Sustainability Science (2023) 18:335–345
https://doi.org/10.1007/s11625-022-01227-7

SPECIAL FEATURE: OVERVIEW ARTICLE

Globally-Consistent National Pathways towards Sustainable Food and Land-use Systems

How can diverse national food and land-use priorities be reconciled with global sustainability targets? Lessons from the FABLE initiative

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Received: 1 February 2022 / Accepted: 23 August 2022 / Published online: 5 October 2022

Abstract
There is an urgent need for countries to transition their national food and land-use systems toward food and nutritional security, climate stability, and environmental integrity. How can countries satisfy their demands while jointly delivering the required transformative change to achieve global sustainability targets? Here, we present a collaborative approach developed with the FABLE—Food, Agriculture, Biodiversity, Land, and Energy—Consortium to reconcile both global and national elements for developing national food and land-use system pathways. This approach includes three key features: (1) global targets, (2) country-driven multi-objective pathways, and (3) multiple iterations of pathway refinement informed by both national and international impacts. This approach strengthens policy coherence and highlights where greater national and international ambition is needed to achieve global goals (e.g., the SDGs). We discuss how this could be used to support future climate and biodiversity negotiations and what further developments would be needed.

Keywords Food system · Land use · Sustainability · Integrated models · Trade · Climate change

Introduction

Through the 2030 Agenda for Sustainable Development (UN 2015 2015) and the Paris Agreement on Climate Change (UNFCCC 2015), governments have made commitments to make progress toward greater sustainability. More recently, many countries have pledged net-zero GHG emissions, most by mid-century. Adopting long-term targets is necessary to ensure that present and future generations' needs are balanced, and it provides a strong basis for monitoring

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the progress made by each government, but these targets urgently need to be translated into actions.

While the global food system is relatively successful in feeding 7.5 billion people, it leaves a large footprint on the planet. It uses more than half of the world's total land cover (Arneth et al. 2019), accounts for 70% of freshwater withdrawals (UNESCO 2021) and for a third of global anthropogenic GHG emissions (Crippa et al. 2021), and is a major cause of freshwater and coastal eutrophication (de Raús Maúre et al. 2021) and biodiversity loss (IPBES 2019). Limited progress in tackling these challenges is partly because food and land-use systems are characterized by complex dynamic interactions between social, ecological, and economic factors, which are difficult to measure and understand (Friedlingstein et al. 2022).

Decisions made today include significant risks of lock-ins in the form of long-lasting infrastructure, land ownership, or land use (Leclère et al. 2014). Food production is scattered across millions of producers who are exposed to high risks and uncertainty, which leads to more difficult changes in practices than in other sectors (Komarek et al. 2020). Food and land-use systems are deeply embedded in local biophysical, cultural, historical, and socio-economic conditions and they are often at the heart of intense debates (OECD 2021), e.g., on land reform and dietary shifts. An additional difficulty for decision-makers, though not specific to food and land-use systems, is the need to consider international trade that has reinforced interdependences between countries over the last decades.

For instance, consumption in Europe and North America has long driven the production of tropical commodities and related deforestation (Byerlee and Rueda 2015). Dietary shifts resulting from rapid urbanization in sub-Saharan Africa has led to increasing dependence on livestock products and cereal imports from Europe, South America, and Asia (Arouna et al. 2021; Ragasa et al. 2020). More recently, the combination of higher demand for vegetable oils and the transition to large-scale animal farming dependent on industrial feed has led to widespread deforestation in Indonesia for oil palm plantations (Austin et al. 2017) and Brazil and Argentina for soy (Jamet and Chaumet 2016; Yao et al. 2018). Even well-intentioned policies are wrought with unexpected consequences due to spillovers: restrictions on natural forest logging in Vietnam led to higher deforestation in Cambodia and Laos (Meyfroidt and Lambin 2009) and military repression of illegal gold mining in French Guiana displaced deforestation to Suriname (Dezécache et al. 2017).

