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

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Abstract (approximately 150 words) - 148 words currently

Delaying climate mitigation action and allowing a temporary overshoot of temperature targets requires large-scale negative carbon emissions in the second half of this century that may induce adverse side-effects on land, food and ecosystems. Meanwhile, meeting climate goals without net negative emissions inevitably needs early and rapid emissions reduction measures, which also brings challenges in the near-term. Here we identify the implications of scenarios without a dependence on net-negative carbon emissions through land-based carbon dioxide removal technologies on land-use and food systems. 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 water scarcity. At the same time, however, near-term mitigation pressure in the AFOLU sector and the required land area for energy crops increases, resulting in additional agricultural intensification.

Main text

Climate policy scenario assessments use assumptions describing how society could reduce its greenhouse gas (GHG) emissions. The current global emissions scenarios were criticised because they rely heavily on net negative emissions leading to a temporarily exceedance of a certain temperature limits[1, 2, 3]. The current scenarios that aim to stabilise greenhouse gas concentrations by the end of the 21st century[4, 5] or attempt to limit end-of-century radiative forcing to specific levels,[6, 7, 8] assume an overall limit on total cumulative CO_2 or greenhouse gas 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, leads to a situation in which projected substantial net negative CO_2 emissions in the second half of the century compensate for weaker emission reductions in the near-term, resulting in a temporary exceedance of the targeted temperature level before 2100 (overshoot)[1].

The focus on end-of-century outcomes also results in the perception that meeting stringent climate goals requires substantial amounts of net negative emissions[1, 6, 11, 12, 13]. The potential land-use consequences of large-scale carbon dioxide removal (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, 17, 18, 19]. (For clarification, we use the term “net negative emissions” to refer to the net removal of CO_2 from the atmosphere and use “CDR technologies” to refer to specific technologies or measures.) A key issue is the feasibility of implementing land-based mitigation measures such as non-CO_2 emissions reductions[20] and CDR associated with Afforestation/Reforestation (A/R) and bioenergy combined with CCS (BECCS)[21], which play a vital role in the stringent mitigation scenarios[22, 23, 24] but can affect (positively and/or negatively) other sustainable development goals[25, 26]. (Although the social acceptability and desirability of using CCS or BECCS is also uncertain, here we assumed that BECCS and CCS are socially accepted). Feasibility would depend on the stringency of the climate goals, associated emissions pathways and socioeconomic conditions. For example, immediate actions involving rapid emission reductions in the near-term lower the need for negative emissions in the latter period[4, 27] whereas delayed actions would increase the need for deep negative emissions. In addition, the amount of negative emissions required depends on the total carbon budget. There is currently little known about the dynamics of emissions pathways and land-use implications of scenarios without net-negative emissions. 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[28]. However, the impacts of scenario choice regarding reliance on net negative emissions and carbon budget caps on the Agriculture, Forest and Land Use (AFOLU) sector have not been analyzed.

