Planetary boundaries under a land-based climate change mitigation scenario with a food demand transformation: a modelling study

Felicitas D Beier, Jan Philipp Dietrich, Jens Heinke, Gabriel Abrahao, Patrick von Jeetze, Benjamin Leon Bodirsky, Michael Crawford, Florian Humpenöder, Leon Merfort, Isabelle Weindl, Mario Herrero, Daniel Mason-D'Croz, Johan Rockström, Marina Sundiang, Sofie te Wierik, Anna Norberg, David Klein, Christoph Müller, Hermann Lotze-Campen, Alexander Popp

Summary

Background Ambitious climate change mitigation in all economic sectors is crucial for limiting global warming. Cost-effective mitigation pathways to keep global average temperature increases below 1·5°C by the end of the 21st century often rely on land-based greenhouse gas (GHG) emission reductions, increased land-based carbon uptake and biomass supply to other sectors (eg, energy and transport), and demand-side changes in the food system. To evaluate the broader sustainability of land-based climate change mitigation action, we evaluated synergies and trade-offs of individual and combined supply-side mitigation measures across five planetary boundaries. We also examined the role of a food demand transformation aligned with the dietary recommendations of the updated planetary health diet defined in the forthcoming EAT–*Lancet* Commission 2.0 report in shaping planetary boundary outcomes.

Methods In this modelling study, we used the dynamic land-system modelling framework MAgPIE to assess the consequences of land-based GHG reductions, increased land-based carbon uptake, increased biomass supply to other sectors, and a food-system transformation towards the planetary health diet including food waste reductions on five planetary boundary domains (climate change, nitrogen, land-system change, freshwater use, and biosphere integrity) relative to a reference scenario without land-system mitigation throughout the century. For each planetary boundary control variable, we calculated the level of planetary boundary transgression (ie, the extent to which scenario outcomes exceeded the defined safe operating space) and assessed the contributions of land-based mitigation strategies to reducing planetary boundary transgressions projected for the reference scenario.

Findings Our projections show that a food-system transformation together with ambitious land-system and energy-system climate change mitigation can limit global warming to below 1·5°C by 2100, while also reducing planetary boundary transgression (particularly for the climate change, land-system change, biosphere integrity, and nitrogen planetary boundaries). However, a safe operating space was not achieved through these mitigation measures, as most planetary boundaries were still projected to remain transgressed by the end of the 21st century. Increased bioenergy supply alone worsened planetary boundary transgression when only looking at land-system impacts, but combining increased bioenergy supply with GHG pricing in the land system alleviated these trade-offs. Food waste reductions and dietary shifts towards the planetary health diet were projected to ease pressures on the land system and reduce planetary boundary transgression of all assessed planetary boundaries.

Interpretation This research highlights the importance of considering multiple planetary boundaries and the interactions between various mitigation strategies when assessing climate mitigation action in the land system to avoid negative consequences for other aspects of the environment. Following an ambitious climate change mitigation pathway compatible with the Paris Agreement results in a transgression of all assessed five planetary boundaries by 2100. However, the combination of the land-system mitigation measures included in this study produced a substantial shift towards the safe operating space for humanity.

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Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany (F D Beier MA, J P Dietrich PhD, J Heinke PhD, G Abrahao PhD, P von Jeetze MA, B L Bodirsky PhD, M Crawford PhD, F Humpenöder PhD, L Merfort MA, I Weindl PhD, Prof J Rockström PhD, S te Wierik PhD, A Norberg PhD, D Klein PhD, C Müller PhD, Prof H Lotze-Campen PhD, Prof A Popp PhD); **Humboldt-Universität zu Berlin, Albrecht Daniel Thaer-Institut für Agrar- und Gartenbauwissenschaften, Berlin, Germany** (F D Beier, P von Jeetze, Prof H Lotze-Campen); **Global Energy Systems Analysis, Technische Universität Berlin, Berlin, Germany** (L Merfort); **Faculty of Organic Agricultural, University of Kassel, Kassel, Germany** (Prof A Popp); **Department of Global Development, College of Agriculture and Life Science, Cornell University, Ithaca, NY, USA** (Prof M Herrero PhD, D Mason-D'Croz MA, M Sundiang PhD); **Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY, USA** (Prof M Herrero, D Mason-D'Croz, M Sundiang); **Agricultural Economics and Rural Policy Group, Wageningen University and Research, Wageningen, Netherlands** (D Mason-D'Croz); **Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany** (Prof J Rockström)

Introduction

Global agricultural production and land use in their current form have detrimental consequences for the environment and cause substantial greenhouse gas (GHG) emissions, contributing to climate change.[1,2] Globally, the agriculture, forestry and other land use (AFOLU) sector is responsible for 13–21% of total anthropogenic GHG emissions[1] and is a key driver of land and water pollution[3] and biodiversity loss.[4] The AFOLU sector is crucial for climate change mitigation.[1,2] Bioenergy supply from the land system can play an important role in carbon dioxide (CO_2) removal via bioenergy with carbon capture and storage.[5] Supply-side measures, such as GHG pricing in the land sector, can

Correspondence to:
Felicitas D Beier, Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam 14412, Germany
beier@pik-potsdam.de

Research in context

Evidence before this study

Starting with key publications identified through a search of Google Scholar on Feb 25, 2025, with the search terms "planetary health diet and planetary boundaries", "EAT Lancet diet and planetary boundaries", and "land-based climate change mitigation, planetary boundaries, dietary change" with a publication date range from January, 2009, to February, 2025, we traced back connections to earlier, later, and similar research via ResearchRabbit. We found several studies that have examined portfolios of land-based mitigation measures and their synergies and trade-offs with respect to various indicators (eg, the Sustainable Development Goals). One study has focused on the role of dietary change in achieving ambitious climate goals, showing that dietary shifts increase the economic and physical feasibility of 1·5°C pathways. Others have assessed (with lifecycle assessments) whether achieving a safe operating space while also fulfilling basic human needs is possible. Similar studies with static input–output models have quantified the effect of food system interventions on selected planetary boundaries. Dynamic land-use modelling studies have shown that dietary change can improve economic, health, and environmental outcomes. The consequences of both supply-side and demand-side land-system climate change mitigation on planetary boundaries related to agricultural production has not yet been systematically assessed.

