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SPECIAL FEATURE: EDITORIAL

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

Integrated modeling to achieve global goals: lessons from the Food, Agriculture, Biodiversity, Land-use, and Energy (FABLE) initiative

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Abstract

Humanity is challenged with making progress toward global biodiversity, freshwater, and climate goals, while providing food and nutritional security for everyone. Our current food and land-use systems are incompatible with this ambition making them unsustainable. Papers in this special feature introduce a participatory, integrated modeling approach applied to provide insights on how to transform food and land-use systems to sustainable trajectories in 12 countries: Argentina, Australia, Canada, China, Germany, Finland, India, Mexico, Rwanda, Sweden, the UK, and USA. Papers are based on work completed by members of the Food, Agriculture, Biodiversity, Land-use, and Energy (FABLE) initiative, a network of in-country research teams engaging policymakers and other local stakeholders to co-develop future food and land-use scenarios and modeling their national and global sustainability impacts. Here, we discuss the key leverage points, methodological advances, and multi-sector engagement strategies presented and applied in this collection of work to set countries and our planet on course for achieving food security, biodiversity, freshwater, and climate targets by 2050.

Keywords Food systems · Sustainable development · Healthy diets · Climate mitigation · Biodiversity conservation

Introduction

Our food system is a root driver of biodiversity loss, land-use conversion, unsustainable freshwater use, and greenhouse gas (GHG) emissions (Rockström et al. 2020; Willett et al. 2019; Springmann et al. 2018). At the global level, these impacts have reached, or are close to reaching, major tipping points (Armstrong McKay et al. 2022; Steffen et al. 2015). Climate change is already threatening food supply and ecosystem services in many countries and these threats are set to worsen without major actions to curb global temperature increases (Mora et al. 2018). At the same time, our food systems are not supporting healthy human diets. Some 800 million people are undernourished, while some 2 billion are overweight or obese, creating a health crisis (Afshin et al. 2019). Actions are urgently needed to shift food and land-use systems to a sustainable trajectory where people live in harmony with nature in the current and future climates (CBD 2021).

To meet global targets for food security, biodiversity conservation, freshwater use, and GHG emissions, countries need to develop food and land-use policies that amplify cross-sector benefits and minimize trade-offs over short and long-time horizons (Mosnier et al. 2022; Schmidt-Traub et al. 2019). Such policies ideally need to account for cross-sector and temporally displaced feedbacks (e.g., land-use change impacts on biodiversity loss) and geographic spillovers (e.g., food security increases in one place driving freshwater depletion in another). Yet, designing these policies is challenging, because it requires an understanding of processes within and across food, ecological, land-use, water, and climate systems in specific social, economic, and political contexts, through time and across space.

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The Food, Agriculture, Biodiversity, Land-use, and Energy (FABLE) consortium

To address this challenge, the Food, Agriculture, Biodiversity, Land-use, and Energy (FABLE) consortium was convened in 2018 as part of the Food and Land-Use Coalition (FOLU). It is led by the International Institute for Applied Systems Analysis and the UN Sustainable Development Solutions Network, in partnership with the Alliance of Bioversity International and CIAT, EAT, the Potsdam Institute for Climate Impact Studies, and many other institutions.

FABLE is a collaborative initiative which aims to understand how countries can transition toward sustainable land-use and food systems. FABLE brings together over 200 science and policy experts from 88 national institutes currently spanning 20 countries and growing. These country teams learn, share, create, and apply knowledge and tools to develop bottom–up (i.e., grounded in local and national stakeholder knowledge), mid-century, integrated national pathways that aim to address local development priorities, collectively achieve global sustainability objectives, and balance international trade in commodities.

The FABLE approach

FABLE's goal is to empower its members to transition to sustainable food and land-use systems supported by multi-objective assessment tools (Mosnier et al. 2022). This involves country teams (i) agreeing on a set of global long-term targets, broadly consistent with the objectives of the Paris Agreement (Article 4.19), the proposed post-2020 Global Biodiversity Framework, and the Sustainable Development Goals (Table 1); (ii) developing pathways and applying models, adapted to local needs, to explore the evolution of national land-use and food systems and national and global impacts by mid-century following the current trends compared to leveraging policy to seek a more sustainable future; and (iii) in an iterative process, adjusting models to ensure balanced trade flows. Throughout the process, country teams engage local stakeholders and experts to review assumptions, seek advice, and build a shared vision.