Here, we conducted a multi-model intercomparison using seven state-of-the-art global integrated assessment models (IAMs) that aims at an improved understanding concerning the following questions: i) is early climate change mitigation action without global net-negative CO_2 emissions both advantageous and detrimental from the perspective of the agricultural and land-use systems, and ii) is the optimal timing of net-zero GHG emissions 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 a part of the AFOLU sector in this study because bioenergy crops used for BECCS would be the major cause of change in the land use condition. 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 a careful interpretation of the timing of net zero. Two sets of scenarios are analyzed, differentiated by an allowance of global net negative emissions: first, ‘End-of-century (EOC) budget’ scenarios constraining only cumulative CO_2 emissions over this century, thus allowing massive negative emissions in the latter half of the century; second, 'net-zero (NZ) budget' scenarios which limit remaining cumulative CO_2 emissions until carbon neutrality (net zero CO_2 emissions) is reached, and which do not allow for any net negative CO_2 emissions, thus limiting temperature overshoot[28]. This, in turn, may reduce the need for drastic action with more substantial trade-offs in the latter half of the century. For each set, we assume a wide range of carbon budgets (CBs) to fill the gaps between CBs in the IPCC SR1.5 and to 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 **Method** 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 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, Figure S1). NZ scenarios require both faster transitions and an earlier achievement of net-zero while EOC scenarios require more mitigation efforts in the long-term. For the NZ scenarios with CB of 600 $GtCO_2$, which is a median of the CB range consistent with limiting warming to 1.5°C relative to the preindustrial level[29], in 2050, CH_4 and N_2O emissions from AFOLU are 2.8 (1.9 to 4.1) $GtCO_2$eq/year and 1.8 (1.3 to 3.2) $GtCO_2$eq/year, respectively, while CO_2 sequestration of 2.6 (0.39 to 4.5) $GtCO_2$/year and 3.4 (0.73 to 6.2) $GtCO_2$/year is achieved through forest management (here we assumed avoided deforestation and A/R) and BECCS, respectively, at median level across models. BECCS shows the highest carbon sequestration, followed by A/R and avoided deforestation at the end of this century (Fig. 1a). CO_2 emissions decline more rapidly and prominently than non-CO_2, underscoring the difficulty of reducing non-CO_2 emissions in agriculture. The large share of total emissions 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 will be enhanced earlier and deeper mostly by increasing BECCS CDR (228 $MtCO_2$/year) with a small additional reduction of agricultural CH_4 and N_2O emissions of 1.6 $MtCO_2$eq/year, 0.40 $MtCO_2$eq/year 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 forest management to carbon sequestration is high in Latin America and the Middle East and Africa (MEA) (Fig. 1b). Globally, in 2100, BECCS CDR decreases by 3.3 $GtCO_2$eq/year, while carbon sequestration through forest management increases by 270 $MtCO_2eq$/year. The lower BECCS CDR reduces the need for drastic mitigation-induced shifts in land-use in the long-term. In 2100, net emissions are -7.5 (-12.1 to -2.3) $GtCO_2$/year and -10.3 (-14.9 to -5.1) $GtCO_2$/year, respectively, for the NZ and EOC scenarios (Figure S1). This difference comes mainly from BECCS CDR. Non-CO_2 emissions show a wide range between 3.3-7.3 $GtCO_2eq$ across models in 2050 in scenarios with 600 $GtCO_2$ CB (Fig1d). 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 forest management remained almost constant over time from 2030 onwards, hardly affecting net zero timing. Therefore, in OECD countries, where AFOLU's GHG net-zero were 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 is earlier in NZ compared to EOC scenarios (Fig. 2c). When determining future emission pathways, non-CO_2 emissions are expected to be minimized 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 indicated 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. At the same time, land for pasture and non-energy crops decreased as a result of carbon pricing on land-related emissions and increases in the above mitigation options (Fig. 3a). The scale of land-use changes varied across models according to the socioeconomic and model specific parameter assumptions on biomass feedstock (e.g., wood, energy crops or residues), agricultural development of energy and non-energy crop yields and land 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 OECD countries, while pasture area was reduced substantially in all regions except Reforming Economies of Eastern Europe and the Former Soviet Union (REF), with a very large reduction in MEA and LAM (Fig. 3c).

Globally, compared with EOC scenarios, the NZ scenarios had a larger reallocation of non-bioenergy cropland, pastures for 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. The transition 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) compared with the EOC scenarios with 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 to 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 the EOC scenarios.

Implications under different carbon budgets

The stringency of climate mitigation naturally affects the emissions trend in AFOLU sector and land dynamics. In general, the more climate change mitigation required, the deeper emissions reduction and more dynamic land-use change need to be in the AFOLU sector (Fig. 1e, Fig. 3e). Scenarios with low CBs require substantial levels of negative emissions (Fig. 1e). The scenarios with CBs below 1000 $GtCO_2$ show BECCS CDR of 2-3 $GtCO_2$/year in 2050, with a similar range for forests. Total primary bioenergy of 100 (80-120) EJ/year and 80 (63-96) EJ/year is required in 2050, respectively, for the NZ and EOC CB of 600 $GtCO_2$. Note that there are similarities in CDR in AFOLU for scenarios with CBs lower than 1000$GtCO_2$eq in 2050 (Fig. **1**d). These are due to the relatively lower cost of mitigation in forest management than other mitigation options, leading to early implementation. Across all scenarios with CBs below 1000 $GtCO_2$, land area for pasture and non-energy crops decreased with the development of biotechnology and rising land productivity (crop yield) (Fig. 3e). Most models exhibited a ceiling in cropland area for bioenergy at a certain level (300–600 Mha), which varied across models but was almost constant at CB values below 1000 $GtCO_2$ due to the limited land availability for bioenergy production.

