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To cite this article: Aline Mosnier *et al* 2023 *Environ. Res. Lett.* **18** 045001

IOP Publishing
Environ. Res. Lett. **18** (2023) 045001
https://doi.org/10.1088/1748-9326/acc044

ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
12 September 2022

REVISED
27 February 2023

ACCEPTED FOR PUBLICATION
1 March 2023

PUBLISHED
21 March 2023

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 CO_2 sink of 3.7 $GtCO_2e\ yr^{-1}$ 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, Havlík *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 heterogenous 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 $GtCO_2e\ yr^{-1}$ 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,

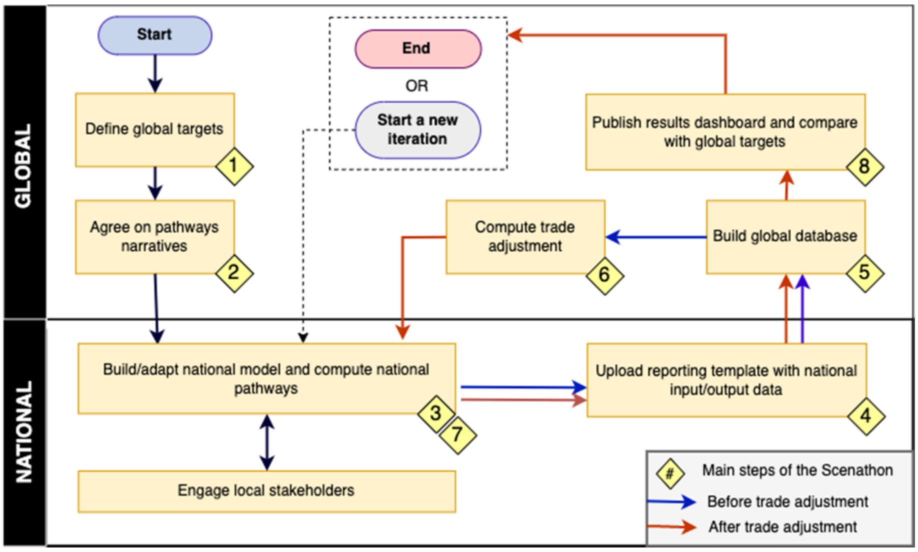

Figure 1. Overview of the iterative stepwise FABLE modelling approach to integrate national and global scales: the 'Scenathon' approach.

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 recomputed 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.

<table>
<tr><th></th><th>FABLE calculator</th><th>MAgPIE</th></tr>
<tr><td>**FABLE countries/regions using this model in this study**</td><td>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)</td><td>India *(MAgPIE is a global model solved for 12 regions in this exercise -but results are only used for India)*</td></tr>
<tr><td>**Model type**</td><td>**Agricultural and land use accounting model**</td><td>**Agricultural and land use sector equilibrium economic model**</td></tr>
<tr><td>**Objective function**</td><td>**No objective function** (no optimization)</td><td>**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)</td></tr>
<tr><td>**Software**</td><td>Microsoft **Excel**</td><td>Written in **R** and **GAMS**; Solved in GAMS using the CONOPT solver</td></tr>
<tr><td>**Main constraints**</td><td colspan="2">**National or regional market balance:**
Food + Food waste + Feed + Process + Bioenergy + Other Non-Food = Production—Losses—Imports + Exports
Cropland balance:$\sum_{i=1}^{N}$ planted area crop_i = cropland area
Land balance: Cropland + pasture + primary forest + secondary forest + other land area + urban area = total land area (fixed)</td></tr>
<tr><td></td><td>**Other land balances:**
harvested area crop_i / harvesting intensity = planted area crop_i
ruminant number × ruminant density per ha = pasture area</td><td>**Global market balance:**
Global supply $\geqslant$ Global demand
Other land balance:
pasture area × pasture yield = animal product × feed basket for pasture
Water balance:
Water availability = irrigated area × water requirements × irrigation efficiency + livestock production × water requirements</td></tr>
<tr><td>**Model outputs**</td><td colspan="2">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)</td></tr>
<tr><td></td><td>Planted area by crop (1000 ha), Number of livestock units (1000 TLUs)</td><td>Irrigated and rainfed crop specific area (1000 ha), Crop Prices in USD of 2005 Market Exchange Rate, per ton of dry matter</td></tr>
<tr><td>**Products**</td><td>**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
Processed products: cotton lint, vegetable oils (11 types), oilseed cakes (7 types), sugar raw
Livestock products: chicken, eggs, milk, pork, mutton-goat, pork, beef, other meat
Bioenergy: first generation biofuels</td><td>**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
Processed products: oils, oilcakes, sugar, molasses, alcohol, ethanol, grain distillers, brans, single cell protein, fibers
Livestock products: ruminant meat, pork, chicken, eggs, milk, fish
Bioenergy: first generation bioenergy, second generation bioenergy (bioenergy grasses, bioenergy trees)
Feed roughage: fodder, grass</td></tr>
</table>

(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 $GtGO_2$) and limited to 3.8 $GtCO_2e$ 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 $GtCO_2e$ 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.