Local researchers have a crucial role to play to propose sustainable solutions that can respond to national priorities and sovereignty (United Nations Secretary-General 2021). Many models on food and/or land systems exist and new ones are being developed (Popp et al. 2017a; Nelson et al. 2014) but, beyond some strategic partnership agreements, they often have limited usefulness for local researchers. Global models often focus on the biggest countries and aggregate the other countries into large regions (Huppmann et al. 2018). Also, they usually rely on a small team located in one institute and this cannot reflect the diversity of countries' policies, cultural contexts, and local information sources (O'Neill et al. 2020). FABLE therefore aims to make modeling tools for the food and land-use systems easier to access and use by researchers who are interested in working with decision-makers at national and sub-national levels.

The FABLE Consortium was created in 2017, with the ambition to support countries in designing more ambitious, nationally autonomous, but globally aligned food and land-use strategies. Researchers from universities and national research centers have joined the Consortium, forming interdisciplinary country teams in Argentina, Australia, Brazil, Canada, China, Colombia, Ethiopia, Finland, Germany, India, Indonesia, Malaysia, Mexico, Norway, Russia, Rwanda, South Africa, Sweden, UK, and the USA. Other institutes with a more global lens—Sustainable Development Solutions Network (SDSN), International Institute for Applied Systems Analysis (IIASA), the Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT), and Potsdam Institute for Climate Impact Research (PIK)—provide support to country teams in the form of free transfer of existing modeling tools, development of new modeling tools, curated datasets, a platform for sharing experience among members, and methods and infrastructure to bridge the gap between national and global scales. The major innovation of FABLE is that it allows countries to develop their own national pathways that meet domestic priorities, and iteratively refine them to collectively meet global sustainability goals while maintaining the international balance of trade. FABLE can thus play a vital role in supporting countries to develop policies and targets to meet their international climate and biodiversity commitments while maintaining domestic food security and a viable land-use sector.

Here, we present the achievements of the FABLE initiative on three critical components of the framework: the definition of global sustainability targets, the computation of long-term country-driven transparent pathways, and the organization of an iterative process to ensure trade consistency across countries and to monitor collective progress toward the achievement of global targets (Schmidt-Traub et al. 2019; FABLE 2019, 2020). We then discuss how FABLE could support countries in international climate and biodiversity negotiations and what developments could increase the impact of our work in the next years.

The FABLE approach

Global targets

To ensure that the sum of national and regional pathways meets sustainable development objectives, global benchmarks are needed. Global targets are strongly related to planetary boundaries (Rockström et al. 2009). For food and land-use systems, we focus on global targets across five critical food and land-use system domains: (1) land and biodiversity, (2) climate change, (3) food and nutritional security, (4) freshwater use, and (5) nitrogen and phosphorus pollution (Table 1). We use as few global targets as necessary, use a mix of science-based targets and political targets, and ensure that they can be monitored at different scales. The proposed global targets must be regularly revised, as well as the indicators to monitor the achievement of each target.

For land and biodiversity, our global targets are based on the New York Declaration on Forests' goal of halting deforestation by 2030 reaffirmed by the Glasgow Leaders' Declaration on Forests and Land use (COP26, 2021), and the post-2020 biodiversity framework that will be discussed at the next CBD conference (cf. SI). We have developed a biodiversity indicator termed "land where natural processes predominate" that we use to compute the baseline area for this target, which is the union of three datasets: low-impact areas (Jacobson et al. 2019), intact forest landscapes (Potapov et al. 2017), and key biodiversity areas (BirdLife International 2019).

Climate targets are based on the Paris Agreement requirement of staying within 1.5 °C of global warming, since the additional risks of 2 °C warming are now understood to be high, particularly for land-use and food systems (Masson-Delmotte et al. 2018; Arneth et al. 2019). Our global targets are informed by the Integrated Assessment Models (IAM) scenario ensembles (Popp et al. 2017a, b; Riahi et al. 2021; Rogelj et al. 2018) (cf. SI). Due to higher uncertainty in the required mitigation level from Land Use, Land Use Change and Forestry (LULUCF) (Fyson and Jeffery 2019), we consider separate targets for emissions from crops and livestock (agriculture), and emissions and removals from LULUCF.

