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Food and land system transformations under different societal perspectives on sustainable development

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Abstract

The future of food and land systems is crucial for achieving multiple UN Sustainable Development Goals, given their essential role in providing adequate nutrition and their significant impact on Earth system processes. Despite widespread consensus on the need for transformation, discussed strategies vary widely, from technology-driven to sufficiency-focused approaches, emphasizing different agents of change and policy mixes. This study assesses the implications of a new generation of target-seeking scenarios incorporating such diverse sustainability perspectives. We apply two integrated assessment models to explore food and land futures under three whole-economy sustainable development pathways (SDPs): Economy-driven Innovation, Resilient Communities, and Managing the Global Commons. Our assessment shows that the SDPs align sufficient food supply with progress towards planetary integrity, halting biodiversity loss, mitigating adverse impacts from irrigation, and significantly reducing nitrogen pollution. While all SDPs comply with the Paris climate target, they diverge in the timing of climate mitigation efforts and focus on different greenhouse gases and emission sources. The Economy-driven Innovation pathway rapidly achieves net-negative CO_2 emissions from the land system, whereas the pathways Resilient Communities and Managing the Global Commons significantly decrease agricultural non-CO_2 emissions. Moreover, sustainability interventions attenuate trade-offs associated with narrowly focused mitigation scenarios and reduce reliance on carbon dioxide removal strategies like bioenergy with carbon capture and storage.

1. Introduction

The future of food and land systems plays a critical role in achieving the Paris climate target and the UN Sustainable Development Goals (SDGs), particularly in efforts to 'end hunger' and 'ensure healthy lives' while safeguarding planetary integrity (Rockström *et al* 2020, Soergel *et al* 2021b). Human use of land has left a lasting imprint on the Earth system, altering global biogeochemical cycles, reshaping landscapes, and causing biodiversity loss (Vitousek *et al* 1997, Foley *et al* 2005, Jaureguiberry *et al* 2022).

Agriculture, the dominant global land use, also drives nitrogen pollution (Liu *et al* 2010, Schulte-Uebbing *et al* 2022) and violates the environmental flows required to sustain freshwater ecosystems in many regions (Jägermeyr *et al* 2017). Across the supply chain, food systems account for one-third of anthropogenic greenhouse gas (GHG) emissions (Crippa *et al* 2021).

Food is intrinsically linked to human health through both nutrition-related channels and indirect effects, such as agricultural pollution of air and water (Pozzer *et al* 2017, Ward *et al* 2018, Wang *et al* 2024). Dietary and metabolic risks constitute the largest contributors to the total burden of disease (GBD 2017 DALYs and HALE Collaborators 2018). The nutrition transition towards affluent diets is altering the risk landscape, increasing those associated with overnutrition (Popkin *et al* 2012, Bodirsky *et al* 2020). Meanwhile, efforts to combat undernutrition are insufficient, with approximately 9% of the world population suffering from hunger—more than before the COVID-19 pandemic (FAO, IFAD, UNICEF, WFP and WHO 2023).

The importance of delineating the role of food and land systems in pathways to sustainability is increasingly emphasized (von Braun *et al* 2023). These pathways can be translated by modelling approaches into target-seeking scenarios (IPBES 2016), building quantitatively consistent bridges from the current to a desirable future state (van Vuuren *et al* 2022). Modelling capacities in this field have advanced significantly. First, improved indicator coverage has enabled the assessment of pathways across domains highly relevant to the SDGs, such as biodiversity (Hof *et al* 2018, Leclère *et al* 2020, Ambrósio *et al* 2024), food security (Hasegawa *et al* 2018, Fujimori *et al* 2022), and planetary boundaries (Springmann *et al* 2018, Willett *et al* 2019, Gerten *et al* 2020). Second, increased granularity in process representation has expanded the portfolio of modelled interventions targeting areas such as consumption, nature conservation, and efficiency improvements (van Vuuren *et al* 2015, FOLU 2019, Searchinger *et al* 2019, Bodirsky *et al* 2022, Doelman *et al* 2022, Humpenöder *et al* 2022a, Kok *et al* 2023), aligning with priorities for sustainable food and land systems (Schmidt-Traub *et al* 2019). Finally, exploring sustainable food and land futures as integral parts of whole-economy transformations has underscored that they are both a prerequisite for, and dependent on, transformations in other sectors (Soergel *et al* 2021b, Humpenöder *et al* 2024, Ruggeri Laderchi *et al* 2024).

Despite these advancements, many studies have focused on a single sustainable pathway, such as the most optimistic of the Shared Socioeconomic Pathways (van Vuuren *et al* 2017, Moallemi *et al* 2022, Pereira *et al* 2024) or a more comprehensive transformation scenario aimed at boosting progress towards several targets (FOLU 2019, Soergel *et al* 2021b). However, while the Paris Agreement and the SDGs offer a politically negotiated target space for designing target-seeking scenarios, additional value-specific factors are involved in identifying desirable futures within that space and preferred ways to achieve them (Leach *et al* 2018). Thus, there is a need for alternative target-seeking scenarios to provide a more balanced representation of different societal perspectives (Aguiar *et al* 2020) and make assessments less policy-prescriptive (Edenhofer and Kowarsch 2015). Yet, no study has investigated multiple internally coherent food and land system transformations, limiting the exploration of the plurality of debated interventions and their underlying paradigms for steering these systems towards sustainability.

We address this gap by providing a multi-model assessment of three alternative food- and land-system futures embedded in distinct cross-sectoral visions for sustainable development (SD), using a new generation of target-seeking scenarios (Kriegler *et al* in preparation, Soergel *et al* 2024b). The narratives of these novel sustainable development pathways (SDPs) differ regarding their preferences for different forms of societal organization and global governance, the role of markets, societal or technological innovations, and the balance of interventions targeting primarily demand or supply. While Soergel *et al* (2024a) provide an overview of the whole-economy outcomes of three quantified SDPs (*Economy-driven Innovation* (EI), *Resilient Communities* (RC), and *Managing the Global Commons* (MC)), this multi-model study offers a detailed assessment of how these SDPs affect food and land systems. We evaluate the characteristics, strengths, and challenges of the SDPs using a comprehensive set of indicators, ranging from nutrition and agricultural demand drivers to environmental impacts in the domains of resource use, biodiversity loss, nitrogen pollution and GHG emissions.

2. Methods

2.1. Narratives for sustainable food and land systems

The SDPs are a new set of scenarios describing transformation pathways aimed at achieving the UN Agenda 2030 and the Paris Agreement. The underlying narratives were co-created through a trans-disciplinary stakeholder process (Kriegler *et al* in preparation), involving the identification of 12 dimensions in which sectoral and societal organization is shaped. Within each dimension, alternative SD strategies were elaborated, reflecting different paradigms and societal debates. These strategies were then combined across all dimensions to construct the SDPs, which are holistic in their ambition, covering a broad range of interacting societal and biophysical systems. This adaptable methodology facilitates the creation of several SDPs, of which three archetypal variants were selected for scenario quantification. In the following summary, we focus on the 'Land and Food' dimension, while other dimensions are detailed in Kriegler *et al* (in preparation) and Soergel *et al* (2024a). An overview of the overarching features of the three selected SDP narratives is provided in supplementary table S1.

2.1.1. SDP-EI: Economy-driven Innovation

Technological progress and global cooperation are endorsed to promote sustainability. Competitive markets are perceived as catalysts for innovation and prosperity, while governments act as regulators to align market outcomes with societal goals. Food and land systems are characterized by the principle of sparing land, achieved by constraining spatial expansion while intensifying production and improving the efficiency of the agricultural and land use sectors, applying increasingly automated and partially landless biomass production, artificial intelligence and sensor technologies. Market dynamics are harnessed to boost innovation, including novel foods and food storage, decrease resource use, waste and environmental pollution, increase material provision for the bioeconomy, and improve other ecosystem services like carbon sequestration.

2.1.2. SDP-RC: Resilient Communities

Community- and sufficiency-oriented world views value solidarity and well-being, prioritizing local organization, environmentally conscious lifestyles, and equitable access to resources for sustainability. State and non-state actors collaborate as partners in a wider societal partnership. The transition towards sustainable food and land systems is facilitated by behavioural change towards healthy and sustainable diets with a high share of plant-based foods, alongside societal support for agroecological practices and diversified farming, rooted in the principle of caring for people, animals and nature. Food supply chains are short and the value of food is high, which is reflected in strong skills for food preparation and storage, resulting in low food waste. Social acceptance of large-scale re/afforestation projects and bioenergy plantations is low.

2.1.3. SDP-MC: Managing the Global Commons

State actors cooperate to advance the transition towards sustainability in a functioning multilateral system, where policy mixes target levers both on the demand- and supply-side to manage resources and safeguard ecosystem services. Food and land systems also combine several approaches to reduce resource use and pollution, including dietary changes and lower food waste. The dichotomy between managed and natural systems is becoming less pronounced, following the principle of sharing resources for reconciling human well-being and ecosystem health. Innovation feeds from many sources, combining technological with traditional approaches, further developing multi-purpose systems like agroforestry and focusing on synergies and whole-system efficiency, e.g. improved nutrient cycling at landscape scale or biodiversity-friendly land-based mitigation.

2.2. Pathway quantification

We apply the two integrated assessment models REMIND-MAgPIE (Kriegler *et al* 2017, Dietrich *et al* 2019, Soergel *et al* 2021b) and IMAGE (Stehfest *et al* 2014, van Vuuren *et al* 2017) to derive scenario quantifications for the above-described SDPs. The two models include detailed representations of food and land systems, including socio-economic components and spatially explicit biophysical data (see Supplementary Material (SM) for model descriptions), and have been compared in previous assessments (e.g. Doelman *et al* 2022). The qualitative characteristics of the SDP narratives are translated into quantitative model parameterization using a structured modelling protocol. An excerpt of the protocol covering the model-specific settings related to food and land systems is available as part of our SM (see SM of Soergel *et al* (2024a) for the complete modelling protocol). Table 1 summarizes the relevant characteristics of the SDP narratives for modelling food and land systems as semi-quantitative specifications, such as low, medium, and high. Important input data like population, economic growth and within-country inequality are harmonized between models (Min *et al* 2024, Soergel *et al* 2024a).

We compare the quantified SDPs with two other scenarios: SSP2-Ref, based on the Shared Socioeconomic Pathway 2 (Riahi *et al* 2017), reflects a continuation of current trends and existing climate policies, while SSP2-1.5C focuses on ambitious climate change mitigation aligned with the Paris Agreement—also including the Nationally Determined Contributions (NDCs)—without additional efforts towards achieving Agenda 2030. The quantification of scenarios does not consider the impacts of climate change beyond the current level of warming.

3. Results

We analyse the implications of the different pathways for food and land systems using a comprehensive set of indicators. Figure 1 provides quantitative insights into demand- and supply-side characteristics of the food system, including nutrition-related health risks, agricultural demand, and productivity. We then explore the impacts of agricultural production and land use on biosphere integrity, covering land resources (figure 2), terrestrial biodiversity and freshwater ecosystems (figure 3), the nitrogen cycle (figure 4), and GHG

Table 1. Characteristics of the SDP narratives relevant to food and land systems. The modelling protocol, detailing the translation of these characteristics into model assumptions and parameterizations specific to food and land systems, is available as part of the Supplementary Material.

Characteristics	Economy-driven Innovation SDP-EI	Resilient Communities SDP-RC	Managing the Global Commons SDP-MC
General			
Population	Low population growth	Low population growth	Low population growth
Urbanization	High in all regions, medium to strong convergence	Low to medium urbanization	High urbanization
GDP growth rate	High in all regions, medium to strong convergence	Post-growth (= gradual convergence to zero growth) in developed countries, medium to high in other countries, strong convergence	Moderate in developed countries, high in other countries, strong convergence
Trade	Globalized	Regionalized	Globalized
Food demand			
Dietary patterns	Partial substitution of livestock products with animal-free alternatives, adoption of novel foods, overcoming hunger	Fast transition to sustainable and healthy diets (e.g. according to the EAT-Lancet Commission), overcoming hunger and overnutrition	Medium-paced transition to sustainable and healthy diets (e.g. according to the EAT-Lancet Commission), overcoming hunger and overnutrition
Food waste	Minor food waste reduction	Strong food waste reduction	Medium food waste reduction
Ecosystem protection			
Land protection	Strong, focus on carbon sequestration and price-based policy instruments, peatland protection and restoration	Medium, focus on biodiversity and regulatory policy instruments, peatland protection and restoration	Co-existence, focus on biodiversity in managed landscapes and in vulnerable habitats, mix of policy instruments, peatland protection and restoration
Environmental flow protection (EFP)	Very high	High	Very high
Agricultural management			
Crop yields and livestock productivity	High increase	Convergence: increase in low productive systems, stable yields in efficient systems	Medium increase
Nitrogen use efficiency (NUE)	High	Medium	High
Irrigation efficiency	High	Medium	High
Land-based mitigation			
Re/afforestation	High carbon sequestration potential through managed plantations, but notable limits on land availability according to the land-sparing principle	Low carbon sequestration through deliberate re/afforestation, preference for natural regrowth on abandoned land	Medium carbon sequestration potential through re/afforestation, with low human intervention and certain limits to land availability for sustainability reasons
Bioenergy (energy crops)	High (irrigation possible)	Low (rainfed only)	Medium (rainfed only)

emissions (figure 5). While most indicators capture endogenous model dynamics, some indicators in figure 1 reflect scenario assumptions or quantified scenario drivers. Supplementary table S2 provides an overview of indicator definition and classification.

3.1. Dietary trends, biomass demand, and agricultural supply dynamics

The three quantified SDPs set different priorities regarding food consumption, reflected in food intake, dietary patterns, and nutrition-related health risks (figure 1; supplementary figure S2). SDP-EI

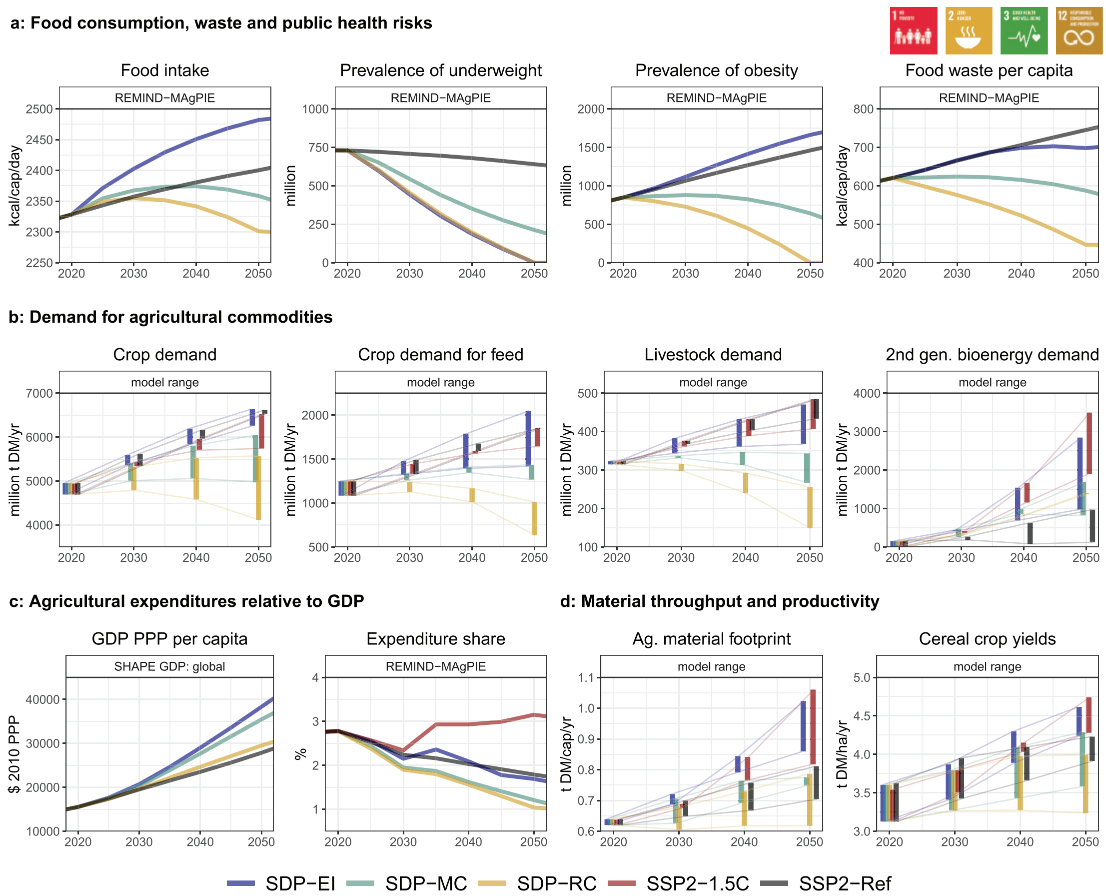

Figure 1. Food consumption, related health risks, and demand- and supply-side characteristics of the food system. (a) Food intake, prevalence of underweight and obesity, and food waste. (b) Total crop demand for food, feed, and material (excluding energy use), livestock demand, crop demand for feed (also included in the panel Crop demand), and demand for second-generation bioenergy crops. (c) GDP per capita and the share of expenditures for agricultural commodities relative to GDP. (d) Agricultural material footprint, calculated as the total crop demand for all purposes (including bioenergy) per capita, and cereal crop yields. Indicators are presented for the three SDP scenarios in comparison to a trends-continued reference scenario (SSP2-Ref) and a climate-policy-only scenario (SSP2-1.5C) for the period between 2020 and 2050. Note that some indicators represent scenario assumptions or quantified scenario drivers (see supplementary table S2 for the classification of indicators) that are not affected by climate policies and, therefore, do not differ between SSP2-Ref and SSP2-1.5C. For indicators quantified by both models, vertical bars show the model range and thin lines the individual models (see also supplementary figures S4 and S5 for results from each model separately).

emphasizes overcoming hunger and promotes innovative alternatives to resource-intensive animal-source foods. SDP-RC and SDP-MC assume comprehensive dietary shifts towards healthy, sustainable diets as recommended by the EAT-Lancet commission (Willett *et al* 2019) until 2050 (SDP-RC) and 2070 (SDP-MC), including eradication of both under- and overnutrition and reduced consumption of animal-source foods.

All SDPs align with the goal of zero hunger (SDG 2), albeit after 2030 and at different speeds. In contrast, prevalence of underweight only declines from 730 to 640 million between 2020 and 2050 in the reference scenario (SSP2-Ref). SDP-RC also eradicates overnutrition by mid-century due to the assumed rapid transition to healthy diets, while the slower pace in SDP-MC makes it more difficult to offset the rising obesity in the baseline. In SDP-EI, prevalence of obesity surpasses that of all other scenarios until 2050, driven by economic growth and income convergence between Global North and Global South (supplementary figure S1), accelerating the transition towards affluent diets in the Global South (supplementary figure S3; see supplementary table S3 for regional mapping). However, prevalence of obesity improves in the second half of the century, falling below SSP2-Ref.

The timing and focus of measures targeting nutrition-related health risks (SDG 3) affect per-capita calorie intake, which increases in the short term across all SDPs compared to SSP2-Ref. Only in SDP-RC, intake falls slightly below current levels by 2050. SDP-EI projects the highest intake, but reductions in food waste (SDG 12) in the Global North lead to global per-capita food calorie demand only moderately exceeding SSP2-Ref during a catch-up phase in low-income regions, reaching lower levels in the long term (REMIND-MAgPIE quantification; supplementary figure S2 and S3). SDP-RC substantially reduces food waste by 2050 (−170 kcal/cap/day

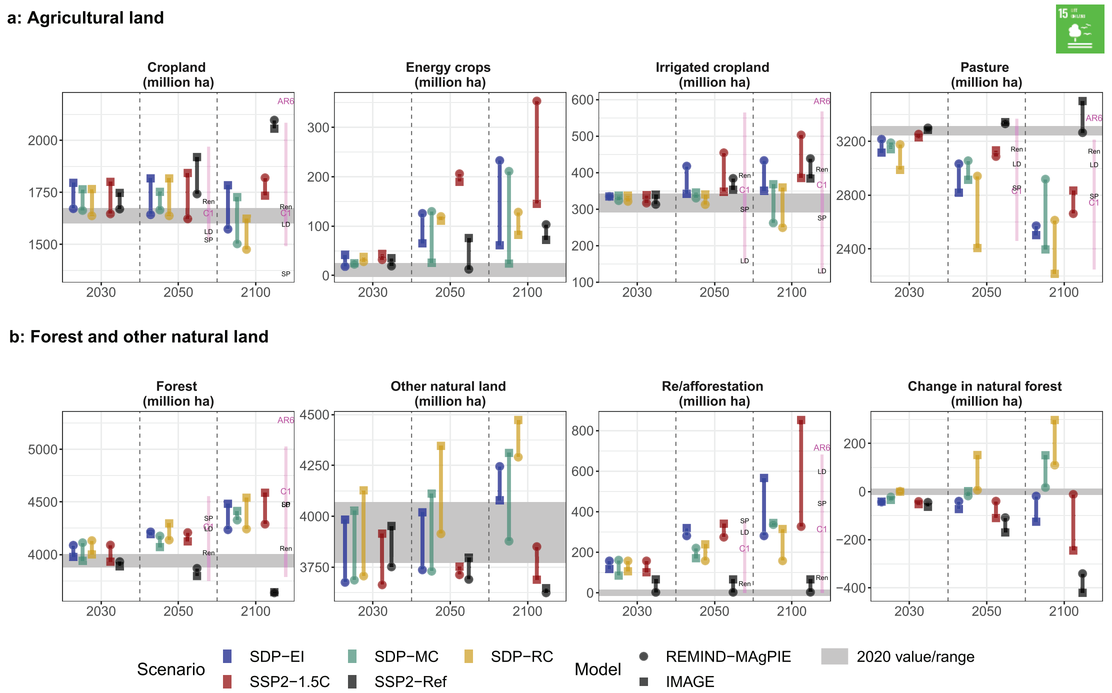

Figure 2. Global land-use dynamics in the 21st century. (a) Projections for agricultural land and (b) forest and other natural land for the three SDP scenarios in comparison to a trends-continued reference scenario (SSP2-Ref) and a climate-policy-only scenario (SSP2-1.5C). The *cropland* panel shows total arable land, including land used for second-generation bioenergy crops and irrigated cropland, which are also displayed separately. *Forest* cover includes the net effect of deforestation, timber plantations, intended re/afforestation, and natural regrowth of forest vegetation following land abandonment. *Other natural land* includes natural land not classified as forest incl. natural succession. *Re/afforestation* shows the gross area increase due to intended re/afforestation compared to 2020. *Change in natural forest* shows the net change in natural forest (excluding re/afforestation and timber plantations) compared to 2020. Vertical bars depict the model range and symbols indicate results from individual models. The shaded grey bands denote the ranges of modelled values for 2020. The vertical magenta lines display the 10%–90% ranges of 1.5 °C scenarios from the IPCC AR6 scenario DB with no/low overshoot (C1), with the label *C1* label representing the median of the ranges and the labels *IMP-SP*, *IMP-Ren* and *IMP-LD* the three illustrative mitigation pathways.

compared to 2020), lowering per-capita food calorie demand below current levels. SDP-MC also reduces food waste and food calorie demand compared to SSP2-Ref, albeit at a slower pace than SDP-RC.

Differences in diets and food waste are reflected in demand projections. Livestock product demand is ranked according to the ambition of demand-side interventions, with both models estimating demand for 2050 below current levels only for SDP-RC. A shift from animal- to plant-based foods increases crop demand for direct consumption or processing, though this increase is smaller than the reduction in feed crop demand, which drives dynamics in SDP-RC and SDP-MC. For SDP-EI, models diverge on the direction of change compared to SSP2-Ref. In REMIND-MAgPIE, partially substituting ruminant meat with animal-free alternatives helps balance the rapid nutrition transition to affluent diets globally. However, in low- and middle-income regions, consumption of animal-source foods still strongly increases until mid-century due to economic growth. However, long-term crop demand for feed is considerably lower than in SSP2-Ref. In IMAGE, the share of animal-source foods in diets declines across all world regions in SDP-EI.

SDP demand projections for second-generation lignocellulosic bioenergy crops are lower than in SSP2-1.5C, particularly in SDP-RC and SDP-MC. Although the agricultural material footprint increases in most scenarios, the SDP-RC quantification from REMIND-MAgPIE—a sufficiency-oriented post-growth scenario—remains close to today's level. Projections for cereal yields indicate that while SSP2-based scenarios and SDP-EI counteract high per-capita material throughput with increased productivity, less material-intensive lifestyles in other SDPs reduce the need for intensification. Lower demand pressure in SDP-RC and SDP-MC is also reflected in expenditures for agricultural commodities, where expenditure shares even fall below SSP2-Ref. In SDP-EI, detrimental impacts of climate policy on commodity prices are substantially reduced compared to SSP2-1.5C (Soergel *et al* 2024a), with fast economic development lowering expenditure shares to levels comparable to SSP2-Ref. Thus, the diverse SD strategies effectively mitigate trade-offs between climate protection and food affordability, addressing food security risks associated with ambitious global climate action (Hasegawa *et al* 2018, Fujimori *et al* 2022).

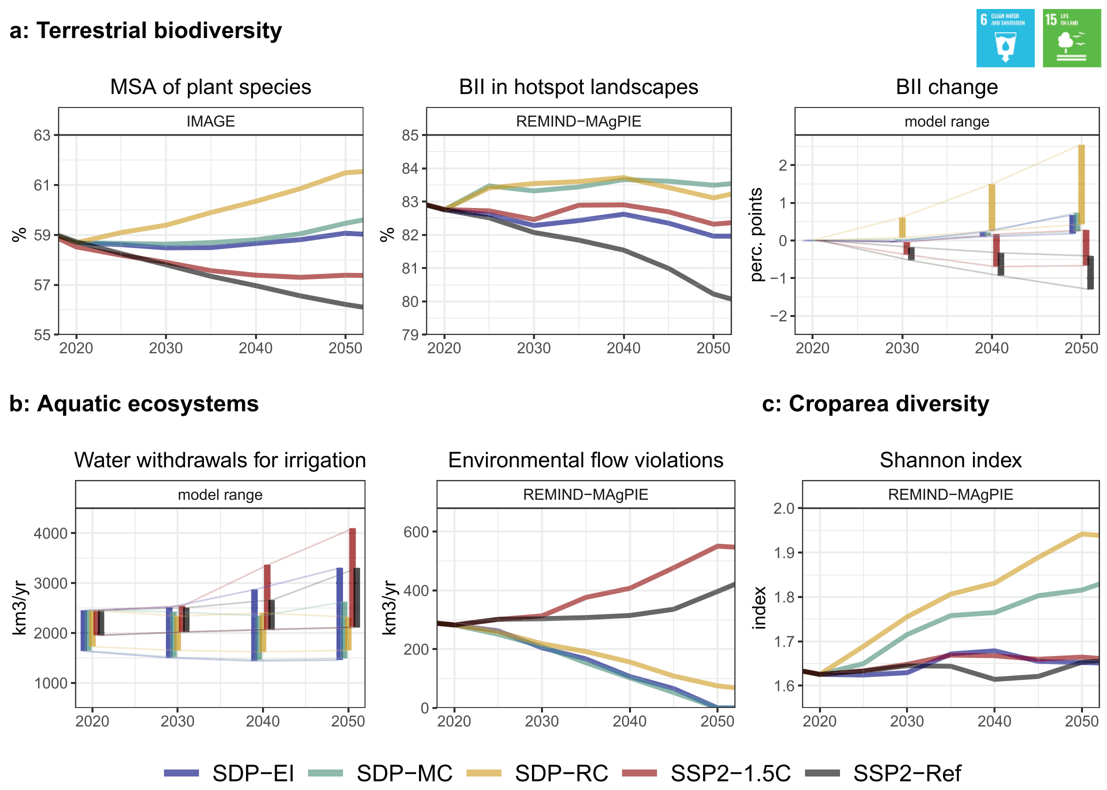

Figure 3. Food- and land-system impacts on terrestrial and aquatic freshwater ecosystems. (a) Biodiversity indicators related to terrestrial ecosystems, measured using Mean Species Abundance (MSA) and the Biodiversity Intactness Index (BII), where the middle panel only considers land within biodiversity hotspots and the right panel depicts changes in BII since 2020. (b) Indicators related to freshwater ecosystems, where environmental flow violations are reported as the volume of withdrawals that exceed environmental flow requirements. (c) Croparea diversity measured by the Shannon index, which accounts for crop richness and abundance. Indicators are presented for the three SDP scenarios in comparison to a trends-continued reference scenario (SSP2-Ref) and a climate-policy-only scenario (SSP2-1.5C) for the period between 2020 and 2050. For indicators quantified by both models, vertical bars show the model range and thin lines the individual models (see also supplementary figure S6 for results from each model separately). All indicators are described in supplementary table S2.

3.2. Natural resource use and implications for biosphere integrity

The different SD strategies regarding demand-side interventions, efficient agricultural management, and land productivity have repercussions on life on land (SDG 15). Land-use dynamics (figure 2) are also shaped by land conservation policies, land-based climate mitigation measures, approaches to landscape structure—whether separating managed and natural spheres or spatially integrating them—and the balance between land and water use (SDG 6, target 6.4 'sustainable withdrawals of freshwater').

In SSP2-1.5C, climate mitigation efforts discernibly affect cropland and pasture dynamics, with cropland decreasing by 277–322 million ha and pasture by 603–665 million ha by 2100 compared to SSP2-Ref, primarily driven by changes in the Global South (supplementary figure S7). Agricultural land use is curbed by pricing emissions from land-use change and allocating land for non-agricultural purposes, such as carbon sequestration through re/afforestation. Cropland dedicated to bioenergy crops increases to 190–206 million ha by 2050 and 145–353 million ha by 2100 in the climate-policy-only scenario. However, this increase is mitigated by SD interventions both in the medium and long term. Although demand for bioenergy and other crops varies across scenarios, cropland projections show little deviation by 2050 with climate policies in place, suggesting that high demand pressures are largely counterbalanced by intensification. In the long term, however, a clear ranking of the SDPs emerges, with SDP-RC having the lowest and SDP-EI the highest cropland levels.

Only one SDP quantification (SDP-EI from REMIND-MAgPIE) notably expands irrigated areas to alleviate land pressure, thereby increasing pressure on water resources in the Global South (supplementary figure S6), though less so than SSP2-1.5C. This is reflected in water withdrawals for irrigation (figure 3(b)) in SDP-EI, which are similar to SSP2-Ref around mid-century, but substantially lower than in SSP2-1.5C for the same model. Although timing differs, all SDPs implement measures to protect water resources, ensuring that, despite continued irrigation demand, transgressions of environmental flow requirements are gradually reduced—key to sustaining freshwater ecosystems in fair condition. In

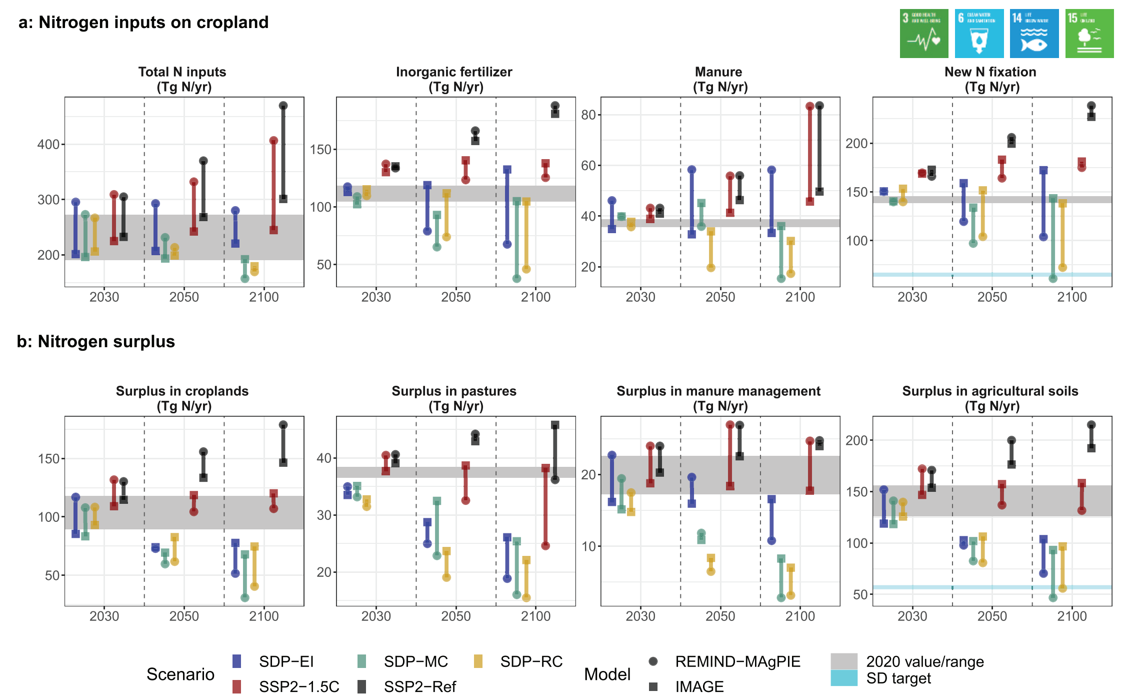

Figure 4. Global nitrogen inputs and surpluses. (a) Nitrogen (N) inputs on cropland, including inorganic fertilizer, manure, and total N inputs. Total inputs also account for biological fixation and atmospheric deposition. New N fixation denotes the sum of inorganic fertilizer and biological fixation by cultivating leguminous crops. (b) N surplus in croplands, pastures, and manure management as well as N surplus in agricultural soils, derived as the sum of surplus from croplands and pastures. Indicators are presented for the three SDP scenarios in comparison to a trends-continued reference scenario (SSP2-Ref) and a climate-policy-only scenario (SSP2-1.5C) for the years 2030, 2050 and 2100. Vertical bars depict the model range and symbols indicate results from individual models. The shaded grey bands denote the ranges of modelled values for 2020. The cyan lines display the global boundaries for the respective N indicators (Schulte-Uebbing *et al* 2022). All indicators are described in supplementary table S2.

contrast, water withdrawals in SSP2-Ref and SSP2-1.5C are projected to increasingly violate environmental flow requirements without these measures in place.

SD interventions also affect pasture dynamics. In SDP-RC, rapid shifts towards healthy diets significantly drive pasture reduction, complemented in IMAGE by ambitious conservation efforts to protect half of Earth's land (Doelman *et al* 2022). In MAgPIE, pastures react less sensitive to declining livestock demand than in IMAGE, due to possible extensification. A combination of high agricultural productivity and partial substitution of ruminant-based products in SDP-EI results in substantial pasture decline in both models until the end of the century. In the REMIND-MAgPIE quantification of SDP-MC, carbon prices are applied to the conversion of both natural and managed land, which disincentivizes the conversion of pastures rich in soil carbon, aligning with the scenario's less dichotomous view on land systems.

The priorities set by the SDPs for sustainable land use also influence the dynamics of non-agricultural land. In the long term, forest cover increases similarly across SDPs but generally remains below SSP2-1.5C levels. However, the contributions of re/afforestation versus natural forest regrowth, as well as their timing, vary significantly. SDP-EI emphasizes the climate benefits of expanding forests, favouring rapid onset and fast carbon sequestration, which results in highest re/afforestation (281–319 million ha) of all SDPs by 2050. Although natural forest cover decreases slightly over the same period, SDP-EI achieves the largest negative CO_2 emissions from the land system (figure 5(b)). SDP-RC sees the smallest increase in re/afforestation by 2100 (in REMIND-MAgPIE only within the scope of the NDCs), while natural regrowth leads to long-term annual negative CO_2 emissions from land-use change at levels similar to SDP-MC. The applied models offer different perspectives on SDP-MC: in REMIND-MAgPIE, re/afforestation is the main driver of forest increase, following growth curves of natural vegetation, suggesting the use of native species. In IMAGE, forest expansion is driven by both natural succession on abandoned land and re/afforestation.

Future land use will affect spatial configuration, croparea diversity, and terrestrial biodiversity (figure 3). Croparea diversity primarily benefits from demand-side SD interventions, which broaden cropping patterns as food consumption shifts towards healthy and sustainable diets. If current trends continue, biodiversity as measured by the Biodiversity

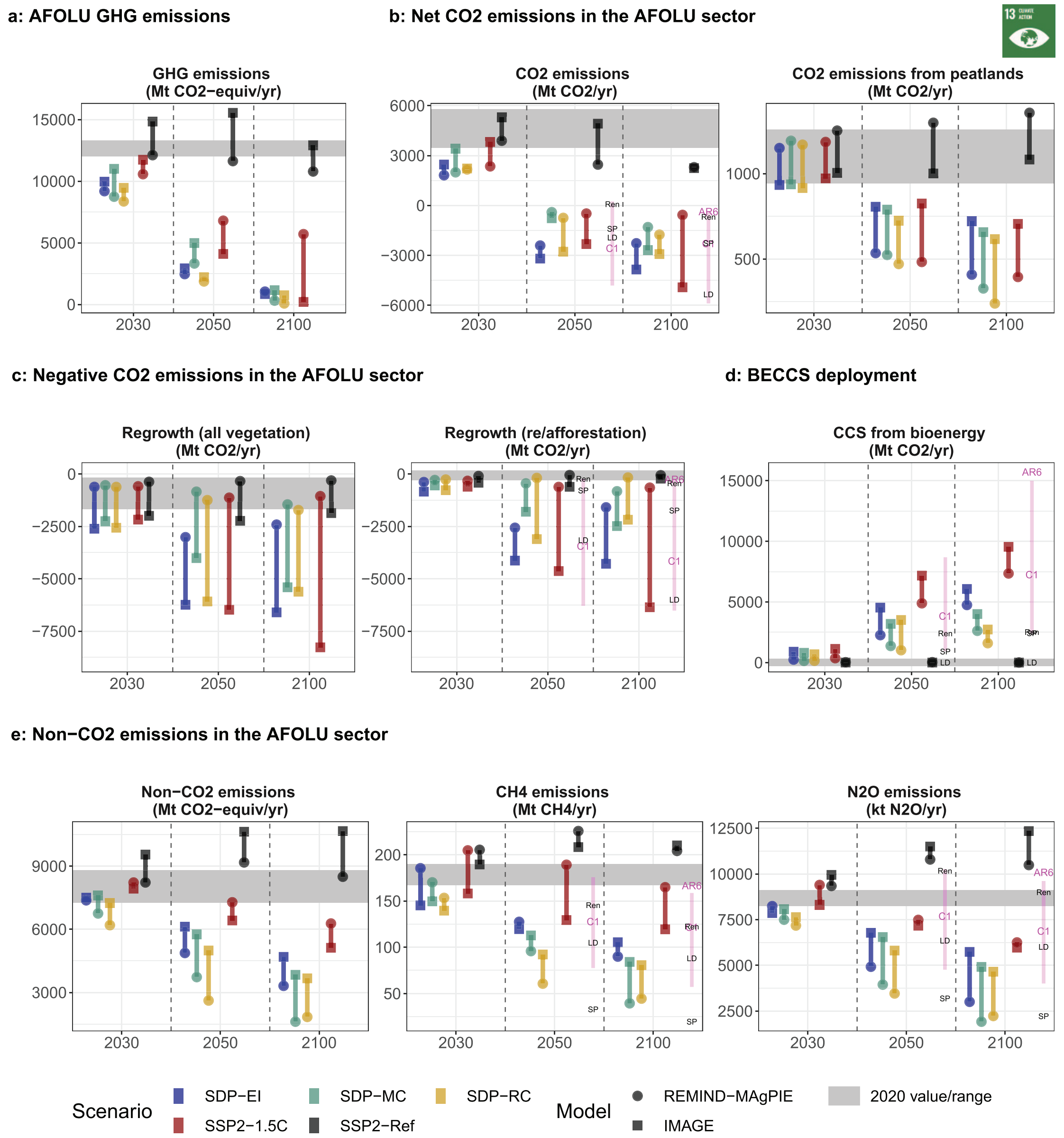

Figure 5. Climate change mitigation strategies impacting agriculture, forestry and other land use (AFOLU). (a) Greenhouse gas (GHG) emissions in the AFOLU sector. (b) Net CO_2 emissions in the AFOLU sector: total net CO_2 emissions from land use, land-use change and forestry (LULUCF), including emissions from managed peatlands. Net CO_2 emissions from managed peatlands (drained and rewetted) are also presented separately. (c) Negative CO_2 emissions in the AFOLU sector: the left panel shows negative CO_2 emissions resulting from vegetation regrowth, including re/afforestation and natural succession following land abandonment (covering forested and non-forested land). The right panel displays negative CO_2 emissions specifically from re/afforestation. (d) Carbon capture and storage (CCS) using bioenergy (BECCS) in the energy system. (e) Non-CO_2 emissions from the AFOLU sector: non-CO_2 emissions are depicted both as total, using IPCC AR6 Global Warming Potential (GWP100) factors of 273 and 27 to convert N_2O and CH_4 emissions into CO_2 equivalents, and individually. Indicators are presented for the three SDP scenarios in comparison to a trends-continued reference scenario (SSP2-Ref) and a climate-policy-only scenario (SSP2-1.5C) for the years 2030, 2050 and 2100. A detailed explanation of the visual elements can be found in the caption to figure 2.

Intactness Index (BII) and Mean Species Abundance (MSA) of plant species will decline beyond today's levels. Land-based mitigation, such as avoided deforestation, is a key lever for tackling both the climate and biodiversity crises. While all climate mitigation scenarios improve on SSP2-Ref, even without accounting for the likely negative impacts of unabated climate change in the baseline, biodiversity impacts of different climate mitigation and SD strategies need to be considered more explicitly to better understand synergies.

The narrower focus of SDP-EI on carbon sequestration, favouring fast vegetation growth over natural succession in newly forested areas, entails the least favourable biodiversity outcomes among the SDPs around mid-century, with BII in biodiversity hotspots falling below SSP2-1.5C levels. The sufficiency-oriented approach of SDP-RC, combined with the ambitious Half Earth protection scheme (IMAGE quantification), clearly bends the curve of biodiversity loss, increasing MSA of plant species more than other scenarios. While SDP-MC shows less pronounced improvements in the aggregated BII across all land types than SDP-RC, the BII in biodiversity hotspots is at the upper end of estimates for 2050 due to land protection measures targeting vulnerable and species-rich areas.

3.3. Nitrogen inputs and agricultural nitrogen pollution

Agricultural nitrogen (N) use affects several SDGs, influencing biodiversity and human health through air and water pollution while enhancing food security (Schulte-Uebbing *et al* 2022). To assess agricultural N pollution, we use indicators for N surplus from croplands, pastures, and animal waste management, defined as N inputs minus N outputs in these subsystems (figure 4). Despite ambitious SD interventions to mitigate N pollution, even the most optimistic scenario (81 Tg N/yr; SDP-RC from REMIND-MAgPIE) fails to reduce *N surplus in agricultural soils* by 2050 below the proposed planetary boundary of 57 Tg N/yr (Schulte-Uebbing *et al* 2022). In SSP2-Ref, N surplus is projected to worsen significantly, while SSP2-1.5C manages to stabilize N pollution at high levels. Overall, both models show a consistent ranking of the SDPs for all surplus indicators, with SDP-EI accomplishing the lowest, but still substantial, reductions compared to current levels and the SSP2-based scenarios. The performance of SDP-RC and SDP-MC varies by subsystem and over time, with SDP-MC benefiting from synergies between demand-side shifts and efficiency gains in the long term, achieving the lowest losses from cropland.

N surplus from cropland soils is a key driver in transgressing the N boundary, with all SDP projections (60–83 Tg N/yr) for this subsystem surpassing the overall surplus threshold by 2050. In SSP2-Ref, N surplus from cropland soils alone is far more than twice the N boundary for agricultural soils by mid-century. While N inputs on cropland show many similar patterns to N surplus indicators, with strong increases in SSP2-Ref and considerable improvements in SDPs, there are notable differences. N inputs continue to increase significantly in SSP2-1.5C. Moreover, in some SDPs, reducing all types of N inputs below current levels remains challenging. This underscores the importance of improving nitrogen use efficiency (NUE) and animal waste management in the SDPs to achieve substantial reductions in N surplus indicators. Consequently, N surplus from agricultural soils is curbed more effectively than new N fixation, especially in the Global South (supplementary figure S8), where new N fixation is defined as the sum of inorganic fertilizer and intentional biological N fixation by leguminous crops.

3.4. GHG emissions and removals under different sustainability priorities

All SDPs and the climate-policy-only scenario align with the Paris Agreement's long-term target, reaching warming levels well below 1.5 °C by the end of the century, after temperatures have peaked at 1.56 °C–1.64 °C (Soergel *et al* 2024a). However, differences exist in the contribution of food and land systems to mitigation efforts, the composition of emission sources and gases from agriculture, forestry and other land use (AFOLU), and their temporal development (figure 5).

In the REMIND-MAgPIE quantification of SSP2-1.5C, the AFOLU sector continues to generate positive annual GHG emissions around 2100, despite net-negative CO_2 emissions from land-use change (−569 Mt CO_2/yr) that cannot counterbalance residual non-CO_2 emissions (6273 Mt CO_2-equiv/yr). Conversely, in the IMAGE quantification of the same scenario, large-scale re/afforestation (852 million ha) contributes to significant net-negative CO_2 emissions from land-use change (−4918 Mt CO_2/yr), with most of these negative emissions occurring in the Global South (supplementary figure S9), which almost offset agricultural non-CO_2 emissions (5121 Mt CO_2-equiv/yr). Across all SDPs, both models agree that the AFOLU sector approaches emission neutrality by the end of the century (83–1161 Mt CO_2-equiv/yr), supported by lower residual non-CO_2 emissions. Notably, none of the scenarios achieves net-negative GHG emissions from the AFOLU sector.

In SDP-RC and SDP-MC, the main levers to reach these marked emission reductions are the profound demand-side transformations, i.e. the shift towards healthy, sustainable diets and low levels of food waste, in combination with technical mitigation measures like better livestock and animal waste management and higher NUE, which substantially reduce CH_4 (mainly from enteric fermentation and animal waste systems) and N_2O emissions (mainly from agricultural soils and animal waste management). These scenarios have their strengths in mitigating agricultural non-CO_2 emissions, going beyond typical C1 scenarios from the IPCC AR6 ensemble (Byers *et al* 2022, Riahi *et al* 2022), which contributes to the low overshoot in SDP-RC due to the early onset of mitigating non-CO_2 emissions (Soergel *et al* 2024a). Both scenarios also achieve net-negative CO_2 emissions from the AFOLU sector, mainly via natural vegetation regrowth following land abandonment in the wake of dietary changes and land protection, but in SDP-MC also via carbon removal in re/afforestation projects (figure 5(c)).

In SDP-EI, net CO_2 emissions from land-use change rapidly become negative, falling below the levels observed in other scenarios (except the IMAGE quantification of SSP2-1.5C with overall high mitigation pressure), mainly due to carbon dioxide removal (CDR) from fast regrowth in re/afforestation projects

(−2565 to −4131 Mt CO_2/yr in 2050). Managed peatlands remain a source of CO_2 emissions in all mitigation scenarios by 2100 (240–721 Mt CO_2/yr), though considerably reduced compared to SSP2-Ref due to peatland protection and restoration. In addition to CDR in the AFOLU sector, the land system also supplies biomass for the energy system. Bioenergy with carbon capture and storage (BECCS) contributes to overall CDR, showing a clear ranking across the SDP scenarios, with considerably less reliance than in SSP2-1.5C.

4. Discussion and conclusion

This study contributes a multi-model assessment of the food and land system implications of a new generation of target-seeking scenarios aimed at meeting the Paris Agreement and accelerating progress towards the UN Agenda 2030. While this 'target space' (van Vuuren *et al* 2022) constrains the set of possible scenarios, the SDPs populate the remaining option space for sustainable food and land systems with diverse pathways consistent with economy-wide transformations.

Despite differences in focus and timing, all SDPs substantially improve planetary integrity while overcoming hunger. Less area than today is used to supply food and other agricultural commodities, without raising the share of income spent on them. Although re/afforestation is more constrained, the AFOLU sector achieves near-emission neutrality by the end of the century, aided by significant reductions in residual non-CO_2 emissions. Biodiversity loss in terrestrial ecosystems is halted, environmental flow requirements of freshwater ecosystems are increasingly protected, and nitrogen pollution is greatly alleviated. These outcomes resonate with insights from a growing body of literature exemplifying transformations that improve indicators across multiple dimensions (van Vuuren *et al* 2015, Springmann *et al* 2018, Willett *et al* 2019, Soergel *et al* 2021b, Bodirsky *et al* 2022, Doelman *et al* 2022, Humpenöder *et al* 2022a).

The SDPs, each offering distinct visions for climate-friendly food and land systems, enrich the set of 1.5 °C scenarios (Byers *et al* 2022, Riahi *et al* 2022) with less typical but much-needed representatives. They rely less on CDR, with mostly reduced re/afforestation areas and limited BECCS deployment, which lowers feasibility risks linked to biogeophysical and technological considerations associated with biomass-sourced primary energy and CCS scale-up (Brutschin *et al* 2021, Soergel *et al* 2024a). SD interventions also lessen other trade-offs inherent in narrowly tailored mitigation pathways, such as impacts on food affordability (Hasegawa *et al* 2018, Fujimori *et al* 2022) and pressures on land and water resources (Hof *et al* 2018, Humpenöder *et al* 2018), corroborating findings from a single-SDP study that integrated policymaking is key to advancing multiple SDGs (Soergel *et al* 2021b). Demand-side changes in the SDPs help to reduce these trade-offs but diverge from historical trends, challenging socio-cultural feasibility depending on ambition levels (Soergel *et al* 2024a).

Each SD paradigm offers a unique mix of benefits, downsides, and risks. SDP-EI relies least on demand-side transformations and meets consumer preferences for protein intake and taste (Fehér *et al* 2020) by substituting livestock products with animal-free alternatives. This strategy, already yielding environmental benefits as an individual measure (Humpenöder *et al* 2022b), synergistically improves mitigation outcomes, achieving highest carbon sequestration and bioenergy provision among SDPs without increasing food expenditures above baseline trends. N pollution improves substantially, albeit less than in other SDPs. However, the limited ambition in addressing the nutrition transition conflicts with the World Health Organization's target to halt the rise in adult obesity, likely increasing diet-related risks (Global Nutrition Report 2021). Technological solutions drive intensification, which risks perpetuating simplification and biotic homogenization of landscapes (Gámez-Virués *et al* 2015, Ellis *et al* 2021), historically linked to strong species decline (Beckmann *et al* 2019, Seibold *et al* 2019). Such biodiversity implications are not quantified in our study, representing an important limitation.

Contrastingly, SDP-MC addresses landscape characteristics both qualitatively, by reducing the dichotomy between managed and natural systems, and quantitatively, by integrating at least 20% (semi-)natural habitat into farmed landscapes to enhance pest control, hydrology, and biodiversity (Garibaldi *et al* 2021, Tscharntke *et al* 2021). While fine-scale implications were beyond our study's scope, recent modelling efforts suggest that this intervention improves configurational landscape heterogeneity and pollination sufficiency (von Jeetze *et al* 2023). Intensification is moderate, facilitated by the transition towards healthy and sustainable diets, pursued more gradually than in SDP-RC, thereby reducing socio-cultural feasibility risks (Soergel *et al* 2024a). Although SDP-MC mostly ranks between the other SDPs (e.g. biomass demand and carbon removal), its combination of demand- and supply-side levers most effectively reduces new N fixation and N surplus from agricultural soils.

Finally, SDP-RC features the most ambitious demand-side transformation, emphasizing rapid adoption of healthy, sustainable diets and effective food waste reduction. Combined with low BECCS deployment, these strategies stabilize agricultural material throughput per capita and reduce food expenditures. Since healthy diets are more expensive than current diets in low-income countries (Springmann *et al* 2021), trends in income and inequality are critical for their adoption. Although

SDP-RC features income growth in the Global South and a rapid reduction in the Gini coefficient (Min *et al* 2024), food affordability may still pose a barrier to dietary transformation, which is not captured by our modelling. However, if successful, it would address malnutrition and align consumption with human needs, fostering a balance between high quality of life and low environmental degradation (Bodirsky *et al* 2022). Additionally, transitioning to healthy diets significantly curtails non-CO_2 emissions, contributing to the low overshoot of 1.5 °C (Humpenöder *et al* 2024, Soergel *et al* 2024a). Despite modest agricultural productivity gains, SDP-RC uses less land than other SDPs, increasing forest cover and other natural vegetation mainly through natural regrowth following land abandonment—benefiting terrestrial biodiversity.

All SDPs increase policy integration by combining various interventions, reflecting preferences for specific policy instruments (Dombrowsky *et al* in review). However, the granularity of modelled interventions remains limited. Unlike some explicitly modelled economic instruments, such as carbon pricing, regulatory instruments are typically represented through exogenous variations in model parameters and constraints (e.g. land protection schemes). The representation of demand-side interventions does not allow for the identification of specific instruments to foster behavioural change, which may partly occur intrinsically, as in SDP-RC, although policy options can be inferred from the SDP narratives (Dombrowsky *et al* in review). SDP-EI might use taxes and subsidies to influence consumption, while SDP-RC could address the personal food environment (e.g. food knowledge), and SDP-MC may target external factors like advertising. As dietary transitions in low-income contexts are contingent on food affordability, these policy options may need to be complemented by measures such as reforms to food distribution systems and poverty alleviation efforts, e.g. through the redistribution of carbon pricing revenues (Soergel *et al* 2021a). How demand-side changes are realized affects the costs, benefits and risks of pathways—such as the regressive impacts of taxes on food availability—, which is not captured quantitatively in our study or many other modelling efforts (Willett *et al* 2019, Doelman *et al* 2022, Humpenöder *et al* 2024, Ruggeri Laderchi *et al* 2024).

Moreover, policy implementation may face constraints due to political economy considerations and institutional capacity (Béné *et al* 2020, Gaupp *et al* 2021). As positive visions of potential futures, the SDPs rely on assumptions of high institutional quality and peace (Dombrowsky *et al* in review). Our methods cannot assess the feasibility of these preconditions, nor can they capture potential repercussions of SD interventions on governance and stability. Further gaps include limited coverage of socio-economic implications, such as changes in agricultural employment and the distributional effects of policies, and limitations in the environmental impact assessment, notably the omission of land degradation and ecosystem services that sustain land productivity (Dainese *et al* 2019, Duflot *et al* 2022). Climate impacts are not considered, which could pose a risk to the permanence of carbon stored in natural or regrown forests (Anderegg *et al* 2020), in addition to their vulnerability to other anthropogenic drivers (Lapola *et al* 2023). However, some climate impact channels are addressed in a complementary analysis exploring the effects of SD interventions on the climate-land-energy-water nexus by Daioglou *et al* (in preparation).

Despite the need for further research to address these limitations, the presented work advances the modelling of food and land system transformations. By quantifying multiple scenarios and applying more than one model, it increases the robustness of results while highlighting areas of uncertainty. Moving towards a more sustainable future requires a target space, a shared perspective on where to go, and a roadmap leading the way from the current to an aspired state. This study offers coherent sets of alternative qualitative visions and quantitative pathways for future food and land systems, illustrating the multitude of options, their impacts on several sustainability goals, and the levels of ambition required to realize such transformations. In doing so, these pathways can serve as valuable reference points for broader societal deliberation on desirable futures.

Data availability statement

The scenario data that support the findings of this study are openly available for interactive exploration at the following URL: https://shape.apps.ece.iiasa.ac.at/. They are also available for download at https://doi.org/10.5281/zenodo.13752116.

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Author contributions

I W conceived the model analysis and led the writing of the manuscript, with inputs from B S, G A, J D and V D. B S, S R, V D, I W, G A and A B performed the scenario model runs with the two participating models. B S and I W designed the figures. JPD provided software engineering solutions and technical support. All authors contributed to scenario design, the development and scenario implementation of individual models, or the writing of the manuscript.

Code availability

The MAgPIE code is available under the GNU Affero General Public License, version 3 (AGPLv3) via GitHub at https://github.com/magpiemodel/magpie. The release used in this study (version 4.6.5) can be found via Zenodo (https://zenodo.org/records/7782037). The technical documentation of model version 4.6.5 is available at https://rse.pik-potsdam.de/doc/magpie/4.6.5/. Instructions for software installation and running the model are available at https://github.com/magpiemodel/magpie.

The food demand model used in this study is available as part of the MAgPIE source code (model version 4.6.5) and documented as part of the full MAgPIE model documentation.

The REMIND code is available under the GNU Affero General Public License, version 3 (AGPLv3) via GitHub at https://github.com/remindmodel/remind. The REMIND source code and configuration of the exact model version used in this study are available at https://github.com/bs538/remind/tree/SHAPE_coupledFinal. The REMIND version 3.2.0 can also be found via Zenodo (https://zenodo.org/records/7852740). The technical documentation of model version 3.2.0 is available at https://rse.pik-potsdam.de/doc/remind/3.2.0/. Instructions for software installation, running the model and coupling to MAgPIE (tutorials subfolder) are available at https://github.com/remindmodel/remind.

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