Added value of this study

We go beyond previous assessments by decomposing a 1·5°C-compatible climate change mitigation pathway into its supply-side and demand-side land-system measures. We investigate the contribution of these mitigation measures to the transgression of five planetary boundaries (climate change, land system change, biosphere integrity, freshwater, and nitrogen) related to agricultural production and the land sector with a dynamic land-use modelling framework. We assess the interactions, synergies, and trade-offs between the different supply-side land-system measures (ie, increased bioenergy supply, land protection via emissions pricing, and improved agricultural management via non-CO_2 emissions pricing) in a world with and without a food demand transformation in line with the planetary health diet as defined by the second EAT–*Lancet* Commission. Given the long time period (until 2100) that is required to assess the effect of climate change mitigation on planetary boundary transgression, the use of a dynamic land-use modelling framework that captures land-system dynamics resulting from projected socioeconomic drivers and climatic changes reflected in biophysical conditions is important.

Implications of all the available evidence

A food demand transformation including food waste reductions and a shift of diets towards the planetary health diet as defined by the forthcoming EAT–*Lancet* 2.0 Commission report reduces the pressure in the land system (as has also been shown in previous studies) and improves all five planetary boundaries assessed in this study. It also alleviates trade-offs from supply-side land-system mitigation (eg, increased freshwater consumption due to increasing pressure on water resources alongside land-system mitigation measures that increase land competition). Land-system trade-offs of single mitigation measures (such as those observed from increased bioenergy supply) are alleviated when combined with greenhouse gas pricing in the land sector. A combination of all land-system measures (both on the demand side and the supply side) leads to a substantial shift towards the safe operating space. Nevertheless, the assessed 1·5°C-compatible climate change mitigation pathway leaves the assessed planetary boundaries transgressed by the end of the 21st century.

contribute to the reduction of CO_2 emissions as they incentivise land conservation, reforestation and afforestation, and the reduction of non-CO_2 emissions (eg, methane [CH_4] and nitrous oxide [N_2O]) from agricultural activities.[2] On the demand-side, dietary changes and food waste reductions that lower agricultural production requirements can considerably contribute to achieving ambitious climate goals.[6]

Some climate change mitigation measures, such as increased bioenergy supply, can have trade-offs with other environmental aspects (eg, increased deforestation and CO_2 emissions from land-use change,[7,8] water stress,[9] and biodiversity loss[10,11]). Others, such as a food demand transformation in line with the planetary health diet defined by the EAT–*Lancet* Commission on healthy diets from sustainable food systems,[12] ease pressures on the land system, decreasing environmental impacts.[12–14]

The planetary boundary framework[15] defines a safe operating space for Earth-system stability for nine environmental domains including quantifiable control variables. Currently, six of the nine planetary boundaries have been transgressed.[16] All six (land-system change, biosphere integrity, biogeochemical flows, novel entities, freshwater use, and climate change) are closely related to agricultural production and the food system and could be affected by land-based climate change mitigation.

In this study, we aimed to examine the consequences of land-based climate change mitigation on future planetary boundary outcomes in the 21st century with a dynamic land-use modelling framework. We evaluated the synergies and trade-offs of individual and combined supply-side land-based mitigation measures (ie, increased bioenergy supply, protection of forests and peatlands via carbon pricing in the land system, and technical mitigation of agricultural emissions via emissions pricing) across five planetary boundaries (ie, climate change, land-system change, biosphere integrity, freshwater use, and nitrogen surplus). We also examined the role of a food demand transformation aligned

	Planetary boundary control variable	Planetary boundary value	Upper-end value	Reference details
Climate change	Atmospheric CO_2 concentration (parts per million)	350	450	As in Richardson et al (2023),[16] Steffen et al (2015),[31] and Rockström et al (2009)[15]
Climate change	Global mean surface temperatue increase (°C)	1·0	2·0	As described in main text of Richardson et al (2023)[16]
Land-system change	Area of forested land on the ice-free land surface (million ha)	4790	3449	Values derived from control variables expressed as a percentage of the potential area of forested land in Steffen et al (2015)[31]
Biosphere integrity: natural ecosystem area	Share of largely intact land area	0·5	0·6	As in Rockström et al (2023)[32]
Biosphere integrity: functional integrity	Share of land area that satisfies landscape target	1	..	Planetary boundary value as in Rockström et al (2023);[32] the zone of increasing risk value has not been defined
Freshwater use	Total blue water consumption (km^3/year)	2800	4500	As defined in Gerten et al (2013)[33]
Biogeochemical flows: nitrogen	Agricultural nitrogen surplus (teragrams of reactive nitrogen per year)	61	84	Critical agricultural nitrogen surplus is based on the approach of Schulte-Uebbing et al (2022);[34] the planetary boundary value and upper-end value are taken from Rockström et al (2023)[32]

The planetary boundary value refers to the transgression point between the safe operating space and the zone of increasing risk of planetary boundary control variables as defined in existing literature on planetary boundaries. The upper-end value refers to the transgression point between the zone of increasing risk and the high-risk zone (either defined in the literature or derived from uncertainty ranges when not already available).

***Table:* Planetary boundary control variables and the respective safe and upper-end values used in this study**

with the dietary recommendations of the updated planetary health diet of the forthcoming EAT–*Lancet* Commission 2.0 report[17] in shaping these planetary boundary outcomes.

A dynamic modelling approach is essential, as it accounts for changing biophysical and socioeconomic developments over time, which influence future demand and productivity. This study goes beyond previous assessments[13,18,19] by using a dynamic land-use modelling framework and by decomposing a 1·5°C-compatible climate change mitigation pathway aligned with the Paris Agreement into its land-system and food-system measures. This approach enables a detailed analysis of the contributions, synergies, and trade-offs of land-based mitigation measures, providing new insights into their consequences for planetary boundary transgressions related to the land system.

Methods

Models

Our ambitious climate change mitigation pathway including energy and land system mitigation (FDT+LSM, where FDT stands for food demand transformation and LSM stands for land-based, supply-side mitigation) was determined by the integrated assessment modelling framework REMIND (version 3.4.0)–MAgPIE (version 4.9.1)[20–23] with a target-seeking run aiming for a temperature increase trajectory below 1·5°C by 2100. This scenario encompasses energy and land-system climate change mitigation, including a food demand transformation, and considers feedbacks between the energy and land systems while targeting a cumulative carbon budget of 650 giga tonnes (Gt) CO_2 from 2020 onwards until net-zero CO_2 emissions are reached. This target-seeking run results in a carbon price that increases to US\$310/tonne CO_2 by 2050 and bioenergy demand from the energy sector of 116 exajoules per year in 2100 (appendix 1 pp 7–8, 10).

