al. (2018) recalculated the Millar et
 140 al. carbon budget and found that a comparable globally-representative 2018-2100 avoidance
 141 budget would be somewhere between 25 GtCO₂ and 375 GtCO₂, overlapping with the majority
 142 of SSP Database IAM 1.9 w/m² budgets. Thus, we suggest that these recent exceedance budget
 143 studies are not necessarily at odds with the 1.5°C budgets used in this paper. Similarly, while the
 144 IPCC SR15 provides a best-estimate remaining 1.5C carbon budget of 420 GtCO₂, this value is
 145 not inconsistent with IAM-derived 2018-2100 cumulative budgets due to the differences in
 146 exceedance and avoidance calculations.

147
 148 The IAM studies show a dramatic transformation of the energy and land sectors. Energy system
 149 transformation is generally characterized by a fossil fuel phase out, energy efficiency
 150 improvement, more rapid decarbonization of electricity compared to industry, buildings and
 151 transport, and extensive use of CO₂ capture and storage (CCS)⁹. The land sector transformation
 152 includes a dramatic decline in deforestation, a significant increase in afforestation and
 153 reforestation (A/R) and forest management, and reduced agricultural emissions after 2030-2040,
 154 facilitated by improved crop production efficiencies and yields^{13,14}. These broad transformations
 155 are in line with those observed in the main IPCC AR5 RCP 2.6 scenario.

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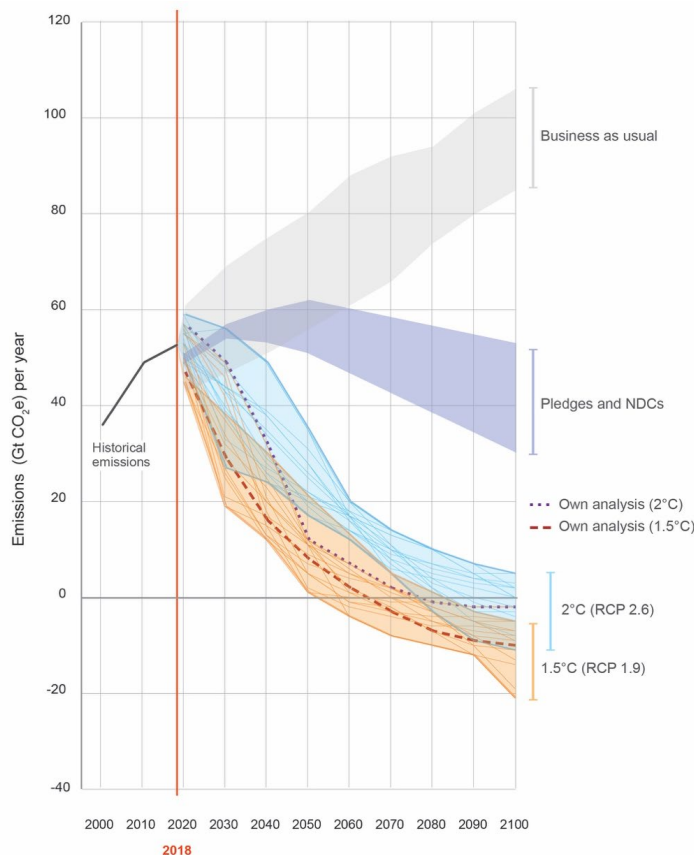


Figure S1. Greenhouse gas emission trajectories (in GtCO₂e per year using 100-year global warming potential values) of 2°C and 1.5°C scenarios. This figure includes major anthropogenic greenhouse gas emissions (CO₂, CH₄, N₂O, and various halocarbons) and is a variant of the main text Figure 1 (which only includes CO₂). 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.

157

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

159
160 To gauge the contribution of the land sector in 1.5°C and 2°C pathways, we conducted a
161 comparative assessment of model outputs from the Integrated Assessment Modeling Consortium
162 (IAMC) Database³ and Shared Socioeconomic Pathways (SSP) Database^{1,2}. We reviewed
163 emission pathways and land cover balances of the various pathways. We also conducted a
164 sensitivity analysis to test the effect of reducing BECCS.

165 Emission pathways

166 We used the IAMC Database³ (Version 1.0) to assess net CO₂, CH₄, and N₂O emissions
167 trajectories to 2100 in 1.5°C (1.9 w/m²), 2°C (2.6 w/m²), and Reference (BAU) scenarios in
168 LULUCF, Agriculture and BECCS (Figure 2a). We combined the LULUCF and Agriculture
169 categories to derive trajectories for AFOLU. We calculated the mitigation potential for the land
170 sector in the 1.5°C scenarios by summing mitigation potentials from AFOLU and BECCS
171 (Figure 2c). Mitigation potential for all other sectors represents global mitigation minus land
172 sector mitigation. Mitigation potential is the difference between the reference scenario and the
173 1.5°C scenario for each model and scenario, summed for AFOLU, BECCS and Other sectors.
174 The Database represents 19 models and 90 model scenarios. More detailed information is
175 provided in the IPCC Special Report on 1.5°C Chapter 2¹⁵ and the IAMC Database website³.

176
177 The IAMC Database does not have data for specific activities in agriculture, therefore, we used
178 the updated SSP Database (Version 2.0)^{1,2} to assess the N₂O emission pathways for Cropland
179 Soils, Manure, and Pastures, the CH₄ emission pathways from Enteric Fermentation, Manure,
180 and Rice, and CO₂ emission pathways for Land-use change, A/R and Forest Management, and
181 BECCS in a 1.5°C scenario (1.9 W/m²) (Figure 2b). We also calculated the mitigation potentials
182 for the mentioned activities (Difference between BAU and 1.5°C for each model scenario) to
183 compare with the bottom-up assessment of literature (Figure 4). The SSP Database represents
184 five Shared Socio-economic Pathways (SSPs – described in Box S1) and includes six integrated
185 assessment models (AIM, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND-MAgPIE, and
186 WITCH-GLOBIOM). Popp et al. (2017)¹³ provide a comparative assessment of emission
187 pathways, land use changes, prices and consequences for the agricultural system across the SSPs
188 in the BAU, 2°C (2.6 w/m²), and 4°C (4.6 w/m²) scenarios – but not for 1.5°C (1.9 W/m²). More
189 detailed information on the SSPs and the six models in the SSP Database, including their
190 underlying assumptions for the energy sector (energy demand, supply and conversion
191 technologies) and the land sector is provided in Riahi et al. (2017)¹ and the Supplementary
192 Information of the same study.

193

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

195 Developed by the scientific community for the IPCC, four RCPs have been developed to provide climate
196 modelers a consistent framework of possible development trajectories for the main forcing agents of climate
197 change (van Vuuren et al., 2011). RCPs can be used in General Circulation Models (more complex, full Earth
198 System Models) and in Integrated Assessment Models (simpler models that use socio-economic development
199 pathways) to project temperature increases and related impacts. Other concentration pathways have been
200 developed, including one with radiative forcing of 1.9 W/m² which is consistent with 1.5°C of warming. The
201 four RCPs include:

- 202 • RCP 2.6: Peak in radiative forcing at ~3 W/m² (~490 ppm CO₂e) and then decline to 2.6 W/m² by 2100

- 203 • RCP 4.5: Stabilization without overshoot pathway to 4.5 W/m² (~650 ppm CO₂e) at stabilization after
- 204 2100
- 205 • RCP 6: Stabilization without overshoot pathway to 6 W/m² (~850 ppm CO₂e) at stabilization after 2100
- 206 • RCP 8.5: Rising radiative forcing pathway leading to 8.5 W/m² (~1370 ppm CO₂e) by 2100

207
208 Five Shared Socioeconomic Pathways (SSP1-SSP5) have been developed by the climate modelling
209 community to facilitate comparable integrated assessments of future climates. The SSPs are based on different
210 socio-economic development narratives, including:

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

216
217 References: ^{1,13}

218

219 **Land cover balance**

220 To assess projected land cover changes, we used the updated SSP Database (Version 2.0)^{1,2} to
221 compare land cover (Mha) trajectories in 1.5°C (1.9 w/m²), 2°C (2.6 w/m²), and BAU scenarios
222 until 2100. We used the SSP Database instead of the IAMC Database as there are more land
223 cover categories (e.g. managed vs unmanaged forests). Two land cover change calculations were
224 assessed: the change in 2050 and 2100 compared to 2020, and compared to BAU for each model
225 and scenario (Table S1).

