ARTICLES
https://doi.org/10.1038/s41893-021-00772-w

nature sustainability

Land-based implications of early climate actions without global net-negative emissions

Tomoko Hasegawa[1,2] ✉, Shinichiro Fujimori[2,3,4], Stefan Frank[4], Florian Humpenöder[5], Christoph Bertram[5], Jacques Després[6], Laurent Drouet[7], Johannes Emmerling[7], Mykola Gusti[4,8], Mathijs Harmsen[9,10], Kimon Keramidas[6], Yuki Ochi[11], Ken Oshiro[3], Pedro Rochedo[12], Bas van Ruijven[4], Anique-Marie Cabardos[4], Andre Deppermann[4], Florian Fosse[6], Petr Havlik[4], Volker Krey[4], Alexander Popp[5], Roberto Schaeffer[12], Detlef van Vuuren[9,10] and Keywan Riahi[4,13]

Delaying climate mitigation action and allowing a temporary overshoot of temperature targets require large-scale carbon dioxide removal (CDR) in the second half of this century that may induce adverse side effects on land, food and ecosystems. Meanwhile, meeting climate goals without global net-negative emissions inevitably needs early and rapid emission reduction measures, which also brings challenges in the near term. Here we identify the implications for land-use and food systems of scenarios that do not depend on land-based CDR technologies. We find that early climate action has multiple benefits and trade-offs, and avoids the need for drastic (mitigation-induced) shifts in land use in the long term. Further long-term benefits are lower food prices, reduced risk of hunger and lower demand for irrigation water. Simultaneously, however, near-term mitigation pressures in the agriculture, forest and land-use sector and the required land area for energy crops increase, resulting in additional risk of food insecurity.

Climate policy scenario assessments use assumptions describing how society could reduce its greenhouse gas (GHG) emissions. The current global emission scenarios were criticized because they rely heavily on carbon dioxide removal (CDR), leading to temporary exceedance of certain temperature limits[1–3]. The current scenarios that aim to stabilize GHG concentrations by the end of the 21st century[4,5] or attempt to limit end-of-century radiative forcing to specific levels[6–8] assume an overall limit on total cumulative CO_2 or GHG emissions over the 21st century as a proxy for the global mean temperature rise in the year 2100[1,9,10]. A focus on end-of-century outcomes, combined with the application of an optimization computation to achieve these objectives in a cost-effective manner, can lead to a situation in which projected substantial net-negative emissions in the second half of the century compensate for weaker emission reductions in the near term, resulting in a temporary exceedance (overshoot) of the targeted temperature level before 2100[1].

The focus on end-of-century outcomes also results in the observation that the scenarios that achieve the stringent long-term climate goal invoke CDR strategies to meet the goal[1,6,11–13]. The potential land-use consequences of large-scale CDR in mitigation scenarios[6,14,15] with stringent climate goals could be considered infeasible or socially undesirable due to sustainability and intergenerational equity concerns[1,12,16–19]. (For clarification, we use the term 'net-negative emissions' to refer to the global net removal of CO_2 from the atmosphere and 'CDR technologies' to refer to specific technologies or measures.) A key issue is the feasibility of implementing land-based mitigation measures, such as CDR associated with afforestation/reforestation (A/R) and bioenergy combined with carbon capture and storage (BECCS)[20], which play a vital role in the stringent mitigation scenarios[21–23] but can affect (positively and/or negatively) other sustainable development goals[24,25]. (Although the social acceptability and desirability of using BECCS is also uncertain, here we assumed that BECCS are socially accepted). Feasibility of the land-based CDR would depend on the stringency of the climate goals, associated emission pathways and socioeconomic conditions. For example, immediate actions involving rapid emission reductions in the near term would lower the need for land-based CDR in the latter period[4,26], whereas delayed actions would increase the need for large-scale CDR. In addition, the amount of CDR required depends on the total carbon budget (CB) caps. Little is currently known about the dynamics of emission pathways and land-use implications of scenarios without net-negative emissions under different total CB caps. For these purposes, a new set of scenarios was generated that focuses on capping global warming at various levels of a specific maximum with either temperature stabilization or reversal thereafter (K.R. et al., manuscript in preparation). The impacts of scenario choice regarding reliance on net-negative emissions and CB cap pathways on the agriculture, forest and land-use (AFOLU) sector have not been analysed using the scenarios.

---

[1]College of Science and Engineering, Ritsumeikan University, Kusatsu, Japan. [2]Center for Social and Environmental Systems Research, National Institute for Environmental Studies (NIES), Tsukuba, Ibaraki, Japan. [3]Department of Environmental Engineering, Kyoto University, Kyoto, Japan. [4]International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. [5]Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany. [6]European Commission, Joint Research Centre (JRC), Seville, Spain. [7]RFF-CMCC European Institute on Economics and the Environment, Centro Euro-Mediterraneo sui Cambiamenti Climatici, Milan, Italy. [8]Lviv Polytechnic National University, Lviv, Ukraine. [9]PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands. [10]Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, the Netherlands. [11]E-Konzal Co. Ltd., Yodogawa, Osaka, Japan. [12]Centre for Energy and Environmental Economics (CENERGIA-COPPE), Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil. [13]Graz University of Technology, Graz, Austria. ✉e-mail: thase@fc.ritsumei.ac.jp