The Sustainable Development Goal (SDG) two calls for ensuring universal food security and nutrition security by 2030 in every country. Drawing on the FAO definition of the population at risk of hunger (Cafiero 2014), we require the average daily energy intake per capita after excluding food waste to be above the number of calories needed for good health, i.e., the minimum daily energy requirement (MDER). We also plan to add two further targets: undernutrition must be lower than 5% (Laborde et al. 2016) in all countries by 2030, and premature diet-related mortality must be below 5% by 2050 (Afshin et al. 2019; Wang et al. 2019). These require new developments in the underlying models we have used.

Table 1 The global targets within each of the five selected domains of food and land-use systems

Target domain	Proposed quantitative long-term target
Land and biodiversity	Zero net deforestation by 2030
SDG 15, New York Declaration of Forests, Glasgow Leaders' Declaration on Forests	At least 30% of the terrestrial area under protection by 2030
	No net loss of area where natural processes predominate by 2030
SDG 14, SDG 15, planetary boundary, post-2020 CBD targets	An increase of area where natural processes predominate by at least 20% by 2050
Climate change	GHG emissions from agriculture < 4GT CO_2e year^{-1} by 2050
Paris Climate Agreement, SDG 7, SDG 13, planetary boundary	Negative net GHG emissions from land use, land use change and forestry (LULUCF) by 2050
Food and nutrition security	Average energy intake per capita above minimum intake requirement by 2030
SDG 2, SDG 3	Population below the minimum intake requirement below 5% by 2030
	Premature diet-related mortality below 5% by 2050
Water	Bluewater consumptive use for irrigation < 2,453 km^3 year^{-1} (global estimates in the range of 670–4,044 km^3 year^{-1}) by 2050
SDG 6, planetary boundary	
Nitrogen and phosphorus	*Nitrogen release from agriculture*
Planetary boundary	N use < 69 Tg N year^{-1} total industrial and agricultural biological fixation by 2050
	N loss from agricultural land < 90 Tg N year^{-1} by 2050
	Phosphorus release from agriculture
	P use < 16 Tg P year^{-1} flow from fertilizers to erodible soils
	P loss from ag soils and human excretion < 8.69 Tg P year^{-1} flow from freshwater systems into the ocean by 2050

The term "land where natural processes predominate" is used to describe low-impact areas, but are not necessarily places with intact natural vegetation, ecosystem processes, or faunal assemblages (Jacobson et al. 2019). The Supplementary Information explains how these targets have been chosen

While increasing land productivity could limit further conversion of rich ecosystems to agriculture, this could lead to important trade-offs with water resources. Water use for agriculture irrigation is projected to strongly increase by 2050 compared to current levels and future climate change might further increase this demand (Campbell et al. 2017; Hejazi et al. 2014; Wada and Bierkens 2014). Fertilizer use can help close yield gaps, but runoffs into freshwater and marine ecosystems have severe environmental consequences (Rockström et al. 2009; Steffen et al. 2015; Stevens 2019). Our targets for global blue water consumption, nitrogen, and phosphorus are based on a literature review (cf. SI).

Country-driven integrated pathways

The determination of the pathway at the national level is key to ensure representation of local priorities, cultures, and contexts, and to inform national policies. We have developed three key components of national pathways. First, we simulate the current situation based on available statistics and analysis, and check the ability of the FABLE modeling tools to reproduce past trends since 2000. Next, each FABLE country team holds discussion(s) with the different actors of the system to understand the main constraints and levers for change, including ongoing policy processes in the country, and to understand the key objectives of the government. Some work is usually needed to adapt the modeling tools to be able to represent these main constraints, levers for change, and national objectives. Finally, the country teams work on the definition of contrasting pathways, i.e., choosing the value of key parameters of the model to reflect a certain narrative about the future, and comparing their impacts on the achievement of multiple objectives (Fig. 1). In some cases, scenarios reflect some elements of existing national policies, e.g., protected areas should cover 30% of total land area by 2030 and regulations on forest conversion. In other cases, this can reflect the results of future potential policies, rules, or incentives that could be implemented, e.g., dietary shifts and productivity growth (cf. country chapters in FABLE reports 2019 and 2020).

