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Agriculture and land use implications of early climate change mitigation efforts without reliance on net-negative emissions

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Article

Keywords: AFOLU, climate mitigation, net zero, bioenergy and CCS, afforestation, carbon budget, model comparison, integrated assessment models.

Posted Date: December 29th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-128052/v1

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Version of Record: A version of this preprint was published at Nature Sustainability on October 7th, 2021. See the published version at https://doi.org/10.1038/s41893-021-00772-w.

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Abstract (approximately 150 words) - 157 words currently

Allowing delayed climate mitigation actions and overshoot of temperature targets requires large scale negative carbon emissions that may induce adverse side-effects on land, food and ecosystems in the second half of this century. Meanwhile, meeting climate goals without net negative emissions inevitably needs the implementation of early and quick 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 on land-use and food systems. We find that early climate actions without the reliance on net-negative carbon emissions have multiple benefits and trade-offs in land-use and food systems, and avoid the need for drastic (mitigation-induced) shifts in land-use in the long term. Further long-term benefits are lower food prices, a reduced risk of hunger and lower water scarcity. At the same time, however, near-term mitigation pressure in the AFOLU sectors and the required land area for energy crops increases, resulting in additional agricultural intensification.

Key words

AFOLU, climate mitigation, net zero, bioenergy and CCS, afforestation, carbon budget, model comparison, integrated assessment models.

Main text (<3500 words) – 3212 words currently

To understand how global warming can be limited to a certain level of temperature increase, climate policy scenario assessments use assumptions that describe how society could reduce its greenhouse gas (GHG) emissions. Emissions scenarios used in the IPCC SR1.5[1] are heavily based on major model intercomparison studies[2, 3, 4] where the carbon budget (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 being outdated by the choice of CB and climate science[5]. Future emissions scenarios for the IPCC Sixth Assessment Report should explore the CB space in a systematic manner so that policy implications can be adequately assessed[5]. Furthermore, current scenarios typically focus on reaching specific climate goals in 2100. This choice may encourage risky pathways that delay action, reach higher-than-acceptable mid-century warming (overshoot), and rely on a net removal of carbon dioxide thereafter to reverse their initial shortfall in emission reductions[6]. 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[7]. However, the impacts of scenario choice and carbon budget caps on the Agriculture, Forest and Land Use (AFOLU) sector have not been analyzed so far.

Currently, the main argument concerned with long-term climate stabilization is gradually shifting from seeking emissions pathways that reach climate targets to identifying the feasibility of the pathways shown in the literature[1, 8] and how to realize them. One of the key issues that we still have not figured out is the feasibility of implementing land-based mitigation measures such as non-CO_2 emissions reductions[9] and so-called negative emissions technologies via afforestation and bioenergy combined with CCS (BECCS)[10], which play a vital role in the stringent mitigation scenarios[4, 11, 12] but at the same time, create negative trade-offs with other sustainable development goals[13]. This would obviously be dependent on the stringency of the climate goals and associated emissions pathways as well as socioeconomic conditions. For example, immediate actions involving rapid emission reductions in the near-term basically lower the need for negative emissions mostly dominated by BECCS in the second half of century[14, 15] whereas delayed actions would increase the need for deep negative emissions. At the same time, the need for negative emissions depends on the total carbon budget. Moreover, bioenergy and afforestation may have different roles from the perspective of energy system implications and technological costs. There is currently little known about the dynamics of emissions pathways and land-use side implications.

Here, we conducted a multi-model intercomparison using integrated assessment models (IAMs) that aims to answer the following questions: i) Is early climate change mitigation action without global net-negative emissions beneficial or harmful from the perspective of the agricultural and land-use systems, and ii) Is the optimal timing of net-zero emissions in the agricultural and land-use sectors the same as for anthropogenic emissions in other sectors of the economy? While mitigation from BECCS is not attributed to AFOLU but rather to the energy sector, bioenergy crops used for BECCs would be the major source that can change the land use condition and we, thus, assess and discuss them as part of AFOLU sector in our study. We carried out a multi-model comparison using seven state-of-the-art global IAMs. 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 century. Secondly, '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[7]. This, in turn, may mitigate the need for negative emissions in the latter half of century. For each set, we assume a wide range of CBsto fill the gaps betweenCBs s in the IPCC SR1.5 and to explore the consequence of mitigation and the timing of net zero emissions across the CB spectrum. See **Method** for more details about the methodology.