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

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

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

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

	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

247

248 *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

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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 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 MtCO ₂ /EJ. As CO ₂ 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 CO ₂ 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 CO ₂ 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
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Sensitivity analysis using GLOBIOM

255 We explored the effect of limiting bioenergy demand on land cover balance, and the impact on
256 natural ecosystems and food security using one of the models in the SSP Database, MESSAGE-
257 GLOBIOM²⁴. In the 1.5°C scenario for MESSAGE-GLOBIOM, a significant amount of
258 unmanaged (natural) forests were converted into managed forests to meet additional demand for
259 bioenergy for BECCS. By optimizing for cost-efficiency, the model increased the intensity of
260 forest resource use (share of total harvest volumes in total forest increment) and harvested large
261 areas instead of enhancing harvest in smaller areas. Therefore, in a sensitivity analysis using SSP
262 2, “middle of the road”, we disentangled bioenergy demand from the carbon price by setting a
263 bioenergy threshold at baseline levels (53 EJ/yr and 59 EJ/yr in 2050 and 2100 respectively
264 compared to 109 EJ/yr and 220EJ/yr in the 1.5°C scenario) while still applying the same carbon
265 price trajectories from the 1.5°C and 2°C scenarios. The results are illustrated in Figure S2. In
266 this sensitivity scenario, lower bioenergy demand, and thus mitigation would need to be
267 counterbalanced by additional, more costly efforts in energy (e.g., CCS), negative emissions
268 (potentially technologies like direct air capture), and agriculture. The carbon price would need to
269 increase in the shorter and mid-term to drive these efforts. If agriculture emissions will need to
270 be reduced further, food prices may likely increase in this scenario, and thus potentially affect
271 food security. However, the sensitivity analysis does not represent a fully consistent 1.5°C
272 scenario across all sectors, hence it was not possible to show this effect.

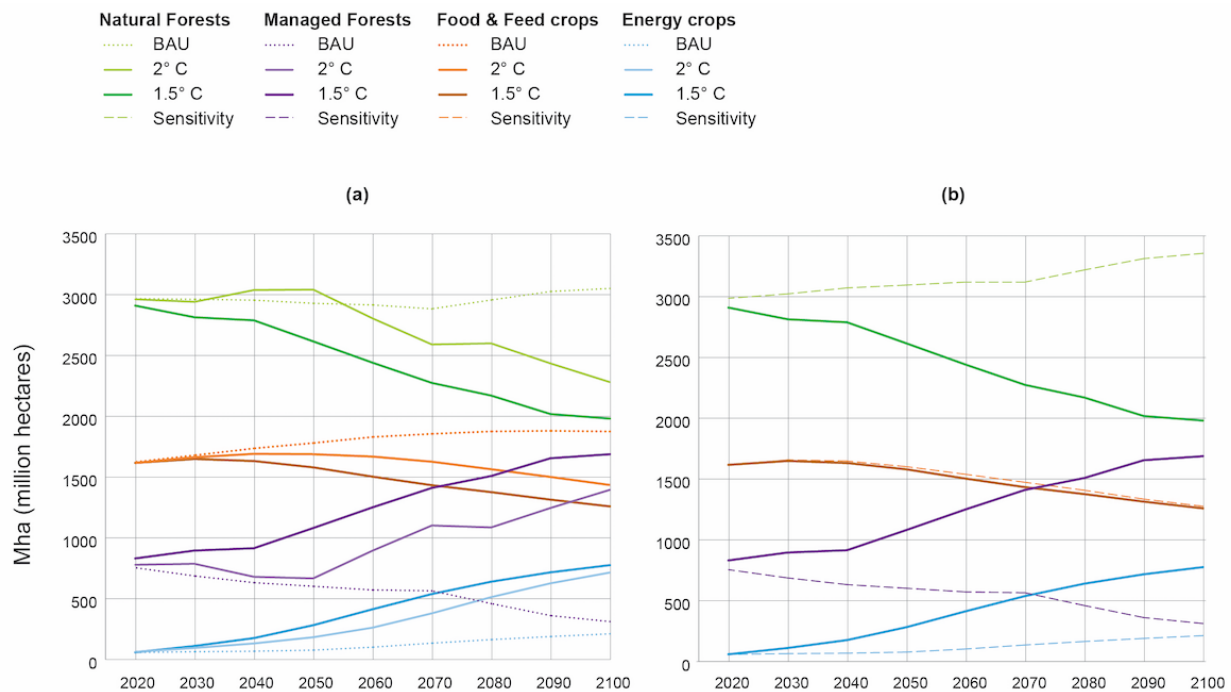
273

274 GLOBIOM is a partial equilibrium model of the global agricultural and forestry sectors. The
275 model is spatially explicit at a high resolution of 5x5 minutes of arc, and depict different
276 production and management systems, differences in natural resource and climatic conditions as
277 well as differences in cost structures and input use. The model explicitly represents technical
278 mitigation options for the agricultural and forestry sectors. For the agriculture sector, mitigation
279 is based on the EPA database on mitigation options²⁵, structural adjustments in the crop- and
280 livestock sector i.e. through transition in management systems or reallocation of production
281 within and across regions²⁴, and consumers’ response to model endogenous price signals²⁶. For
282 the forestry sector the model considers the reduction of deforestation area, increase of
283 afforestation area, and change in forest management activities such as rotation length, thinnings,
284 harvest intensity etc. The carbon price is implemented in the objective function of the model as a
285 tax on GHG emissions, consequently mitigation options get adopted if the carbon price exceeds
286 the marginal cost of a mitigation practice. More information on the mitigation options in the

287 model is provided in Frank et al. (2018)²⁷ and Gusti and Kindermann (2011)²⁸. More detailed
 288 information on GLOBIOM is available in Havlík et al. (2014)²⁴.

289
 290 GLOBIOM is coupled with the MESSAGE²⁹ energy model which calculates carbon prices, as
 291 well as biomass demand for energy use, compatible with the respective climate stabilization
 292 scenarios. Biomass demand in GLOBIOM can be satisfied from multiple sources: managed
 293 forests, short rotation tree plantations and forest industry residues. Bioenergy plantations are
 294 accounted for in the land sector (under forest management) until harvest, then bioenergy,
 295 processing, use and carbon removal through CCS is accounted for in the energy sector. In the
 296 event of conversion of natural forests into managed forests for BECCS, the deforested biomass is
 297 used for BECCS. The MESSAGE energy model and its methodologies and assumptions on
 298 future energy demand and use of fossil fuels, nuclear, renewables, and biomass for energy are
 299 outlined in Fricko et al. (2017)¹⁹.

300



301
 302 *Figure S2. (a) Land cover balance in million hectares (Mha) in BAU, 2°C and 1.5°C scenarios, (b) Land cover balance in*
 303 *Mha in the 1.5°C and sensitivity (bioenergy threshold) scenarios. Unmanaged forests (natural forests) are defined as*
 304 *primary, secondary, and protected forests with no planned timber production and tree felling either for wood extraction or for*
 305 *silvicultural purposes such as pre-commercial thinnings. Managed forests are forests which are managed either for timber*
 306 *production and/or carbon sequestration, including BECCS. Energy Crops are short rotation plantations for bioenergy*
 307 *including BECCS, and consist of willow, poplar, eucalyptus or other fast-growing species.*

308

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 \$/tCO₂. 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 11³⁰ 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.