The Food System Dialogues hosted by the United Nations Food Summit have highlighted the importance of discussions among diverse groups of stakeholders in each country to build pathways. Modelers can support this type of dialog providing (i) clear explanations of intertwined processes and causality chains, (ii) a sense of proportion to the scale of the challenge, (iii) a structured way to provide feedback, and (iv) numbers that facilitate the comparison of different actions and highlight the potential for unintended consequences. But this requires that the modeling team is based in the country to interact as frequently as possible with the local stakeholders, often on short notice (Jasanoff 2006; O'Neill et al. 2020; van Soest et al. 2019). This process leads to greater ownership, relevance, legitimacy, and use of results in policy negotiations (Waisman et al. 2019). The challenge is to have teams able to operate and develop integrated models for food and land use in all countries.

FABLE Consortium members use different models depending on the team's modeling skills, model availability for their country, and policy questions (Pye and Bataille 2016). Models used need to satisfy a set of minimum requirements: the ability to report on the evolution of imports and exports by agricultural commodity, to report on the evolution of the indicators used to monitor the achievement of the global targets (Table 1), and to compare a *Current Trends*

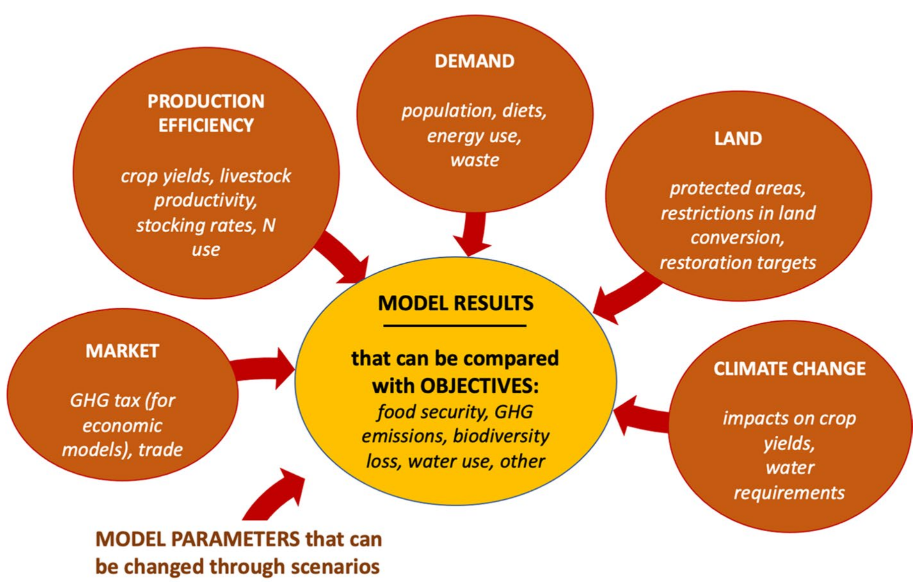

Fig. 1 Overview of the model parameters that are changed through alternative scenarios and the main model results that are compared with national and global targets

pathway and a *Sustainable* pathway to highlight the impacts of the main actionable drivers of the systems. But to ensure that all country teams could quickly have access to a model for their country, we built a new modeling tool, the FABLE Calculator (Box 1).

An important aspect is transparency. We focus here on four requirements: (1) the general documentation of the model is regularly updated and understandable by non-modelers; (2) the model's source code is documented and publicly accessible; (3) each publication is accompanied by a public database that covers the key results and additional data necessary to analyze the results of the model (e.g., data on assumed productivity changes); (4) modelers inform stakeholders of limitations in model functionality, correct any flawed reasoning about the model, and identify where there is poor data and evidence to support decisions (Nikolic et al. 2019). We acknowledge that this list of requirements is demanding in terms of practical model-based analysis work. Model simplicity certainly increases the model transparency and eases use of the model itself but sometimes stakeholders expect a very detailed representation of a sub-sector or a specific process. This requires finding the appropriate balance between adding model complexity, and still allowing a model's accessibility to many users. All FABLE Consortium members are encouraged to keep things as simple as possible when doing new model developments.