A key objective of the FABLE consortium is to build capacity among its members to use multi-objective assessment tools to help understand options and design integrated food and land-use policies. Integrated Assessment Models (IAMs) can be used for this purpose (van Soest et al. 2019). Two recognized spatially explicit partial-equilibrium IAMs that include agricultural, food and land-use systems are the Global Biosphere Management Model (GLOBIOM) (Havlík et al. 2014) and the Model of Agricultural Production and its Impact on the Environment (MAgPIE) (Dietrich et al. 2019). GLOBIOM and MAgPIE are coded in GAMS, a high-level system for mathematical programming and optimization, which requires a fee for its use. The technical and cost requirements can create barriers to access and use of these IAMs. The FABLE Calculator (Mosnier et al. 2020) is a simpler integrated model designed to help remove such barriers. It is an open-source, Excel-based food and land-use system assessment tool, that is relatively easy to learn and use yet complex enough to provide reasonable estimates of multi-objective impacts. Its limitations include that—like GLOBIOM and MAgPIE—it uses broad land-cover categories (cropland, grassland, urban, forest, and other natural land) and does not account for differences in productivity, biodiversity value, or carbon storage of agricultural land and forested areas under different management categories (e.g., agroforestry versus monoculture cropland, or extensive versus intensively managed pasture). In addition, the FABLE

Table 1 FABLE global sustainability targets (FABLE 2021)

Theme	Target
Biodiversity conservation	A minimum share of earth's terrestrial land supports biodiversity conservation. No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate
	A minimum share of Earth's terrestrial land is within protected areas. At least 30% of global terrestrial area by 2030
	Zero net deforestation. Forest gain should at least compensate for the forest loss at the global level by 2030
Climate mitigation	GHG emissions from crops and livestock compatible with keeping the rise in average global temperatures to below 1.5 °C, which we interpret as below 4 $GtCO_{2e}$ yr^{-1} by 2050 (3.9 Gt for non-CO_2 emissions and 0.1 Gt for CO_2 emissions)
	GHG emissions and removals from Land-Use, Land-Use-Change, and Forestry (LULUCF) compatible with keeping the rise in average global temperatures to below 1.5 °C. Negative global GHG emissions from LULUCF by 2050
Food security	Zero hunger. Average daily energy intake per capita higher than the minimum requirement in all countries by 2030
	Low dietary disease risk. Diet composition to achieve premature diet-related mortality below 5%
Freshwater use	Water use in agriculture within the limits of internally renewable water resources, taking account of other human water uses and environmental water flows. Blue water use for irrigation < 2453 $km^3 yr^{-1}$ (global estimates in the range of 670–4044 $km^3 yr^{-1}$) given future possible range (61–90%) in other competing water uses

Calculator is not spatially explicit at the sub-national level, meaning that further analysis is required to validate the feasibility of some of the future land-use assumptions (e.g., productivity on new agricultural land) and to determine possible spatial configurations for future land-use accounting for local values and constraints (e.g., biodiversity conservation value, cultural importance). A key strength of the FABLE Calculator is that it can be used to explore how different assumptions affect sustainability outcomes in an iterative, participatory way, as the assumptions are changed in a user-friendly excel spreadsheet and the calculations of estimated impacts are fast and transparent. This makes it a valuable tool for cross-sector stakeholder engagement, exploration, and dialogue.

This Special Feature presents applications of GLOBIOM, MAgPIE, and the FABLE calculator, applied to explore impacts of a range of future national food and land-use scenarios on food security, biodiversity, GHG, and freshwater outcomes to 2050. The scenarios are based on assumptions about trends in diet, food waste, energy supply, climate change, population growth, agricultural expansion and productivity, water use, international trade, reforestation, deforestation, and protected areas (Fig. 1).

Results from FABLE

In this special feature, we present the conceptual framework and results from applying the FABLE approach in 12 countries. Together, the articles contribute to defining integrated food and land-use mid-century pathways and the critical actions required at the national level to meet global challenges to conserve biodiversity, halt global warming, safeguard freshwater resources, and secure human nutrition. All authors are part of the FABLE consortium and the articles are based on work completed in 2020–2021 as part of the FABLE work program.