See Online for appendix 1

The consequences of the land-based mitigation mesures included in this ambitious pathway on planetary boundaries were assessed with the global, partial-equilibrium, land-use modelling framework MAgPIE (version 4.9.1) in stand-alone mode.[22,23] MAgPIE projects future land use and land-use change for 200 spatial clusters in 12 world regions[22] (appendix 1 pp 2–3) together with data on crop yields, irrigation water requirements, carbon stocks, and freshwater availability from the dynamic global vegetation, hydrology, and crop model LPJmL.[24,25] For every 5-year time step, the model satisfies food, feed, seed, bioenergy, and biomaterial demand and optimises land cover of irrigated and rainfed cropland, pasture areas, planted and natural forest area, non-forest vegetation, and urban area following a constrained production cost minimisation approach, and reports AFOLU emissions (ie, CO_2 emissions from land-use change and agricultural CH_4 and N_2O emissions).[26] MAgPIE also has the option of increasing agricultural productivity following an endogenous investment process.[27] In mitigation scenarios, forest and peatland protection and technical mitigation in agricultural management are incentivised via GHG emission pricing. In MAgPIE, GHG emission pricing incentivises cost-effective emission reductions. Costs for technical mitigation options are derived from marginal abatement cost curves.[28,29] While such mitigation action increases production costs and food

	RFS	RFS+bioen	RFS+mngt	RFS+prot	RFS+LSM	RFS+LSM-prot	RFS+LSM-mngt	RFS+LSM-mngt
Ambitious energy-system mitigation with land-system mitigation according to NPi	X	X	X	X	X	X	X	X
Increased bioenergy supply for energy-system climate change mitigation (bioen)		X			X	X	X	
Improved agricultural management via pricing of non-CO_2 emissions (mngt)			X		X	X		X
Protection and restoration of natural carbon sinks via GHG pricing (prot)				X	X		X	X
Food consumption in line with the planetary health diet and food waste reduction								

Reference food system

	FDT	FDT+bioen	FDT+mngt	FDT+prot	FDT+LSM	FDT+LSM-prot	FDT+LSM-mngt	FDT+LSM-mngt
Ambitious energy-system mitigation with land-system mitigation according to NPi	X	X	X	X	X	X	X	X
Increased bioenergy supply for energy-system climate change mitigation (bioen)		X			X	X	X	
Improved agricultural management via pricing of non-CO_2 emissions (mngt)			X		X	X		X
Protection and restoration of natural carbon sinks via GHG pricing (prot)				X	X		X	X
Food consumption in line with the planetary health diet and food waste reduction	X	X	X	X	X	X	X	X

Demand-side, food-system transformation

Figure 1: **Scenario overview including the main scenarios (RFS [red] and FDT [blue]) and the combination of these scenarios with LSM measures (RFS+LSM and FDT+LSM) and decomposition scenarios for single supply-side mitigation measures (bioen, mngt, and prot)**

bioen=increased bioenergy supply. FDT=food demand transformation. GHG=greenhouse gas. LSM=land-based, supply-side mitigation. mngt=improved agricultural management incentivised through non-CO2 emissions pricing. NPi=national policies implemented. prot=land protection through land-use change and peatland emissions pricing. RFS=reference food system.

prices, food demand in the model is inelastic to such price changes.[6]

To calculate the resulting warming potential of the transformation pathways, the land sector emissions resulting from the MAgPIE scenarios are used with the energy system emissions from REMIND (as determined in the target-seeking integrated assessment modelling run) in the reduced complexity climate model MAGICC (version 7.5.3).[30]

For a detailed description of the models that form part of the modelling framework, please refer to appendix 1 (pp 2–5).

Planetary boundary control variables

The planetary boundary framework defines nine realms crucial for Earth system stability and quantifies boundary levels for a safe operating space for humanity.[15,16,31] Seven of these boundary domains (land-system change, climate change, biosphere integrity, freshwater use, biogeochemical flows, novel entities, and atmospheric aerosol loading) are closely related to agricultural production and the food system. An overview of the control variables used to represent the five planetary boundaries covered in this study is provided in the table (novel entities and atmospheric aerosol loading cannot be covered by the model). More details on the implementation of these control variables in MAgPIE can be found in appendix 1 (pp 9–11). For each planetary boundary domain, a safe operating space (and for its transgression, a zone of increasing risk and a high-risk zone) is defined.[16] As such, we report two thresholds for each control variable: the planetary boundary (ie, the transgression point between the safe operating space and the zone of increasing risk) and the upper end of the zone of increasing risk (ie, the transgression point between the zone of increasing risk and the high-risk zone) where defined.[16]

Scenarios

We decomposed our climate change mitigation scenario (ie, FDT + LSM) with respect to its land-system supply-side and demand-side measures. The land-based, supply-side mitigation bundle (ie, LSM) is decomposed into three measures: increased bioenergy supply (bioen), which eases the energy system transformation due to its ability to replace fossil energy sources and its CO_2 reduction potential via bioenergy with carbon capture and storage; land protection through land-use change and peatland emissions pricing (prot), which also incentivises reforestation and afforestation and peatland rewetting; and improved agricultural management incentivised through non-CO_2 emissions pricing (mngt), which leads to a reduction of agricultural CH_4 and N_2O emissions via technical mitigation options (appendix 1 pp 5–7).

To estimate the contribution of single land-system supply-side mitigation measures (figure 1) to reductions in planetary boundary transgressions resulting from a reference scenario without land-system mitigation (RFS), we followed the scenario decomposition approach proposed by Marangoni and colleagues[35] based on Borgonovo[36] (appendix 1 pp 8–9) with a set of MAgPIE runs (figure 1). This approach helps in identifying the direction of change and relevance of the measures by computing both the individual effect of each measure when implemented in isolation and the interaction effect of each measure when all other land-system supply-side measures are implemented at the same time. This range is important because of the interaction effects between mitigation measures. A detailed description of all scenario components depicted in figure 1 is provided in appendix 1 (pp 5–7).