GHG emissions in AFOLU in climate mitigation not relying on net-negative emissions

Scenarios from IAMs indicate the substantial and essential role of AFOLU sectors in climate stabilization for low CB scenarios. Projected net GHG emissions from the AFOLU sectors (CO_2 reductions through avoided deforestation, afforestation/reforestation and non-CO_2 emissions from agriculture) and BECCS carbon sequestration combined must decline towards net-zero where emissions and sequestrations are equally balanced in the mid-century for both NZ and EOC scenarios (Fig. 1a, Figure S **1**). NZ scenarios tend to require both faster transitions and an earlier achievement of net-zero while EOC scenarios require more mitigation in the long-term. For example, for the scenarios with CB of 600 $GtCO_2$, which is a median of the range of remaining CBs consistent with limiting warming to 1.5°C relative to the preindustrial level[1], global net-zero emissions are achieved around 2052 in NZ scenarios while net-zero is achieved in 2060 in EOC scenarios at median levels across models. For the NZ scenarios, 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 such as avoided deforestation and afforestation/reforestation and BECCS, respectively, at median level across models.

BECCS, which is usually not counted as a part of AFOLU but is strongly interlinked, shows the highest CDR, followed by afforestation/reforestation 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 portfolio of land-based mitigation measures in IAMs is limited, because the CO_2 removal technologies incorporated in the current IAMs are mainly BECCS and afforestation/reforestation. Despite this, the large share of total mitigation highlights the importance of the land sector in achieving low emissions pathways.

Globally, by shifting from EOC to NZ budgets, emission reductions will be enhanced earlier and deeper mostly by increasing the BECCS carbon sequestration (228 $MtCO_2$/year) with a small additional reduction of agricultural CH_4 and N_2O emissions of 1.6 $MtCO_2eq$/year, 0.40 $MtCO_2eq$/year respectively (Fig. 1b) in the medium-term (2050). In 2050, the contribution of BECCS to deeper decarbonization in NZ scenarios is high in OECD countries, while forest management's contribution to carbon sequestration is high in Latin America and Middle East and Africa (MEA) (Fig. 1b). In the long-term (2100), BECCS carbon sequestration decreases by 3.3 $GtCO_2eq$/year while forest management's carbon sequestration increases by 270 $MtCO_2eq$/year. The lower BECCS carbon sequestration in the second half of the century 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 to) $GtCO_2$/year and -10.3 (-14.9 to -5.1) $GtCO_2$/year, respectively for the NZ and EOC scenarios (Figure S **1**). This difference comes mainly from BECCS carbon sequestration. 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 is concerned with the baseline assumptions of food demand as well as the emissions abatement potential.

Net Zero GHG emissions timing of AFOLU

Globally, the net zero GHG emissions timing of AFOLU is about 10 to 30 years earlier, at median levels, than that of total anthropogenic CO_2 emissions 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 such as stabilization at 1.5 °C. The relationship between the net-zero timing of total anthropogenic CO_2 emissions and AFOLU's GHG emissions varies across regions (Fig. 2b). Net-zero GHG emissions from AFOLU is achieved earlier than total anthropogenic CO_2 emissions in OECD countries, while the opposite is seen in other regions such as Latin America, Asia and MEA. The net-zero GHG emissions timing of AFOLU depends on BECCS carbon sequestration and the amount of non-CO_2 emissions for two reasons. First, BECCS carbon sequestration changes significantly over time throughout this century while CO_2 emission reduction and sequestration through avoided deforestation and/or afforestation/reforestation remains almost constant over time from 2030 and hardly affects the net-zero timing. Second, net-zero is achieved when non-CO_2 emissions are offset by carbon sequestration in BECCS or forest management. In OECD countries, where AFOLU's net-zero GHG emissions are reached earlier than total anthropogenic CO_2 emissions, the dependency of carbon sequestration on BECCS is higher compared to other regions and non-CO_2 emissions are low enough to be offset by BECCS sequestration (Fig. 1c). On the other hand, regions such as Latin America, Asia and MEA have a large share of CO_2 sequestration through forest management or have high non-CO_2 emissions relative to CO_2 sequestration (Fig. 1b). For all regions, the net zero GHG emissions timing in the AFOLU sectors is earlier in NZ compared to EOC scenarios (Fig. 2c).

Land dynamics in climate mitigation not relying on net-negative emissions

As for land area, in the medium-term, total forest area and cropland for bioenergy expands substantially due to increased afforestation and reforestation and higher bioenergy demand driven by the energy system. At the same time, land for pasture and non-energy crops (food, feed and fiber) decrease as a result of carbon pricing on land-related emissions and increases in the above mitigation options (Fig. 3a). The substantial land-use changes are caused by carbon price impositions, BECCS deployment and afforestation/reforestation, the scale of which varies 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, forest area expands in Asia and LAM while cropland for bioenergy increases in Asia and OECD countries (Fig. 3c). Non-energy cropland will decrease in Asia, OECD countries and LAM, while pasture area will be reduced in MEA and LAM (Fig. 3c).