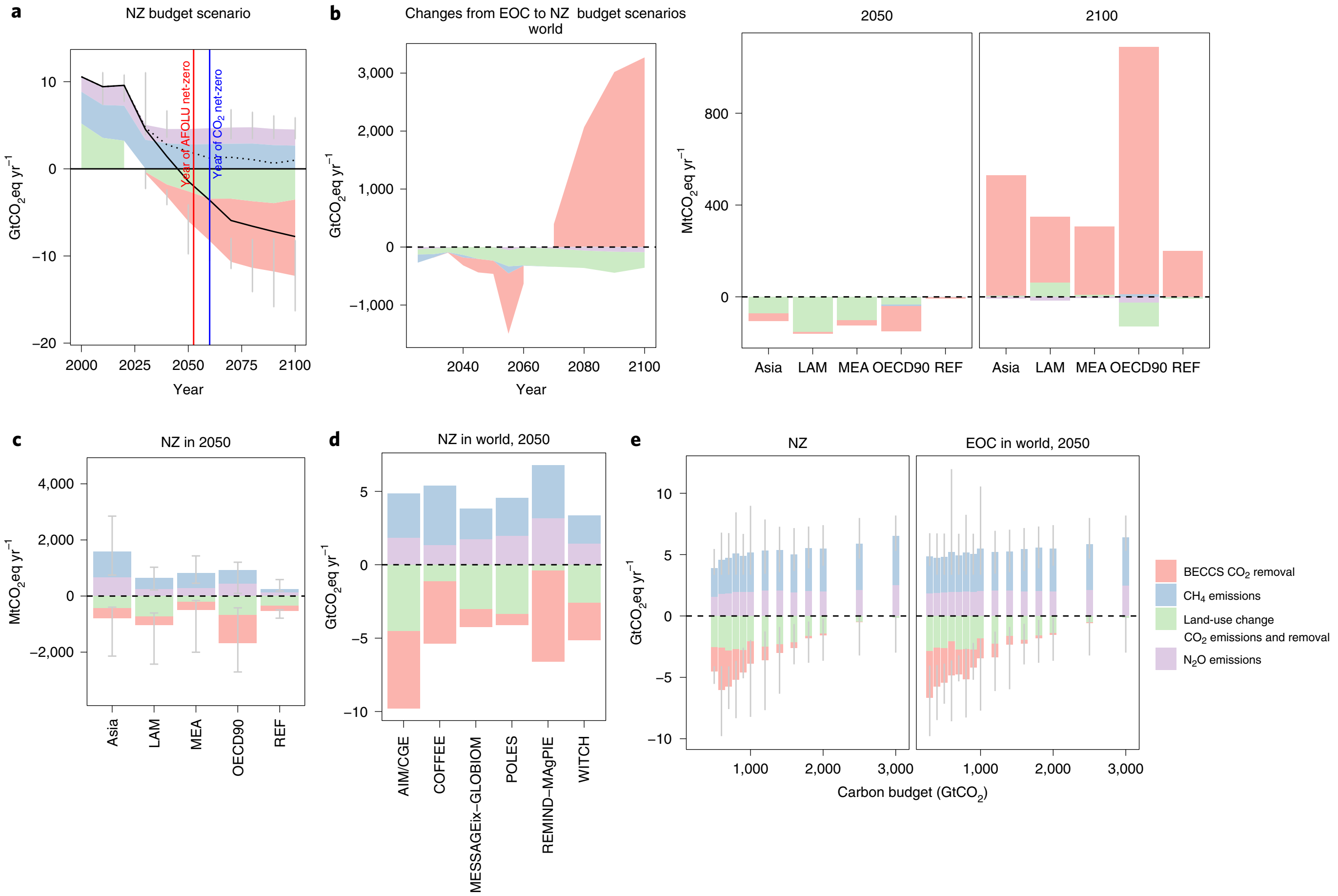

Fig. 1 | AFOLU-related GHG emissions and sequestrations. a–d, Global emissions and sequestrations with 600 GtCO$_2$ carbon budget (CB) in the NZ scenarios (**a**), changes in the NZ scenario relative to the EOC scenario at global and regional levels in 2050 and 2100 (**b**), and changes in 2050 for the NZ scenarios for regions (**c**) and globally by individual models (**d**). **e**, Global emissions and sequestrations in 2050 with respect to 2010 at different CBs. Bars or areas, multi-model median levels; whiskers, ranges across models. In **a**: solid black line, net emissions in AFOLU including BECCS CDR; dotted black line, net emissions in AFOLU excluding BECCS CDR; red and blue lines, timing of net-zero for AFOLU's GHG emissions and total anthropogenic CO$_2$ emissions, respectively. Land-use change CO$_2$ emissions include emissions from deforestation and removals through A/R. Supplementary Fig. 1 shows **a** for both NZ and EOC scenarios. Supplementary Fig. 3 shows more detailed individual model information. Regions: Asia, Latin America and Caribbean (LAM), Middle East and Africa (MAF), developed regions (OECD90) and reforming economies of Eastern Europe and the former Soviet Union (REF).

Here we conduct a multi-model intercomparison using seven state-of-the-art global integrated assessment models (IAMs) aimed at improving understanding of the following questions: (1) does early climate change mitigation action without net-negative emissions lead to positive and negative outcomes for different aspects of land-use systems, and (2) is the optimal timing of net-zero GHG emissions where emissions and sequestration are equally balanced in the AFOLU sector the same as for total anthropogenic CO$_2$ emissions in all sectors? BECCS CDR is often attributed to the energy sector but is assessed as part of the AFOLU sector in this study because bioenergy crops used for BECCS would be the major cause of change in land use. While this change in attribution would not affect the main findings of this study highlighting the co-benefits and adverse side effects of the scenarios without any net-negative emissions, there must be careful interpretation of the timing of net-zero on a sectoral basis. Two sets of scenarios are analysed, differentiated by CB cap scenarios with and without an allowance of net-negative emissions: first, 'end-of-century (EOC) budget' scenarios constraining only cumulative CO$_2$ emissions over this century, thus allowing massive net-negative emissions in the latter half of the century; second, 'net-zero (NZ) budget' scenarios that limit remaining cumulative CO$_2$ emissions until carbon neutrality (net-zero CO$_2$ emissions) is reached and do not allow for any net-negative emissions, thus limiting temperature overshoot (K.R. et al., manuscript in preparation). This limitation in the NZ scenarios, in turn, may reduce the need for large-scale land-based CDR with more substantial trade-offs in the latter half of the century. Moreover, emission scenarios used in the Intergovernmental Panel on Climate Change (IPCC) SR1.5[27] relied heavily on major model intercomparison studies[21,28,29] where the CB spaces are prescribed and potentially biased to several specific points (for example, 400, 1,000 and 1,600 GtCO$_2$). This is problematic and involves a risk of becoming outdated by the choice of CB and climate science[19]. Future scenarios for the IPCC Sixth Assessment Report should explore the CB space in a systematic manner so that policy implications can be adequately assessed[19]. Therefore, for each set, we assumed a wide range of CBs to fill the space between CBs in the IPCC SR1.5[27] and explore the consequences of mitigation and the timing of net-zero emissions across the CB spectrum. The CDR technologies incorporated in the IAMs are mainly BECCS and A/R. See Methods for more details about the methodology.

AFOLU's emissions without global net-negative emissions

Scenarios from IAMs indicate the substantial and essential role of the AFOLU sector in climate stabilization for low CB scenarios. Projected net GHG emissions from the AFOLU sector (here we