The effect of each LSM measure was assessed in both a world with a reference food system (RFS) and in an alternative world with an FDT. In the RFS scenario, food consumption and waste followed business-as-usual trends driven by population growth, income projections, and physical activity levels and parameterised to a shared-socioeconomic-pathway-2 (SSP2) scenario (appendix 1 p 5).[37] The FDT scenario included an exogenously prescribed shift towards the planetary health diet of the forthcoming EAT–*Lancet* Commission 2.0 report and food waste reductions to a maximum of roughly 50% of the current levels observed in high-income countries. The planetary health diet provides minimum and maximum per-capita food intake recommendations for a healthy diet (eg, a maximum of 15 g (44 kcal) of red meat per day and a minimum of 300 g (95 kcal) of vegetables per day). Furthermore, it prescribes an active physical lifestyle to the population. More details regarding the implementation of the food demand model and the FDT are provided in appendix 1 (pp 6–7).

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Both of these scenarios (RFS and FDT) without LSM measures follow national policies implemented (NPi) in the scenarios with no further climate change mitigation assumed in the land system (ie, no GHG prices are applied to the land system and bioenergy supply is substantially lower than in the scenarios including LSM measures). For all parameters not targeted by any of the scenarios, SSP2 settings were applied. As opposed to the majority of previous MAgPIE applications, which assume prioritisation of food crops over bioenergy crops in terms of irrigation,[6,8,22,38,39] irrigated bioenergy production was assumed to be possible in our study to assess potential trade-offs with respect to water usage.[11]

Because the objective of this study was to decompose land-system mitigation contributions to various planetary boundaries, emissions from the energy system were held constant at the level obtained by the target-seeking scenario (ie, FDT + LSM). We therefore assumed the same energy-system mitigation as that calculated in the target-seeking scenario for all assessed decomposition scenarios—even those in which the land system did not provide the biomass amount assumed for this pathway (ie, RFS, RFS + mngt, RFS + prot, RFS + LSM-bioen, FDT, FDT + mngt, FDT + prot, and FDT + LSM-bioen). This approach allowed us to isolate the land sector contribution and assess the associated trade-off of increased bioenergy supply in the land sector, including with respect to the climate change planetary boundary, but implies an underestimation of energy system emissions in counterfactual scenarios (eg, RFS and FDT).

For each of the planetary boundary control variables, we calculated the level of planetary boundary transgression (ie, the extent to which scenario outcomes exceeded the safe operating space). Furthermore, we assessed the contributions of the land-based mitigation strategies to reducing the planetary boundary transgressions resulting from the reference scenario (ie, RFS) in 2100.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Several planetary boundary domains have already been transgressed in 2020 (eg, climate change, nitrogen, land-system change, and biosphere integrity) and are projected to further deteriorate in the RFS scenario (figure 2) due to a continuation of population growth and economic development following SSP2 trends that drive food demand, increasing pressure on agricultural production. Our projections show transgressions of all five planetary boundary domains included in this study in the RFS scenario in 2100: climate change (transgression by 92 parts per million [ppm] for CO_2 concentration and 0·9°C for temperature warming); nitrogen (transgression by 142 megatonnes nitrogen [Mt Nr] per year); land-system change (transgression by 961 million ha), freshwater consumption (transgression by 512 km³/year), and biosphere integrity (transgression by 18 percentage points for largely intact area and 11 percentage points for functional integrity). All detailed data on planetary boundary values, planetary boundary transgression values, and planetary boundary transgression reductions compared with the RFS scenario can be found in appendices 2–7.

See Online for appendices 2–7

For temperature change, the transgression of the safe planetary boundary is projected to further increase until 2050 in the RFS scenario and then level off until 2100 (figure 2B). This trend is due to the prescribed energy-system mitigation. Nevertheless, the climate change planetary boundary is still transgressed by 0·9°C in the RFS scenario (figure 3B; ie, the baseline scenario with only energy-system mitigation and no climate change mitigation in the land sector beyond the NPi). For all other assessed planetary boundaries, our results show a continued deterioration in the RFS scenario (figure 2C–G).

Reduced pressure in the land system as a result of the FDT allows for forest expansion and less irrigation expansion, mainly in sub-Saharan Africa and Latin America, compared with RFS scenarios (appendix 1 pp 21–22). This transformation alone contributes to reducing the planetary boundary transgressions of climate change (15–43% [the range indicates the reduction in planetary boundary transgression of two control variables of the same planetary boundary domain—in this case, CO_2 concentration and temperature warming]), land-system use (14%), biosphere integrity (0–11%), and nitrogen (45%), and allows the freshwater use planetary boundary to return to the safe operating space (figure 2D). The FDT scenario projected a stabilisation of agricultural nitrogen surplus and a slowing down of deforestation, with forest cover stabilising at around 3900 million ha (a 14% reduction in planetary boundary transgression compared with RFS; figure 2E; appendix 7). This trend also improves the biosphere integrity planetary boundary outcome, reducing the transgression for largely intact land by 11% (figure 2F; appendix 7).

Land-based supply-side climate change mitigation (ie, LSM) incentivises reforestation and afforestation and disincentivises emissions in the model. The LSM scenario was projected to reduce planetary boundary transgression by 25–29% for climate change, 37% for land-system change, 17–18% for biosphere integrity, and 52% for nitrogen, but resulted in trade-offs with freshwater consumption (increasing planetary boundary transgression by 94%; figure 2D).