Globally, the transition from EOC to NZ budgets will increase the area for forestry and cropland for bioenergy by 21 (19 to 46) Mha and 27 (19 to 42) Mha respectively and decrease the area used for non-energy cropland and pasture by 62 (29 to 70) Mha and 52 (3.7 to 108) Mha, respectively, in 2050 in the 600 $GtCO_2$ CB scenarios (Fig. 3b). Similar trends are shown in all regions, but in MEA, pasture land is significantly reduced, leading to large changes in total land area use. In the long-term, the avoided BECCS carbon sequestration reduces the need for drastic mitigation-induced shifts in land-use and saves land for food. In 2100, globally, land for bioenergy crops and forest decreases by 205 (153 to 213) Mha and 17 (-20 to 42) Mha, while the area for pasture and cropland for non-energy crops increases by 27 (14 to 31) Mha and 11 (-26 to 36) Mha respectively (Fig. 3b).

AFOLU's emissions and land dynamics under different carbon budgets

The stringency of climate mitigation naturally affects the emissions trend in AFOLU sectors and land dynamics. In general, the stronger the degree of climate change mitigation levels, the deeper emissions reduction and more dynamic land use change are needed in the AFOLU sector (Fig. 1e, Fig. 3e). Scenarios with low CBs require substantial levels of net negative emissions (Fig. 1e).

The scenarios with CB of less than 1000 $GtCO_2$ show CDR associated with BECCS 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 carbon budget of 600 $GtCO_2$. Note that there are similarities in CO_2 removal 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 such as avoided deforestation and afforestation compared with other mitigation options, which consequently leads to early implementation. Across all scenarios with less than 1000 $GtCO_2$ CB, land area for pasture and non-energy crops decreases with the development of biotechnology and rising land productivity (crop yield) (Fig. 3e). Most models exhibit a sort of ceiling in cropland area for bioenergy at a certain level (300 to 600 Mha), which varies across models but is not dependent on CB below 1000 $GtCO_2$ (equivalent to 1.5 and 2°C scenarios).

Benefits and trade-offs for food and land systems of climate mitigation not relying on net-negative emissions

Our statistical results from regression analysis show that allowing net negative emissions (EOC versus NZ budgets) significantly affects emission trends, sequestrations, land use, and food systems both in the medium- and long-term (Table 1). In the medium-term (2040-2060), switching from an EOC to NZ budget significantly reduces AFOLU-related CO_2 emissions and agricultural non-CO_2 emissions by 160$MtCO_2$/year and 60$MtCO_2$/year, respectively, while increasing carbon sequestration of BECCS by 350$MtCO_2$/year. Over the same period, agricultural intensification increases by 0.051 tonne dry matter (DM)/ha/year and forest area expands by 19Mha and land for food crops decreases by 11Mha for NZ scenarios compared to the EOC scenario with the same CB. As a result, the reduced agricultural area reduces the demand for irrigation water and nitrogen fertilizer by 8.8 km^3/year and 2.5TgN/year, respectively, and protects land in the medium-term. On the other hand, there are some trade-offs. Carbon prices are higher by 200US\$/tCO_2 in NZ scenarios compared to EOC in the medium-term. In addition, land pressure increases due to higher deployment of bioenergy in the medium-term, leading to higher food prices and higher risk of hunger.

In the long-term, switching from EOC to NZ budgets significantly lowers carbon prices, by 800US\$2010/tCO_2, and largely reduces carbon sequestration from BECCS by 1290$MtCO_2$/year. The reduced deployment of BECCS saves land for bio crops (by 75Mha) and increases cropland for food (by 11Mha) and pasture (by 16Mha) and protects forest area (by 11Mha). This induces lower food prices, higher food consumption (by 14kcal/cap/day) and lower risk of hunger (4.8 million fewer people at risk of hunger). Lower land pressure reduces agricultural intensification by -0.15 tonne DM/ha/year, while increased food production increases nitrogen fertilizer use (by 4.2TgN/year). Carbon sequestration through forest management is not significantly different between EOC and NZ scenarios in the long-term because the scale of carbon sequestration by afforestation/reforestation is primarily constrained by the potential area rather than the cost of forest management, which is relatively lower than other measures.

The statistical results from regression analysis show that the stringency of the imposedCB significantly affects emission trends, sequestrations, land use, and food systems both forin the medium- (2040-2060) and long-term (2080-2100) (Table S 1). Almost all variables indicate significant slopes in the CB coefficient, meaning that they vary significantly across the different CBs in the medium- and long-term. This would also imply that the degree of the benefits and trade-off mentioned above can differ significantly depending on both the stringency of the CB and the choice of CB scheme, e.g. whether we allow net negative emissions or not. For the medium –term in particular, the size of the CB is more important for AFOLU-related variables rather than allowing net negative emissions or not.