Benefits and trade-offs for the food and land systems

To summarize and describe the model outputs, we used a fixed-effect regression analysis. This is a sort of 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 (See Methods). A coefficient for indicators of global total CBs was used to identify the effects of climate warming while a coefficient for dummy budget cap schemes was used to identify the effects of CB scheme choice 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 thirty years each and 14 CB levels (200 to 2000 $GtCO_2$) for two CB schemes (NZ and EOC). The number of observations thus varied between 200 to 400 for the different outcome variables (See Table S 1 for the number of observations and Table S 2 for the data submission status). We acknowledge that the set of the models we are using 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. Thus, statistical significance cannot be attached to the current regression coefficients. Although some climate modellers using model ensembles have addressed these problems[30, 31], it is not easy to remove bias 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 water and nitrogen fertiliser, and a higher risk of hunger until the mid-century.

Switching from an EOC to NZ budget reduced AFOLU-related CO_2 emissions and agricultural non-CO_2 emissions by 160 $MtCO_2$/year (8.6%) and 60 $MtCO_2$/year (1.2%), respectively, while increasing the CDR associated with BECCS by 350 $MtCO_2$/year (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 200 USD2005/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 fertiliser by 8.8 km^3/year (0.3%) and 2.5 TgN/year (2.5%), respectively, from the EOC levels. An additional 42 million people were at risk of hunger (12% higher relative to the EOC scenarios) in the medium-term than in the long-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 security 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/year (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 to lower the risk of hunger. Switching from an EOC to NZ budget considerably reduced carbon prices by 800USD2005/tCO_2 (140%) and reduced BECCS CDR by 1290 $MtCO_2$/year (60%) compared with EOC scenario levels. 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/day (0.4%)) and a reduced risk of hunger (4.8 million fewer people (-5.3%)). The decrease in land pressure reduced agricultural intensification by −0.15 tonnes DM/ha/year (2.6%), while more food production increased the area of cropland used for food and nitrogen fertiliser use (by 4.2 TgN/year (5.1%)) compared with the EOC level. Carbon sequestration through forest management 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 forest management, 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) (Table S1). 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 scheme. For the medium-term in particular, the size of the CB is more important for AFOLU-related variables than the choice to allow net negative emissions or not.

Discussion

We conducted a multi-model intercomparison using IAMs that aims 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[32]. 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. At the same time, however, near-term mitigation pressure in the AFOLU sector and 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[33].

The NZ budget scheme has several benefits compared to an EOC budget scheme. 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 environmental challenges between the medium- and long-term, but the results show that the benefits can be large when biodiversity and food security 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 and food security.

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 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[34]. The primary barrier to an upscaling of direct air carbon capture and storage (DACCS) is its high cost[35] (200–1000 USD/tCO_2[36]). 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[34, 37, 38]. 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, emissions scenarios used in the IPCC SR1.5[29] relied heavily on major model intercomparison studies[22, 39, 40] where the CB spaces are prescribed and potentially biased to several specific points (e.g., 400, 1000 and 1600 GtCO_2). However, 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]. The estimates from the regression analysis of this study (Table 1 and Table S1) 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. To explore the CB space, all data and methodologies presented here are available to the wider community.