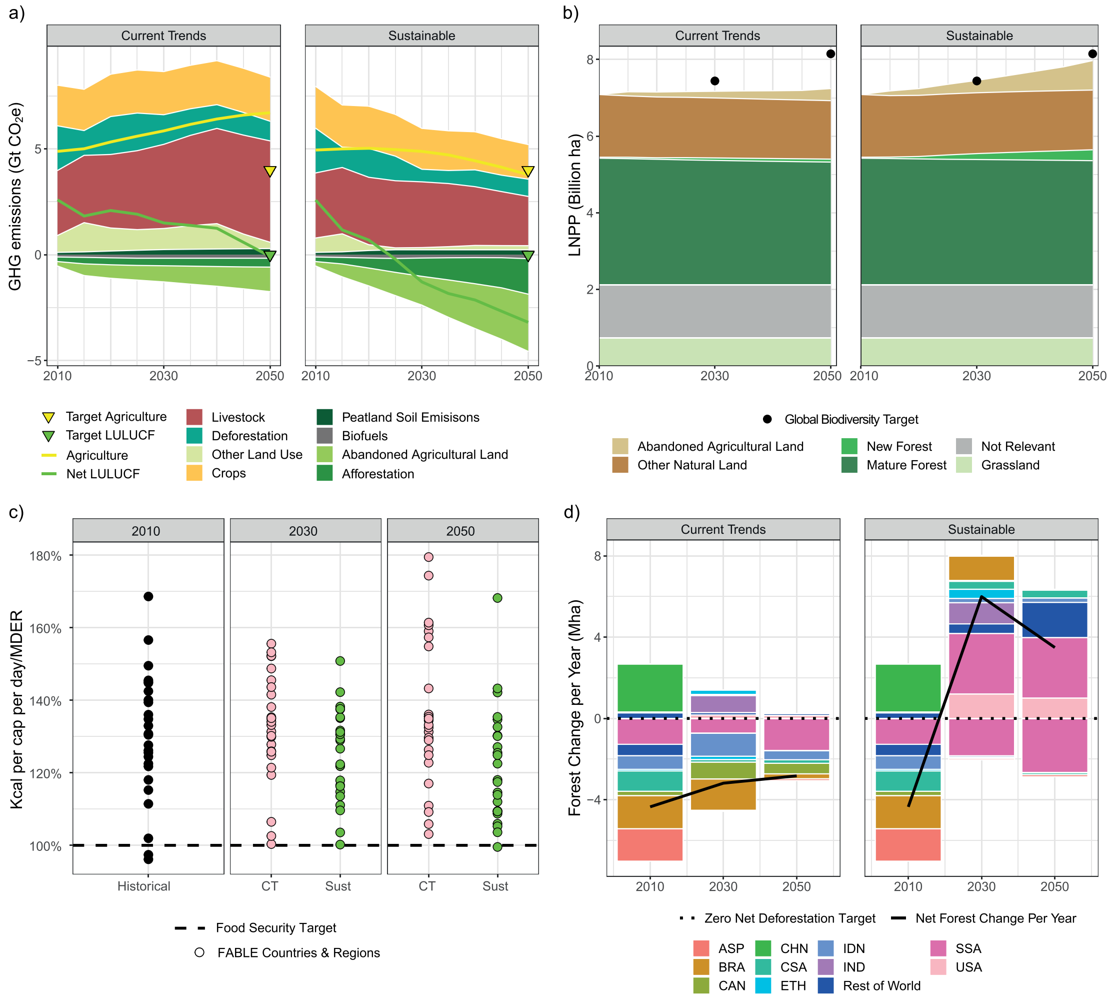

Figure 3. Comparison of the global targets under the current trends and sustainable pathways by 2030 and 2050 after global trade adjustment.
Note: (b) The biodiversity indicator is the land where natural processes predominate (LNPP). It refers to land where there is a low human disturbance and/or ecologically 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

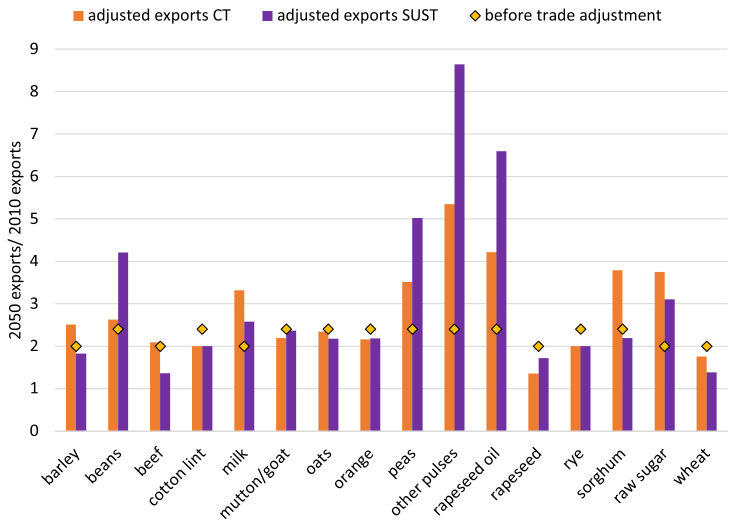

Figure 4. Impact of trade adjustment on Australian exports for key commodities.

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 $MtCO_2e$ (−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 heterogenous 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.

Acknowledgments

This work was supported by Norway's International Climate and Forest Initiative, the MAVA Foundation, and the Gordon and Betty Moore Foundation. The authors would like to thank the Food and Land Use Coalition (FOLU) and the World Resources Institute for their support, Lucie Adenäuer and Marluce Scarabello for their comments on the manuscript, and two anonymous referees for their thorough review of the paper and their constructive feedback.

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