Discussion and Conclusions

We conducted a multi-model intercomparison using IAMs that aims to answer the question whether early climate action, with relatively large emission reductions in the first half of the century and no net-negative emissions in the second half of century, is beneficial or harmful from the perspective of the 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 (Drouet et al., submitted), and 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, lower risk of hunger and less water scarcity in the long-term. At the same time, however, near-term mitigation pressure in the AFOLU sectors and required land area for energy crops increase, resulting in additional agricultural intensification as well as higher food prices than if action were delayed, which increases 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[16].

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 on land system 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. The benefits can be large when we assess the biodiversity and food security aspects. Considering this, these results suggest that moving forward with earlier actions and not allowing net-negative emissions would not only lower peak warming but also benefit land-related ecosystems.

Our results indicate that globally the timing of net-zero GHG emissions in the agricultural and land-use sectors is about 10 to 30 years earlier than for total anthropogenic CO_2 emissions at multi-model median. This trend is seen in particularly in OECD countries where the dependency on BECCS carbon sequestration is relatively high. This highlights the importance of fast transitions and early climate actions in the AFOLU sector in these countries. Carbon budgets or net-zero emissions are often discussed only for CO_2 emissions. For non-CO_2 emissions, the minimization of emissions is expected and hardly discussed due to the characteristics of non-CO_2 gases such as the long life of N_2O and uncertainty in radiative forcing. This study indicates that non-CO_2 emission reductions do play a role in determining future emission pathways.

In this study, BECCS carbon sequestration is assessed as a part of AFOLU sector although mitigation from BECCS is often attributed to the energy sector. Bioenergy without CCS (not including iLUC) is usually deemed carbon neutral and additional carbon sequestration comes from the CCS part. This CCS would be counted as the CCS industry's carbon credit. If this were to be imputed to purely non-AFOLU-related sectors, the net zero GHG emissions timing in AFOLU would be much later than presented in this study, and potentially not evenbe 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 NZ budget scenarios, there must be a careful interpretation of the timing of net zero.

We quantified the effects of different CBs on the AFOLU sector by performing regression analysis. The parameters generated in this study (Table 1 and Table S 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[1, 5]. Furthermore, a new scenario framework includes multiple options for climate goals in 2100, carbon budget sizes and allowance of overshoot. This may reduce the risk of delayed action, reaching higher-than-acceptable mid-century warming, and a reliance on the net removal of large volumes of CO_2 thereafter to undo the initial shortfall in emission reductions.