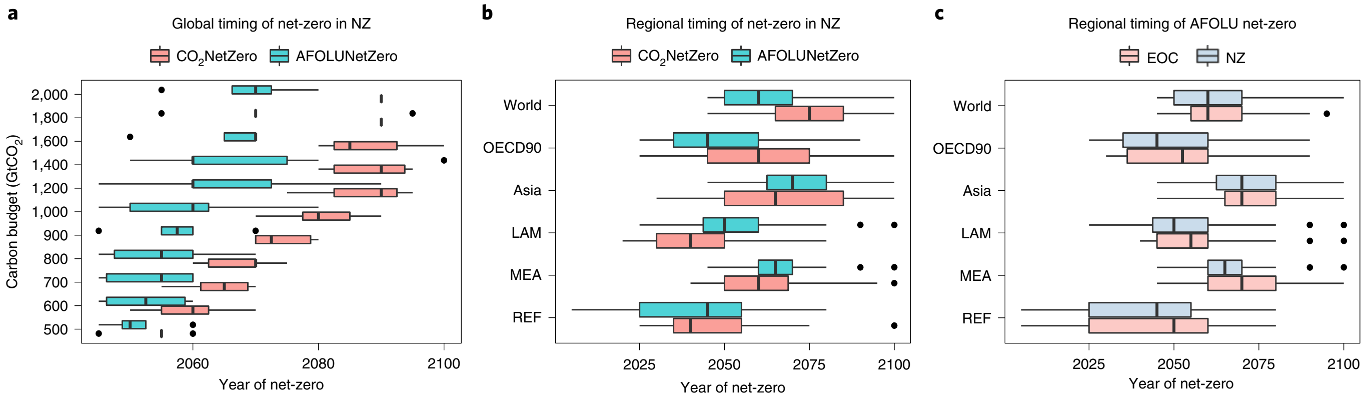

Fig. 2 | Timing of net-zero emissions for total anthropogenic CO_2 emissions (based on GWP100) and AFOLU's GHG emissions. a–c, Global timing at different CBs (**a**) and regional timing at all CB levels (**b**) in NZ scenarios, and regional timing of AFOLU net-zero emissions in NZ and EOC scenarios (**c**). Thick black lines, multi-model median levels; whiskers, ranges across models. See Supplementary Table 2 for the scenarios and models used in this analysis. The boxplots correspond to the first and third quartiles (25th and 75th percentiles). The right whisker extends to the largest value within 1.5 times the interquartile range (IQR), which is the distance between the first and third quartiles, above the 75th percentile. The left whisker extends to the smallest value within 1.5 times the IQR below the 25th percentile. Black dots represent outliers beyond the end of the whiskers.

include CO_2 emissions from deforestation, non-CO_2 emissions from agriculture, CO_2 sequestration from A/R and BECCS CDR in the AFOLU sector) declined towards net-zero in the mid-century in both the NZ and EOC scenarios (Fig. 1a and Supplementary Fig. 1). NZ scenarios required both faster transitions and an earlier achievement of net-zero, while EOC scenarios required more mitigation efforts in the long term. For the NZ scenarios with CB of 600 $GtCO_2$, which is the median of the CB range consistent with limiting warming to 1.5 °C relative to the pre-industrial level[27]: in 2050, methane (CH_4) and nitrous oxide (N_2O) emissions from AFOLU were projected to be 2.8 (1.9 to 4.1) $GtCO_2$eq yr^{-1} and 1.8 (1.3 to 3.2) $GtCO_2$eq yr^{-1}, respectively, while CO_2 sequestration of 2.6 (0.39 to 4.5) $GtCO_2$ yr^{-1} and 3.4 (0.73 to 6.2) $GtCO_2$ yr^{-1} were achieved through A/R and BECCS, respectively, at median level across models. BECCS showed the highest carbon sequestration, followed by A/R at the end of this century (Fig. 1a). CO_2 emissions declined more rapidly and prominently than non-CO_2 emissions, underscoring the difficulty of reducing non-CO_2 emissions in agriculture. The large share of total emission reductions in the land sector highlights the importance of AFOLU in achieving a low-emission pathway.

Globally, by shifting from EOC to NZ budgets, emission reductions are projected to be enhanced earlier and deeper mostly by increasing BECCS CDR (228 $MtCO_2$ yr^{-1}), with a small additional reduction in agricultural CH_4 and N_2O emissions of 1.6 $MtCO_2$eq yr^{-1} and 0.40 $MtCO_2$eq yr^{-1}, respectively (Fig. 1b) in 2050. In 2050, the contribution of BECCS to deeper decarbonization in NZ scenarios is high in OECD countries, while the contribution of A/R to carbon sequestration is high in Latin America and the Middle East and Africa (MEA) (Fig. 1b). Globally, in 2100, the carbon sequestration through BECCS decreases by 3.3 $GtCO_2$eq yr^{-1}, while the carbon sequestration through A/R increases by 270 $MtCO_2$eq yr^{-1}. The lower BECCS CDR reduces the need for drastic mitigation-induced shifts in land use in the long term. In 2100, net emissions for the NZ and EOC scenarios are −7.5 (−12.1 to −2.3) $GtCO_2$ yr^{-1} and −10.3 (−14.9 to −5.1) $GtCO_2$ yr^{-1}, respectively (Supplementary Fig. 1). This difference comes mainly from BECCS CDR. Non-CO_2 emissions show a wide range between 3.3–7.3 $GtCO_2$eq across models in 2050 in scenarios with 600 $GtCO_2$ CB (Fig. 1d). This large uncertainty results from the baseline assumptions of food demand and the emissions abatement potential.

Net-zero emissions timing of AFOLU

It is meaningful to explore the timing and conditions required for sectoral and regional net-zero emissions because many countries have established long-term climate mitigation goals based on net-zero emissions or becoming carbon neutral. Globally, the timing of net-zero GHG emissions in AFOLU (AFOLU's GHG net-zero) was about 10 to 30 years earlier, at median levels, than for total anthropogenic CO_2 emissions in all sectors (total CO_2 net-zero) across different CBs in the NZ scenarios (Fig. 2a). This highlights the competitiveness of the sector in contributing to GHG mitigation efforts and the importance of fast transitions in the AFOLU sector for reaching stringent climate change targets. The relationship between the timing of AFOLU's GHG net-zero and total CO_2 net-zero varied across regions (Fig. 2b). AFOLU's GHG net-zero was achieved earlier than total CO_2 net-zero in OECD countries, while the opposite was seen in other regions such as Latin America, Asia and MEA. The timing of AFOLU's GHG net-zero was dependent on BECCS CDR. This was because BECCS CDR changed considerably over time throughout the century, while carbon sequestration of A/R remained almost constant over time from 2030 onwards, hardly affecting net-zero timing. Therefore, in OECD countries, where AFOLU's GHG net-zero was reached early, the dependency on BECCS CDR was relatively higher than in other regions. This highlights the importance of fast transitions and early climate actions in the AFOLU sector in these countries. On the other hand, in Asia, the amount of BECCS CDR was high and non-CO_2 emissions were also high. Thus, AFOLU's GHG net-zero was reached later than in other sectors because net-zero was only achieved when non-CO_2 emissions were offset by carbon removal (Fig. 1c). For all regions, the timing of AFOLU's GHG net-zero was earlier in NZ compared with EOC scenarios (Fig. 2c). When determining future emission pathways, non-CO_2 emissions are minimized in an optimization computation to achieve a certain objective or rarely discussed due to the characteristics of non-CO_2 gases such as the long life of N_2O and uncertainty in radiative forcing. These results indicate the importance of including non-CO_2 emission reductions when determining future emission pathways.

Land dynamics without global net-negative emissions

As for land area, in the medium term, total forest area and cropland for bioenergy expanded substantially due to increased A/R and higher bioenergy demand driven by BECCS deployment.