In this editorial, we seek to consolidate the shared learning and key messages that stand out from the spectrum of FABLE country experiences and contributions. We find that: (1) integrated modeling reveals a set of critical leverage points, synergies, and trade-offs, for shifting to national and global sustainability, (2) methodological advances are enabling clearer and co-designed recommendations for policy action but key gaps remain, and (3) accessible multi-objective tools provide a foundation for engaging and fostering dialogue among cross-country and multi-sector research and policy actors.

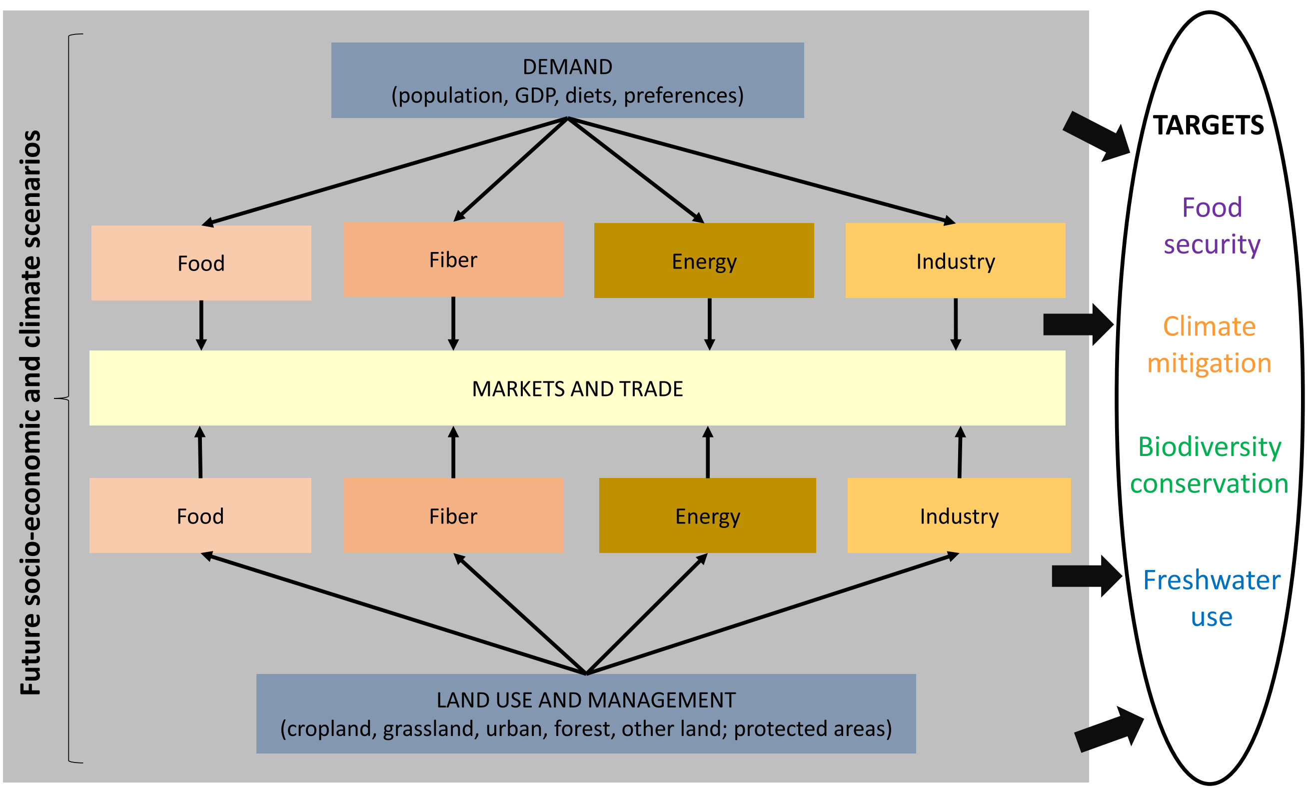

Fig. 1 An overview of the FABLE approach to developing food and land-use pathways using multi-objective assessment tools. Societal demand for food, material goods, and energy must be met through human use of land, such as croplands, grasslands, and urban areas, while also taking account of future socio-economic development (such as global markets, trade, and population) and climate change. FABLE explores pathways for meeting these societal demands within planetary boundaries, demonstrating that it is possible to provide healthy food to all of humanity in a sustainable way