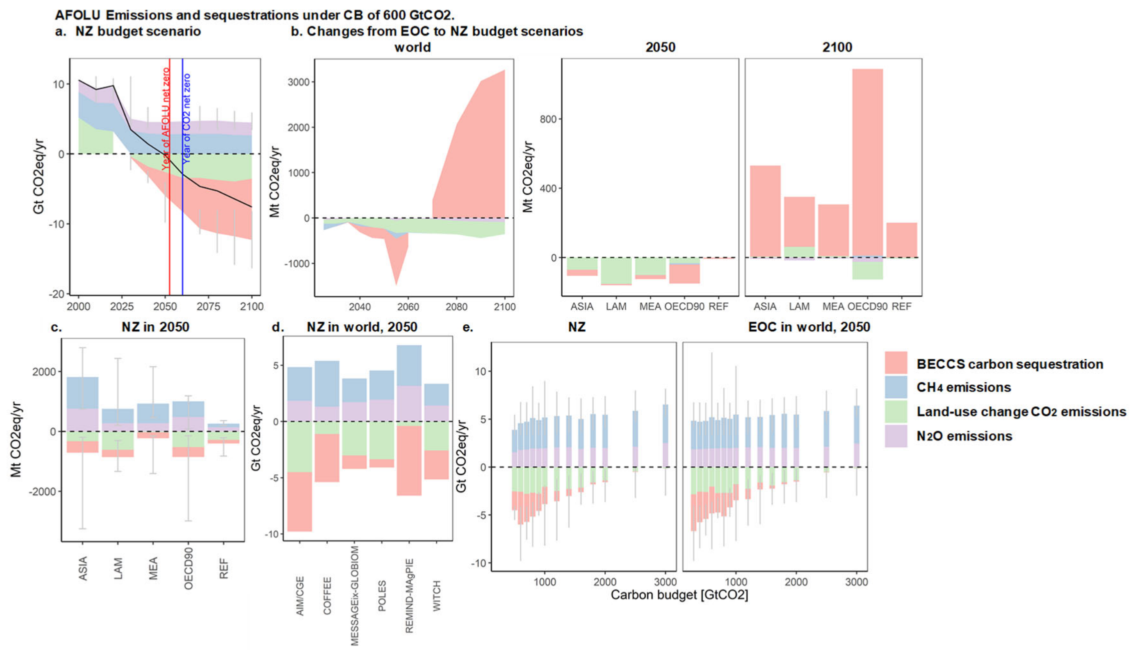

Fig. 1 AFOLU related GHG emissions and sequestrations. a) Global emissions and sequestrations in the NZ scenarios with 600 $GtCO_2$ carbon budget (CB), b) changes in the NZ scenario relative to the EOC scenario at global and regional levels in 2050 and 2100, with 600 $GtCO_2$ CB, c,d) changes in 2050 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 level while whiskers represent ranges across models. Black lines in a) show net emissions in AFOLU and BECCS carbon sequestration. The red and blue lines in a) indicate the timing of net-zero timing of AFOLU's GHG emissions and total anthropogenic CO_2 emissions respectively. Land-use change CO_2 emissions includes emissions from deforestation and removals due to afforestation/reforestation. Figure S 1 shows panel a) for both NZ and EOC scenarios. Figure S 3 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).

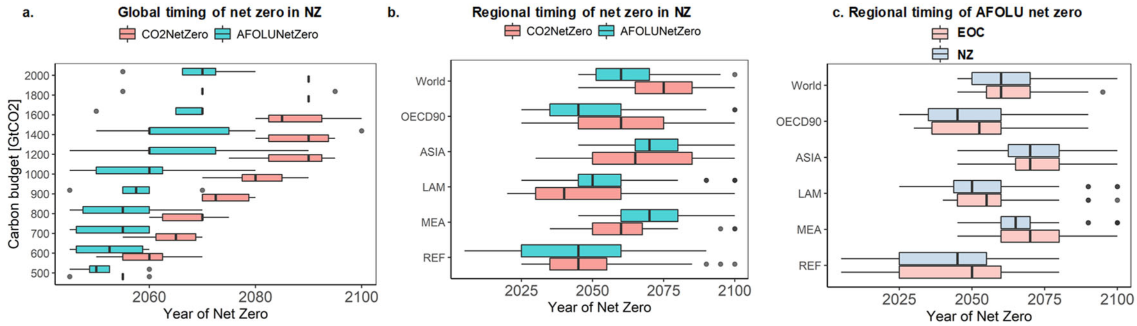

Fig. 2 Global and regional timing of net zero emissions for total anthropogenic CO_2 emissions and AFOLU's GHG emissions in NZ scenarios, with different CBs for global a) and for regional level and all the CB levels b), and c) regional timing of AFOLU net zero emissions. Black thick lines show multi-model median level while whiskers represent ranges across models. See **Table S 2** 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 S 2** shows panel a) for both NZ and EOC scenarios. Figure S 4 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 the coefficient to a dummy for schemes of the emission caps (β). This value can be interpreted as the degree of the effects of making more immediate mitigation efforts and moving from an EOC to NZ budget scheme for each variable. See Table S 1 for the comprehensive results of this regression analysis.

		Medium-term (2040-2060)	Effects	Long-term (2080-2100)	Effects
Benefit	Emissions and carbon price	Less AFOLU-related CO2 emissions*	-160 Mt CO2/yr	Low carbon price***	-800 US$2010/t CO2
		Less agricultural non-CO2 emissions*	-60 Mt CO2/yr		
		Carbon sequestaration of BECCS*	+350 Mt CO2/yr	Carbon sequestaration of BECCS***	-1290 Mt CO2/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 km3/yr	Less irrigation water	-7.2 km3/yr
		Less fertilizer use***	-2.5 Tg N/yr		
Trade-offs	Emissions and carbon price	High carbon price*	+200 US$2010/t CO2		
	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 fertilizer use***	

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

Methods(<3000 words)

Modelling framework

Global integrated assessment models (IAMs) are used for the quantification of the scenarios in this study, which are involved in the ENGAGE project[7]. The objective of the scenarios in ENGAGE 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 uncertainties across different IAMs[7]. Furthermore, we have two kind 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, considering different carbon caps consistently: AIM/CGE [17, 18, 19], COFFEE, IMAGE, MESSAGEix-GLOBIOM 1.0 [20, 21, 22], POLES[23], REMIND-MAgPIE 2.0-4.1 [24, 25] and WITCH 5.0[26].