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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%	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	

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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

356

357 **Supply-side Measures**

358 **Reduce land use change**

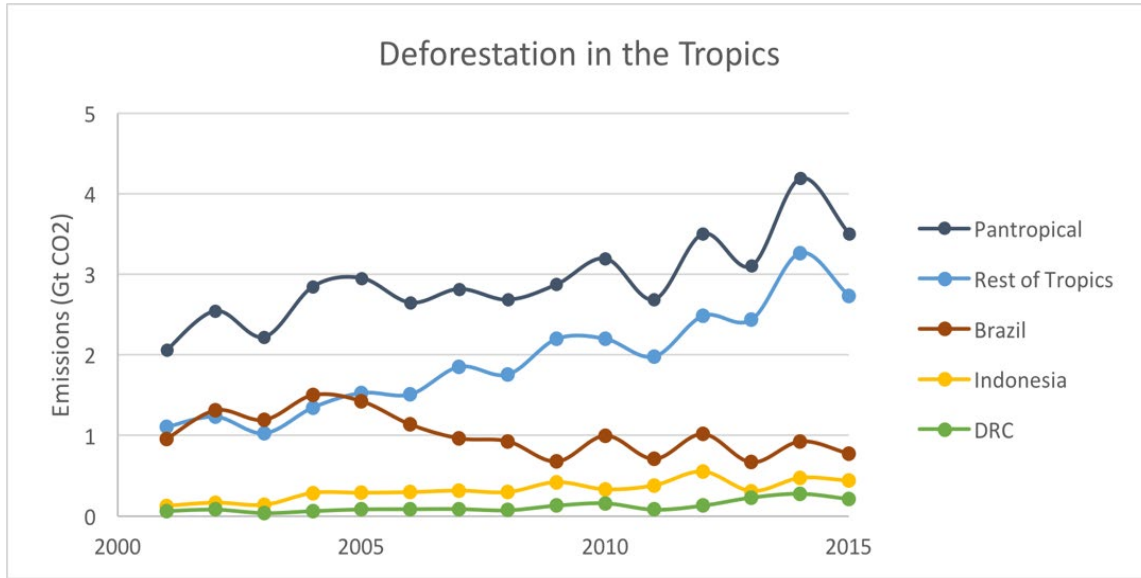
359 *The overall mitigation potential for the land use change category include deforestation + coastal*
360 *wetlands + savannas and natural grasslands. We do not include the estimates for degradation*
361 *and reduced conversion and burning of peatlands as some deforestation estimates include*
362 *degradation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

363
364 Land conversion is the single largest source of land sector emissions, with estimates ranging
365 between 2.3 – 5.8 Gt CO₂/yr for deforestation and 2.1 – 3.67 GtCO₂/yr for degradation^{32,33,39–44}.
366 Agriculture drives 50-80% of tropical deforestation, primarily from commodity-driven
367 agribusiness⁴⁵. Peatland conversion (fires and peat decomposition from drainage) account for 0.6
368 – 1.2 GtCO₂e/yr^{46,47}. Globally, the drainage of peatlands generates 32% of cropland emissions
369 yet only produce 1.1% of total crop calories⁴⁷. While only 10% of peatlands are located in the
370 tropics, they account for more than 80% of peatland soil emissions, primarily in Indonesia
371 (~60%) and Malaysia (~10%)^{46,48}. Wetlands (mangroves, tidal marshes, and seagrasses) have
372 also been converted, with over 25-50% of wetlands lost in the last 50-100 years due to
373 aquaculture, agriculture, industrial use, upstream dams, dredging, eutrophication of overlying
374 waters, and urban development^{49–51}. Limiting warming to 1.5°C will require a near halt of all
375 gross deforestation and conversion by 2040.

376
377 Land can be spared and conserved through direct activities (e.g., REDD+, land planning policies,
378 and supply chain interventions), and indirect activities (agricultural intensification to increase
379 yields and reduce conversion pressure, reduce food waste to increase yields, and shift diets to
380 reduce demand for commodities that cause deforestation.

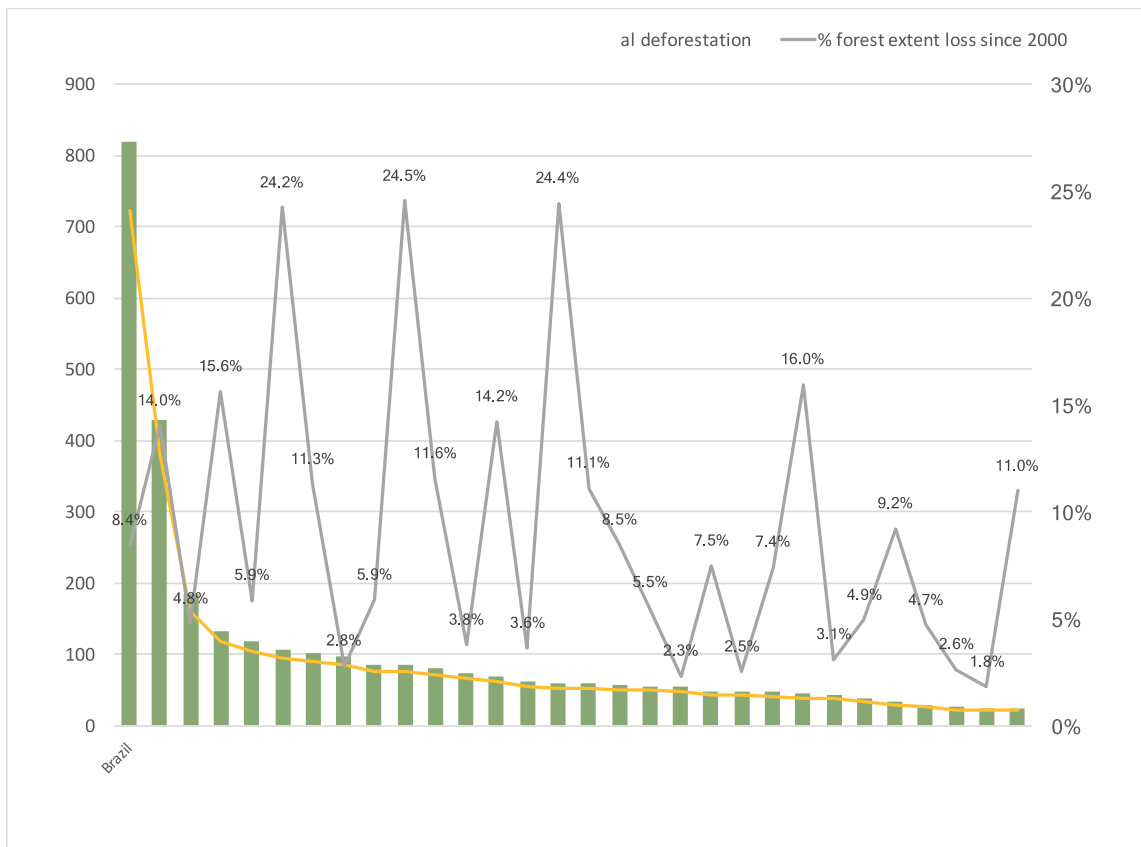
381
382 Countries with the highest area of deforested lands include Brazil, Indonesia and the Democratic
383 Republic of Congo (DRC), while countries with the highest deforestation rates include West
384 African and Southeast Asian countries, as well as Paraguay in South America (Figure S3 - S4).
385 Tropical peatland forests have a deforestation rate of 4% per year, significantly higher than the
386 average rate for tropical forests at 0.5%^{44,52}.

387
388 The potential for reducing emissions from reducing and/or halting deforestation range between
389 0.4 – 5.8 Gt CO₂/yr, with the higher figure representing a complete halting of land use
390 conversion in forests and peatlands and accounting for biomass and soil carbon^{31,33,35,42,53–58}.
391 Reducing annual emissions from peatland conversion, draining and burning would mitigate 0.45
392 – 1.22Gt CO₂e/yr^{31,46,53}, while reducing the conversion of coastal wetlands (mangroves, seagrass
393 and marshes) would realize mitigation of 0.11 – 2.25 Gt CO₂e/yr of emissions^{31,49,53,59}. These
394 estimates represent biophysical and technical potential (higher ranges) and economic and
395 feasible mitigation potential (lower ranges). The upper estimates reflect the theoretical avoidance
396 of all land-use change emissions. Differences in estimates also stem from varying land cover
397 definitions, time periods assessed, and carbon pools included (most lower estimates only include
398 aboveground biomass, and most higher estimates include all five IPCC carbon pools:
399 aboveground, belowground, dead wood, litter, soil, and peat).