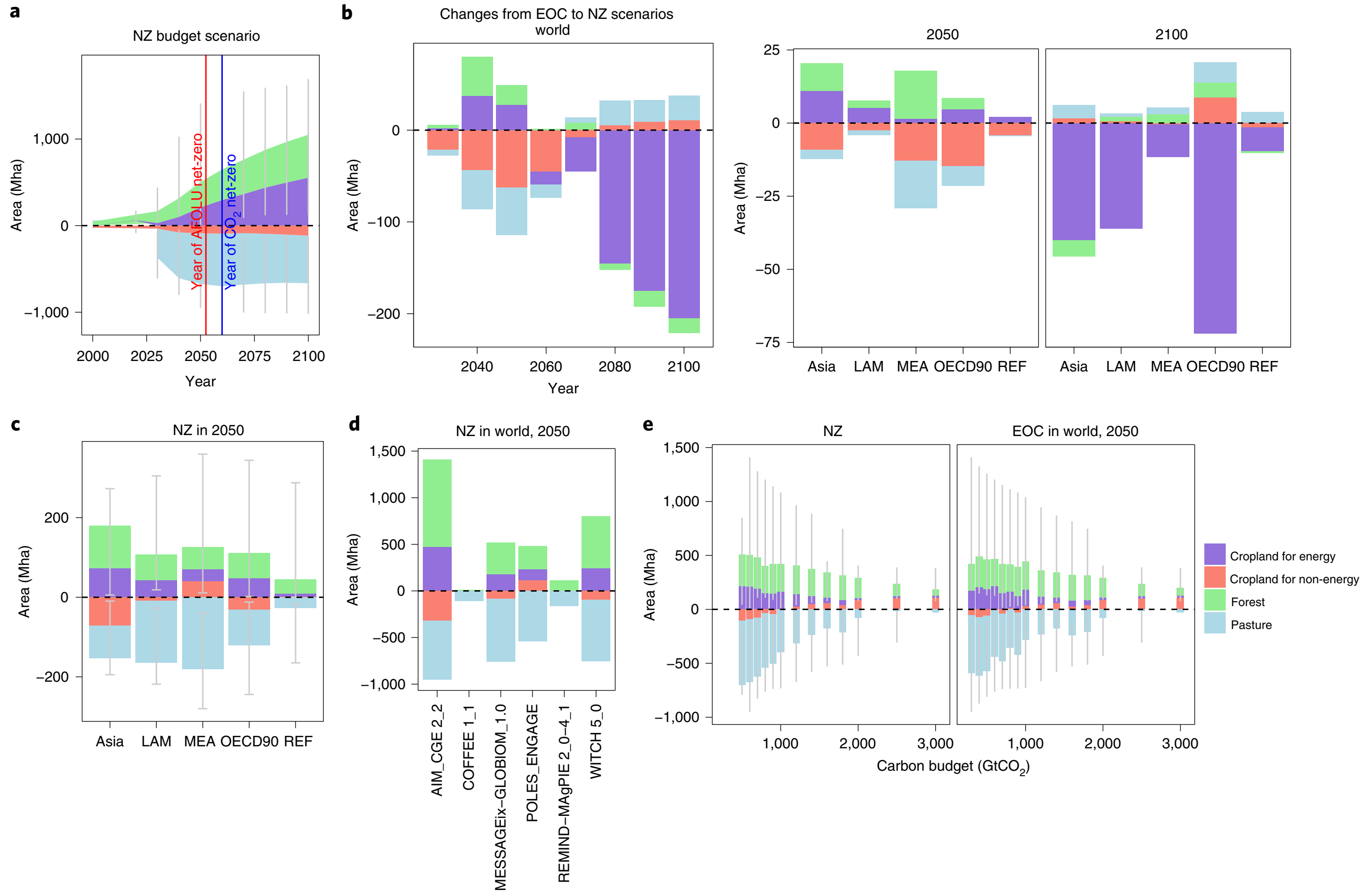

Fig. 3 | Land-use changes with respect to 2010 in the scenarios with different CB caps. **a**, Global land-use change in the NZ budget scenarios with 600 $GtCO_2$ CB. **b**, Changes from the EOC to the NZ scenarios at global and regional levels in 2050 and 2100 for a 600 $GtCO_2$ CB. **c**,**d**, Changes in 2050 for the regional budget scenarios with 600 $GtCO_2$ CB for regions (**c**) and globally by individual models (**d**). **e**, Global land-use change in 2050 with different CBs. Bars or areas, multi-model median levels; whiskers, ranges across models. In **a**, red and blue lines indicate the net-zero timing of AFOLU's GHG emissions and of total anthropogenic CO_2 emissions, respectively. Supplementary Fig. 2 shows **a** for both NZ and EOC scenarios. Supplementary Fig. 4 shows more detailed individual model information.

At the same time, land for pasture and non-energy crops decreased as a result of carbon pricing on land-related emissions and the above mitigation options increased (Fig. 3a). The scale of land-use changes varied across models according to the socioeconomic and model-specific parameter assumptions on biomass feedstock (for example, wood, energy crops or residues), increase in energy and non-energy crop yields and conversion efficiencies (Fig. 3d). At the regional level, the area of forest and bioenergy cropland expanded most in Asia (Fig. 3c). Non-energy cropland area decreased in Asia and in OECD countries, while pasture area was substantially reduced in all regions except reforming economies of Eastern Europe and the former Soviet Union (REF), with a very large reduction in MEA and Latin America and Caribbean (LAM) (Fig. 3c).

Globally, compared with EOC scenarios, the NZ scenarios had a larger re-allocation of non-bioenergy cropland and pastures to A/R and bioenergy cropland until the mid-century. In contrast, the lower need for A/R and especially bioenergy crop cultivation to support BECCS in the second half of the century resulted in less total land-use change (Fig. 3b). Agricultural land use for food increased, but there was considerably lower need for bioenergy crop cultivation, which more than outweighed the expansion of land use for food and led to an increase in natural land. Land developed for bioenergy in the EOC scenarios remained undeveloped in the NZ scenarios. The shift from the EOC to NZ budgets increased the area of forest and bioenergy cropland by approximately 40 Mha each (1.0% and 84%, respectively) until 2040 and reduced the area used for non-energy cropland and pasture by approximately 40 Mha each (2.8% and 1.4%, respectively) at a CB of 600 $GtCO_2$. In 2100, global land use for bioenergy crops and forest was approximately 200 Mha (33%) and 17 Mha (0.4%) less than in the EOC scenarios, while the area for pasture and non-bioenergy cropland increased by 30 Mha (1.0%) and 10 Mha (0.8%), respectively, compared with EOC scenarios (Fig. 3b). Similar trends were apparent in all regions. The OECD countries, Asia and LAM had much lower land demand for bioenergy crops in the NZ scenarios than in the EOC scenarios.