Leverage points for sustainability

The papers in this special feature demonstrate that a higher level of ambition is needed in most countries to meet national food security, biodiversity, climate, and water targets in tandem. All the papers show that, if current trends continue, future changes in food production, consumption, and land use will make it impossible to achieve biodiversity, freshwater use, food security, and climate mitigation targets by 2050. Yet, many papers also show that implementing current policy pledges will be insufficient to reverse the situation, and countries will still fall short of most targets without more ambitious pledges (Frank et al. 2022; Jha et al. 2022; Lehtonen and Rämö, 2022; Smith and Harrison et al. 2022; Zerriffi et al. 2022). Integrating pathways from the 12 countries represented in this special feature together with those from all other regions in the world shows that a lack of national ambition will make it challenging to meet global targets, particularly on biodiversity conservation (FABLE 2022b) and climate mitigation (FABLE 2021). Achieving national and global food, biodiversity, water, and climate goals in tandem will require substantial changes in behavior at all levels (individual, community, food and forestry businesses, and local and national government) and many of these changes require going beyond the current levels of political ambition.

This special feature shows that there are several key leverage points for shifting to sustainable food and land-use systems consistently identified in multiple studies, across countries and continents (Fig. 2). These include changing diets, improving crop and livestock productivity, reducing deforestation, and restoring natural forests, shrubland, and grasslands. Other levers identified in several papers include reducing food waste and post-harvest losses, and reducing demand for food, water, and land including by slowing population growth. These levers contribute, to varying degrees, to achieving global food, biodiversity, water, and climate targets in tandem. Successful achievement of multiple targets