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



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Figure S4. Land use change emissions (deforestation) in MtCO₂e/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

428 Enhance carbon sequestration

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

436
437 Increasing sequestration of vegetation and soil carbon in natural and managed systems can
438 remove a significant amount of carbon emissions in the atmosphere. Currently, the terrestrial
439 carbon sink removes 30% of anthropogenic emissions⁶⁰. Land-based activities that could
440 sequester additional carbon include A/R, forest management, agroforestry, peatland restoration,
441 coastal wetland restoration, agricultural soil carbon enhancement, biochar, harvested wood
442 products and bioenergy with carbon capture and storage (BECCS).

443
444 Afforestation, the conversion of non-forested land into forests, and reforestation, restoring and
445 replanting deforested or degraded forests, can increase carbon sequestration in both vegetation
446 and soils by 0.5 – 10.12 Gt CO₂/yr^{31,53,54,56,61–68}. The lower estimate represents the lowest range
447 from an earth system model⁶⁶ and of sustainable global negative emissions potential⁶³, and the
448 higher estimate³¹ reforests all areas where forests are the native cover type, constrained by food
449 security and biodiversity considerations. Recent mitigation potential estimates for A/R provide
450 “plausible” figures of 3.04 GtCO₂/yr by 2030 with environmental, social and economic
451 constraints (<\$100/tCO₂)³¹, and 3.64 GtCO₂/yr between 2020-2050 based on a conservative
452 scenario of restoration commitments and smaller scale afforestation⁵³. The annual reforestation
453 in 2015 was reported at 27 Mha, and countries have committed to restore another 161 Mha of
454 forests by 2030 led by China, Brazil, India and the US^{69,70}.

455
456 Improving forest management includes extending rotation cycles between harvests, reducing
457 damage to remaining trees when harvesting, reducing logging waste, implementing soil
458 conservation practices, fertilization, and using wood more efficiently. Forest management could
459 potentially mitigate 0.44 – 2.1 Gt CO₂/yr^{31,71,72}, where the low estimate is the “low cost”
460 (<\$10/tCO₂) implementation of natural forest management and improving plantations³¹ and the
461 upper estimate represents switching from conventional logging to reduced-impact logging
462 practices⁷². A new study asserts that Climate Smart Forestry, a technique addressing the
463 ecosystem, wood products and the energy supply chain in Europe, could double the forest
464 management climate mitigation potential by 2050⁷³.

465
466 Agroforestry is a land management system that combines woody biomass (e.g., trees or shrubs)
467 with crops and/or livestock, and can include fruit or timber trees for harvest, windbreaks, riparian
468 buffers, and silvopasture. Agroforestry systems have a long tradition in temperate regions around
469 the world and have also been developed as a land management practice in many developing
470 countries, particularly for smallholder systems. The mitigation potential ranges between 0.11 –
471 5.68 Gt CO₂/yr^{31,36,53,74}, where the low estimate represents a conservative adoption of
472 agroforestry practices in mixed crop-livestock systems in humid and tropical highland areas of
473 the developing world, and the high estimate represents the “optimum” implementation scenario
474 of “silvopasture” + “tree intercropping” + “multistrata agroforestry” + “tropical staple trees.”⁵³
475

476 Wetland and peatland restoration includes rewetting peat soils and replanting peatland and
477 mangrove vegetation. Approximately 0.6 Gt CO₂/yr can be mitigated if 30% of the 65 Mha of
478 drained peatlands were rewetted to stop continued emissions from carbon oxidation, and about
479 3.2 Gt CO₂/yr if all ongoing CO₂ emissions from continued peat oxidation were ceased^{75,76}. The
480 mitigation potential range is between 0.15 – 0.81 Gt CO₂/yr from studies since 2010^{31,75}, where
481 the lower estimate represents “low cost” (<\$10/tCO₂) restoration³¹ and the higher estimate
482 represents biophysical potential constrained by food security and environmental considerations³¹.
483 Mangrove restoration can mitigate the release of 0.20 Gt CO₂/yr through “cost effective”
484 (<\$100/tCO₂) restoration³¹ and 0.84 Gt CO₂/yr from biomass and soil enhancement³¹. Peatland
485 restoration, as well as agroforestry and forest management mitigation potential are included in
486 some of the A/R estimates and are therefore not added to the total terrestrial carbon enhancement
487 mitigation potential.

488
489 Sequestering carbon in agricultural systems through regenerative and conservation agriculture
490 practices (including use of perennials or deeper rooted cultivars, reduced tillage, crop residue
491 management, organic amendment and fire management), and grazingland management
492 (including managing stocking rates, timing and rotation of livestock, higher productivity grass
493 species or legumes, and nutrient management) have considerable mitigation potential. Soil
494 carbon sequestration (SCS) in croplands have a potential range of 0.25 – 6.78 Gt
495 CO₂/yr^{14,31,36,38,53,77–82}, where the low estimate is the “low cost” (<\$10/tCO₂) implementation of
496 conservation agriculture³¹, and the high estimate is the increase of soil organic carbon in 0-30 cm
497 of all cropland soils from 0.27% to 0.54%⁸³. The SCS potential in grazing lands is 0.13 – 2.56
498 CO₂/yr^{14,31,53,61,77,78,80,82–86}, where the low estimate is the “low cost” (<\$10/tCO₂) implementation
499 of “grazing - optimal intensity” + “grazing - legumes in pasture” and “fire management in
500 savannas”³¹, and the high estimate is a maximum biophysical potential⁸⁰. Storing carbon by
501 converting biomass into recalcitrant biochar to use for soil amendment also has the potential to
502 mitigate 0.030 – 6.6 Gt CO₂/yr^{31,36,53,62,63,68,77,84,87–90}. The higher end of the estimate assumes
503 bioenergy crops can be used to make biochar and includes syn-gas production as offsetting fossil
504 fuel usage⁹⁰, while the lower estimate uses a fraction of available residues only (no purpose
505 grown crops)⁵³. While soil carbon and biochar have large mitigation potential, there continues to
506 be a great deal of uncertainty in the science of soil carbon, specifically on issues of storage
507 capacity and permanence^{77,84}. Levels of carbon in the soil, as well as biomass, trend towards a
508 new equilibrium level, meaning that sequestration rates steadily drop to negligible levels over the
509 course of several decades for most soils⁹¹. In the future, that carbon can also be released back
510 into the atmosphere depending on the crop management practice and climatic conditions.
511 Additionally, there is great inconsistency in observed carbon sequestration rates from different
512 management practices (particularly on tillage), primarily due to variety of environmental factors
513 including soil type, moisture, temperature, microbial and fungi composition, nutrient
514 availability⁹², and the particulars of how the management is actually applied.

515
516 Carbon can also be removed through technologies that use land such as bioenergy with carbon
517 capture and storage (BECCS). Biomass used for BECCS (trees, energy crops and residues)
518 sequester carbon as they grow, the biomass is then processed in plants to produce energy, and
519 finally the CO₂ is stored in geological reservoirs to produce net negative emissions. The
520 mitigation potential is estimated to be approximately 0.4 – 11.3 Gt CO₂/yr in 2050^{61–63,68,89,93,94}.
521 The low estimate only uses available residues⁹³ and the high estimate is the upper range from a
522 modelling study⁸⁹. BECCS is included in our mitigation potential estimate, however, it is
523 important to note that BECCS deployment is still in the development, exploration, and piloting
524 stages.