Implications under different carbon budgets

The stringency of climate mitigation naturally affects the emission trends in the AFOLU sector as well as land dynamics. In general, the more climate change mitigation is required, the deeper the emission reduction and the greater the magnitude of land-use change need to be in the AFOLU sector (Figs. 1e and 3e). Scenarios with low CBs required substantial levels of negative emissions (Fig. 1e). The scenarios with CBs below 1,000 $GtCO_2$ showed BECCS CDR of 2–3 $GtCO_2\ yr^{-1}$ in 2050, with a similar range for forests. Total primary bioenergy of 100 (80–120) EJ yr^{-1} and 80 (63–96) EJ yr^{-1} were required in 2050 for the NZ and EOC CB of 600 $GtCO_2$, respectively. Note that the carbon sequestration of A/R was almost constant at CB levels below 1,000 $GtCO_2$ in 2050 (Fig. 1e). This is due to the relatively lower cost of mitigation in A/R than in other mitigation options, leading to early implementation. Across all scenarios with CBs below 1,000 $GtCO_2$, land area for pasture and non-energy crops decreased with the development of biotechnology and rising land productivity (crop yield) (Fig. 3e). Most models showed that cropland area for bioenergy varied across models but was almost constant at the CB levels below 1,000 $GtCO_2$ due to the limited land availability.

Benefits and trade-offs for food and land systems

To summarize and describe the model outputs, we used a fixed-effect regression analysis. This is a meta-analysis in which individual model outputs are assumed to be independent experimental results. A linear regression was applied to several AFOLU-related outcome variables at the global level (Methods). A coefficient for indicators of global total CBs was used to identify the effects of climate warming, while a coefficient for a dummy for CB cap scenarios (NZ and EOC) was used to identify the effects of the choice of CB cap scenarios on the AFOLU sector. These results indicated whether or not an NZ or EOC budget assumption would linearly influence the implications for AFOLU. We pooled all scenario data and classified the data into two periods, namely medium term (2040–2060) and long term (2080–2100). The regression coefficients were individually estimated for each variable and period so that the periodic characteristics could be obtained from this analysis. The data for each variable consisted of seven IAMs, two time periods of 30 years each and 14 CB levels (200 to 2,000 $GtCO_2$) for two CB cap scenarios (NZ and EOC). The number of observations thus varied between 200 to 400 for the different outcome variables (see Supplementary Table 1 for the number of observations and Supplementary Table 2 for the data submission status). We acknowledge that the set of the models we used cannot be viewed as a random sample from the population of possible models, and thus we cannot associate standard statistical properties with the regression coefficients. This limitation could be addressed to some degree in future research by using a large set of models. Although some climate modellers using model ensembles have addressed these problems[30,31], it is not easy to remove bias caused by model types from the current model ensemble at this time.

Our results showed that allowing net-negative emissions (EOC versus NZ budgets) largely affected emission trends, carbon sequestration, land-use and food systems in both the medium and long term (Table 1). In the medium term (2040–2060), compared with the EOC scenarios, the NZ scenarios reduced AFOLU-related emissions, with a large expansion of land use for A/R and bioenergy cropland, and high land pressure, leading to lower food demand, reduced use of irrigation water and nitrogen fertilizer, and a higher risk of hunger until the mid-century. Switching from an EOC to an NZ budget reduced AFOLU-related CO_2 emissions and agricultural non-CO_2 emissions by 160 $MtCO_2\ yr^{-1}$ (8.6%) and 60 $MtCO_2\ yr^{-1}$ (1.2%), respectively, while increasing the CDR associated with BECCS by 350 $MtCO_2\ yr^{-1}$ (31%). Over the same period, bioenergy cropland and forest area expanded by 15 Mha (17%) and 19 Mha (0.5%), respectively, and the land used for food crops decreased by 11 Mha (0.7%) in the NZ scenarios compared with the EOC scenarios with the same CB. Carbon prices were US\$200 (2005) per tCO_2 (150%) higher in the NZ scenarios compared with the EOC scenarios in the medium term. In addition, increased land pressure resulted in benefits and trade-offs. Land pressure increased due to greater use of bioenergy in the medium term, leading to higher food prices, lower food demand and an increased risk of hunger. The lower food demand reduced demand for irrigation water and nitrogen fertilizer by 8.8 $km^3\ yr^{-1}$ (0.3%) and 2.5 $TgN\ yr^{-1}$ (2.5%), respectively, from the EOC levels. An additional 42 million people (12%) were at risk of hunger relative to the EOC scenarios in the medium term, while in the long term, the number of people at risk of hunger was lower in the NZ scenarios (4.8 million fewer people, or 5.3% lower relative to the EOC). Despite a long-term reduction in the population at risk of hunger, the substantial increase in the medium term underscores the high risk of food insecurity in the NZ scenarios. Another effect of increasing land pressure was a rise in the global average crop yield of 0.051 tonnes dry matter (DM) $ha^{-1}\ yr^{-1}$ (1.1%) from the EOC levels.

In the long term, the lower need for A/R and cropland for bioenergy during the second half of the century resulted in a reduction of land pressure, less expansion of cropland for food, lower food prices and a reduction in the scale of agriculture intensification needed to meet food demand and lower the risk of hunger. Switching from an EOC to an NZ budget considerably reduced carbon prices by US\$800 (2005) per tCO_2 (140%) and reduced BECCS CDR by 1,290 $MtCO_2\ yr^{-1}$ (60%). Lower BECCS deployment reduced bioenergy cropland by 75 Mha (15%) and increased the amount of cropland used for food by 11 Mha (0.8%) and pasture by 16 Mha (0.6%) from EOC scenarios. This resulted in lower food prices, higher food consumption (by 14 $kcal\ cap^{-1}\ d^{-1}$ (0.4%)) and a reduced risk of hunger. The decrease in land pressure reduced agricultural intensification by 0.15 tonnes DM $ha^{-1}\ yr^{-1}$ (2.6%), while more food production increased the area of cropland used for food and nitrogen fertilizer use (by 4.2 $TgN\ yr^{-1}$ (5.1%)) compared with the EOC level. Carbon sequestration through A/R did not differ considerably between the EOC and NZ scenarios in the long term because the scale of carbon sequestration by A/R was primarily constrained by the potential area rather than the cost of A/R, which was relatively lower than for other measures.

The results from regression analysis show that the stringency of the imposed CB primarily affects emission trends, sequestrations, land-use and food systems both for the medium (2040–2060) and long term (2080–2100) (Supplementary Table 1). Almost all variables indicate steep slopes in the CB coefficient, meaning that they vary widely across the different CBs in both terms. This also implies that the degree of the benefits and trade-offs mentioned above can differ depending on both the stringency of the CB and the choice of CB cap scenarios. For the medium term in particular, the size of the CB is more important for AFOLU-related variables than the CB scenario choice to allow net-negative emissions.

Discussion

We conducted a multi-model intercomparison using IAMs that aim to improve understanding concerning the question of how early climate action can be both advantageous and detrimental from the perspective of agricultural and land-use systems. We find that early climate actions have multiple benefits and trade-offs. Early climate action avoids temperature overshoot along with the additional climate change impacts (L.D. et al., manuscript in preparation). It reduces the reliance on net-negative emissions as well as the need for drastic (mitigation-induced) shifts in land use in the long term. Land demand pressure in the second half of the century would be eased because there would not be such a strong need for massive negative emissions. Further benefits include lower food prices and lower risk of hunger in the long term. Simultaneously, however, near-term mitigation pressure in the AFOLU sector and the required land area for energy crops both increase, resulting in higher food prices than if action were delayed, intensifying concerns of food insecurity in the medium term. Therefore, food support systems for the most vulnerable groups would contribute to avoiding these adverse effects of earlier action[32].