Methods(<3000 words)

Modelling framework. Global integrated assessment models (IAMs) are used for the quantification of the scenarios in this study, assessing scenarios which were developed in the ENGAGE project[28]. The objective of the ENGAGE scenarios is to cover a range of carbon budgets consistent with low stabilization targets in a systematic way, and thus help to robustly understand implications of carbon budget (CB) uncertainties across different IAMs[28]. Furthermore, we use 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 [41, 42, 43], COFFEE, IMAGE, MESSAGEix-GLOBIOM 1.0 [44, 45, 46], POLES[47], REMIND-MAgPIE 2.0-4.1 [48, 49] and WITCH 5.0[50].

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 fertiliser use, and manure management but do not consider pesticides. Among them, 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[51].

The modeling 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 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 CCS component , i.e.

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 iLUC) 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 a 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 use a set of scenarios from the ENGAGE project[28] 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. The use of different CB schemes allows us to compare the effects of allowing net negative emissions and overshoot.

For the systematic exploration of the scenario space, the following CBs are applied by referring to cumulative CO_2 emissions budgets from 2018 onwards: 300 to 900 $GtCO_2$ in 100 $GtCO_2$ steps as the range of CBs associated with 1.5°C, and 1000 to 2000 $GtCO_2$ in 200 $GtCO_2$ steps as 1.5°C-2°C and 2500, 3000 $GtCO_2$. These cumulative CO_2 budgets are 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 represent climate policy by exogenously implementing a global uniform carbon price on greenhouse gas (e.g., CO_2, CH_4, and N_2O) emissions from energy, agriculture and land sectors. This carbon price induces changes in production systems, technological mitigation options and food demand via consumer responses (the models include changes in preferences due to the price change), and hence decreases emissions. In comparison, in scenarios with no carbon price, the production cost is 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 applies a price ceiling of \$200/tCO_2-eq 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[52]. Socioeconomic conditions, including population demographics, GDP, consumer preferences, food loss and waste are varied in each model according to qualitative “middle-of-the-road” [shared socioeconomic pathway (SSP) 2] narratives[45] through 2100. GWP100 is used to convert non-CO_2 to CO_2 emissions in this study. See Riahi et al.[28] for detailed information on the representation of scenarios settings.

Regression analysis. To identify the effects of climate warming and CB scheme choices on the AFOLU sector, we performed a regression analysis on the scenarios with the following linear equation. 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 NZ budgets, which takes on the value of 0 for EOC budgets. This yields whether the NZ or EOC budget assumption would linearly change the AFOLU implications. See the main text and Tables S1 and S2 for the data used for this analysis.

$$X_{m,i,t,s} = C_{i,t} + \alpha_{i,t} \cdot CB + \beta_{i,t} \cdot SceDum_{i,t} + \sum_m \delta_{m,i,t} \cdot ModDum_{m,i,t} + \varepsilon_{m,i,t,s} \qquad (1)$$

where,

i: indicator, t: period (medium- or long-term), s: scenario, m: model,

$X_{m,i,t,s}$: AFOLU output from the models,

CB: level of global total carbon budget cap,

$SceDum_{i,t}$: dummy for emission cap schemes (1 for NZ budget; 0 for EOC budget),

$ModDum_{m,i,t}$: dummy for different models,

$\alpha_{i,t}$: coefficient for indicators of carbon budgets,

$\beta_{i,t}$: coefficient for dummy for schemes of the budget caps,

$\delta_{m,i,t}$: coefficient for dummy for models,

$C_{i,t}$: constant term.

Data availability

The data that support the findings of this study are available from the corresponding author upon request.

Data used in the study is available at the repository: XXXX

Code Availability Statement

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

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Acknowledgements
S.F, T.H and K.O. are supported by the Environment Research and Technology Development Fund (JPMEERF20202002) 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. are 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; S.F., V.K., D.v.V., K.R. designed the scenario protocol; T.H. and S.F carried out analysis of the modelling results with notable contributions from T.H., S.F., K.O. (AIM/CGE), P.R., R.S. (COFFEE), M.H. (IMAGE), S.F., M.G., B.v.R, A.D., H.V., V.K., (MESSAGEix-GLOBIOM), J.D., K.K, F.F. (POLES), F.H., C.B., A.P. (ReMIND-MAgPIE) and L.D., J.E. (WITCH); T.H. created figures and wrote the draft of the paper; all authors provided feedback and contributed to writing the paper.