525 Reduce direct agricultural emissions

526 *The overall mitigation potential for the agriculture category includes all direct CH₄ and N₂O*
527 *emissions: CH₄ and N₂O from manure management, N₂O emissions from cropland nutrient*
528 *management and manure on pasture, CH₄ emissions from rice cultivation and enteric*
529 *fermentation, and all emissions from synthetic fertilizer production. We do not include cropland*
530 *and pastureland management as they are accounted for in the soil carbon enhancement*
531 *category.*

532
533 Sustainable intensification reduces the emissions intensity of agriculture by using inputs more
534 efficiently or adding new inputs that address limiting factors of production. These practices are
535 typically based on changes or increases in the use of direct inputs, such as improved
536 varieties/breeds, nutrient and organic amendments, water and mechanization. In addition, a
537 variety of farming practices can be adopted that optimize density, rotations and precision of
538 inputs.

539
540 Reducing emissions intensity from agriculture: cropland nutrient management, enteric
541 fermentation, manure management, rice cultivation and fertilizer production has a total
542 mitigation potential of 0.30 – 3.38 Gt CO₂/yr (Figure 4). The mitigation potential of cropland
543 nutrient management (fertilizer application) 0.03 – 0.71 Gt CO₂/yr^{25,31,36,53,77}, and manure on
544 pasture is 0.01 Gt CO₂/yr³⁷.

545
546 Enteric fermentation is responsible for over 40% of direct agricultural emissions with beef and
547 dairy cattle accounting for approximately 65%³⁸. The three main measures to reduce enteric
548 fermentation include improved diets (higher quality, more digestible livestock feed),
549 supplements and additives (reduce methane by changing the microbiology of the rumen), and
550 animal management and breeding (improve husbandry practices and genetics)³⁶. Applying these
551 measures can mitigate 0.12 – 1.18 Gt CO₂/yr^{31,34,36,38}. Most livestock production systems in
552 highly developed countries (e.g., the U.S., E.U., Australia, and Canada) have intensified systems
553 and thus have lower mitigation potential per unit compared to developing countries with large
554 livestock herds managed at low productivity levels, suboptimal diets, nutrition and herd structure
555 (e.g., India, Latin America and Sub-Saharan Africa). These developing countries have higher
556 mitigation potential gains from sustainable intensification.

557
558 Manure from livestock cause both nitrous oxide and methane emissions, and account for roughly
559 one quarter of direct agricultural GHG emissions³⁶. Although stored manure accounts for a
560 relatively small amount of direct agricultural emissions, it is technically possible to mitigate a
561 high percentage of these emissions (as much as 70% for most systems)^{34,36}. The mitigation
562 potential ranges from 0.01 – 0.26 Gt CO₂/yr^{36,38}. The highest manure management emissions
563 come from China, India, the US and the EU (Figure S6). Measures to manage manure include
564 anaerobic digestion for energy use, composting as a nutrient source, reducing storage time, and
565 changing livestock diets. Improved manure management practices have important co-benefits
566 including reducing water and air pollution, and increased yields and income from nutrient and
567 energy inputs produced.

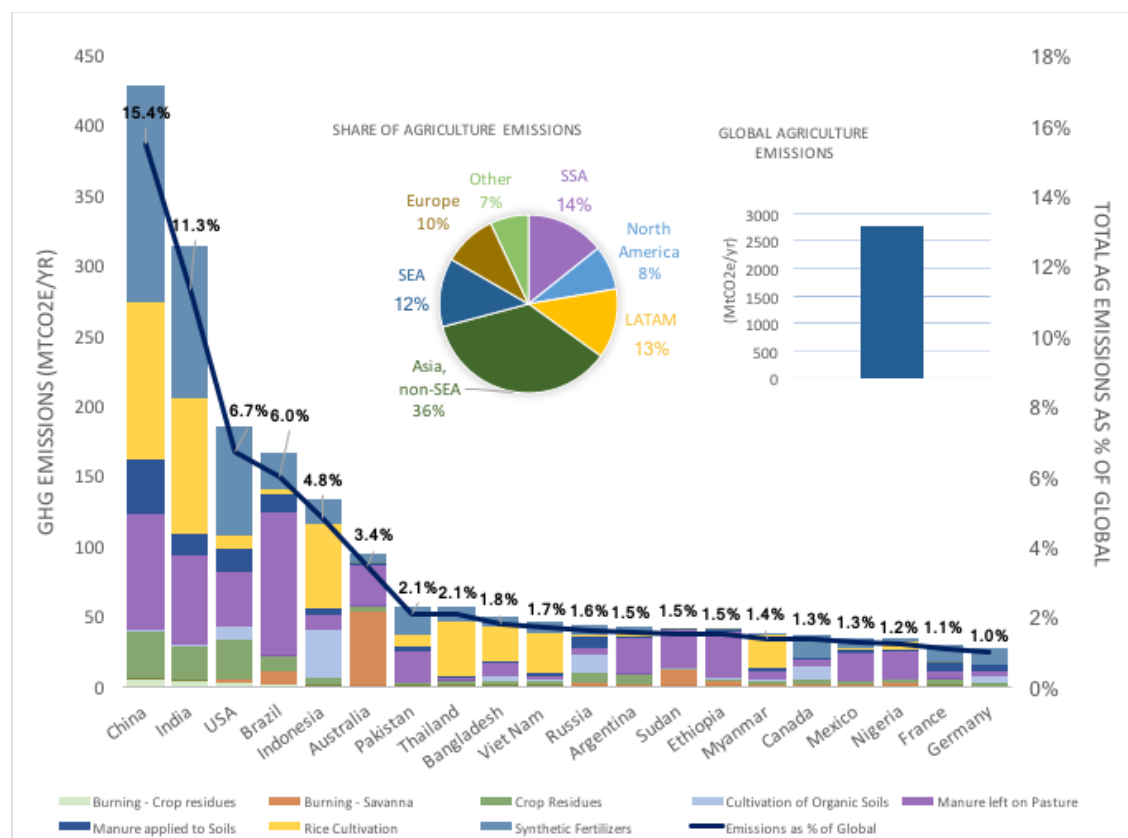
568
569 Rice production contributes about 11% of emissions from agriculture and 90% of this is from
570 Asia⁹⁵. The top rice producing countries—China, India, Indonesia, Thailand, Philippines,
571 Vietnam Bangladesh, and Myanmar—account for more than 85% of global rice emissions
572 (Figure S5). Reducing emissions from rice production through improved water management
573 (periodic draining of flooded fields to reduce methane emissions from anaerobic decomposition),

574 and straw residue management (apply in dry conditions instead of on flooded fields, avoid
 575 burning to reduce methane and nitrous oxide emissions) has the potential to mitigate up to 60%
 576 of emissions⁹⁶ or 0.08 – 0.87 Gt CO₂/yr^{25,31,36,53,77,96}. While well managed rice fields can increase
 577 yields and reduce water needs, correct management of water levels requires precise control of
 578 irrigated systems and high technical capacity that may present barriers to adoption³⁶.

579
 580 Synthetic fertilizer production is a major source of GHG emissions and air pollution as it
 581 requires a large amount of energy to produce and uses fossil fuels (natural gas or coal) as
 582 feedstocks. China has the largest emissions from synthetic fertilizer production as they have
 583 older, less efficient plants and use coal feedstocks³⁶. Improvements in industrial efficiency are
 584 typically cost effective, would improve the productivity of the sector, reduce pollution, and have
 585 the potential to mitigate 0.05 to 0.36 Gt CO₂e/yr in China (there are no global estimates)^{36,97}.