Evidence is emerging that openness and collaboration in science can achieve breakthroughs far more quickly with greater co-benefits to researchers relative to traditional closed practices (Lowndes et al. 2017; Zastrow 2020). It is important to ensure that the analysis can be scrutinised and repeated by other persons than the authors (Goodman et al. 2016; Wilkinson et al. 2016). Within FABLE, we have seen the benefits of model co-development. The fact that several teams of researchers have worked on the same tool, the FABLE Calculator, has significantly accelerated the identification and resolution of problems in the model and new developments of the tool (Box 1). The FABLE Secretariat is responsible for mainstreaming the developments of the tool for all users through the release of update packages.

Box 1: the FABLE Calculator

An Excel-based tool, the FABLE Calculator (Mosnier et al. 2020), has been created to quickly provide a model to each country team in the FABLE Consortium to make projections of their food and land-use systems up to 2050. It is a public mass-balance model that does not require programming skills, solves in a few seconds, and can test a wide range of parameters' values, resulting in millions of alternative pathways. The FABLE Calculator covers the main domains of food and land-use systems: food and nutrition security, land-use and land cover change, water use, some proxy indicators for biodiversity impacts, and GHG emissions from agriculture and land-use change. The agricultural sector is at the core of the model with the representation of > 60 products. Each country model is one Excel file that includes the national database, computation formulas, scenarios selection options, and a dashboard to monitor national targets. Future improvements are planned to cover further dietary nutrition aspects, nitrogen cascade, forestry sector, and link to socio-economic indicators.

An iterative process to reconcile national food and land-use priorities with global sustainability

FABLE national pathways are progressively aligned with global goals through an iterative process (Fig. 2). This starts with the harmonization of trade. Most attempts to link national/regional scale and global scale have focused on representing some countries/regions with greater detail within a global model (Mosnier et al. 2012; Soterroni et al. 2018), linking a country or regional economic model with a global economic model (Britz and Hertel 2011), or focusing on balancing trade projections from countries through a mix of expert judgment and the use of a global trade model as in the OECD–FAO annual outlooks (OECD/FAO 2021).

We have established a two-step method for trade adjustment in the same spirit of the OECD–FAO annual agricultural outlook approach. First, assumptions regarding the evolution of imports and exports for each commodity are set by each country independently, i.e., without considering the domestic changes that are foreseen by the other exporting and importing countries (Fig. 2, step 1). Because the FABLE consortium does not include all countries globally, we built models for six 'rest of the world' regions. Trade is balanced once all national and regional pathways are uploaded to an online platform. The FABLE Consortium has used a pragmatic approach with a proportional reduction or increase of exports to match global imports (e.g., a demand-driven approach). The updated trade assumptions become hard constraints in the next iteration of the national pathways (Fig. 2, step 2). The main advantages of this method are that it can connect heterogeneous modeling tools at the national level, test different algorithms to balance trade, and quickly compute consistent national and global pathways.

Following the trade adjustment, national indicators are summed up and potential gaps between the collective achievement and the global targets are highlighted on an online public dashboard (http://www.scenathon.org). Each country is invited to update its pathway after considering its contribution and the remaining gaps in attaining both national and global goals. Except for the food security target, which is imposed on all country teams, the other national goals are determined independently. These national