In 2020, freshwater consumption for non-agricultural and agricultural usage amounts to 1614 km³/year, well below the boundary of 2800 km³/year. However, increasing pressure on the land system due to population and income growth leads to agricultural intensification,

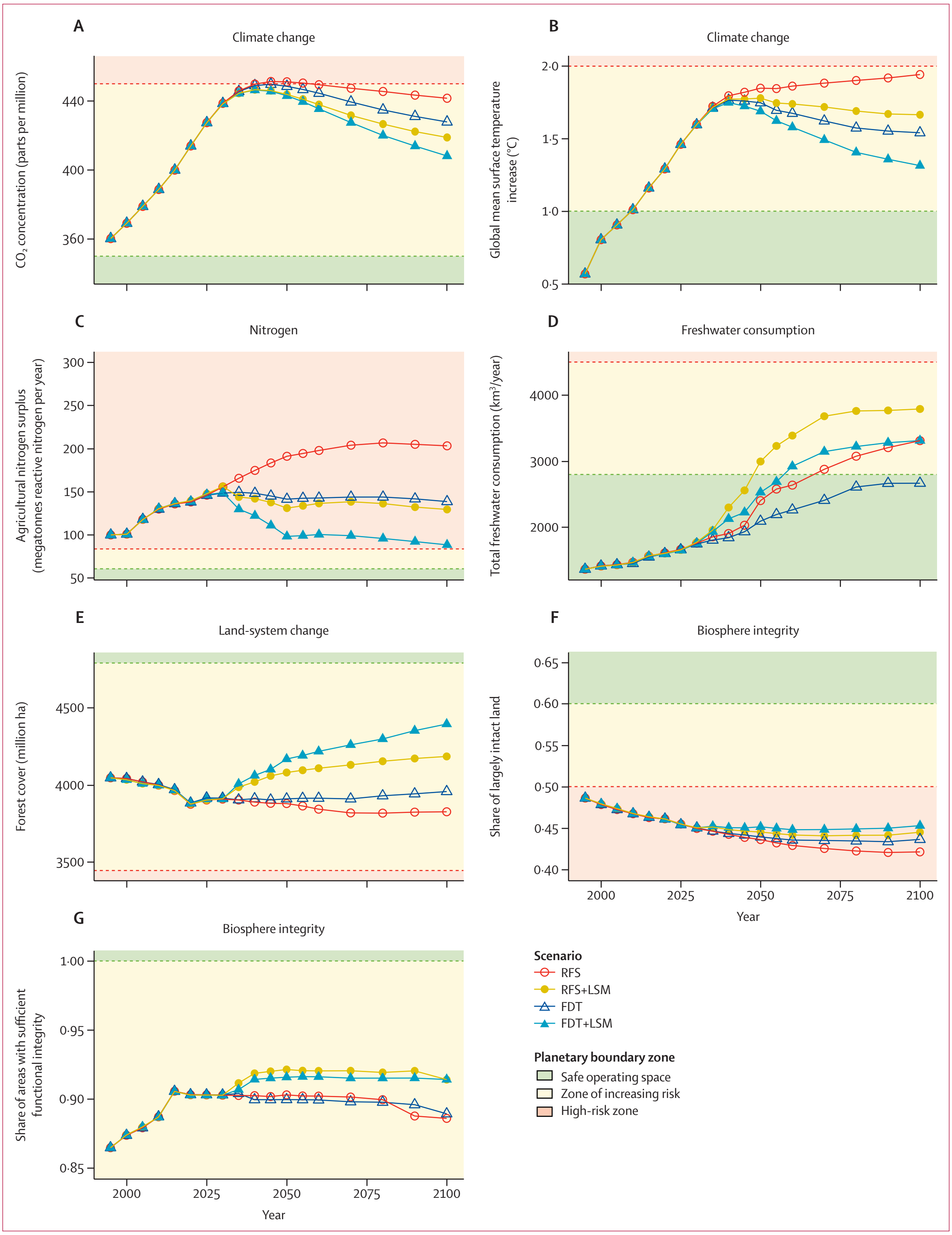

Figure 2: **Planetary boundary control variables for the core scenarios over time**

In all scenarios, ambitious energy-system climate change mitigation is assumed. The green dashed line indicates the safe planetary boundary (ie, the transgression point between the safe operating space and the zone of increasing risk). The red dashed line indicates the transgression point between the zone of increasing risk and the high-risk zone. The upper end of the zone of increasing risk is not defined for the biosphere (functional integrity) planetary boundary (G). FDT=food demand transformation. FDT+LSM=food demand transformation with land-based, supply-side measures. RFS=reference food system. RFS+LSM=reference food system with land-based, supply-side mitigation measures.