AIM/CGE, COFFEE, IMAGE, MESSAGEix-GLOBIOM and REMIND-MAgPIE incorporate explicit agricultural commodity markets and land-use representation whereas POLES and WITCH use 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 carbon budgets and climate policy assumptions depending on whether net negative emissions are allowed or not. For the food demand side, population and income growth increase food demand, shift the demand curve rightward, and raise prices. Responding to the higher price, producers increase their production by expanding cropland and pasture areas and increasing land productivity, while consumers lower their consumption or shift to less-expensive goods. Some people might consume insufficient food and face a risk of hunger. Trade globalization helps to reallocate supply and demand and dampens the impact of producer-side price shocks on consumer prices, and contributes to a lower risk of hunger. Similarly, climate mitigation increases the demand for land through energy system changes leading to bioenergy demand increases and 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 land use change and agriculture including fertilizer 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 three models exogenously assuming food consumption from results for food consumption and the population at risk of hunger.

Scenarios

To explore a comprehensive view of the relationship between carbon budget caps and agriculture and land use responses, we use a set of scenarios from the ENGAGE project[7] that covers two dimensions: 1) different levels of climate stabilization and therefore climate change mitigation efforts, represented by a global total carbon budget and 2) whether the 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 carbon budget (CB) caps allows us to explore the effects of climate change mitigation efforts on agriculture and land dynamics. The use of different carbon budget schemes allows us to compare the effects of allowing net negative emissions and overshoots.

For the systematic exploration of the scenario space, the following carbon budgets 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 for the time period 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.

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/tCO2-eq for CH_4, N_2O and CO_2 emitted from agriculture and land sectors to both near- and long-term as well as for all scenarios (NZ and EOC scenarios) to avoid high impacts on food security[27]. Socioeconomic conditions, including the 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 [21] through 2100. GWP100 is used to convert non-CO_2 to CO_2 emissions in this study. See Riahi et al.[7] for detailed information on the representation of scenarios settings.

Regression analysis

To identify the effects of climate warming and CB regime choices on AFOLU sectors, we performed a meta regression analysis on the scenarios with the following equation. The equation has been applied to AFOLU related variables. The basic idea behind this regression analysis is that the coefficients of CB (alpha) can be interpreted as a marginal variable change to the carbon budget. The second critical parameter is a dummy variable for SceDum (beta), which distinguishes between NZ or EOC budgets. This yields whether the NZ or EOC budget assumption would linearly change the AFOLU implications. We pooled all scenario data and classified the data into two periods, namely mid-century (2040-2060) and the end of this century

(2080-2100). They are individually estimated so that the periodic characteristics can be obtained from this analysis.

$$X_{i,t,s,m} = X0_{i,t,s,m} + \alpha_{i,t,s} \cdot CB + \beta_{i,t,s} \cdot SceDum_s + \delta_{i,t,m} \cdot ModDum_m + C_{i,t,s} \quad (1)$$

where,

i: indicator, t: year, r: region, s: scenario, m: type of model,

$X_{i,t,r,s,m}$: outputs from models,

$X0_{i,r,s,m}$: values in 2010,

CB: level of global total carbon budget cap,

SceDum: dummy for emission cap schemes (1 for NZ budget; 0 for EOC budget).

ModDum: dummy for type of model.

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

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

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

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Figures

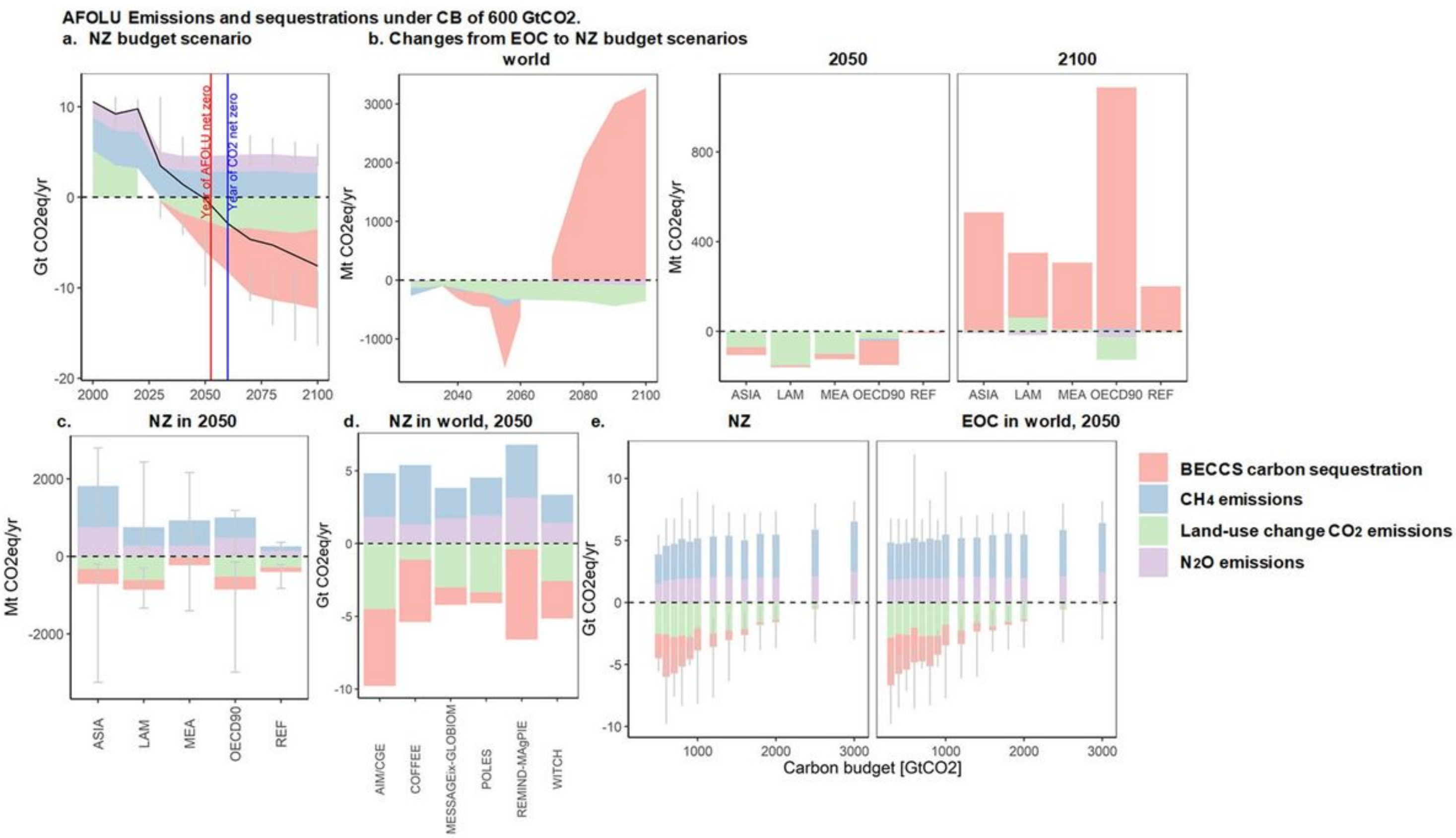

Figure 1

AFOLU related GHG emissions and sequestrations. a) Global emissions and sequestrations in the NZ scenarios with 600 GtCO2 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 GtCO2 CB, c,d) changes in 2050 for the NZ scenarios with 600 GtCO2 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 level while whiskers represent ranges across models. Black lines in a) show net emissions in AFOLU and BECCS carbon sequestration. The red and blue lines in a) indicate the timing of net-zero timing of AFOLU's GHG emissions and total anthropogenic CO2 emissions respectively. Land-use change CO2 emissions includes emissions from deforestation and removals due to afforestation/reforestation. Figure S 1 shows panel a) for both NZ and EOC scenarios. Figure S 3 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).

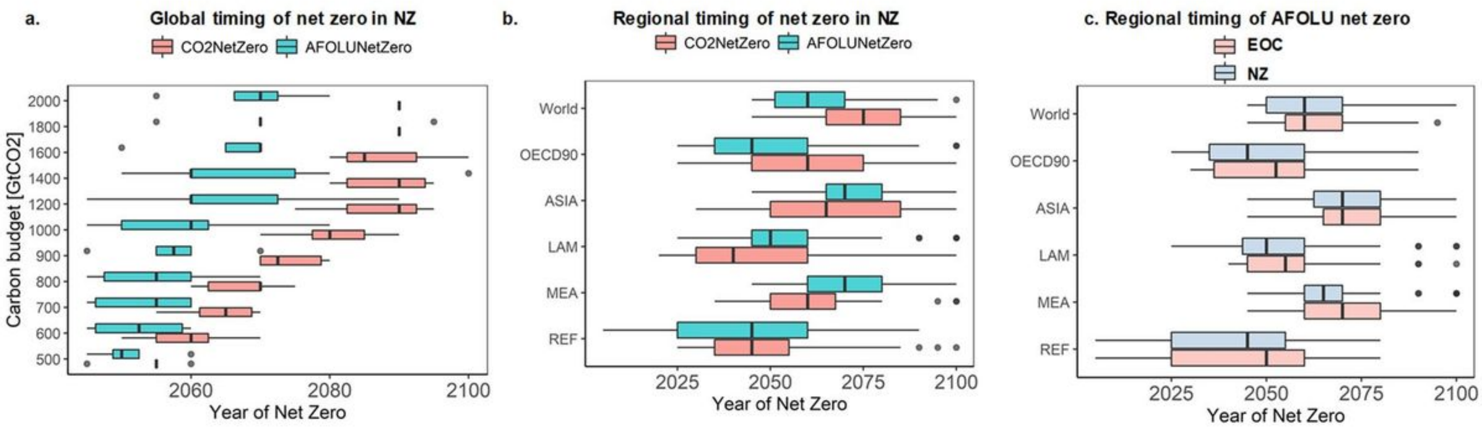

Figure 2

Global and regional timing of net zero emissions for total anthropogenic CO2 emissions 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. Black thick lines show multi-model median level while whiskers represent ranges across models. See Table S 2 for the scenarios and models used in this analysis.

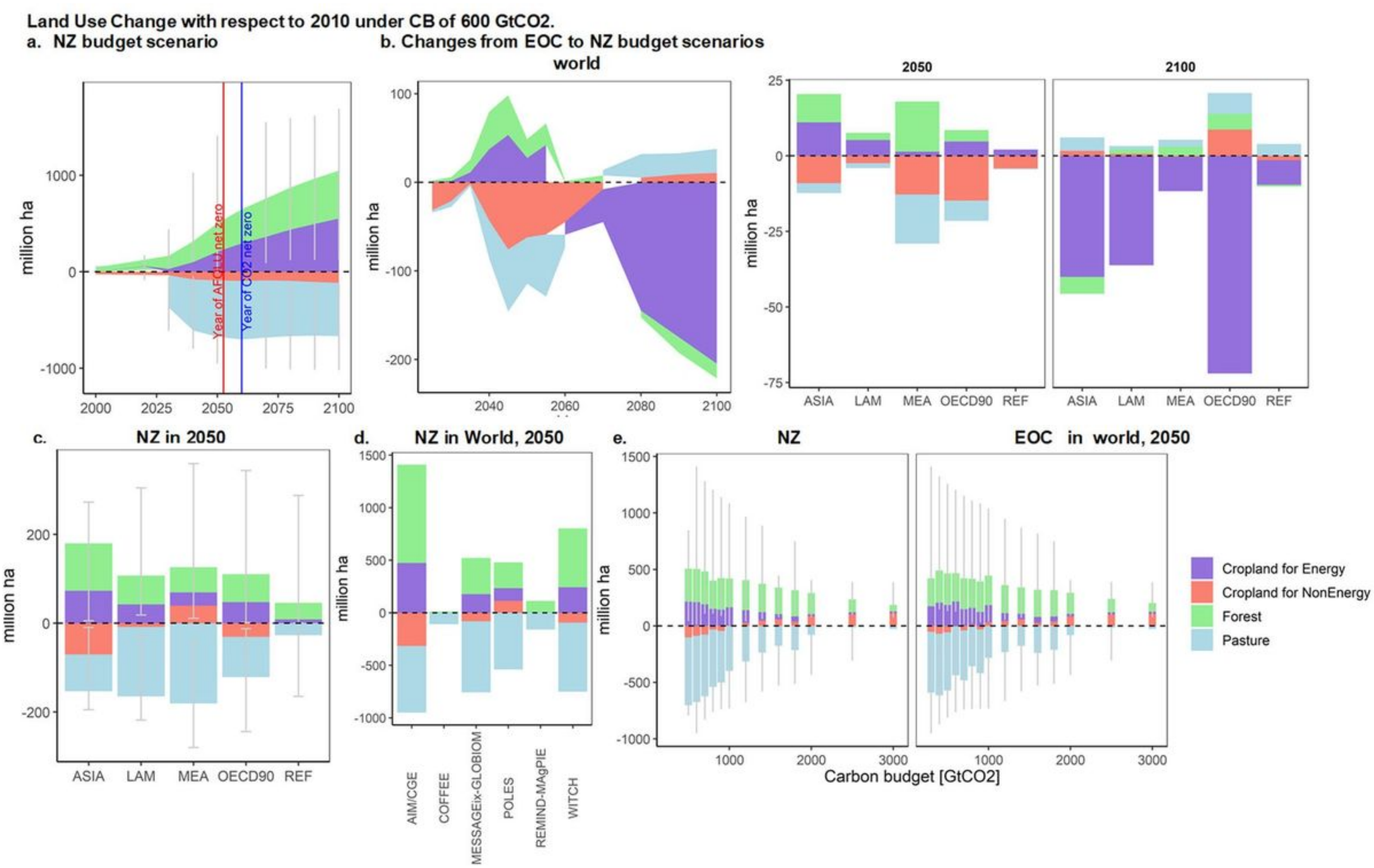

Figure 3

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 S 2 shows panel a) for both NZ and EOC scenarios. Figure S 4 shows more detailed individual model information.

Supplementary Files

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