The NZ budget scenario has several benefits compared with an EOC budget scenario. First, making earlier efforts lowers the peak temperature and reduces the risk of climate change impacts on many sectors. Second, some benefits for land systems in the long term can be observed for OECD countries, Asia and Latin America, some of which concern the invasion of habitats of local species and serious food insecurity. It is difficult to directly compare food and

Table 1 | The results of regression analysis for the effects of moving from EOC budgets to NZ scenarios on selected AFOLU-related indicators

Benefits and trade-offs of making more immediate actions

	Medium term (2040–2060)	Effects	Long term (2080–2100)	Effects
Benefits				
Emissions and carbon price	Less AFOLU-related CO$_2$ emissions*	−160 MtCO$_2$ yr^{-1}	Low carbon price***	−US$800 (2005) tCO$_2^{-1}$
	Less agricultural non-CO$_2$ emissions*	−60 MtCO$_2$ yr^{-1}		
	Carbon removal of BECCS*	+350 MtCO$_2$ yr^{-1}	Carbon removal of BECCS***	−1,290 MtCO$_2$ yr^{-1}
Food	Agricultural intensification	+0.051 tDM ha^{-1} yr^{-1}	Low food price***	−0.042 (2005 = 1)
			High food demand***	+14 kcal cap^{-1} d^{-1}
			Low risk of hunger	−4.8 million people
Land	Forest protection*	+19 Mha	Less land for biocrops***	−75 Mha
			More land for food crops*	+11 Mha
			More land for pasture**	+16 Mha
			Protect forest	+11 Mha
Other	Less irrigation water	−8.8 km^3 yr^{-1}	Less irrigation water	−7.2 km^3 yr^{-1}
	Less fertilizer use***	−2.5 TgN yr^{-1}		
Trade-offs				
Emissions and carbon price	High carbon price*	+US$200 (2005) tCO$_2^{-1}$		
Food	High food price	+0.012 (2005 = 1)	Low agricultural intensification***	−0.15 tDM ha^{-1} yr^{-1}
	Low food demand*	−10 kcal cap^{-1} d^{-1}		
	High risk of hunger*	+42 million people		
Land	More land for biocrops	+15 Mha		
	High pressure on land for food crops*	−11 Mha		
	High pressure on land for pasture***	−35 Mha		
Other			More fertilizer use***	+4.2TgN yr^{-1}

Values show the results of applying the coefficient to a dummy for carbon budget cap scenarios (β). This value can be interpreted as the degree of the effects of making more immediate mitigation efforts and moving from an EOC to an NZ budget scenario for each variable. Positive (+) (negative (−)) value means increase (decrease) in a variable by the shift from an EOC to an NZ budget scenario. See Supplementary Table 1 for the comprehensive results of this regression analysis. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

environmental challenges between the medium and long term, but the results show that the benefits of the NZ can be large when biodiversity aspects are assessed. These modelling results provide an argument for placing a relatively higher priority on near-term mitigation to reduce the rate of warming. This would lower peak warming and appears to have benefits for biodiversity.

There are available CDR technologies that were not considered in this analysis. Currently, IAMs have only been used to model the deployment of BECCS and A/R. Other CDR technologies (for example, direct air carbon capture and storage (DACCS), enhanced weathering and ocean-based CDR technologies) have not been considered in IAMs primarily because they are connected to sectors that are not yet included in these models, and because parameterizing these technologies is speculative given that CDR technologies are not currently commercially deployed[33]. The primary barrier to an upscaling of DACCS is its high cost[34] (US$200–1,000 per tCO$_2$; ref. [35]). Thus, it is unlikely that DACCS, if considered, will be implemented more widely than A/R and BECCS. For other CDR technologies, the trade-offs/adverse side effects require further research and are challenging to model in IAMs given how little we know about how these technologies might be deployed at scale[33,36,37]. It is therefore unlikely that these technologies can be implemented in the current models or considered in further analysis at this time.

This study showed the impact of avoiding a strong reliance on net-negative emissions and suggested that avoiding this dependence on net-negative emissions not only had benefits but also side effects for land-use and food systems when climate mitigation was strengthened, especially in the medium term. This analysis should be extended to other fields in the future, with a discussion of whether negative emissions should be included and to what extent they should be allowed, considering the multiple effects on various fields. Moreover, the estimates from the regression analysis in this study (Table 1 and Supplementary Table 1) can be used to assess the benefits and trade-offs of moving between CBs and to fill the missing spaces in the CB spectrum in SR1.5[27]. To explore the CB space, all data and methodologies presented here are available to the wider community.

Methods

Modelling framework. Global integrated assessment models (IAMs) were used for the quantification of the scenarios in this study, assessing scenarios which were developed in the Exploring National and Global Actions to reduce Greenhouse gas Emissions (ENGAGE) project (K.R. et al., manuscript in preparation). The objective of the ENGAGE scenarios is to cover a range of CBs consistent with low stabilization targets in a systematic way, and thus help to robustly understand implications of CB uncertainties across different IAMs (K.R. et al., manuscript in preparation). Furthermore, we used two kinds of scenario sets differentiated by the possibility of net-negative emissions. We selected seven state-of-the-art models that allow us to compute energy, emissions, economy, agriculture and land-use market interactions while consistently considering different carbon caps: AIM/CGE[38–40], COFFEE, IMAGE, MESSAGEix-GLOBIOM 1.0[41–43], POLES[44], REMIND-MAgPIE 2.0–4.1[45,46] and WITCH 5.0[47].

AIM/CGE, COFFEE, IMAGE, MESSAGEix-GLOBIOM and REMIND-MAgPIE incorporate explicit agricultural commodity markets and land-use representation, whereas POLES and WITCH use a simplified look-up table based on multiple scenario runs from a model that has detailed representations and parameterizations for biophysical and socioeconomic processes (GLOBIOM). Here we focus on the endogenous responses of land-use and bioenergy-related variables to the given changes in the underlying CBs and climate policy assumptions depending on whether net-negative emissions are allowed or not. Climate mitigation increases the demand for land through energy system changes leading to increased demand for bioenergy and more afforestation, which raise the price of land and then food consumption, resulting in the same responses to higher prices. All models represent land-use competition among food production, bioenergy crop production and afforestation in some way. All models consider emissions from changing land use and from agriculture, including fertilizer use and manure management but do not consider pesticides. AIM, MESSAGEix-GLOBIOM and WITCH endogenously determine food consumption in response to food price or income (in AIM), whereas COFFEE, IMAGE, POLES and REMIND-MAgPIE determine food consumption exogenously. We excluded the four models exogenously assuming food consumption from results for food consumption and the population at risk of hunger. The population at risk of hunger was estimated using an approach developed in an earlier study[48].