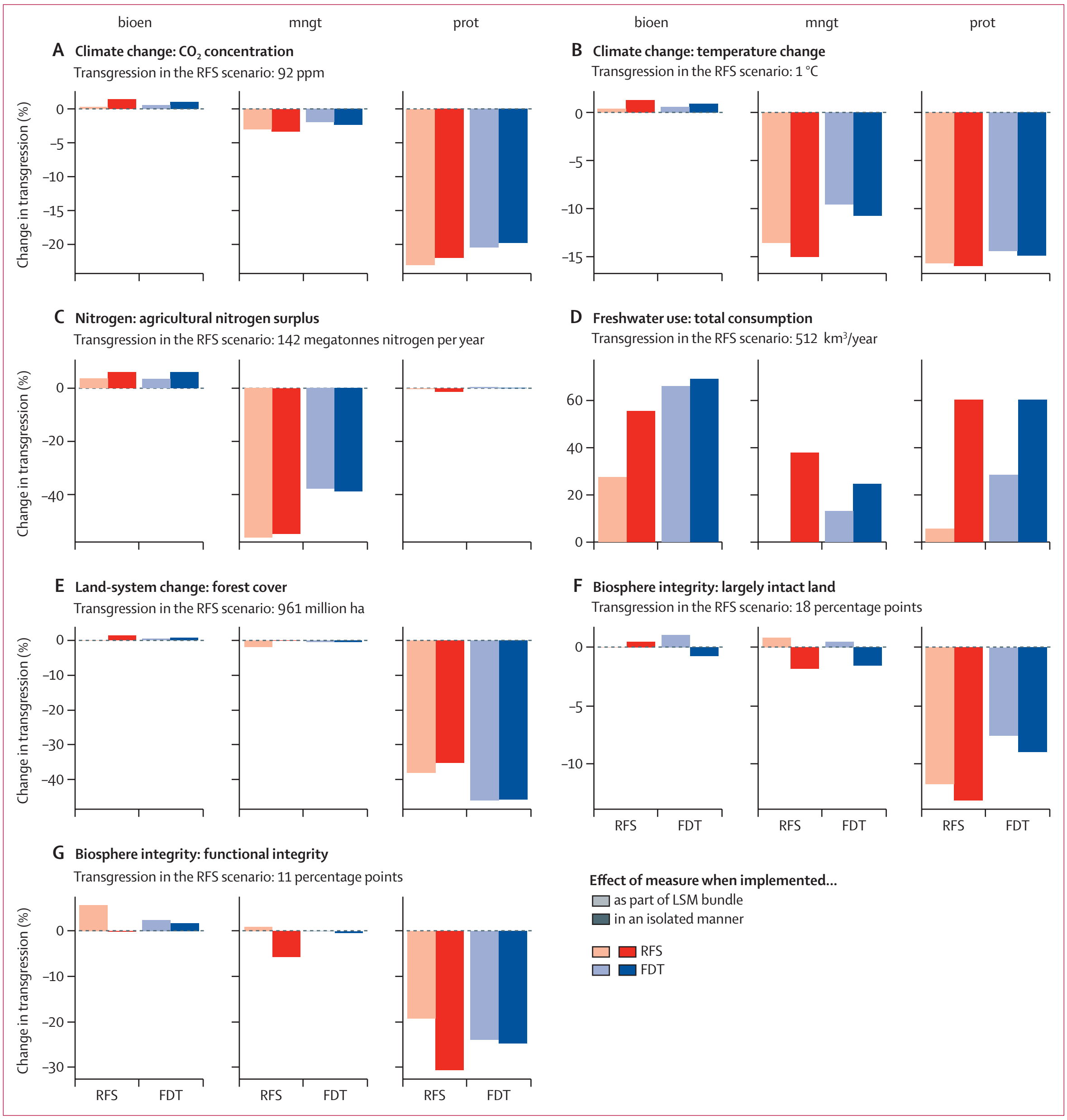

Figure 3: **Contribution of individual mitigation measures to reducing the planetary boundary transgression of the RFS scenario in 2100**

Positive signs indicate an increase in transgression compared with the RFS scenario. Negative signs indicate a decrease in transgression compared with the RFS scenario. Darker bars represent the effects of single measures implemented in isolation, whereas lighter bars show the measure's effect when implemented as part of the LSM bundle. If the values of light bars are smaller than their dark counterfactuals, synergies with other measures exist that enhance the measure's effectiveness. Red bars show the effect of mitigation measures under the RFS scenario and blue bars show the effect of mitigation measures under the FDT scenario. bioen=increased bioenergy supply. FDT=food demand transformation. LSM=land-based, supply-side mitigation. mngt=improved agricultural management incentivised through non-CO_2 emissions pricing. ppm=parts per million. prot=land protection through land-use change and peatland emissions pricing. RFS=reference food system.

increasing freshwater consumption to 3312 km³/year by 2100 in the RFS scenario (transgressing the planetary boundary by 511 km³/year; figure 2D; appendix 5). Land-system supply-side mitigation measures were projected to increase total freshwater consumption to 3790 km³/year when implemented without food demand changes (ie, in RFS + LSM; figure 2D), increasing the planetary boundary transgression to 990 km³/year.

The combination of the FDT and supply-side mitigation measures (ie, FDT+LSM) was generally projected to lead to substantial improvements in various planetary boundary control variables (eg, it reduced the agricultural nitrogen surplus to 89 Mt Nr/year [an 81% reduction in planetary boundary transgression; figure 2C; appendix 7] and increased forest cover to 4396 million ha [a 59% reduction in planetary boundary transgression; figure 2E; appendix 7] in 2100). Nevertheless, most planetary boundaries were projected to remain transgressed by the end of the 21st century in our 1·5°C-compatible mitigation scenario. In particular, agricultural nitrogen surplus and largely intact areas still breach the upper end of the zone of increasing risk (figure 2C, F). Freshwater consumption almost reaches the safe zone in FDT+LSM (figure 2D), since the FDT decreases the pressure on land and irrigation expansion.

These general trends and the direction of change of supply-side and demand-side, land-based mitigation measures are robust across varying socioeconomic assumptions in MAgPIE (the sensitivity analysis is provided in appendix 1 [pp 13–14, 27–30]). Among the five socioeconomic scenarios assessed in the sensitivity analysis, a safe operating space for the freshwater and nitrogen planetary boundaries is only achieved under SSP1 and SSP5 for our land-based climate change mitigation scenario (FDT+LSM). The climate change, biosphere integrity, and land-system change planetary boundaries are transgressed in all sensitivity scenarios (SSP1–SSP5) in 2100. For the land-based climate change mitigation scenario (FDT+LSM), the only planetary boundaries that achieve a safe operating space by 2100 are the freshwater and nitrogen planetary boundaries, but for only two scenarios (ie, under SSP1 and SSP5 assumptions). The percentage contributions of each mitigation measure in the reference food system (ie, RFS) setting and with a FDT setting to reducing planetary boundary transgression relative to the RFS scenario in 2100 are shown in figure 3. The results show the individual effects of each single measure (darker coloured bars) alongside the effects of each measure as part of the technical mitigation bundle (LSM; lighter coloured bars). This therefore shows the effect of each measure when all other LSM measures have already been implemented relative to the planetary boundary transgression of the RFS scenario (RFS–PB), and visualises the range of the effect of each measure and the measure's direction of change alongside its relevance within the climate change mitigation pathway combining all measures (LSM+FDT).

In most cases, the direction of change is unequivocal. Land protection and restoration via pricing land-use change and peatland emissions (prot) contributes to reducing the transgression of the climate change, land-system change, and biosphere integrity planetary boundaries (figure 3A–B, E–G) both when implemented as individual measures or as additional measures in an already existing mitigation bundle and for both the RFS and FDT scenarios. Similarly, pricing non-CO_2 emissions to incentivise climate change mitigation in agricultural management (ie, mngt) contributes to reducing the transgression of the nitrogen and climate change planetary boundaries (figure 3A–C).

Generally, supply-side mitigation measures in the land system that increase land competition (eg, via afforestation [prot] or increased bioenergy production [bioen]) amplify the need to intensify crop yields via irrigation, yield-increasing technological change, and fertiliser application. For the freshwater use planetary boundary (figure 3D), the need to intensify worsens transgression due to an expansion of irrigated areas both for food crops and bioenergy crops. Irrigation expansion in reaction to increased pressure on the land system can be observed, for example, in sub-Saharan Africa and Asia, where irrigated areas, bioenergy plantations, and forest areas increase compared with scenarios without land-based climate change mitigation (appendix 1 pp 20–22). For agricultural nitrogen surplus, four effects almost balance out at the global scale (figure 3C). First, agricultural intensification increases per-hectare fertiliser application. Second, reduced land expansion reduces the extent of land that receives fertiliser application. Third, additional cultivation of nutrient-efficient grasses and trees for bioenergy production requires additional fertilizer. Finally, pricing N_2O emissions (ie, mngt) increases fertiliser efficiency and reduces fertiliser application, therefore also reducing the nitrogen surplus.