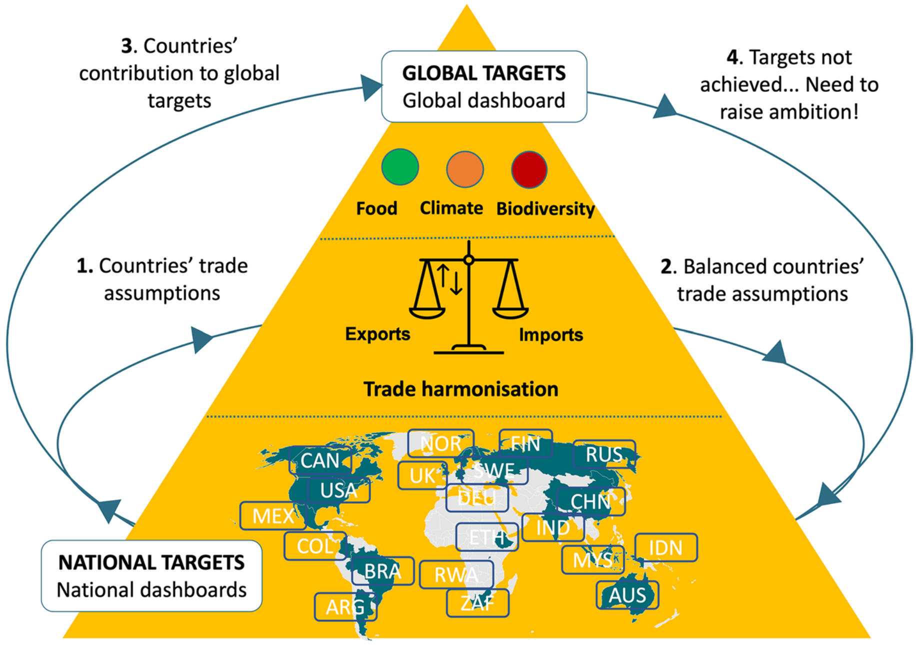

Fig. 2 The iterative bottom-up approach to ensure consistency between national and global scales

objectives can reflect existing policy targets. In many cases, quantitative targets are not available, so the national targets are either extrapolated by country modelers or expressed in broad terms, i.e., if there should be an increase or a decrease of a certain indicator over time. Another iteration can be run to try to close the gap with global targets (Fig. 2). We call this approach a "Scenathon", from the combination of "scenario" and "marathon".

How can the FABLE approach support future climate and biodiversity negotiations?

Consistent submissions

Building in-country capacity to operate integrated models can ensure consistency: (1) across the different submissions, e.g., in the case of the UNFCCC, the submission of the nationally determined contributions (NDCs), the long-term low emission development strategies (LT-LEDS), the forest reference emission levels (FREL) for reducing emissions from deforestation and forest degradation (REDD+) in developing countries, (2) across the time scales of the submissions, i.e., 2030 targets from the NDCs with mid-century and beyond targets from the LT-LEDS, (3) across different updates of the submissions, e.g., the NDCs that are to be updated every five years or revised National Biodiversity Strategies and Action Plans (NBSAPs), and (4) between different sectors, e.g., the climate and biodiversity strategies, the SDGs, and the development plan.

FABLE can play an important role by making several datasets from different sources coherent with each other, e.g., the land cover map obtained through satellite data and the agricultural production statistics, to build a coherent baseline model, which is the starting point for testing alternative sustainable pathways. This means that the same baseline model can be used to inform the climate mitigation strategy from agriculture and land (AFOLU), and the biodiversity strategy, so that they can be modeled together. The national FABLE models can thus identify synergies and trade-offs between the policy levers that can be used to reduce emissions from agriculture, increase land carbon sinks, and bend the curve of biodiversity loss (Leclère et al. 2020).

The FABLE approach can also facilitate the comparison and technical review of the submissions across countries, through standard reporting aligned with the international guidelines (comparability), the open model and documentation (transparency), and automatic verification and comparison of key model outputs with multiple benchmarks (accountability).

Progress toward global targets

There are assessments of national pledges compared to the ambition and action required to meet the Paris Agreement targets, but they often exclude land-use change emissions due to large uncertainties and lack of reliable data (Fyson and Jeffery 2019; Christensen and Olhoff 2019). Moreover, they come after the submissions of the revised NDCs and targets. The FABLE approach links the global ambition with national priorities, as well as the international trade dynamics that influence countries' courses of action, which can help countries prepare revisions of their NDCs, knowing in advance the remaining gaps to global climate targets. The FABLE approach can be used to discuss countries' contributions in light of the principle of common but differentiated responsibilities and respective capabilities (CBDR). All countries need to make efforts to reduce emissions, but they have different historical responsibilities and current capacity to implement transformations, especially on the land side.