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Conflict of interest
The authors declare no competing interests.

Table and figures

Fig. 1 AFOLU related GHG emissions and sequestrations. a) Global emissions and sequestrations in the NZ scenarios with 600 $GtCO_2$ carbon budget (CB), b) changes in the NZ scenario relative to the EOC scenario at global and regional levels in 2050 and 2100, with 600 $GtCO_2$ CB, c) and d) changes in 2050 for the NZ scenarios with 600 $GtCO_2$ CB for regions and global by individual models, e) global emissions and sequestrations in 2050 with respect to 2010 with different CBs. Bars or areas show multi-model median levels while whiskers represent ranges across models. The black line in a) shows net emissions in AFOLU including BECCS CDR. The dotted line in

a) shows net emissions in AFOLU excluding BECCS CDR. The red and blue lines in a) indicate the 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. Figure S1 shows panel a) for both NZ and EOC scenarios. Figure S3 shows more detailed individual model information. Regions: Asia (ASIA), Latin America and Caribbean (LAM), Middle East and Africa (MAF), developed regions (OECD 90) and Reforming Economies of Eastern Europe and the Former Soviet Union (REF).

Fig. 2 Global and regional timing of net zero emissions for total anthropogenic CO_2 emissions (based on GWP-100) and AFOLU's GHG emissions in NZ scenarios, with different CBs for global a) and for regional level and all the CB levels b), and c) regional timing of AFOLU net zero emissions. Thick black lines show the multi-model median level while whiskers represent ranges across models. See Table S2 for the scenarios and models used in this analysis.

Fig. 3 Land use changes in the scenarios with different carbon budget (CB) caps. a) Global land use change with respect to 2010 in the NZ budget scenarios with 600 $GtCO_2$ CB. b) changes from the EOC scenario to the NZ scenario at global and regional levels in 2050 and 2100 for a 600 $GtCO_2$ CB. c,d) changes in 2050 with respect to 2010 for the regional budget scenarios with 600 $GtCO_2$ CB for regions and global by individual models. e) global land use change in 2050 with respect to 2010 with different CBs. Bars or areas show multi-model median levels while whiskers represent ranges across models. The red and blue lines in a) indicate the net-zero timing of AFOLU's GHG emissions and total anthropogenic CO_2 emissions respectively. Figure S2 shows panel a) for both NZ and EOC scenarios. Figure S4 shows more detailed individual model information.

Table 1 The results of regression analysis for the effects of moving from EOC budgets to NZ scenarios on selected AFOLU relative indicators. Values shows the results of applying the coefficient to a dummy for emission cap schemes (β). This value can be interpreted as the degree of the effects from making more immediate mitigation efforts and moving from an EOC to NZ budget scheme for each variable. See Table S1 for the comprehensive results of this regression analysis.

Benefit and trade-offs by making more immediate actions

		Medium-term (2040-2060)	Effects	Long-term (2080-2100)	Effects
Benefit	Emissions and carbon price	Less AFOLU-related CO_2 emissions*	-160 Mt CO_2/yr	Low carbon price***	-800 US$2005/t CO_2
		Less agricultural non-CO_2 emissions*	-60 Mt CO_2/yr		
		Carbon removal of BECCS*	+350 Mt CO_2/yr	Carbon removal of BECCS***	-1290 Mt CO_2/yr
	Food	Agricultural intensification	+0.051 t DM/ha/yr	Low food price***	-0.042 [2005 = 1]
				High food demand***	+14 kcal/cap/day
				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	Less irrigation water	-7.2 km^3/yr
		Less fertiliser use***	-2.5 Tg N/yr		
Trade-offs	Emissions and carbon price	High carbon price*	+200 US$2005/t CO_2		

Food	High food price	+0.012 [2005 = 1]	Low agricultural intensification***	-0.15t DM/ha/yr
	Low food demand*	-10 kcal/cap/day		
	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 fertiliser use***	+4.2Tg N/yr

* Asterisks identify significance of P value (*: P<0.05. **: P<0.01, ***: P<0.001)