The interplay between the measures included in this study highlights the importance of a decomposition analysis differentiating individual and combined effects. Three types of interactions can be observed in our results. First, the observed trade-offs of increased bioenergy production (bioen) across several planetary boundaries (eg, climate change and nitrogen, but especially freshwater use) are reduced when implemented in combination with GHG pricing in the land sector. To a lesser extent, such an effect is visible in the fact that the model tends to expand bioenergy production in carbon-rich areas, leading to incentives to deforestation (figure 3E, F). Introducing a carbon price diminishes this effect by protecting carbon-rich areas, contributing to a lessening of the trade-off in the climate change planetary boundary (figure 3A). Second, for some control variables, synergies can be observed when combining measures. For example, the effect of prot on CO_2 concentration and forest cover is enforced when implemented as part of the LSM bundle (figure 3A, E). In the case of the FDT, prot contributes more strongly to forest protection and restoration than in the RFS scenario. Third, in many cases, we see an overlapping system response to interventions that decreases the role of single measures in the mitigation bundle. For example, bioenergy expansion (bioen) and increased protection (prot) both exert pressure on the land system, which responds by intensifying cropland use through expanding irrigation. However, when these measures are implemented simultaneously, the areas targeted for irrigation by one measure often overlap with those targeted by the other. Similarly, for most planetary boundaries (eg, climate change, nitrogen, and biosphere integrity), the effect of reducing the planetary boundary transgression of the RFS scenario is weaker in the FDT scenario because part of the reduction in transgression is achieved by demand-side changes (eg, dietary change in line with the planetary health diet and food waste reductions), which ease the pressure on the land system (figure 3A–C, F, G).

Discussion

To limit global warming to less than 1·5°C by the end of the 21st century, very ambitious climate change mitigation action is required in both the energy and land systems. Our mitigation scenario results in a bioenergy demand from the energy sector of 116 exajoules per year in 2100 and a carbon price of \$310/tonne CO_2 from 2050 onwards, applied in the energy and land sectors. When implemented in isolation, increased bioenergy supply (bioen) leads to intensification and expansion of agricultural production mainly in low-income and middle-income countries (eg, in sub-Saharan Africa and Asia) and shows land-system trade-offs with all the assessed planetary boundaries. This finding aligns with previous studies showing that increased bioenergy demand from the energy system increases land competition.[5,7,40,41] In our analysis of these trade-offs, the positive effect of bioenergy on the climate change planetary boundary via energy system decarbonisation and CO_2 removal through bioenergy with carbon capture and storage is already accounted for by holding energy system emissions constant even in scenarios excluding bioenergy in the land system. The assumed mitigation action in the energy sector explains the increase in the transgression of the climate change planetary boundary domain in bioen scenarios and the RFS scenario staying below 2°C warming. Without increased bioenergy supply to the energy system, reaching the same climate target would require a substantially higher carbon price, otherwise the CO_2 concentration of 450 ppm would probably be transgressed due to higher energy system emissions.[8]

The trade-offs of increased bioenergy supply are alleviated when implemented as part of the LSM bundle. The supply-side measures in this study target subsectors of the land sector. Technical mitigation options in livestock farming (eg, using anaerobic digesters to cut CH_4 and N_2O emissions from animal waste management or altered animal feed to reduce CH_4 emissions from enteric fermentation through altered animal feed) and crop farming (eg, improved water management in wet rice cultivation to reduce CH_4 emissions and optimised fertilizer application to reduce N_2O emissions from agricultural soils) are triggered by GHG pricing of non-CO_2 emissions from agricultural production (mngt).[6,29] Similarly, pricing of land-use change emissions to protect carbon-rich natural land (prot) incentivises reforestation and afforestation, and conservation of natural areas in MAgPIE. Given environmental and cost constraints, the model chooses the cost-optimal mitigation option or relocates production.[22] Incentivised by different mitigation measures, all regions contribute to emission reductions, but there are shifts of production that affect regions differently. Land protection and restoration (prot) contributes to considerable increases in forest cover (figure 3E), especially in Latin America and sub-Saharan Africa. Beyond the intended positive effect on the climate change planetary boundary, the forest cover increase shows synergies with the land-system change and biosphere integrity planetary boundaries. Changes in agricultural production as a consequence of the mngt measure result in a reduction of the agricultural nitrogen surplus (figure 3C), driven by livestock production shifts to high-income regions with lower emissions per product unit, fertilizer efficiency increases in China and India, and reduced fertilizer use across all regions. Together with reductions in CH_4 emissions (eg, emissions from enteric fermentation), this reduction in surplus nitrogen contributes to a reduction in global warming (figure 3B). More details regarding the regional dynamics of the model are provided in appendix 1 (pp 12–13).

A global FDT contributes substantially to reducing planetary boundary transgression across all the assessed control variables. This finding aligns with previous studies on the role of dietary change for climate change mitigation,[6,42] and the impacts of dietary changes, food waste reductions, and productivity increases on planetary boundaries in static input–output analyses.[13,18] Especially in Latin America, the reduced pressure resulting from demand-side shifts (particularly in high-income and middle-income countries in Europe and North and South America) in which total kilocalorie demand decreases and the share of animal-based protein in dietary composition decreases, allows for less irrigation expansion, a reduction in pasture areas, and forest recovery. The FDT scenario shows the role consumers can play in reducing food waste and resource-intensive food intake. In this study, these changes in food intake are exogenously prescribed. We do not model how such a transformation could come about. Given the influence of culture and habit on dietary choices, such a far-reaching transformation, which includes both dietary shifts and food waste reductions, would probably require a policy mix (eg, education campaigns, product labelling, and price incentives) and the involvement of various food system actors (eg, food processing industries, supermarkets, and restaurants).[43–45] According to previous studies, dietary changes towards healthy and sustainable diets lead to food cost decreases in high-income and upper-middle-income countries, but higher food costs in low-income countries. In combination with food waste reductions, these changes result in lower food costs across all countries.[46] This result shows that welfare considerations are also important for a food demand transformation.