The modelling teams made their own assumptions on mitigation technologies or measures. The CDR technologies incorporated in the models are mainly BECCS and A/R. A/R provides only carbon storage in forests and not in wood. Here we use the term BECCS to refer to the transfer of CO_2 from the atmosphere to robust storage sites, which is achieved via the carbon capture and storage (CCS) component, that is, not including any net change in land carbon storage associated with the biomass supply system or the substitution effects from using bioenergy instead of other energy sources. Bioenergy without CCS (not including indirect land-use change) is usually deemed carbon neutral and additional carbon sequestration comes from the CCS part. If this CCS were to be imputed to purely non-AFOLU-related sectors, the timing of net-zero GHG emissions in AFOLU would be much later than presented in this study, and would potentially not even be achieved this century. While this change in attribution would not affect the main findings of this study highlighting the co-benefits and adverse side effects of the scenarios without any net-negative CO_2 emissions, there must be careful interpretation of the timing of net-zero.

Scenarios. To explore a comprehensive view of the relationship between CB caps and agriculture and land-use responses, we used a set of scenarios from the ENGAGE project (K.R. et al., manuscript in preparation) that covers two dimensions: (1) different levels of climate stabilization and therefore climate change mitigation efforts, represented by a global total CB, and (2) whether net-negative emissions are allowed or not, which we call EOC or NZ scenarios. Allowing global net-negative emissions implicitly considers the question of delayed versus early actions because scenarios without net-negative emissions require rapid emission reductions in the first half of this century. This also corresponds to whether we would determine temperature targets by the level of peak warming reached over the century or the warming level at the end of this century with overshoot. The use of different CB caps allows us to explore the effects of climate change mitigation efforts on agriculture and land dynamics, while the use of different CB cap scenarios allows us to compare the effects of allowing net-negative emissions and overshoot.

For the systematic exploration of the scenario space, the following CBs were applied by referring to cumulative CO_2 emission budgets from 2018 onwards: 300 to 900 $GtCO_2$ in 100 $GtCO_2$ steps as the range of CBs associated with 1.5 °C; 1,000 to 2,000 $GtCO_2$ in 200 $GtCO_2$ steps as 1.5 °C–2 °C; 2,500 $GtCO_2$; and 3,000 $GtCO_2$. These cumulative CO_2 budgets were calculated from 2018 to the time of reaching net-zero CO_2 emissions for the NZ scenarios and from 2018 to 2100 for the EOC scenarios. 'Net-zero' was assumed from the perspective of avoiding the overshoot, which would lead to climate impacts and a reliance on CDR technologies. It should be noted that the net-zero-emissions condition did not actually lead to a freeze on the global mean temperature. There were still small and slow temperature decreases caused by the carbon cycle dynamics accompanied by the offset of the radiative forcing associated with non-CO_2 residuals.

All of the models represented climate policy by exogenously implementing a global uniform carbon price on GHG (for example, CO_2, CH_4 and N_2O) emissions from energy, agriculture and land sectors. This carbon price induced changes in production systems, technological mitigation options and food demand via consumer responses (the models included changes in preferences due to the price change), and hence decreased emissions. In comparison, in scenarios with no carbon price, the production cost was low due to the lack of additional costs for land expansion and fertilizer. This practice normally triggers penalties under the implementation of climate policies. Concerning the land-use and food security trade-offs of climate policies, each model applied a price ceiling of US\$200 per tCO_2eq for CH_4, N_2O and CO_2 emitted from agriculture and land sectors for both the near and long term, as well as for all scenarios (NZ and EOC scenarios) to avoid high impacts on food security[49]. Socioeconomic conditions, including population demographics, gross domestic product (GDP), consumer preferences, food loss and waste were varied in each model according to qualitative 'middle-of-the-road' (Shared Socioeconomic Pathway (SSP) 2) narratives[42] through 2100. Global warming potential (GWP) 100 was used to convert non-CO_2 to CO_2 emissions in this study.

Regression analysis. To identify the effects of the stringency of climate warming and the choices of CB cap scenarios (NZ and EOC) on the AFOLU sector, we performed a regression analysis on the scenarios with equation (1). The equation has been applied to several AFOLU-related outcome variables at the global level. The basic idea behind this regression analysis is that the coefficients of CB, $\alpha_{i,t}$, can be interpreted as a marginal effect of the CB on the different outcome variables. The second critical parameter is the coefficient of a dummy variable for the CB cap scenario choices, which takes on the value of 1 for NZ scenarios and 0 for EOC scenarios. This shows whether the NZ or EOC assumption would linearly change the AFOLU implications. See the main text and Supplementary Tables 1 and 2 for the data used for this analysis.

$$X_{m,i,t,s} = C_{i,t} + \alpha_{i,t} \times \mathrm{CB} + \beta_{i,t} \times \mathrm{SceDum}_{i,t} + \sum_{m} \delta_{m,i,t} \times \mathrm{ModDum}_{m,i,t} + \varepsilon_{m,i,t,s} \tag{1}$$

where: i is the indicator; t is the period (medium or long term); s represents the scenario; m represent the model; $X_{m,i,t,s}$ is the AFOLU output from the models; CB is the level of global total carbon budget cap; $\mathrm{SceDum}_{i,t}$ is the dummy for carbon budget cap scenarios (1 for NZ budget; 0 for EOC budget); $\mathrm{ModDum}_{m,i,t}$ is the dummy for different models; $\alpha_{i,t}$, is the coefficient for indicators of carbon budgets; $\beta_{i,t}$, is the coefficient for the dummy for scenarios of the carbon budget caps (NZ and EOC); $\delta_{m,i,t}$ is the coefficient for the dummy for models; $\varepsilon_{m,i,t,s}$ is an error term; and $C_{i,t}$ is a constant term.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Data used in the study are available at the repository https://doi.org/10.5281/zenodo.5078072.

Code availability

Code used in the study is available at the repository https://doi.org/10.7910/DVN/ZDXB6F.

Received: 13 December 2020; Accepted: 16 August 2021;

References

1. Rogelj, J. et al. A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573**, 357–363 (2019).
2. Anderson, K. & Peters, G. The trouble with negative emissions. *Science* **354**, 182–183 (2016).
3. Peters, G. P. & Geden, O. Catalysing a political shift from low to negative carbon. *Nat. Clim. Change* **7**, 619–621 (2017).
4. Clarke, L. et al. International climate policy architectures: overview of the EMF 22 international scenarios. *Energy Econ.* **31**, S64–S81 (2009).
5. Kriegler, E. et al. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Clim. Change* **123**, 353–367 (2014).
6. Clarke, L. K. J. et al. in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) 413–510 (IPCC, Cambridge Univ. Press, 2014).
7. *World Energy Outlook 2015* (IEA, 2015).
8. van Vuuren, D. et al. A new scenario framework for climate change research: scenario matrix architecture. *Clim. Change* **122**, 373–386 (2014).
9. Meinshausen, M. et al. Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458**, 1158–1162 (2009).
10. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459**, 829–832 (2009).
11. Fuss, S. et al. Betting on negative emissions. *Nat. Clim. Change* **4**, 850–853 (2014).
12. Shue, H. Climate dreaming: negative emissions, risk transfer, and irreversibility. *J. Hum. Rights Environ.* **8**, 203–216 (2017).
13. Williamson, P. Emissions reduction: scrutinize CO_2 removal methods. *Nature* **530**, 153–155 (2016).
14. Smith, P. et al. Biophysical and economic limits to negative CO_2 emissions. *Nat. Clim. Change* **6**, 42–50 (2016).
15. Popp, A. et al. Land-use futures in the Shared Socio-economic Pathways. *Glob. Environ. Change* **42**, 331–345 (2017).
16. Field, C. B. & Mach, K. J. Rightsizing carbon dioxide removal. *Science* **356**, 706–707 (2017).