We do not expect that countries would disclose strategic information and formally agree to follow the FABLE approach, but we hope that researchers involved in FABLE could provide early warnings to their government on the gap between the envisaged measures listed in their strategic documents and the realization of global objectives, and highlight alternative promising solutions that should be integrated.

Outlook

We are experiencing multiple crises that require urgent action. Global networks of national knowledge institutions can foster problem-solving and learning across countries, e.g., through experience sharing on stakeholder engagement, co-development of common open tools, or learning on policies implemented in countries that face similar challenges. Over the last years, FABLE has put in place a consortium and the modeling architecture to support the transition toward more sustainable food and land-use systems at national and global scales. In the following paragraphs, we will highlight some areas where future developments and new collaborations are needed to increase the impact of our work.

FABLE members have been especially concerned when trade adjustment led to a deterioration in achievement of their national objectives. For instance, lead exporters highlighted the fact that if the trade adjustment method would consider economic competitiveness, their exports would be proportionally less reduced or proportionally more increased compared to other exporting countries. In the future, we would like to test alternative trade adjustment methods based on economic criteria to better reflect the current trade structure (Haveman and Hummels 2004) or use reinforcement learning methods (Drugan et al. 2017) to design trade in a way that would help to achieve the global sustainability objectives. Greater collaboration with the private sector would be also beneficial to share views on the evolution of food and agricultural trade. Another improvement related to trade is the possibility for countries to easily track their consumption-based footprint depending on interventions within and outside the country.

We have not yet assessed what should be each country's expected contribution to each global objective: when we did not meet a global target, everybody was called to increase the level of ambition, and we did not track who did or did not. We can easily monitor the changes in the future, but we need more indicators in the FABLE dashboard to better reflect countries' heterogeneity in size, ecosystems, historical responsibilities, vulnerability, and current capacity to implement transformations (Leach et al. 2018; Holz et al. 2018). The objective of FABLE is not "to name and shame", but policymakers can be sensitive to cross-country comparisons, and they can be inspired by countries performing better.

We have accepted that some targets have not been met at the end of previous Scenathons. This is explained by two factors. The first is the fact that local researchers have worked on adapting food and land-use models in 20 countries, but the other countries are included in large regions piloted by the FABLE Secretariat. These regions have been "played" in a conservative way to avoid driving the global results to a too optimistic outcome without requiring significant changes in the 20 focus countries. Having more country teams represented in the FABLE Consortium, especially from Africa, would be important in the future.

The second aspect is related to the current limitations of our models. For instance, we are missing important mitigation options from agriculture, or carbon sequestration in managed forests and agroforestry systems which might reduce our ability to achieve global climate targets. The fact that we do not have spatially explicit scenarios that could especially avoid biodiversity loss, or that we do not consider the representation of specific practices to increase on-farm biodiversity can also reduce the chance to meet our biodiversity targets. We are working on new model developments and linkages with open and complementary existing tools to fill these gaps.

Assumptions on the evolution of future crop and livestock productivity have large impacts on the results and our capacity to meet all our sustainability targets. But what will be the extent of productivity growth, how this will be achieved, and how it will be impacted by more frequent climate shocks are subject to large uncertainties. Working with other modeling teams and the private sector to build open databases on improved technologies that could support the transformation of food and land-use systems would be of great value. Because socio-economic aspects are very sensitive for most governments, our priority will be to include the impacts of our pathways on jobs, production costs, and incomes.

International networks such as FABLE would benefit from more funding opportunities that aim at strengthening the science-policy interface, i.e., ensuring a good balance between scientific innovation and policy impacts. The right incentives should be put in place to encourage researchers to make their work more transparent and freely available because it often implies compromising between academic and policy targets. For example, documenting the model and databases, engaging stakeholders, or training others require resources and time that may slow down production of publications and innovative model developments that remain at the core of the scientific performance evaluation.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-022-01227-7.

Acknowledgements 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 to the FABLE Secretariat.

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