MAgPIE does not model policy instruments, but rather land-based climate change mitigation measures that are technically triggered by a GHG price in the model. The transaction costs of policies are not considered. In reality, a bundle of policies, including, for example, farmers' training or subsidies, would be necessary to achieve smooth implementation alongside GHG pricing.[28,47] The level of the GHG price in this study ($310/tonne CO_2 from 2050 onwards) aligns with previous literature on similar climate mitigation pathways.[6,48,49] Whether such high prices are politically and institutionally feasible is questionable given that the land sector is currently mostly exempt from carbon pricing.[50–53] For farmers, pricing GHG emissions increases production costs, which translates into higher food prices, especially in lower-income countries.[54] Within countries, carbon pricing has been found to have a greater effect on lower-income households.[43,55] To increase public acceptance (and therefore the feasibility of such an ambitious mitigation pathway), such equity and welfare considerations should be considered when including the land sector in a GHG pricing scheme (eg, by combining it with compensatory measures).[50,56] One limitation of this study is that the response of food demand to changes in final consumer prices is not considered. However, since food intake has been found to be inelastic with respect to price changes[57] and since agricultural producer prices make up only a small share of final consumer prices,[58] the expected impact on demand is probably small.

Other studies show that major policy efforts and societal changes would be necessary to operate within or move towards the safe operating space.[18,19,59,60] Such findings align with our finding that several planetary boundary control variables transgress the safe operating space by 2100 even in our ambitious climate change mitigation scenario, which combines supply-side and demand-side climate change mitigation, regardless of socioeconomic variations in the land system. Rather than determining precise transgression values, which would require a multimodel intercomparison, this study focuses on assessing the contributions, synergies, and trade-offs of land-system mitigation measures within one climate change pathway. Our results highlight that this combination of measures can yield interaction effects, strengthening synergies and alleviating trade-offs. Given that planetary boundary outcomes are also sensitive to socioeconomic assumptions in energy and land-system models, future research should explore targeted measures aimed at achieving a safe operating space and assess their role within whole-economy sustainable development pathways (similar to those developed by Soergel and colleagues[61] and Weindl and colleagues[62]) while also considering highly ambitious and novel options, such as circular food systems (van Zanten H, Wageningen University, personal communication) and animal-free meat and milk production,[19] and the interdependencies between different measures. Furthermore, improving the representation of planetary boundaries in integrated assessment models remains an important research priority. In this study, several planetary boundaries influenced by land-use dynamics—such as phosphorus, novel entities, and atmospheric aerosol loading—could not be assessed. The freshwater planetary boundary is represented by global freshwater consumption, which does not fully capture hydrological complexity. The mechanisms driving nitrogen and freshwater boundary transgressions are inherently regional but are only considered at a global scale. Similarly, the resolution used to calculate the landscape target probably overestimates the share of areas with sufficient functional integrity. Future research should focus on enhancing planetary boundary quantifications in integrated assessment models by integrating missing control variables and improving the spatial resolution in their quantification. This work could involve feeding integrated assessment model results into crop and vegetation models to capture processes not covered in economic land-system models.

To conclude, this study evaluates the impact of ambitious climate change mitigation on planetary boundaries, focusing on land-based supply-side measures and a food demand transformation aligned with the EAT-*Lancet* Commission 2.0 report's updated planetary health diet. Our results show that combining a food demand transformation with a GHG price of $310/tonne CO_2 in the energy and land systems can limit global warming to below 1·5°C by 2100, while reducing planetary boundary transgression, particularly in the climate change, land, biosphere, and nitrogen domains.

However, even this ambitious climate change mitigation pathway, which is compatible with the Paris Agreement, leaves all the planetary boundaries assessed in this study (ie, climate change, nitrogen surplus, freshwater change, land-system change, and biosphere integrity) transgressed by the end of the century. Still, the combination of all land-system measures (ie, both demand-side and supply-side measures) leads to a substantial shift towards the safe operating space for humanity. Through a scenario decomposition approach, we assessed the relevance of individual supply-side climate change mitigation measures, revealing interactions between the different measures. Land-system, supply-side mitigation through improved agricultural management, protection, and restoration of natural ecosystems, and bioenergy provision to the energy system reduces transgressions for most planetary boundaries. However, trade-offs are evident for freshwater use. Although increased bioenergy supply alone exacerbates planetary boundary transgression in the land system, its adverse effects are alleviated when combined with other supply-side measures. Additionally, demand-side changes in the food system through shifting to a planetary health diet and reducing food waste to roughly 50% of its current level in high-income countries eases land-system pressure, benefits all the assessed planetary boundaries, and alleviates trade-offs.

Contributors

FDB, AP, JH, JPD, FH, BLB, HL-C, MH, and DM-D'C formulated the study's overarching research goals and aims. FDB was responsible for management and coordination of the research activity planning and execution, the formal analysis, data visualisation, and writing of the original draft. FDB, JPD, JH, BLB, IW, PvJ, FH, LM, GA, MC, and DK were involved in the development of the model and methodology. FDB, JPD, GA, DK, LM, IW, PvJ, BLB, FH, MC, and CM were responsible for programming model code and testing existing code components. FDB, JPD, JH, PvJ, GA, and DK were involved in validation of research outputs. FDB, GA, FH, and PvJ conducted the investigation of involved data. FDB and JPD were responsible for data curation. FDB was supervised by AP, JPD, and JH. AP and HL-C were responsible for the acquisition of financial support for the project. All authors commented on, reviewed, and edited the draft manuscript. FDB and JPD directly accessed and verified the underlying data. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

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Data sharing

The open-source code of MAgPIE (version 4.9.1) and REMIND (version 3.4.0) are available on GitHub. Precompiled binaries of MAGICC 7 are available online. The AR6 climate assessment tool (version 0.1.2) is available on GitHub. The scripts used to create tables and figures for this publication and all model code and outputs are available at Zenodo.

For **MAgPIE** see https://github.com/magpiemodel/magpie/releases/tag/v4.9.1

For **REMIND** see https://github.com/remindmodel/remind/releases/tag/v3.4.0

For **MAGICC 7** see https://magicc.org/

For the **AR6 climate assessment tool** see https://github.com/iiasa/climate-assessment

For **code and scripts available on Zenodo** see https://doi.org/10·5281/zenodo.14870633

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For **ChatGPT** see https://chatgpt.com

For **Claude** see https://claude.ai/chat

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