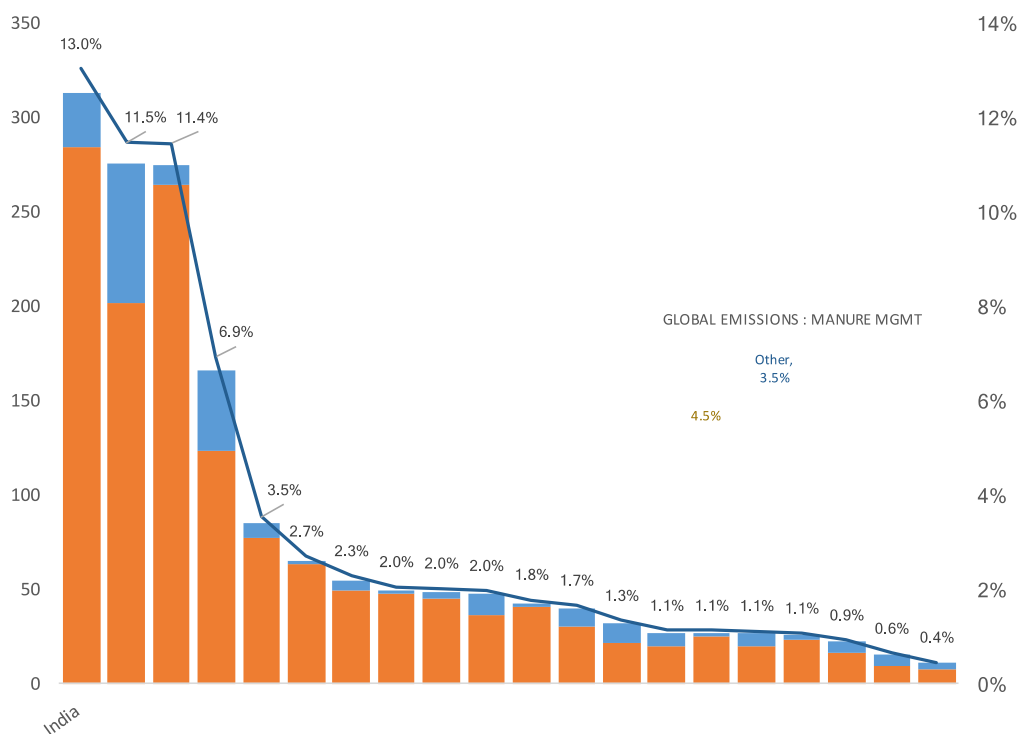
586
 587 Efficiency improvements from sustainable intensification generally produce productivity gains
 588 and improve farmers' livelihoods, especially smallholders. If managed well, intensification can
 589 also spare land/avoid land conversion because greater agricultural production occurs on the same
 590 area of land. However, efficiency improvements also carry the risk of environmental and social
 591 trade-offs that need to be managed. Intensification will likely produce an increase in fertilizer use
 592 and other agrochemicals which may increase emissions and pollution. Further, more efficient
 593 production methods can reduce costs and increase yields, and therefore, may encourage farmers
 594 to further increase production and expand land use (deforest)⁹⁸. Sustainable intensification will
 595 need to go hand in hand with improved land-use planning, environmental safeguards and
 596 standards, and law enforcement to avoid these negative impacts.

597



598
 599 *Figure S5. Agriculture emissions (crops and soils) in MtCO₂e/yr by country and region, using a five-year average*
 600 *(2010-2014). The blue line represents share of global emissions by country – data is not continuous. Data source:*
 601 *FAOSTAT, 2015*

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Figure S6. Livestock emissions (enteric fermentation in orange and manure management in blue) in MtCO₂e/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

609 Demand-side Measures

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

613
 614 Demand-side measures reduce GHG emissions by cutting down the overall level of production
 615 and increasing the efficiency of high emission intensity products, thus sparing land and
 616 decreasing direct agriculture emissions. Most of the impacts from demand-side interventions are
 617 therefore generally positive as they reduce competition and pressure on land, water and other
 618 inputs in contrast to supply-side measures that require more land and/or more inputs³⁵.

619
 620 The discussion on food security and agriculture mitigation over the last two decades has almost
 621 exclusively focused on ways to increase productivity and reduce net GHGs emissions from
 622 production – i.e., the supply side. However, as the global population grows and incomes rise, the
 623 demand-side of the equation will become more important, including which products are
 624 consumed, how much is consumed, and how much food is wasted. Demand-side measures have
 625 the potential to significantly mitigate emissions of 1.81 – 14.31 Gt CO₂e/yr from reductions in
 626 food loss and waste (food wastage), changes in diets, the substitution of wood for cement and
 627 steel in construction, and the use of cleaner cookstoves. Approximately 55% of the upper bound

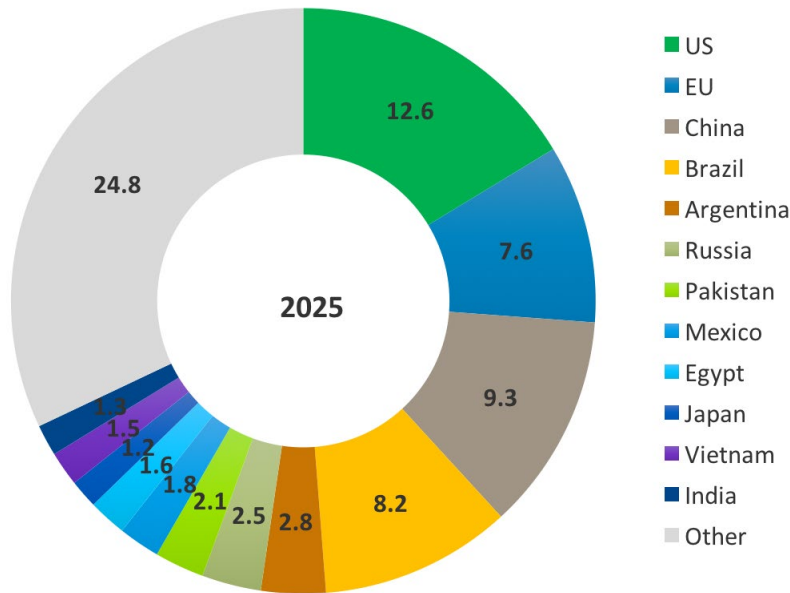
628 of this estimate comes from changes in diet, and another 30% comes from reductions in food
629 wastage.

630
631 Shifting away from emissions-intensive foods like beef delivers a substantial mitigation potential
632 of 0.7 – 8 Gt CO₂e/yr^{35,36,38,53,99–102}, with the high estimate representing a vegan diet⁹⁹. The
633 production of beef produces the highest GHG, water, land, and energy footprint of all proteins –
634 approximately 10 times higher in GHG emissions than any other animal protein (dairy cattle,
635 pigs, chicken)^{36,45,100}. Countries with the highest overall and projected beef consumption include
636 predominantly developed and emerging countries: US, EU, China, Brazil, Argentina, Russia
637 (Figure S7). A recent study finds “plausible” mitigation potential of 2.2 GtCO₂e/yr (0.9
638 GtCO₂e/yr without land-use change impacts) if 50% of the global population adopted “plant-
639 based diets” constrained to 2500 kilocalories/ person/day and 57g of meat protein per day⁵³. In
640 addition to reduced emissions, shifting diets has the potential to deliver additional environmental,
641 health and economic co-benefits. Decreasing meat consumption, primarily of ruminants, reduces
642 water use, soil degradation, pressure on forests, and manure and pollution into water systems³⁶.
643 Reducing the amount of land and grains used for livestock could also increase food supply by
644 50% by freeing available resources¹⁰³. Given the established links between diet-related diseases
645 and high levels of meat consumption, keeping global average per capita meat consumption at
646 healthy levels will also have important health benefits (reduced risks of cardiovascular diseases,
647 cancer, stroke and diabetes)⁹⁹.

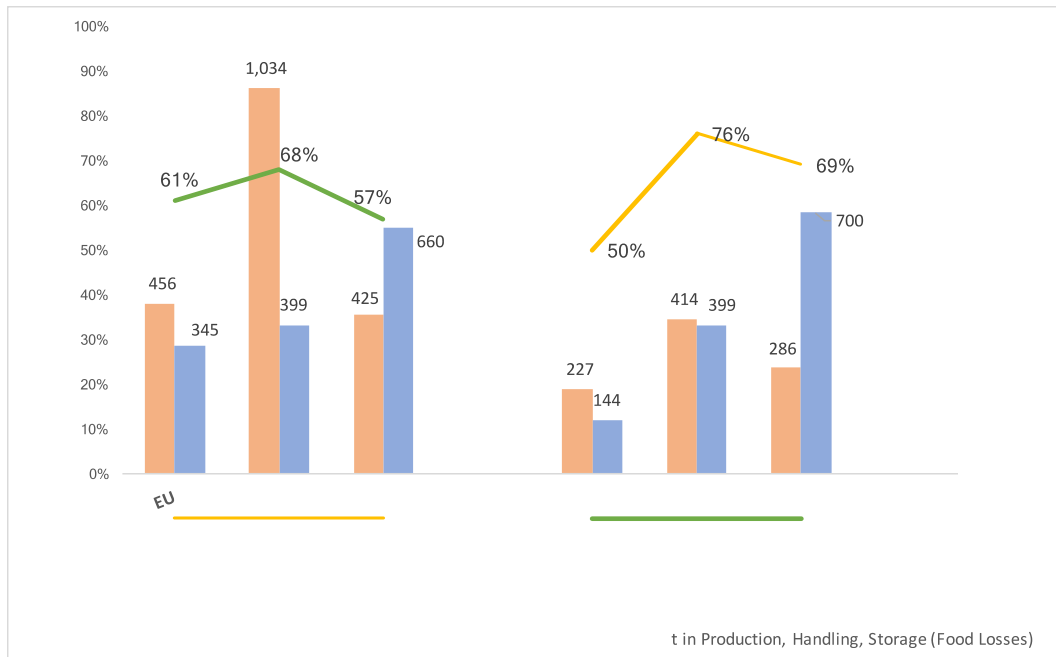
648
649 Reducing food losses and waste increases the overall efficiency of food value chains, reduces
650 land pressure, and could contribute to reducing 0.76 – 4.5 of CO₂e/year^{36,53,101}. A recent study
651 finds “plausible” mitigation potential of 2.4 GtCO₂e/yr (0.9 GtCO₂e/yr without land-use change
652 impacts) if food waste is reduced by 50% in 2050⁵³. In the developing world, losses mainly occur
653 postharvest as a result of financial and technical limitations in production techniques, storage and
654 transport¹⁰⁴ (Figure S8). In contrast, losses in the developed world are mostly incurred by end
655 consumers¹⁰⁴. The highest overall food waste occurs in China, the US and the EU, while the
656 highest food losses occur primarily in Southeast Asia and Sub-Saharan Africa. When considering
657 per capita waste and losses however, the US is almost double that of the EU and China.
658 Strategies to reduce food loss and waste include improving harvesting, handling and storage
659 techniques for the downstream losses, and consumer awareness campaigns and policies for the
660 upstream food waste. Cutting current food loss and waste levels in half has the potential to close
661 the 70% gap of food needed to meet 2050 demand by roughly 22%, potentially making the
662 reduction of food wastage a leading strategy in achieving global food security¹⁰⁴. As food
663 wastage is a by-product of inefficiency, the negative trade-offs are limited and there are vast
664 opportunities for savings along the entire supply chain.

665
666 Increasing demand of wood products in construction to substitute more GHG intensive materials
667 like cement and steel could also present an opportunity for emissions reductions. Pathways to
668 reduce emissions include increasing carbon storage in harvested wood products (HWP) and
669 avoiding emissions from the production of concrete and steel^{105,106}. Various studies have
670 calculated the displacement factor, or the substitution benefit in CO₂, when wood is used instead
671 of another material – with a range of -2.3 to 15 tC of emission reduction per tC in wood product
672 and a mode range of 1.0 to 3.0 tC¹⁰⁵. Displacement factors, as well as calculations of carbon
673 storage from HWPs have been used to calculate mitigation potential of wood substitution in
674 various countries including Canada¹⁰⁶, the EU¹⁰⁷, Japan¹⁰⁸ and the US¹⁰⁹. However, there are
675 limited estimates of global mitigation potential from increasing the demand of timber products to
676 replace construction materials, as well as their potential risks and co-benefits. The range of 0.25

677 – 1.0 GtCO₂ of mitigation potential^{61,110} is relatively small compared to other demand-side
 678 measures. There is concern that increased demand for wood products may reduce forest stocks
 679 and have other environmental risks, however studies have shown that increased wood demand
 680 led to higher wood prices and investments in forest management in some parts of Europe, China
 681 and New Zealand^{19,73,111}. Additional studies are needed to better understand the global dynamics
 682 (GHG emissions, trade, deforestation impacts) of increasing wood products in construction.
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 684
 685



686
 687
 688 *Figure S7. Beef consumption projected by 2025 in total tons of kcal by country. Data source: FAOSTAT, 2015*
 689
 690



691
 692 *Figure S8. Food loss and food waste in Kcal/capita/day by region. Data source: World Resources Institute, 2014*
 693

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

695
696 We developed a roadmap of priority activities and geographies to deliver on the 1.5°C
697 temperature goal, drawing upon our modelled pathways and the bottom-up mitigation potential
698 assessment. Drawing upon the median top down modelling (13.5 GtCO₂e/yr) and bottom up
699 literature review (14.6 GtCO₂e/yr) estimates, we established a viable mitigation target (sum of
700 emission reductions and removals) for the land sector of ~14 GtCO₂e/yr (15 GtCO₂e/yr with
701 BECCS) in 2050. We then divided the mitigation effort into eight priority mitigation measures,
702 or “wedges”¹¹². The wedges incorporate activity types from all four main mitigation categories:
703 reduced land-use change, reduced agricultural emissions, reduced overall production through
704 demand shifts, and carbon removal through enhanced carbon sinks. The amount of mitigation for
705 the individual wedges were determined by first qualitatively weighing associated risks and co-
706 benefits (Table S6), and then identifying feasible estimates (plausible, cost effective, sustainable,
707 desirable) in the bottom-up assessment of the literature (Table S5). Given the strong interaction
708 effects of land-based mitigation activities on each other (e.g. land competition, prices, yields), on
709 ecosystem services (e.g. water, air and biodiversity) and on biophysical impacts (e.g. radiative
710 cooling/warming and albedo), we prioritized measures that minimize risks, maximize co-benefits
711 and overlap with Sustainable Development Goals, the New York Declaration on Forests (NYDF)
712 and United Nations Convention on Biological Diversity (UNCBD), Aichi Targets (Table S6).
713 The wedges are measures which are individually accounted for with the intent of avoiding
714 double counting of emissions reductions so that the measures are additive (Table S5, described in
715 activity types and source).

716
717 To assess for relative cost, we compared our priority wedges and mitigation trajectories to our
718 modelled results. For each wedge, we then disaggregated action into geographies, prioritizing
719 countries/regions according to their mitigation potential (Section 3 above, Table S4, Figures S7
720 and S8), and constrained by our political feasibility assessment as outlined in the next section.