17. Boysen, L. R. et al. The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future* **5**, 463–474 (2017).
18. Morrow, D. & Svoboda, T. Geoengineering and non-ideal theory. *Public Aff. Q.* **30**, 83–102 (2016).
19. Fujimori, S., Rogelj, J., Krey, V. & Riahi, K. A new generation of emissions scenarios should cover blind spots in the carbon budget space. *Nat. Clim. Change* **9**, 798–800 (2019).
20. Fuss, S. et al. Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).
21. Bauer, N. et al. Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Clim. Change* **163**, 1553–1568 (2018).
22. Roe, S. et al. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Change* **9**, 817–828 (2019).
23. Hanssen, S. V. et al. The climate change mitigation potential of bioenergy with carbon capture and storage. *Nat. Clim. Change* **10**, 1023–1029 (2020).
24. Hasegawa, T. et al. Food security under high bioenergy demand toward long-term climate goals. *Clim. Change* **163**, 1587–1601 (2020).
25. Ohashi, H. et al. Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation. *Nat. Commun.* **10**, 5240 (2019).
26. Riahi, K. et al. Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change* **90**, 8–23 (2015).
27. Rogelj, J. et al. in IPCC *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) 93–174 (WMO, 2018).
28. Luderer, G. et al. Residual fossil CO_2 emissions in 1.5–2 °C pathways. *Nat. Clim. Change* **8**, 626–633 (2018).
29. McCollum, D. L. et al. Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nat. Energy* **3**, 589–599 (2018).
30. Tebaldi, C. & Knutti, R. The use of the multi-model ensemble in probabilistic climate projections. *Phil. Trans. R. Soc. A* **365**, 2053–2075 (2007).
31. Thompson, S. G. & Higgins, J. P. T. How should meta-regression analyses be undertaken and interpreted? *Stat. Med.* **21**, 1559–1573 (2002).
32. Fujimori, S. et al. Inclusive climate change mitigation and food security policy under 1.5 °C climate goal. *Environ. Res. Lett.* **13**, 074033 (2018).
33. Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W. & Clarens, A. F. From zero to hero? Why integrated assessment modeling of negative emissions technologies is hard and how we can do better. *Front. Clim.* **1**, 11 (2019).
34. Nemet, G. F. et al. Negative emissions—Part 3: Innovation and upscaling. *Environ. Res. Lett.* **13**, 063003 (2018).
35. Realmonte, G. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Commun.* **10**, 3277 (2019).
36. Beerling, D. J. et al. Farming with crops and rocks to address global climate, food and soil security. *Nat. Plants* **4**, 138–147 (2018).
37. *High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques* (GESAMP, 2019).
38. Fujimori, S. et al. SSP3: AIM implementation of Shared Socioeconomic Pathways. *Glob. Environ. Change* **42**, 268–283 (2017).
39. Fujimori, S., Masui, T. & Matsuoka, Y. *AIM/CGE [Basic] Manual* (Tsukuba Center for Social and Environmental Systems Research, NIES, 2012).
40. Hasegawa, T., Fujimori, S., Ito, A., Takahashi, K. & Masui, T. Global land-use allocation model linked to an integrated assessment model. *Sci. Total Environ.* **580**, 787–796 (2017).
41. Frank, S. et al. Reducing greenhouse gas emissions in agriculture without compromising food security? *Environ. Res. Lett.* **12**, 105004 (2017).
42. Fricko, O. et al. The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. *Glob. Environ. Change* **42**, 251–267 (2017).
43. Havlík, P. et al. Climate change mitigation through livestock system transitions. *Proc. Natl Acad. Sci. USA* **111**, 3709–3714 (2014).
44. Keramidas, K., Kitous, A., Després, J. & Schmitz, A. *POLES-JRC Model Documentation* (JRC, 2017).
45. Popp, A. et al. Land-use protection for climate change mitigation. *Nat. Clim. Change* **4**, 1095–1098 (2014).
46. Bodirsky, B. L. et al. Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nat. Commun.* **5**, 3858 (2014).
47. Emmerling, J. et al. *The WITCH 2016 Model - Documentation and Implementation of the Shared Socioeconomic Pathways* (FEEM Working Paper No. 42, 2016).
48. Hasegawa, T. et al. Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Change* **8**, 699–703 (2018).
49. Fujimori, S. et al. A multi-model assessment of food security implications of climate change mitigation. *Nat. Sustain.* **2**, 386–396 (2019).

Acknowledgements

T.H., S. Fujimori and K.O. were supported by the Environment Research and Technology Development Fund (JPMEERF20202002 and JPMEERF20211001) of the Environmental Restoration and Conservation Agency of Japan and Sumitomo Foundation. T.H. was supported by the Ritsumeikan Global Innovation Research Organization (R-GIRO), Ritsumeikan University. P.R. and R.S. were supported by the Brazilian National Council for Scientific and Technological Development (CNPq). All authors excluding J.D., K.K. and F.F. received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 821471 (ENGAGE).

Author contributions

T.H. designed the research, created figures and wrote the draft of the paper; S. Fujimori, V.K., D.v.V. and K.R. designed the scenario protocol; T.H. and S. Fujimori carried out analysis of the modelling results with notable contributions from T.H., S. Fujimori, Y.O., K.O. (AIM/CGE), P.R., R.S. (COFFEE), M.H. (IMAGE), S. Frank, M.G., B.v.R, A.-M.C., A.D., P.H., V.K. (MESSAGEix-GLOBIOM), J.D., K.K, F.F. (POLES), F.H., C.B., A.P. (ReMIND-MAgPIE), L.D. and J.E. (WITCH); all authors provided feedback and contributed to writing the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-021-00772-w.

Correspondence and requests for materials should be addressed to Tomoko Hasegawa.

Peer review information *Nature Sustainability* thanks John Antle and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

nature research

Corresponding author(s): Tomoko Hasegawa

Last updated by author(s): Jun 28, 2021

Reporting Summary

Nature Research wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Research policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☒	☐	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used.
Data analysis	No software was used.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

The data repository is stored on URL (to be prepared). Other data will be provided upon request.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study provides an analysis on effects of climate mitigation without a reliance on net negative emissions.
Research sample	n/a
Sampling strategy	n/a
Data collection	n/a
Timing and spatial scale	n/a
Data exclusions	n/a
Reproducibility	n/a
Randomization	n/a
Blinding	n/a

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging