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LETTER

A decentralized approach to model national and global food and land use systems

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Keywords: agricultural models, food security, deforestation, climate change mitigation, biodiversity, trade

Supplementary material for this article is available [online](#)

Abstract

The achievement of several sustainable development goals and the Paris Climate Agreement depends on rapid progress towards sustainable food and land systems in all countries. We have built a flexible, collaborative modeling framework to foster the development of national pathways by local research teams and their integration up to global scale. Local researchers independently customize national models to explore mid-century pathways of the food and land use system transformation in collaboration with stakeholders. An online platform connects the national models, iteratively balances global exports and imports, and aggregates results to the global level. Our results show that actions toward greater sustainability in countries could sum up to 1 Mha net forest gain per year, 950 Mha net gain in the land where natural processes predominate, and an increased CO₂ sink of 3.7 GtCO₂e yr⁻¹ over the period 2020–2050 compared to current trends, while average food consumption per capita remains above the adequate food requirements in all countries. We show examples of how the global linkage impacts national results and how different assumptions in national pathways impact global results. This modeling setup acknowledges the broad heterogeneity of socio-ecological contexts and the fact that people who live in these different contexts should be empowered to design the future they want. But it also demonstrates to local decision-makers the interconnectedness of our food and land use system and the urgent need for more collaboration to converge local and global priorities.

1. Introduction

We have less than a decade to meet the sustainable development goals (SDGs), our carbon budget to limit future global warming is rapidly shrinking (Friedlingstein *et al* 2022), and we are responsible for an unprecedented biodiversity loss (IPBES 2019). Food and land use systems are critical to achieving these objectives, and land-based production activities are also the most threatened by climate change and the loss of ecosystem services (Porter *et al* 2014, Arneth *et al* 2019). Therefore, many researchers and experts have called for a transformation of our food and land use systems, i.e. a radical shift away from paradigms that steered agricultural production in the previous century (Caron *et al* 2018). These paradigms promoted the production of more and cheaper food by the agricultural sector through economies of scale and led to an increase in the average food availability per person despite a fast-growing world population. New paradigms put a stronger focus on nutrition security and healthy diets and highlight the need to minimize the environmental footprint of agriculture and food production (Willett *et al* 2019).

Models enable possible future outcomes for different actions to be compared and thus can provide valuable knowledge for planning the transformation of food and land use systems. For that purpose, a model that can show the long-term value of new alternatives to current practices and policies (*normative dynamic mechanistic approaches*) might be more useful than a tool focused on predicting the behavior of different actors which strongly depends on historical data (*positive static empirical approaches*) (Buysse *et al* 2007). Other critical model properties include consideration of the economic, environmental, and social dimensions of the transformation

and the simultaneous evolution of several objectives, so that potential trade-offs or synergies, on the supply and demand side, can be identified (WCED 1987, Sachs *et al* 2019). While most policies are designed at national and sub-national levels, countries are strongly interconnected through international trade and financial markets (Jang *et al* 2016). Consequently, models are needed at the national level that capture interlinkages with the global level (Hertel *et al* 2019).

Progress has been made to integrate economic and biophysical processes in projection models to track the economic performance of the agricultural sector and its impacts on the environment. However, while models exist at different scales, the national scale is poorly covered. Dynamic farm bioeconomic models allow a detailed representation of technologies and practices, farm interactions, and sometimes risk (Janssen and van Ittersum 2007) but they are mostly available at the sub-national scale and are not easily adaptable to the national level or another context (Flichman and Allen 2014, Kremmydas *et al* 2018). Integrated assessment models (IAMs) for agricultural systems also integrate models from natural sciences and economics and refer to different spatial and temporal scales (Bouwman *et al* 2013, Havlik *et al* 2014, Beach *et al* 2015, Dietrich *et al* 2019). However, extending the range of country applications of these IAMs requires considerable effort and knowledge (Ewert *et al* 2009) and has been limited to a few large countries so far (Soterroni *et al* 2018).

Ex-ante assessments of agriculture and land use sustainability that consider feedback between local and global levels are dominated by global models that do not capture the local-level details of land use and food systems (Villoria *et al* 2013, Hertel *et al* 2019). This is problematic for several reasons: these models are usually based on limited contextual information

from local stakeholders and representation of countries' policies (O'Neill *et al* 2017, Aguiar *et al* 2020), and model results at the country level are rarely available for decision-makers beyond the few results included in the related publication. Other methods to integrate national and global scales include the integration of a reduced form of one of the models into the other (Pérez Domínguez *et al* 2009), or linking a national and a global model developed independently (Pelikan *et al* 2015, OECD & FAO 2022). While there are interesting applications, they are not easily available or replicable with other models, and they do not consider the linkage of more than two models which limits the possibility of cross-country collaboration.

Within the food, agriculture, biodiversity, land, and energy (FABLE) initiative, we built a new decentralized modelling framework to foster the availability of models for the food and land systems at the national level that can account for feedback between the national and global scales. In this analysis, local researchers adapted the MAgPIE model (Dietrich *et al* 2019) for India and the FABLE Calculator (Mosnier *et al* 2020), an agricultural and land use accounting tool with flexible scenario design, for other countries. We built an online platform to iteratively integrate national and global scales to ensure that global results reflect heterogeneous countries' assumptions about the future and international trade balance. Here we present our methods and results on the possibility of simultaneously achieving food security, climate change mitigation, reduced deforestation, and biodiversity conservation. We provide examples for the U.S. and Australia on how the integration of national and global scales can affect our global and national results.

2. Methods

Local and global scale integration is achieved through an iterative process called 'Scenathon' (a marathon of scenarios). In section 2.1 we describe the eight steps of this iterative method, in section 2.2 we describe the models used at national and regional levels, and in section 2.3. The key assumptions made for different countries and regions in the 2050 modelled pathways.

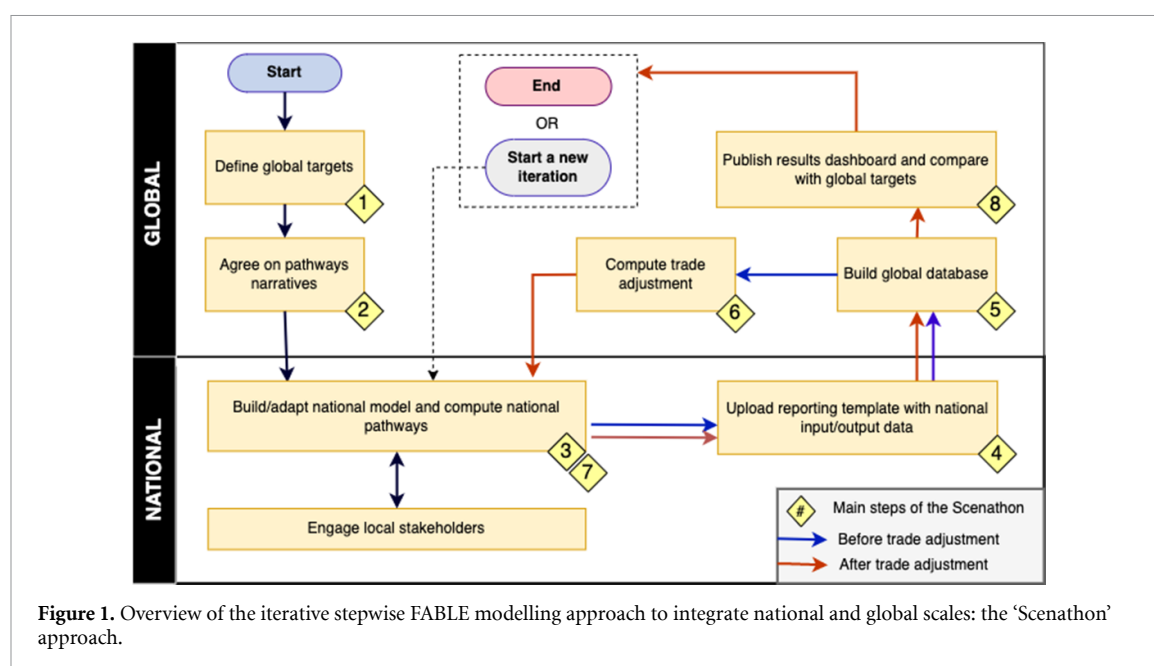
2.1. An iterative approach to integrate national and global scales

The different required steps are summarized in figure 1 and explained below.

- Step 1 The FABLE Consortium members agree on global sustainability targets based on a mix of science-based targets and political targets (Mosnier *et al* 2022). We focus on: (1) zero net forest loss from 2030 onwards (New York Declaration on Forests, 2014); (2) an increase of at least 15% in the land where natural processes predominate

(FABLE 2022; Jacobson *et al* 2019) by 2050 with a milestone of 5% increase in 2030 (CBD 2021); and (3) at maximum 1.5 °C of global warming by the end of the century (Paris Climate Agreement 2015) that we translate as greenhouse gas (GHG) emissions from agriculture below 4 GtCO₂e yr⁻¹ and negative net emissions from land use and land use change (Popp *et al* 2017, Rogelj *et al* 2018, Huppmann *et al* 2018, Riahi *et al* 2021). The fourth target is the food security target that every country and region should try to meet based on both domestic production and imports (SDG2).

- Step 2 The FABLE Consortium members agree on the broad narratives for the national and regional pathways. We compare the outcomes of two pathways: a *Current Trends* (CTs) pathway that depicts a low ambition of feasible action towards environmental sustainability with a future strongly dependent on current policy and historical trends, and a *Sustainable* pathway that corresponds to a stronger national political action toward the achievement of global sustainability targets.
- Step 3 National quantitative pathways are developed independently by local research teams, and regional quantitative pathways are developed by the FABLE Secretariat. In this analysis, the FABLE Calculator is used for 19 countries and 6 rest-of-the-world regions, and the MAgPIE model is used for India (cf section 2.2).
- Step 4 Key input and output data from national and regional models and narratives describing modelled pathways are submitted through an online platform using a standard reporting template (cf SI). This ensures the comparability of the results across countries and allows for aggregating results at the global level. The online platform and computational environment of the Scenathon is called the Linker tool.
- Step 5 The global database is compiled after the backend applications of the online portal automatically compute a set of review quality processes, e.g. on tables structure and number format.
- Step 6 Export quantities from each exporter are proportionally adjusted to match global imports for each product and each time step, i.e. if total imports are 30% lower than total exports, assumed exports from all countries and regions are decreased by 30% (cf SI). This means that the evolution of total trade volume is driven by countries' and regions' assumptions about the evolution of the internal demand for each product,



while the market share by each exporter does not account for changes in the international competitiveness of different countries, i.e. it only depends on initial assumptions on export quantities by country teams and regions. We use the historical imbalance for each product in 2010 according to FAOSTAT as the minimum threshold to start to correct trade imbalances in the future.

Step 7 National and regional pathways are re-computed with the same assumptions as in step 1 using newly adjusted export quantities, i.e. trade becomes exogenous in the national and regional models and updated pathways are reviewed by local researchers. As in steps 4 and 5, reporting templates and the global database are updated after the trade adjustment.

Step 8 Results on each global target are displayed on an online dashboard (Scenathon.org) and depending on the gap between the computed target indicators and the global targets after trade adjustment, the FABLE Consortium members decide if another cycle of national-global interactions should be launched.

2.2. National models and pathways

Both the FABLE Calculator and MAGPIE focus on agriculture as the main driver of land use and land use change and rely on the assumption of equilibrium between demand and supply quantities in each region and country for each commodity and each time step. Their main outputs are the harvested area, production of crops and animal-based commodities, consumption and trade quantities for different agricultural products, and conversion and expansion of different land cover types. The main difference

is that MAGPIE’s solution is obtained through economic optimization with the minimization of global costs, prices are endogenous, and it is a global model. In the FABLE Calculator, there is no optimization: the production is derived from an exogenous demand minus imports plus exports with a feedback loop that can reduce targeted domestic consumption and exports if there is not enough land available (cf table 1; SI). The FABLE Calculator is an open tool and can be downloaded (cf. Data availability statement). The code of the MAGPIE model is available on GitHub.

The adaptation of the model to fit the local contexts varies across countries but encompasses: (1) the replacement of the input data from global datasets (table 1) with country datasets, e.g. land cover map in the UK (Smith *et al* 2022b) and Australia (Navarro Garcia *et al* 2022), (2) the implementation of new features, e.g. representation of locally important crops such as teff, a cereal used as a staple food in Ethiopia (Molla and Woldeyes 2020), the distinction of forests on mineral and organic land in Indonesia (Fuad *et al* 2020), (3) the calibration of key parameters to align model’s results with historical statistics over 2000–2015, e.g. Brazil for historical deforestation (Costa *et al* 2020), China for changes in animal feed requirements (Jin *et al* 2020), (4) the improvement of the scenarios to better represent domestic policies or policy ambitions, e.g. bioenergy policy in the USA (Wu *et al* 2022) and India (Jha *et al* 2022) and reforestation commitments in Mexico (González-Abraham *et al* 2022).

2.3. Scenarios

Figure 2 provides an overview of some key assumptions made by each country for the CTs and the Sustainable (SUST) pathways for food and land use

Table 1. Overview of the main characteristics of the FABLE Calculator and the MAGPIE model.

	FABLE calculator	MAGPIE
FABLE countries/regions using this model in this study	Argentina, Australia, Brazil, Canada, China, Colombia, Ethiopia, Finland, Germany, Indonesia, Malaysia, Mexico, Norway, Russia, Rwanda, South Africa, Sweden, United Kingdom, United States, Rest of Asia and Pacific (ASP), Rest of Central and South America (CSA), Rest of European Union (ROEU), Rest of Europe non EU27 (NEU), Rest of North Africa, Middle East and Central Asia (NMC), Rest of Sub-Saharan Africa (SSA)	India (<i>MAGPIE is a global model solved for 12 regions in this exercise -but results are only used for India</i>)
Model type	Agricultural and land use accounting model	Agricultural and land use sector equilibrium economic model
Objective function	No objective function (no optimization)	Minimization of global production costs (large-scale nonlinear optimization) (Costs include agriculture production, land use change, yield-increasing technology, transport, trade, processing, irrigation expansion, and GHG emissions abatement costs in case of mitigation policy)
Software	Microsoft Excel	Written in R and GAMS ; Solved in GAMS using the CONOPT solver
Main constraints	<p>National or regional market balance: Food + Food waste + Feed + Process + Bioenergy + Other Non-Food = Production—Losses—Imports + Exports</p> <p>Cropland balance: $\sum_{i=1}^N \text{planted area crop}_i = \text{cropland area}$</p> <p>Land balance: Cropland + pasture + primary forest + secondary forest + other land area + urban area = total land area (fixed)</p> <p>Other land balances: harvested area crop_i / harvesting intensity = planted area crop_i ruminant number × ruminant density per ha = pasture area</p>	<p>Global market balance: Global supply ≥ Global demand</p> <p>Other land balance: pasture area × pasture yield = animal product × feed basket for pasture</p> <p>Water balance: Water availability = irrigated area × water requirements × irrigation efficiency + livestock production × water requirements</p>
Model outputs	Harvested area by crop, Area by land cover class, Land use change (incl. deforestation), GHG emissions, Kilocalorie consumption per capita, Blue water use, Net trade with the rest of the world per product, Land where natural processes predominate (LNPP)	
	Planted area by crop (1000 ha), Number of livestock units (1000 TLUs)	Irrigated and rainfed crop specific area (1000 ha), Crop Prices in USD of 2005 Market Exchange Rate, per ton of dry matter
Products	<p>Crops: abaca, apple, banana, barley, beans, cassava, other cereals, other citrus, clove, cocoa, coconut, coffee, corn, cotton, date, other fruits, grape, grapefruit, groundnut, jute, lemon, millet, nuts, oats, oil palm fruit, other oilseeds, olive, onion, orange, peas, pepper, piment, pineapple, plantain, potato, other pulses, rapeseed, rice, rubber, rye, sesame, sisal, sorghum, soyabean, other spices, sugar beet, sugarcane, sunflower, sweet potato, tea, tobacco, tomato, other tubers, other vegetables, wheat, yams</p> <p>Processed products: cotton lint, vegetable oils (11 types), oilseed cakes (7 types), sugar raw</p> <p>Livestock products: chicken, eggs, milk, pork, mutton-goat, pork, beef, other meat</p> <p>Bioenergy: first generation biofuels</p>	<p>Crops: Temperate cereals (wheat), maize, tropical cereals (sorghum, millet), rice, soy, rapeseed, groundnut, sunflower, pulses, potato, cassava, sugar cane, sugar beet fruits and vegetables, cotton</p> <p>Processed products: oils, oilcakes, sugar, molasses, alcohol, ethanol, grain distillers, brans, single cell protein, fibers</p> <p>Livestock products: ruminant meat, pork, chicken, eggs, milk, fish</p> <p>Bioenergy: first generation bioenergy, second generation bioenergy (bioenergy grasses, bioenergy trees)</p> <p>Feed roughage: fodder, grass</p>

(Continued.)

Table 1. (Continued.)

	FABLE calculator	MAGPIE
Scenario parameters	Population, diets, biofuel use, food waste at the consumer level, livestock and crop productivity, agricultural land expansion restrictions including protected areas, afforestation, climate change impacts on crops	
	Share of domestic consumption that is imported, export quantity, share of the production lost during storage and transportation (i.e. post-harvest losses), ruminant density per hectare of pasture	GDP, nitrogen use efficiency, irrigation of bioenergy crops, protection of environmental flows, animal waste management systems, GHG price

Note: the main model inputs and sources are listed in the SI.

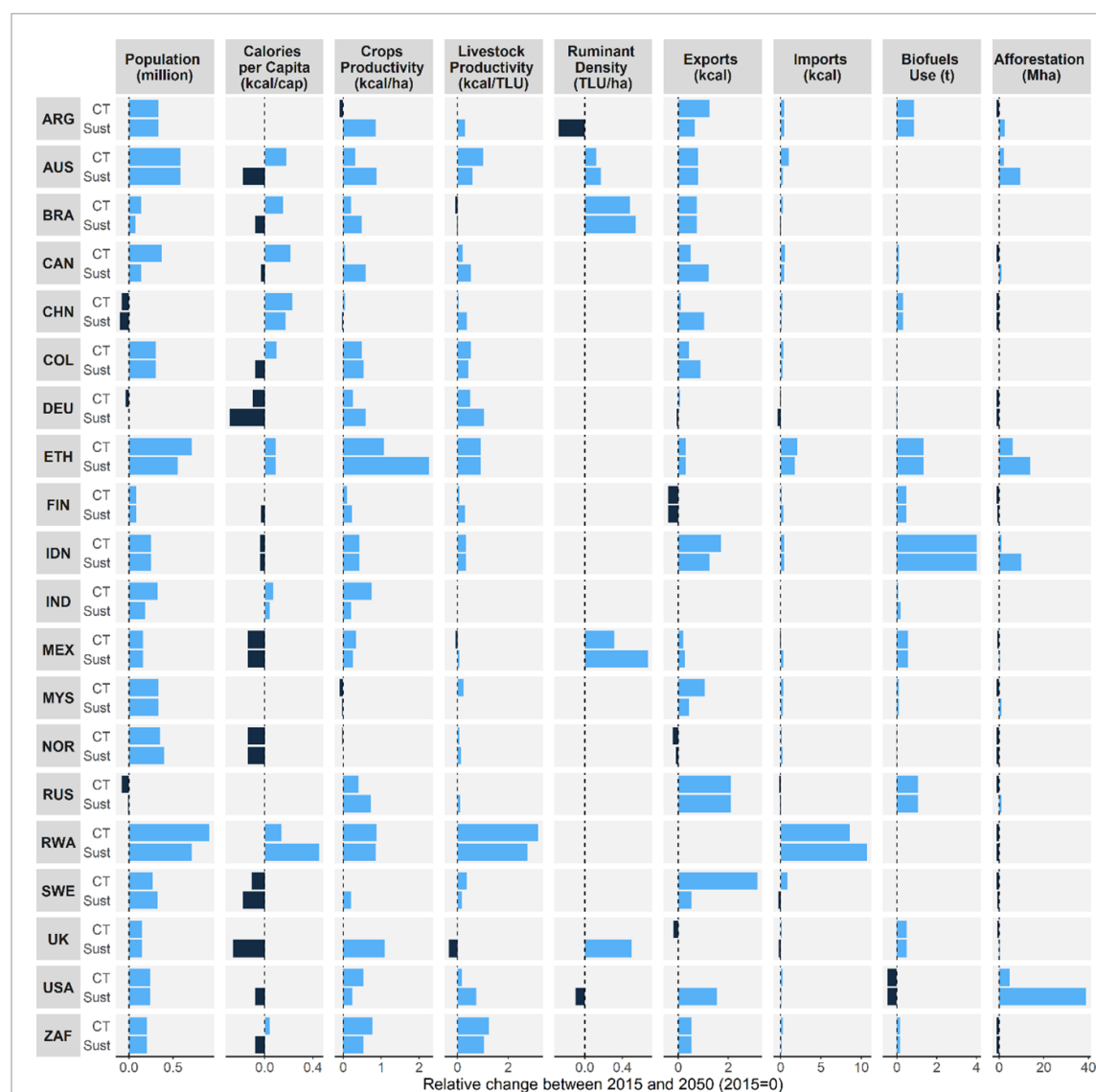


Figure 2. Overview of scenarios by FABLE countries and for the rest of the world regions for the current trends and sustainable pathways before trade adjustment.

Notes: CT: Current Trends. Sust: Sustainable. ARG: Argentina; AUS: Australia; BRA: Brazil; CAN: Canada; CHN: China; COL: Colombia; DEU: Germany; ETH: Ethiopia; FIN: Finland; IDN: Indonesia; IND: India; MEX: Mexico; MYS: Malaysia; NOR: Norway; RUS: Russia; RWA: Rwanda; SWE: Sweden; UK: United Kingdom; USA: United States of America; ZAF: South Africa. Assumptions for the Rest of the world regions are available in SI. Crop productivity is measured in average kilocalorie output per hectare of cropland and livestock productivity is measured in average kilocalories per Tropical Livestock Unit (TLU—one unit is equivalent to 250 kg animal weight). Ruminant density is measured in TLU per hectare of pasture. Exports and imports are measured in kilocalories to aggregate all commodities. Afforestation is measured in change in million hectares between 2015 and 2050. For many countries and regions, the afforestation target has been set using Bonn Challenge commitments that end in 2030.

systems, before the implementation of the corrected export quantities to match global imports (cf section 2.1, Steps 6 and 7). These assumptions typically come from local researchers' expertise, consultation with local stakeholders, desk review of existing policies, historical trends, and publicly available projections. For the rest of the world regions, assumptions are made by the FABLE Secretariat (cf SI).

For instance, ambitions regarding diets differ a lot between countries. Fifteen countries have assumed the adoption of healthier diets in the *Sustainable* pathway compared to *CTs*. National dietary recommendations have been used by the US team (U.S. Department of Health and Human Services & U.S. Department of Agriculture, 2015) and the UK team (Scarborough *et al* 2016). The Norway, Sweden, and Finland teams have based their scenarios on reports from the Norwegian Institute of Bioeconomy Research, the Nordic Council of Ministers (Karlsson *et al* 2018), and the Finland Government Research Publication Series (Saarinen *et al* 2019) respectively. The German, Mexican, Chinese, and Rwandan teams have used a combination of estimates from experts, and national and international recommendations. In other countries, the recommended diet by the EAT-Lancet Commission has been used (Willett *et al* 2019). When summed up to the global level, the total and the animal-sourced foods (excluding fish) calorie per capita consumption increase by 6% and 42% respectively in the *CT* pathway but decrease by 4% and 15% in the *SUST* pathway by 2050 compared to the 2015 level.

In most countries, productivity gains are considered a means to achieve higher sustainability. Exceptions include Argentina and the US which assume a moderate reduction in ruminant density because lower grazing intensity is considered more sustainable. In the FABLE Calculator, the assumption on future productivity growth mainly depends on historical trends per commodity. For crop productivity in the rest of the world regions, we set upper yield limits to maximum yield potential in 2050 (Grassini and van Ittersum 2020). In the MAgPIE model, productivity change is endogenous and results in additional costs. In addition, we draw on the inter-sectoral impact model intercomparison project (Warszawski *et al* 2014, Frieler *et al* 2017) to include climate change impacts on crop yields and water requirements for corn, rice, soy and wheat. We assume a global GHG concentration trajectory that would lead to a global mean warming increase likely between 2 °C and 3 °C above pre-industrial temperatures by 2100 (RCP 6.0) in the *CTs* pathway and a global GHG concentration trajectory that aims to keep global warming likely below 2 °C above pre-industrial temperatures by 2100 (RCP 2.6) (van Vuuren *et al* 2011) in the *Sustainable* pathway. When summed up to the global level, this results in a 0.85% annual compound average productivity increase expressed in kcal per ha of cropland

in *CT* and 0.88% in the *Sustainable* pathway which is lower than the 1.7% growth observed between 1990 and 2010. Further work will be needed to review our productivity projections for all products (Rattalino Edreira *et al* 2021, van Ittersum *et al* 2016) and make a better link with input requirements.

3. Results

3.1. Achievement of the global targets

In the *CTs* pathway the food security target and the target related to land emissions are met while in the *Sustainable* pathway, nearly all targets are met (figure 3).

Sustainable pathway—The surplus between the average per capita consumption and the minimum daily energy requirement (MDER) reduces on average but still increases in low-income countries, pointing to a reduction in overconsumption in high and middle-income countries (figure 3(c)). The global net forest cover change stays positive from 2020 onwards, peaking at 7 Mha per year in 2025 before flattening out at 4 Mha per year in 2050 (figure 3(d)). This is partly explained by our afforestation scenario being based on the Bonn Challenge pledges that end in 2030 for many countries and regions. Increases in afforestation compared to the *CT* pathway mostly come from the US, Australia, Ethiopia, and India. The only region to experience an increase in deforestation in the *Sustainable* pathway compared to *CT* is the rest of the Sub-Saharan Africa region. This is due to higher per capita calorie consumption and large-scale afforestation. Afforestation takes place on agricultural land and other natural non-forest land that indirectly leads to a higher encroachment of agricultural land to forests. Global GHG emissions are negative for land (−3.2 GtGO₂) and limited to 3.8 GtCO₂e for agriculture by 2050 leading to total net emissions from agriculture and land close to zero in 2050 (figure 3(a)). This amounts to total savings of 150 GtCO₂e over 2020–2050 compared to *CT*, mainly through the reduction of emissions related to livestock production (due to lower global demand for animal-based products) and increased sequestration on land through natural vegetation regrowth on abandoned agricultural land and planned afforestation. Carbon sequestration in managed forests is excluded from this analysis (cf SI). The land where natural processes predominate increases by 12.5% in 2050 compared with 2010 levels (figure 3(b)) (FABLE 2022), also driven by higher afforestation and abandoned agricultural land. Assumed dietary shifts and productivity improvement play a key role in achieving our global sustainability targets in the *Sustainable* pathway. By 2050, only dietary shifts achieve 60% of the AFOLU emissions reduction between the *Sustainable* and *CT* pathways, and only productivity shifts achieve 19% of this reduction.

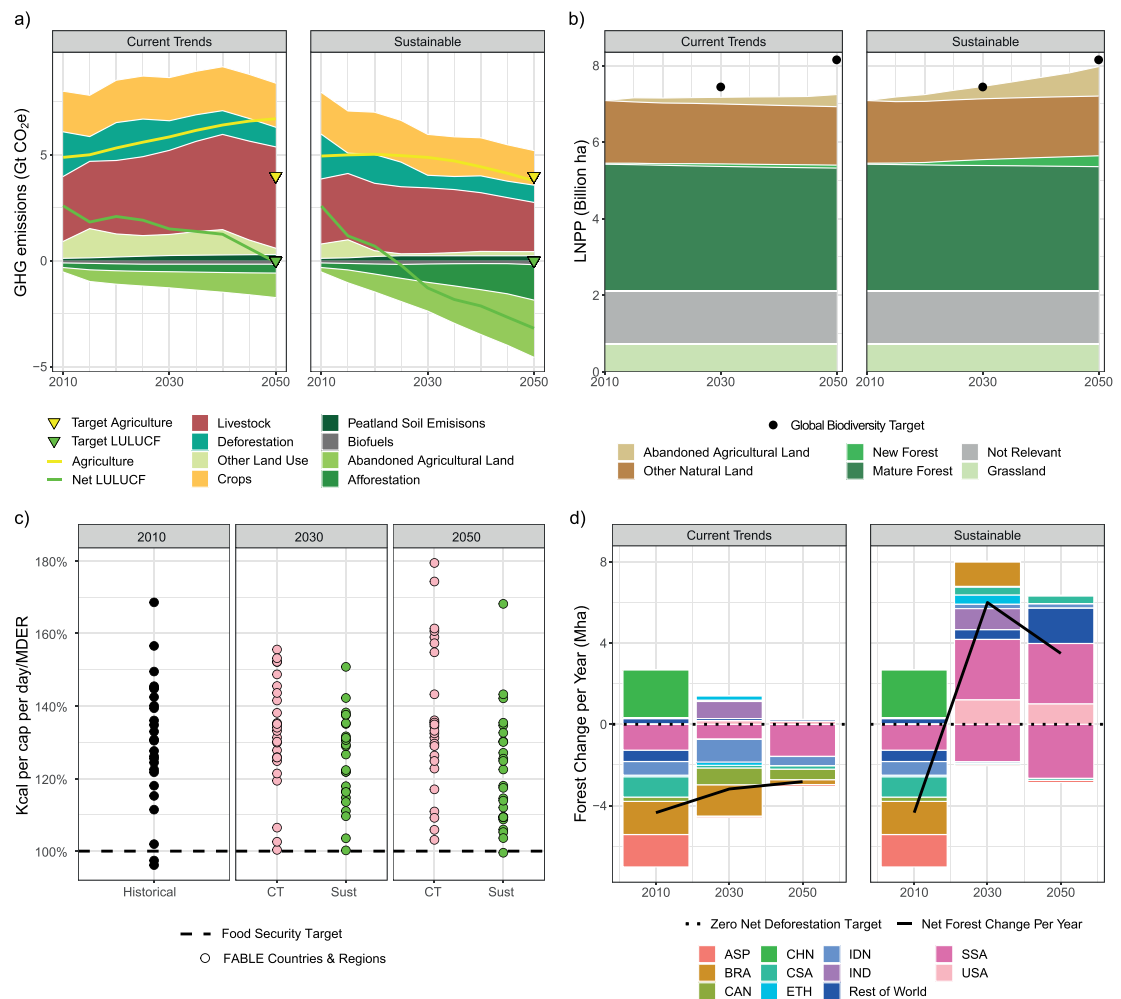


Figure 3. Comparison of the global targets under the current trends and sustainable pathways by 2030 and 2050 after global trade adjustment.

Note: (b) The biodiversity indicator is the land where natural processes predominate (LNPP). It refers to land where there is a low human disturbance and/or ecologically relatively intact vegetation, providing space and habitat for biodiversity to thrive (FABLE 2022) (c) The average daily kilocalorie consumption per capita excludes food waste at the household level. MDER: average minimum daily energy requirement per country and region. (d) BRA—Brazil, CAN—Canada, CHN—China, ETH—Ethiopia, IDN—Indonesia, IND—India, ASP—Asia and Pacific, CSA—Central and South America, SSA—Sub-Saharan Africa, RoW—Rest of the World. Countries and regions can simultaneously have gains and losses in the forest area that are shown separately in the figure.

Our results for global emissions from agriculture and land use change are comparable to results from global IAMs but in the lower range (Huppmann *et al* 2018, Frank *et al* 2019). If we isolate the impacts of dietary shifts, we find a 31% reduction in global AFOLU emissions by 2050 compared to CTs. This is close to the 25% average reduction of GHG emissions associated with sustainable diets reported in the literature (Jarmul *et al* 2020). Our biodiversity impacts under CTs are more optimistic than (Leclère *et al* 2020), while our estimates of how soon biodiversity decline could be reversed by implementing ambitious actions are comparable. One reason for these more optimistic results compared to the literature could be the assumptions on carbon stock growth and biodiversity recovery on agricultural land when it is no longer needed in the FABLE Calculator. The representation of more precise land dynamics after

agricultural abandonment will help to reflect the variable quality of the semi-natural landscapes in the future (Fayet *et al* 2022).

3.2. National policies that have large impacts on our global results

Some policies have a large potential to help achieve both national and global targets. We take here the example of the dietary shift assumed in the U.S. in the *Sustainable* pathway (cf section 2.3) (Wu *et al* 2022). Compared to diets in CT, which are unchanged from today, the sustainable dietary shift is characterized by a large increase in per capita consumption of fruits and vegetables, pulses, nuts, roots, and fish, a small increase in cereals and dairy consumption, and a large reduction in meat, eggs, sugar, and oil and fat consumption. This would reduce the surplus

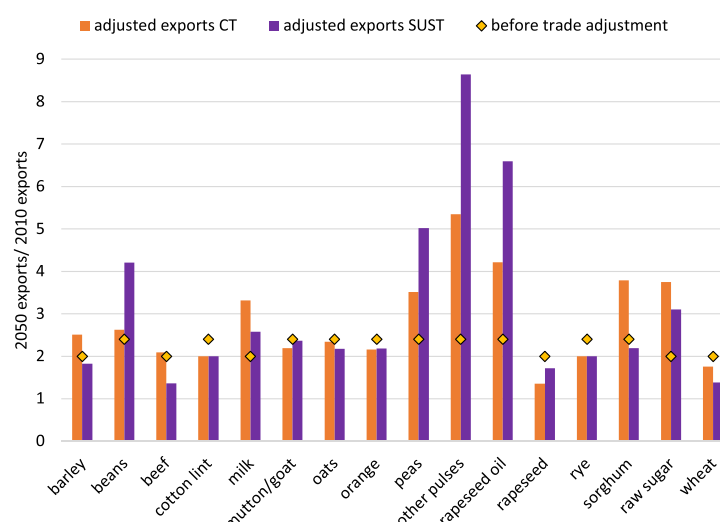


Figure 4. Impact of trade adjustment on Australian exports for key commodities.

of average calorie intake per capita compared to the average MDER from 35% to 23% in 2050.

Here we isolate the impacts of this single policy on our global results, i.e. maintaining all the other assumptions in the U.S. and in the rest of the world the same as in the *CT* pathway, and comparing results with the *CT* pathway. If U.S. external trade would not adjust after this dietary shift, the land where natural processes predominate would increase by 109 Mha, annual GHG emissions from agriculture would be reduced by 106 MtCO₂e (−38%), and the U.S. would shift from net positive to net negative GHG emissions from agriculture and land use change in 2050 following the high reduction in beef production. However, if part of the reduction in domestic demand will be offset by higher exports, domestic beef production would not reduce so dramatically and important spillovers could be expected in other countries. We estimate that the reduction of national meat consumption in the US would ‘free’ domestic production equivalent to 2/3 of global exports of beef and pork, 50% of global exports of corn, and 43% of global exports of chicken in 2050 in *CT*. In the *Sustainable* pathway, the US team assumed that only a portion of the reduced consumption was assumed to be offset by higher exports: 22% for beef, 50% for pork, and 74% for chicken by 2050. Even these amounts, however, had large impacts on the other meat-exporting countries (section 3.3).

There is significant disagreement in the literature about whether the Dietary Guidelines for Americans have lower GHG emissions than the average American diet today (Reinhardt *et al* 2020). Impacts range from a 23% decrease to a 7% increase with environmentally extended input-output modelling approaches finding higher carbon emissions reduction (Behrens *et al* 2017, Hitaj *et al* 2019).

3.3. National results that significantly change after the implementation of the global trade balance constraint

We take here the example of the impacts of trade adjustment on Australia. In 2019, Australia ranked second, third, and fourth in total world exports of sheep, beef, and wheat, respectively and an important domestic target is to strengthen this position in international markets (National Farmers Federation 2020, DAWE 2021). When trade is computed without interactions between national and global scales, i.e. before trade adjustment, assumptions by the Australian team are aligned with this objective with increased export quantities for key products between 100% and 140% from 2010 to 2050 (Navarro Garcia *et al* 2022). However, after the assumptions on consumption and trade from other countries and regions are considered, i.e. after trade adjustment, this leads to more heterogeneous relative changes in exports across commodities and pathways. Beans, peas, other pulses, rapeseed oil, and sugar Australian exports are higher after trade adjustment in both pathways while cereals exports are lower after trade adjustment in the *Sustainable* pathway due to lower international demand for animal feed (figure 4). This adjustment of Australian exports to the world demand leads to a 10% increase in domestic annual GHG emissions from agriculture in the *CTs* pathway. But in the *Sustainable* pathway, trade adjustment leads to a 25% reduction in domestic annual GHG emissions from agriculture and a 10% increase in the land carbon sink.

These results are consistent with the export-oriented focus of the Australian food production sector and with analysis showing the sector’s dependency on changes in policy and dietary patterns in main trading partners (Wickes *et al* 2021, Zhao *et al*

2021). Industry data shows that the biggest trade effect on future Australian beef production hinges on dietary changes within partners where Australia exports high volumes of beef and enjoys a large percentage of market share (Japan, USA, Korea) and on dietary change and population growth in South East Asia where Australia has some moderate-high market shares (Indonesia, Philippines, Malaysia) (MLA 2020). Future emergence of livestock diseases like the recent African Swine Fever (Mason-D'Croz *et al* 2020) might also impact trade with these countries in the future.

4. Discussion

This paper describes how we have developed and applied a decentralized modelling approach to explore pathways for achieving both national and global objectives within the FABLE initiative. The first results for 20 national mid-century pathways of the food and land use systems and a bottom-up global pathway were available in a relatively short period (2 years) and the obtained global results were in the range of results published in the literature (cf section 3) but based on more heterogeneous assumptions across countries. In some countries, good collaboration with decision-makers has already been established (González-Abraham *et al* 2022, Smith *et al* 2022a). These models can be easily deployed in more countries in the future and combined with other tools, for instance, open spatially explicit land dynamics models, to support finer-scale land use planning (Verburg and Overmars 2009, Frank *et al* 2022).

Our projections of future international trade rely on the individual assumptions of researchers based in many countries. This is quite unique because it provides information that would not be accessible to local researchers otherwise, e.g. how the trade forecasts in a large exporting country intersect with the forecasts of all its main trading partners. In comparison to existing global models, this allows a more dynamic computation of trade and a deeper mutual understanding and appreciation of the perceived national constraints and opportunities in other countries. Exchanges between researchers from local research institutes in different countries may help to open new solution spaces that may be overlooked by more top-down approaches.

However, compared to the dominant approach for ex-ante assessments of agriculture and land use sustainability using global models, our approach faces several challenges. Our decentralized approach requires more coordination efforts with the involvement of about 80 researchers based in different countries, e.g. to ensure timely submissions of all national and regional pathways, to ensure model updates and corrections have been included in national models, to apply trade adjustment, etc. However, coordination

efforts during the Scenathons have reduced over time thanks to more effective processes, progress in our web infrastructure, automatization through the development of dedicated APIs (cf SI), and tool maturation (the FABLE Calculator was created in 2018). We are now confident that more countries can be included in a Scenathon without a significant increase in the coordination efforts.

To ensure consistent trade, researchers need to replace their trade assumptions with adjusted trade quantities. This requires trust across modelling teams since the international adjustment depends on the demand and trade projections from the other country teams and the rest of the world regions. We have developed automatic reports to help identify potential weaknesses or mistakes in national and regional models, i.e. highlighting land and market imbalances and differences between the model's outputs and benchmark values from other sources, that could be used in the future to give more weight to trade quantities submitted by some countries compared to others during the trade adjustment process. Currently, our method to reconcile total imports and total exports ignores economic competitiveness and historical trade relationships. Testing new trade adjustment methods that can take this into account and compute bilateral trade flows is an important axis of development for FABLE.

Finally, connecting heterogeneous national and regional models to reconcile trade and derive a global pathway can be challenging. Since the standard reporting template has been built based on the FABLE Calculator inputs and outputs, some post-processing of MAGPIE's inputs and outputs was required to fit the same template, e.g. to disaggregate results from product groups to single products. Another challenge is to ensure that countries' submissions do not rely on incompatible visions of the state of the world that affects all countries. For instance, we harmonized future climate change assumptions but we refrained from using similar assumptions regarding the evolution of population and Gross Domestic Product (GDP) per capita as is the case in the shared socioeconomic pathways (O'Neill *et al* 2013). Finally, connecting models of different natures can be a challenge.

5. Conclusion

The novelty of this work is the integration of national and global scales through a decentralized approach. This approach relies on a large network of researchers from local research institutes, the collaboration with established modeling teams such as the MAGPIE team, and the development of dedicated tools by the FABLE Secretariat. A national FABLE Calculator can be rapidly transferred to local researchers if necessary to produce mid-century quantitative pathways for the food and land systems for their country. Interactions between national and global scales are

ensured by the Scenathon method and infrastructure. Here we have presented our methodology and some of our results on the achievement of a small set of global sustainability targets. We have also illustrated how the global linkage impacts national results with the example of Australia and how domestic changes can impact global results with the example of the US dietary shift.

Future research will focus on strengthening our modeling tools to support in-country policy processes. Improvements include, for instance, coupling different (open) models to better connect sub-national scale and represent more diverse ecosystem services, improving projections of productivity change in relation to agricultural practices and technological development, and integrating more socio-economic indicators in our pathways. International trade will be an important area of development, e.g. testing different approaches for ensuring the balance between global imports and exports and tracking bilateral trade flows.

To conclude, FABLE is a unique modeling setup that acknowledges the broad heterogeneity of socio-ecological contexts and the fact that people who live in these different contexts should be empowered to design the future they want. It also demonstrates the interconnectedness of our food and land use system and the urgent need for more collaboration and coordination to converge local and global priorities.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.scenathon.org/. The open FABLE Calculator can be downloaded at the following URL: www.abstract-landscapes.com/fable-calculator.

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References

- Aguiar A P D, Collste D, Harmáčková Z V, Pereira L, Selomane O, Galafassi D, Van Vuuren D and Van Der Leeuw S 2020 Co-designing global target-seeking scenarios: a cross-scale participatory process for capturing multiple perspectives on pathways to sustainability *Glob. Environ. Change* **65** 102198
- Arnell A, Barbosa H, Benton T, Calvin K, Calvo E, Connors S, Cowie A and Zommers Z 2019 Climate Change and Land. IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (Intergovernmental Panel on Climate Change)
- Beach R H *et al* 2015 Climate change impacts on US agriculture and forestry: benefits of global climate stabilization *Environ. Res. Lett.* **10** 095004
- Behrens P, Kiefte-de Jong J C, Bosker T, Rodrigues J F D, de Koning A and Tukker A 2017 Evaluating the environmental impacts of dietary recommendations *Proc. Natl Acad. Sci.* **114** 201711889
- BirdLife International 2019 Digital boundaries of important bird and biodiversity areas from the world database of key biodiversity areas. February 2019 version (available at: <http://datazone.birdlife.org/site/requestgis>)
- Bouwman L, Goldewijk K K, Van Der Hoek K W, Beusen A H W, Van Vuuren D P, Willems J, Rufino M C and Stehfest E 2013 Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period *Proc. Natl Acad. Sci.* **110** 20882–7
- Buyse J, Van Huylenbroeck G and Lauwers L 2007 Normative, positive and econometric mathematical programming as tools for incorporation of multifunctionality in agricultural policy modelling *Agric. Ecosyst. Environ.* **120** 70–81
- Caron P *et al* 2018 Food systems for sustainable development: proposals for a profound four-part transformation *Agron. Sustain. Dev.* **38** 41
- CBD 2021 First draft of the post-2020 global biodiversity framework *CBD/WG2020/3/3* (available at: www.cbd.int/doc/c/914a/eca3/24ad42235033f031badf61b1/wg2020-03-03-en.pdf)
- Costa W, Scarabello M, Soterroni A C and Ramos F 2020 Pathways to sustainable land-use and food systems in Brazil by 2050 *FABLE 2020, Pathways to Sustainable Land-Use and Food Systems* pp 130–60
- DAWE 2021 *Delivering Ag2030* (Australian Government: Department of Agriculture Water and the Environment) (available at: www.awe.gov.au/agriculture-land/farm-food-drought/ag2030)
- Dietrich J P *et al* 2019 MAgPIE 4—a modular open-source framework for modeling global land systems *Geosci. Model Dev.* **12** 1299–317
- Ewert F *et al* 2009 A methodology for enhanced flexibility of integrated assessment in agriculture *Environ. Sci. Policy* **12** 546–61
- FABLE 2022 Pathways for food and land systems to contribute to global biodiversity conservation *FABLE Policy Brief* (Bioversity International and SDSN)

- Fayet C M J, Reilly K H, Van Ham C and Verburg P H 2022 What is the future of abandoned agricultural lands? A systematic review of alternative trajectories in Europe *Land Use Policy* **112** 105833
- Flichman G and Allen T 2014 Bio-economic modeling: state-of-the-art and key priorities *Project paper* (International Food Policy Research Institute (IFPRI)) p 34 (available at: www.ifpri.org/publication/bio-economic-modeling-state-art-and-key-priorities)
- Frank F et al 2022 A multi-model approach to explore sustainable food and land use pathways for Argentina *Sustain. Sci.* **18** 347–69
- Frank S et al 2019 Agricultural non-CO₂ emission reduction potential in the context of the 1.5 °C target *Nat. Clim. Change* **9** 66
- Friedlingstein P et al 2022 Global carbon budget 2021 *Earth Syst. Sci. Data* **14** 1917–2005
- Frieler K, Lange S, Piontek F, Reyer C P, Schewe J, Warszawski L, Zhao F, Chini L, Denvil S and Emanuel K 2017 Assessing the impacts of 1.5 °C global warming—simulation protocol of the inter-sectoral impact model intercomparison project (ISIMIP2b) *Geosci. Model Dev.* **10** 4321–45
- Fuad H A H, Winarni N L, Mumbunan S, Supriatna J, Khasanah N, Boer R, Immanuel G, Anggraeni L and Rosita A 2020 Pathways to sustainable land-use and food systems in Indonesia by 2050: FABLE 2020 *2020 Report of the FABLE Consortium* (Pathways to Sustainable Land-Use and Food Systems) pp 386–416
- González-Abraham C, Flores-Santana C, Rodríguez-Ramírez S, Olguín-Álvarez M, Flores-Martínez A, Torres Rojo J M, Bocco Verdinelli G, Fernández Calleros C A and McCord G C 2022 Long-term pathways analysis to assess the feasibility of sustainable land-use and food systems in Mexico *Sustain. Sci.* **18** 469–84
- Grassini P and van Ittersum M K 2020 Global yield gap and water productivity atlas (available at: www.yieldgap.org/web/guest/yieldgaps)
- Havlik P et al 2014 Climate change mitigation through livestock system transitions *Proc. Natl Acad. Sci.* **111** 3709
- Hertel T W, West T A P, Börner J and Villoria N B 2019 A review of global-local-global linkages in economic land-use/cover change models *Environ. Res. Lett.* **14** 053003
- Hitaj C, Rehkamp S, Canning P and Peters C J 2019 Greenhouse gas emissions in the United States food system: current and healthy diet scenarios *Environ. Sci. Technol.* **53** 5493–503
- Huppmann D, Rogelj J, Kriegler E, Krey V and Riahi K 2018 A new scenario resource for integrated 1.5 °C research *Nat. Clim. Change* **8** 1027–30
- IPBES 2019 *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* ed E S Brondizio, J Settele, S Díaz and H T Ngo (Bonn: IPBES Secretariat) (available at: www.ipbes.net/global-assessment-report-biodiversity-ecosystem-services)
- Jacobson A P, Riggio J, M Tait A and E M Baillie J 2019 Global areas of low human impact ('Low Impact Areas') and fragmentation of the natural world *Sci. Rep.* **9** 14179
- Jang J, McSparren J and Rashchupkina Y 2016 Global governance: present and future *Palgrave Commun.* **2** 15045
- Janssen S and van Ittersum M K 2007 Assessing farm innovations and responses to policies: a review of bio-economic farm models *Agric. Syst.* **94** 622–36
- Jarmul S, Dangour A D, Green R, Liew Z, Haines A and Scheelbeek P F D 2020 Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of 'sustainable diets' *Environ. Res. Lett.* **15** 123014
- Jha C K, Singh V, Stevanović M, Dietrich J P, Mosnier A, Weindl I, Popp A, Traub G S, Ghosh R K and Lotze-Campen H 2022 The role of food and land use systems in achieving India's sustainability targets *Environ. Res. Lett.* **17** 074022
- Jin X, Bai Z, Zhao H, Wang X, Chang J, Hua F and Ma L 2020 Pathways to sustainable land-use and food systems in China by 2050 *FABLE 2020, Pathways to Sustainable Land- Use and Food Systems* pp 195–229
- Karlsson J O, Carlsson G, Lindberg M, Sjunnestrand T and Rööfs E 2018 Designing a future food vision for the Nordics through a participatory modeling approach *Agron. Sustain. Dev.* **38** 59
- Kremmydas D, Athanasiadis I N and Rozakis S 2018 A review of agent based modeling for agricultural policy evaluation *Agric. Syst.* **164** 95–106
- Leclère D, Obersteiner M, Barrett M, Butchart S H M, Chaudhary A, De Palma A, DeClerck F A J, Di Marco M, Doelman J C and Dürauer M 2020 Bending the curve of terrestrial biodiversity needs an integrated strategy *Nature* **585** 551–6
- Mason-D'Croz D, Bogard J R, Herrero M, Robinson S, Sulser T B, Wiebe K, Willenbockel D and Godfray H C J 2020 Modelling the global economic consequences of a major African swine fever outbreak in China *Nat. Food* **1** 221–8
- MLA 2020 *Global Beef Snapshot* (Meat and Livestock Australia) (available at: www.mla.com.au/globalassets/mla-corporate/prices-markets/documents/os-markets/red-meat-market-snapshots/2020/global-beef-snapshot-jan2020.pdf)
- Molla K G and Woldeyes F B 2020 Pathways to sustainable land-use and food systems in Ethiopia by 2050: FABLE 2020 *2020 Report of the FABLE Consortium* (Pathways to Sustainable Land-Use and Food Systems) pp 262–91
- Mosnier A et al 2022 How can diverse national food and land-use priorities be reconciled with global sustainability targets? Lessons from the FABLE initiative *Sustain. Sci.* **18** 335–45
- Mosnier A, Penescu L, Perez-Guzman K, Steinhäuser J, Thomson M, Douzal C and Poncet J 2020 *FABLE Calculator Documentation- 2020 Update* (Paris: IIASA (Laxenburg) and SDSN)
- National Farmers Federation 2020 Australian Agriculture's Plan for a \$100 Billion Industry *2030 Roadmap* (available at: https://nff.org.au/wp-content/uploads/2020/02/NFF_Roadmap_2030_FINAL.pdf) (Accessed 17 May 2020)
- Navarro García J et al 2022 Multi-target scenario discovery to plan for sustainable food and land systems in Australia *Sustain. Sci.* **18** 371–88
- O'Neill B C et al 2017 The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century *Glob. Environ. Change* **42** 169–80
- O'Neill B C, Kriegler E, Riahi K, Ebi K L, Hallegatte S, Carter T R, Mathur R and Vuuren van D P 2013 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400
- OECD & FAO 2022 OECD-FAO agricultural outlook 2022–2031 (OECD) (<https://doi.org/10.1787/1b0b29c-en>)
- Pelikan J, Britz W and Hertel T W 2015 Green light for green agricultural policies? An analysis at regional and global scales *J. Agric. Econ.* **66** 1–19
- Pérez Domínguez I, Bezlepina I, Heckelet T, Romstad E, Lansink A O and Kanellopoulos A 2009 Capturing market impacts of farm level policies: a statistical extrapolation approach using biophysical characteristics and farm resources *Environ. Sci. Policy* **12** 588–600
- Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E, Bodirsky B L, Dietrich J P, Doelmann J C and Gusti M 2017 Land-use futures in the shared socio-economic pathways *Glob. Environ. Change* **42** 331–45
- Porter J R, Xie L, Challinor A J, Cochrane K, Howden S M, Iqbal M M, Lobell D B and Travasso M I 2014 Food security and food production systems. (7.2.1. Food Production Systems) *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed

- V R Barros *et al* (Cambridge: IPCC, Cambridge University Press) vol 1–Book p 485
- Rattalino Edreira J I, Andrade J F, Cassman K G, van Ittersum M K, van Loon M P and Grassini P 2021 Spatial frameworks for robust estimation of yield gaps *Nat Food* **2** 773–9
- Reinhardt S L, Boehm R, Blackstone N T, El-Abbadi N H, McNally Brandow J S, Taylor S F and DeLonge M S 2020 Systematic review of dietary patterns and sustainability in the United States *Adv. Nutr.* **11** 1016–31
- Riahi K *et al* 2021 Cost and attainability of meeting stringent climate targets without overshoot *Nat. Clim. Change* **11** 1063–9
- Rogelj J *et al* 2018 Scenarios towards limiting global mean temperature increase below 1.5 °C *Nat. Clim. Change* **8** 325–32
- Saarinen M, Knuuttila M, Lehtonen H, Niemi J, Regina K, Rikonen P, Varho V, Kaljonen M, Mattila T and Seppälä J 2019 Hallittu ruokavaliomuutos voisi tuoda ilmastohyötyjä, parantaa ravitsemusta ja säilyttää maatalouden Suomessa (Policy Brief) *Valtioneuvoston Selvitys- Ja Tutkimustoiminnan Artikkelisarja*, 2019 p 12
- Sachs J D, Schmidt-Traub G, Mazzucato M, Messner D, Nakicenovic N and Rockström J 2019 Six transformations to achieve the sustainable development goals *Nat. Sustain.* **2** 805–14
- Scarborough P, Kaur A, Cobiac L, Owens P, Parlesak A, Sweeney K and Rayner M 2016 Eatwell guide: modelling the dietary and cost implications of incorporating new sugar and fibre guidelines *BMJ Open* **6** e013182
- Smith A C, Harrison P A, Leach N J, Godfray H C J, Hall J W, Jones S M, Gall S S and Obersteiner M 2022b Sustainable pathways towards climate and biodiversity goals in the UK: the importance of managing land-use synergies and trade-offs *Sustain. Sci.* **18** 521–38
- Smith A, Leach N, Jones S and Harrison P A 2022a Environmental and rural affairs monitoring and modelling programme (ERAMMP) Report-72: application of the FABLE Calculator to model pathways to sustainable land use in Wales *Report to Welsh Government (Contract C210/2016/2017)* (UK Centre for Ecology & Hydrology Projects 06297 & 06810) (available at: <https://erammp.wales/en/fable>)
- Soterroni A C, Mosnier A, Carvalho A X, Câmara G, Obersteiner M, Andrade P R, Souza R C, Brock R, Pirker J and Kraxner F 2018 Future environmental and agricultural impacts of Brazil's forest code *Environ. Res. Lett.* **13** 074021
- U.S. Department of Health and Human Services, & U.S. Department of Agriculture 2015 *2015–2020 Dietary Guidelines for Americans* 8th edn (Washington, DC: U.S. Department of Health and Human Services) p 144 (available at: <http://health.gov/dietaryguidelines/2015/guidelines/>)
- van Ittersum M K *et al* 2016 Can sub-Saharan Africa feed itself? *Proc. Natl. Acad. Sci. USA* **113** 14964–9
- van Vuuren D P *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31
- Verburg P H and Overmars K P 2009 Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model *Landsc. Ecol.* **24** 1167
- Villoria N B, Golub A, Byerlee D and Stevenson J 2013 Will yield improvements on the forest frontier reduce greenhouse gas emissions? A global analysis of oil palm *Am. J. Agric. Econ.* **95** 1301–8
- Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O and Schewe J 2014 The inter-sectoral impact model intercomparison project (ISI-MIP): project framework *Proc. Natl Acad. Sci.* **111** 3228–32
- WCED 1987 *Our Common Future* The world commission on environment and development of the United Nations (available at: <https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf>)
- Wickes R, Adams M and Brown N 2021 Economic coercion by China: the impact on Australia's merchandise exports' (Institute for International Trade Working Paper)
- Willett W *et al* 2019 Food in the anthropocene: the eAT–lancet commission on healthy diets from sustainable food systems *Lancet* **393** 447–92
- Wu G C, Baker J S, Wade C M, McCord G C, Fargione J E and Havlik P 2022 Contributions of healthier diets and agricultural productivity toward sustainability and climate goals in the United States *Sustain. Sci.* **18** 539–56
- Zhao H *et al* 2021 China's future food demand and its implications for trade and environment *Nat. Sustain.* **4** 1042–51