721 *Table S5. Priority mitigation measures (“wedges”) in 2050 Land Sector Roadmap. Includes activity types, GHG*
 722 *mitigation potential, and related source and rationale for mitigation estimate.*
 723

	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	Reduce CH ₄ and N ₂ O 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

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726
727

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)		

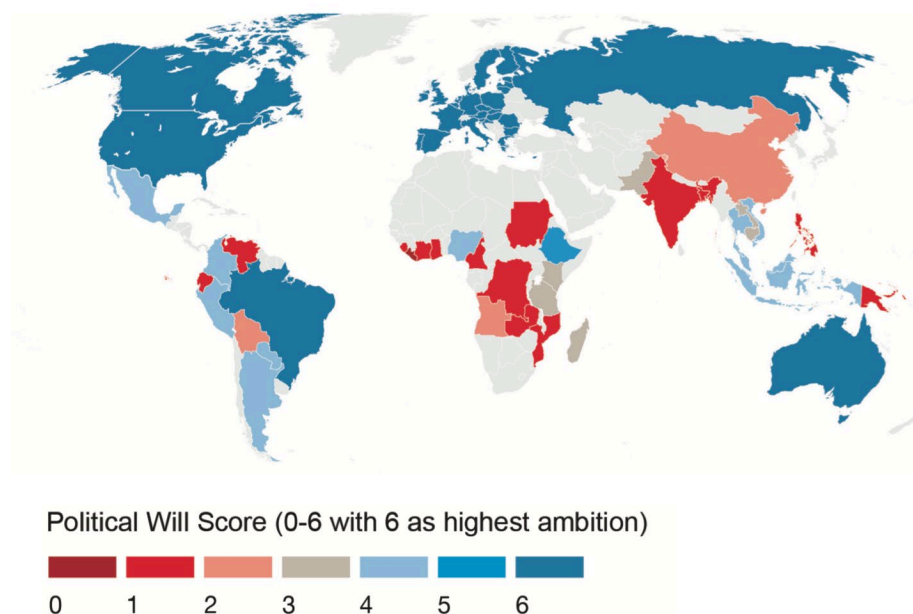
729 **Political feasibility assessment**

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

- 735
- 736 a. Specified activities, policies and measures for the land-use sector (2 points);
- 737 b. Specified land-use targets that are quantifiable in terms of emissions reductions (4
- 738 points);
- 739 c. Specified economy-wide targets that include land use and are quantifiable in terms of
- 740 emissions reductions (6 points).

741

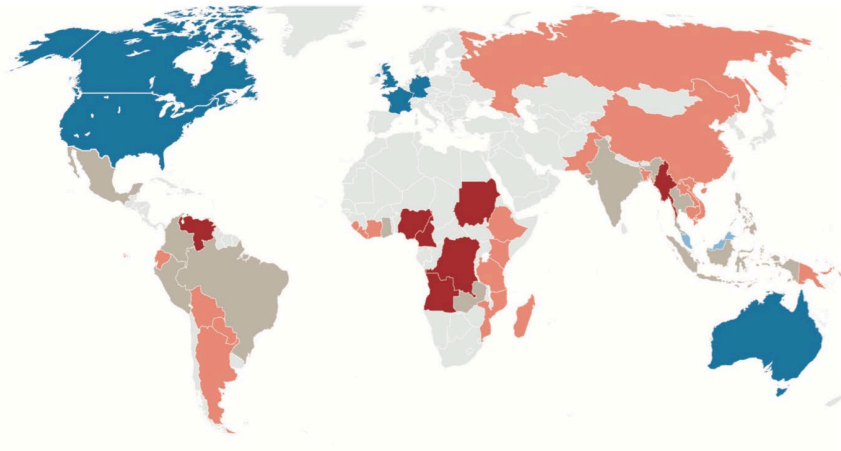
742 Countries were assigned scores according to the category they fall into (Figure S9). NDCs that
 743 achieved the highest score contained quantifiable measures that were economy-wide. Countries
 744 with specified and quantifiable targets for the land-use sector scored slightly lower, while lowest
 745 scores were assigned to NDCs that communicate non-quantifiable activities or measures.
 746 Subtractions were made if emissions reductions targets were made relative to projected business-
 747 as-usual scenarios (-2 points) or if made contingent upon the provision of international climate
 748 finance (-1 point).
 749



750
 751 *Figure S9. Political will of top 40 emitting countries including the European Union which submitted a regional NDC.*
 752 *Scores are based on current NDCs and not political declarations or elections. Data source: UNFCCC submissions*
 753
 754

755 To gauge the ability of countries to implement mitigation policies, we used (a) governance
 756 indicators; and (b) access to finance as indicators. For governance, we used six of the World
 757 Bank governance indicators (government effectiveness, regulatory quality, rule of law, political
 758 stability, control of corruption, and voice and accountability), and averaged the rankings to create
 759 a governance score for each country (Figure S10). For access to finance, we used GDP per capita

760 of a country to serve as proxy (indicator), differentiating countries along four World Bank
761 income categories: low income, lower middle, upper middle, and high income (Figure S11).
762

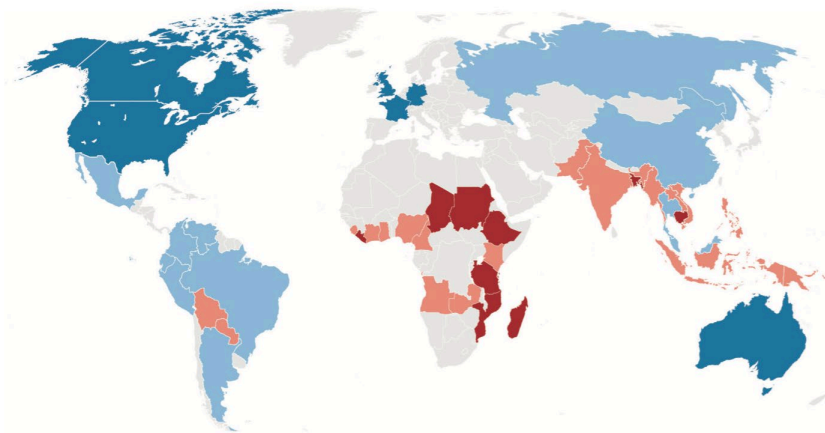


Governance Rank (0-100%, with 100 as the highest ability)



763
764 *Figure 10. Governance rank of top 40 emitting countries. Data source: World Bank governance indicators, 2014*
765 *(government effectiveness, regulatory quality, rule of law, political stability, control of corruption, and voice and*
766 *accountability)*

767
768



2015 GDP per capita (constant 2010 US\$)



769
770 *Figure S11. GDP per capita of top 40 emitting countries. Data source: World Bank, 2014*

771
772
773
774

775 *Geographic priorities*

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

- 779 • High-income and capacity countries with large mitigation potential (210-1500
780 MtCO₂e/yr) that need early aggressive action: the EU, the US, Australia, and Canada.
781 Main areas of action include A/R and restoration, forest management, diet shifts, reduced
782 food waste, reduced enteric fermentation, and improved crop-land management and soil
783 carbon restoration, fertilizer use, and synthetic fertilizer production.
- 784 • Upper-middle-income countries that have high mitigation potential (700-1800
785 MtCO₂e/yr) also need early and aggressive action: Brazil, China and Russia. Main areas
786 of action include A/R, and restoration, forest management, diet shifts, reduced food
787 waste, reduced enteric fermentation, and improved crop-land management and soil
788 carbon restoration, fertilizer use, and synthetic fertilizer production. Deforestation
789 emissions in Brazil, peatland restoration in Russia and rice paddy emissions in China are
790 also of priority.
- 791 • Lower-middle income countries with less financial and governance capacity (will require
792 high levels of assistance) and have high mitigation potential (800-1800 MtCO₂e/yr) need
793 to act by 2025-2030: Indonesia and India. Reduced deforestation, peatland and coastal
794 wetland conversion, A/R and restoration, forest management, food loss and soil carbon
795 enhancement are important actions in Indonesia, while A/R and restoration, enteric
796 fermentation, food loss, synthetic fertilizer production, manure management and rice
797 paddy emissions are priorities for India.
- 798 • Other upper-middle-income countries that have important mitigation potential (150-600
799 MtCO₂e/yr) need to act by 2020-2025: Mexico Colombia, Malaysia, Argentina, Thailand,
800 Venezuela, and Peru. Main areas of action include A/R and restoration, reduced
801 deforestation, peatland and coastal wetland conversion, forest management, food loss and
802 soil carbon enhancement. Enteric fermentation is important in Latin American countries,
803 and rice paddy emissions are important in Asian countries.
- 804 • Other low and lower-middle income countries requiring high levels of assistance with
805 important mitigation potential (150-380 MtCO₂e/yr) need to act by 2030: Myanmar,
806 Paraguay, Vietnam, the Democratic Republic of Congo, Tanzania, Philippines, Bolivia,
807 Cote d'Ivoire. Main activities are the same as the previous bullet.

808

809 **References for Supplementary Information**

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