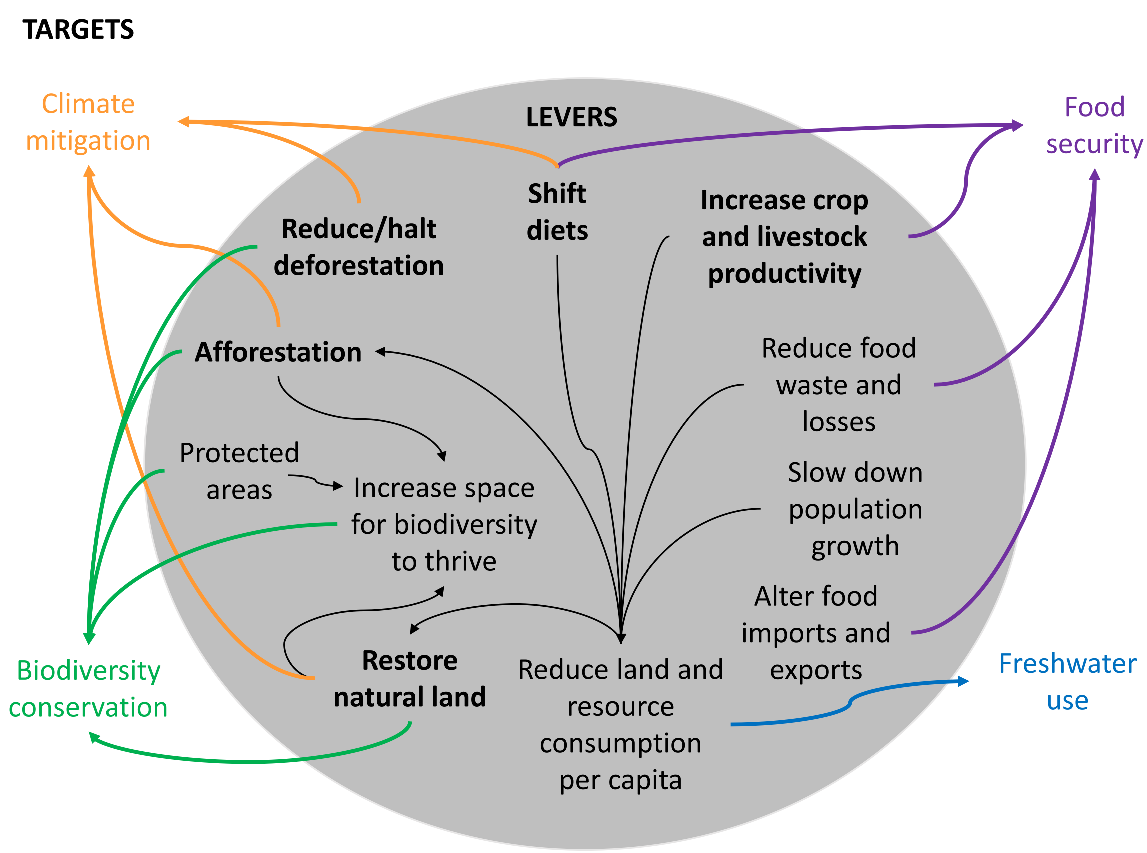

Fig. 2 Main levers identified in papers in this special feature for reaching food, biodiversity, freshwater, and climate targets. The most important levers (in bold) are those identified in multiple papers and/or consistently having a large influence on target achievement. Connections show pathways between levers and targets

is more common when multiple levers are applied simultaneously and when levers apply changes that are major and likely difficult, rather than minimal and easy, to achieve.

Changing diets

Most papers in this SF find that achieving national and global sustainability targets will require a substantial change in eating habits. For example, exploring options for sustainable food and land-use futures in Mexico, González-Abraham et al. (2022) assumed a change toward a healthier diet by reducing fat and oil content and substantially increasing the intake of fruits, vegetables, legumes, nuts, and fish. If the Mexican culture, strongly emblematic in terms of its gastronomy, can achieve such a substantial change in its eating habits, the authors show it is feasible that Mexico's population will have a healthy nutrition by 2050, while also limiting agricultural expansion, expanding forested area, and consequently reducing GHG. In the German context, Rasche et al. (2022) showed that reductions in meat and dairy consumption would reduce GHG emissions from German agriculture from 66 to 22 $TgCO_2e$ by 2050, and increase the land area where natural processes predominate, and biodiversity can thrive, from 19 to 27–32%.

These results provide evidence that dietary shifts can enable food, biodiversity, and carbon targets to be met in tandem from the academic viewpoint. However, the dietary shifts that are feasible and adequate to achieve food, biodiversity, and climate objectives vary from place to place, depending on present-day diets, capacity to increase specific locally produced and imported foods on the existing or new agricultural land, and political and societal willingness to alter cultural norms (FABLE 2021). For example, Perez-Guzman et al. (2022) discuss that in Rwanda, shifting to healthier diets is more likely to be compatible with national production and economic targets if these diets favor crops that underpin Rwandan livelihoods, such as bananas, beans, cassava, and potatoes. However, the previous research in Rwanda highlights the importance of maintaining or increasing local access to, and consumption of, a diversity of foods, such as meat, fish, nuts, and vegetables, to close nutritional gaps (Del Prete et al. 2019). Hence, this must be taken into account when promoting economically important crops. While in some countries, there is a need to increase consumption of certain foods to close nutrition gaps and improve diet-related health outcomes, in others, too much food is consumed. Simply reducing consumption of calories and foods where these exceed nutritional requirements, such as in Canada (Zerriffi et al. 2022), the UK (Smith et al. 2022), and USA (Wu et al. 2022), will help improve nutritional outcomes and reduce diet-related diseases in these countries while also helping achieve food security at the global level.

Increasing crop and livestock productivity

Several papers in this special feature explore the effect of closing yield gaps to meet future food demands. Increasing crop and livestock productivity on the existing agricultural land has the advantage of limiting further land conversion, and can also reduce the existing agricultural land area, freeing up land for restoration. For example, in the UK, raising crop productivity was sufficient to free up 34,000 ha of agricultural land (Smith and Harrison et al. 2022).

In all countries, there is a high uncertainty regarding feasible productivity increases, and the limits of feasibility are likely to shift under climate change. In addition, productivity increases need to be achieved using agroecological approaches to avoid the negative environmental consequences associated with intensification through synthetic pesticide use, excessive use of fertilizers, unsustainable irrigation, and simplification of farms and landscapes (Estrada-Carmona et al. 2022; Sánchez et al. 2022; Tscharntke et al. 2021; Beckmann et al. 2019; Liu et al. 2017; Tuck et al. 2014). Agroecological intensification may not be able to achieve the productivity increases that are possible with high chemical input use, although evidence shows that yield gaps created by removing chemical inputs are reduced and can be closed by increasing crop and non-crop diversity in-field, e.g., with agroforestry, intercropping, cover crops, and use of flower strips (Beillouin et al. 2021; Tamburini et al. 2020; Ponisio et al. 2015). Where yield gaps remain, demand side changes are likely to be needed to alleviate pressure on land-use and meet biodiversity and climate objectives. For example, Basnet et al. (2023) demonstrate that shifting from 20 to 30% organic farmland, in line with Sweden's national target, would only lead to improvements in national food self-sufficiency, biodiversity conservation, and reductions in GHG emissions, when coupled with dietary changes and reduced food waste. When this happens, organic farming forms part of a promising pathway to achieving sustainable food and land-use systems.

Reducing deforestation and restoring natural land

Across the collection of SF papers, achieving net-zero GHG emissions by 2050 generally involves halting deforestation immediately (Frank et al. 2022; Jha et al. 2022; Navarro Garcia et al. 2022) or at least before 2030, while increasing afforestation efforts. This picture gets more complicated when analyzing the different drivers at the forest–agriculture frontier, such as food consumption patterns—particularly excessive meat consumption, and the balance between realistically possible land-based CO_2 removal potential and Agriculture, Food and Land-Use (AFOLU) emission patterns (FABLE 2022a). For example, FABLE countries with the most ambitious afforestation pledges include India

(Jha et al. 2022) and USA (Wu et al. 2022), yet the change in net emissions as a result of afforestation in these countries depends on which other activities are present. India has low levels of meat consumption, and its land-based CO_2 removal potential is not substantial, but AFOLU is currently a net emitter mainly due to livestock production. The analysis presented in this SF suggests that AFOLU could be carbon neutral by 2050 if a reduction in livestock emissions is complemented by other changes, such as afforestation and an increase in agricultural productivity. The United States, on the other hand, currently has an excess of meat consumption, but has a substantial land-based CO_2 removal potential. Its AFOLU sector could convert from being a net emitter to a net sink by 2050, if the afforestation efforts are accompanied by dietary shifts to consume less meat, and an increase in livestock productivity.

At a global level, restoration of natural land—inclusive of afforestation efforts—will be vital to achieve climate and biodiversity objectives (FABLE 2022a, b). The Conventional for Biological Diversity has set global targets of a 5% increase in natural land by 2030 and a 15% increase by 2050, while halting loss of the existing intact and wilderness land by 2030 (CBD 2021). Expanding the 56% of terrestrial land area where natural processes currently predominate, and addressing the relative shortfall of this land within tropical biomes, is going to be challenging, but failure to act will put biodiversity on a perilous trajectory and lead to the AFOLU sector overshooting net emission targets (FABLE 2022b). Countries approach deforestation and restoration pledges from different starting points. The amount of forest and other natural land where natural processes predominate and biodiversity thrives is vast in countries like Australia, Canada, and Russia, and relatively small in India, Germany, the UK and Rwanda, but the latter three countries have substantially higher population densities and smaller land areas intensifying demands on the remaining natural land (FABLE 2022b).

In all countries, restoring more land to nature requires reducing the area used for other purposes, principally agriculture. FABLE's work shows that the best strategies for achieving this are shifting diets toward less land-intensive foods, and increasing crop and livestock productivity, freeing up land for restoration (Frank et al. 2022; González-Abraham et al. 2022; Jha et al. 2022; Lehtonen and Rämö, 2022; Navarro Garcia et al. 2022; Perez-Guzman et al. 2022; Rasche et al. 2022; Smith and Harrison et al. 2022; Zerriffi et al. 2022). Of note, some restoration efforts to date have promoted single or exotic species which do little to restore native ecosystem functioning. The FABLE approach does not explicitly distinguish habitat quality within restored land, yet to benefit biodiversity, afforestation and other restoration efforts need to focus on local, diversified plant species adapted to future climates (FABLE 2022b). In addition, GLOBIOM, MAgPIE, and the FABLE Calculator do not consider the biodiversity conservation and carbon storage and sequestration potential of agricultural land. Several authors point out that further work is needed to incorporate the contribution of improved agricultural land management to sustainability targets, such as zero-chemical agroecological practices and low-intensity livestock systems that incorporate trees and other natural vegetation covers (González-Abraham et al. 2022; Smith and Harrison et al. 2022). Such practices are likely to form a core part of sustainable futures particularly in countries with high pressure on land-use and little remaining natural land.

Other leverage points

Reducing food waste and losses were other actions that contributed substantially to multi-target achievement in several studies, e.g., Australia (Navarro Garcia et al. 2022) and Sweden (Basnet et al. 2023). International trade was also critical for achieving economic growth objectives and food security in some countries. For example, increasing imports of wheat, milk, and nuts will be needed to meet future demand for these foods and close nutritional gaps in Rwanda, while an increase in tea and coffee exports is expected to meet economic targets (Perez-Guzman et al. 2022). In Mexico, feeding the country's projected 146 million people in 2050 while meeting biodiversity and climate targets will require approximately doubling maize, milk, and beef imports, even when assuming a reduction in cereal, meat, and dairy consumption per person, a near doubling of maize productivity, and an increase in livestock productivity (González-Abraham et al. 2022).

Papers in this special feature discuss that reducing food and resource demands, including by slowing population and economic growth, is another key leverage point for shifting to sustainable food and land-use systems (Navarro Garcia et al. 2022; Zerriffi et al. 2022). Humans account for 0.01% of all biomass on the planet, which is 20 times the estimated biomass of all wild terrestrial mammals (Bar-On et al. 2018). While multiple studies show we can feed the 10 billion people predicted to live on the planet in 2050 (Gerten et al. 2020; Bajželj et al. 2014; Foley et al. 2011), substantial changes in consumption patterns, wealth distribution, and/or reduced population growth are needed to ensure that every person has a fair share of resources, technology, and energy without taking the planet over its biological and climate tipping points. For example, the UNEP Emissions Gap Report estimates that, to keep global warming below 1.5°, GHG needs to stay below 2.2 tons per capita (UNEP 2021). Yet currently, the world's richest 10% are predicted to generate per capita emissions ten times above this safe limit in 2030, while emissions for the world's poorest 50% will stay well below the threshold (Oxfam and Institute for European Environmental Policy 2021). The question of how to achieve a just and equitable food access and quality of life for all needs to be more openly discussed and constructively answered now, while there is still time to positively shape current and future family planning decisions, and societal and individual expectations and behaviors regarding resource consumption.

Methodological advances

This special feature demonstrates that integrated assessment tools, notably the FABLE Calculator, GLOBIOM, and MAgPIE, can effectively break down the complexity of food and land-use systems by showing the cross-sector impacts of single and combined national policy decisions (Mosnier et al. 2022). As with all models, the tools used in FABLE have some limitations. Several papers in this special feature present methodological advances applied to expand and extend the capabilities of MAgPIE (Wang et al. 2022) and the FABLE Calculator (Frank et al. 2022; Navarro Garcia et al. 2022; Basnet et al. 2023).

Multi-model approaches

One limitation of the modeling infrastructure used in this collection of papers is that results are generally not spatially explicit. This means that the leverage points at the national level may be clear—such as expanding restored land or protected areas—but FABLE country teams cannot readily provide guidance on where and how best to prioritize actions within a country, or check how spatially explicit changes in land management fit within the existing spatial zoning strategies. In this special feature, Frank et al. (2022) demonstrate that it is possible to combine results from the FABLE Calculator with a land-use allocation model (Dinamica EGO) and conservation prioritization approach (NatureMap), to construct a food and land-use pathway for Argentina that allows it to meet key biodiversity, freshwater use, food production, and carbon storage targets by 2050. Extending the FABLE approach in this way opens a doorway for helping meet the requirement for biodiversity-inclusive spatial planning that countries will make as part of their post-2020 Global Biodiversity Framework commitments to identify the ranges of systemic drivers that achieve multiple sustainability targets.

Applying FABLE tools as part of a multi-model approach can also help to move past the 'what' needs to be done to the 'how' in the transition to sustainable food and land-use systems. Wang et al. (2022) combine land system model outputs from MAgPIE with an econometric model to test the effect of various domestic fertilizer policies on fertilizer use, losses, and pollution, and food security in China. Through this novel approach, they were able to quantify the substantial biophysical and economic benefits of removing subsidies for synthetic fertilizer manufacturing, but also show that China's target of zero growth in nitrogen fertilizer use can only be met by increasing nitrogen management and uptake efficiency.

Expanding the solution space

In applying models, local stakeholders and researchers make assumptions about future conditions (e.g., rate of deforestation, growth in imports or exports). Poor choices, misleading historical data, and unexpected future events, can lead to unrealistic or inaccurate assumptions. Navarro Garcia et al. (2022) use scenario discovery to systematically explore the effect of different parameter ranges on model outputs. Through coupling the FABLE Calculator with a Monte Carlo simulation software, the authors were able to systematically explore the effect of a range of each parameter's values on model outputs and differentiate thousands of possible pathways for food and land-use systems. They distinguish 'resilient' pathways as those that incorporate a diversified portfolio of solutions working together to hit multiple sustainability targets, and more risky pathways that rely on small sets of solutions or individual levers (e.g., afforestation, carbon capture, and storage) increasing the risk of setbacks. They find that livestock productivity and stocking density, afforestation, and dietary shifts are the most influential factors in Australia's aim to meet national targets for food consumption, net afforestation, water consumption, net-zero emissions, and biodiversity conservation, by 2050. Yet, achieving all five targets will require very ambitious actions under optimistic future socio-economic pathways (SSP1) and will be impossible to achieve under SSP2 (continuation of long-term socio-economic trends) or SSP3 (future lack of international cooperation and neglect of environmental and social goals). Navarro Garcia et al. (2022)'s methodology has the advantage of showing policymakers the full suite of options available to them to achieve sets of sustainability targets, and could help multiple sectors find consensus around a feasible pathway.

Future development priorities

The existing tools and methodological advances presented in this special feature already go a long way to ensuring that FABLE outputs are policy relevant and have practical utility. The value of FABLE's approach could be further strengthened by closing several key data and methodological gaps. These include distinguishing effects of agroecologically managed farmland (e.g., agroforestry, zero synthetic inputs, maintenance of natural infrastructures in and around fields, improved rice management) from other farming systems, separating extensive and intensive pasture, better representing forest production systems, and incorporating climate adaptation and resilience assumptions into the scenarios. Data availability is a key constraint to further developing the capacity of FABLE models, and national and global monitoring efforts should continue to try and close data gaps. For example, FABLE tools are dependent on published food supply, demand and trade data, particularly from FAO. This means scenarios do not consider certain foods that are poorly represented in national accounting and are important to farmer livelihoods and consumer diets in some countries, such as fish and some plant-based proteins in USA (Wu et al. 2022), climate-adapted crop species (e.g., fonio), and local crop varieties and livestock breeds. Finally, the full economic benefits and costs associated with transitioning to alternative food and land-use trajectories are not quantified, such as avoided public health costs, investments required to expand protected areas or restore abandoned agricultural land, or changes in agricultural subsidies needed to sustain viable agricultural sector livelihoods. Future work could seek to close this gap and quantify the price of action, and inaction, across scenarios.

Stimulating multi-sector collaborations and dialogue

Food and land-use systems involve the environment, agriculture, forestry sectors but also health, society, and economics. Food itself is a nutritionally essential, culturally valued, profitable product, and what food and how it is produced affects everyone. Its importance means that opinions on how best to manage food and food systems are often deeply entrenched and not easily shifted. For example, in the US, the health and climate benefits of reducing meat consumption are hotly contested (Wu et al. 2022). Entrenched cultural and economic positions mean bringing about major changes in food and land-use systems will not be easy, yet this is what the papers in this SF show is required to meet food, biodiversity, and climate targets in tandem. For example, in the UK (Smith and Harrison et al. 2022), Mexico (González-Abraham et al. 2022), and Argentina (Frank et al. 2022), sustainable food and land-use system trajectories are only possible if assumptions about drastic changes in diets are met.

Creating change

A survey carried out in Germany by Rasche et al. (2022) shows stakeholder perspectives differed substantially regarding the feasibility of reducing beef and pork consumption, reducing food waste, and reducing soy imports, with academics, and to some degree public sector, generally more optimistic than private sector actors (Rasche et al. 2022). These results suggest that food system stakeholders need stronger incentives to make the major changes that are assumed possible, and necessary, by papers in this special feature. Rasche et al. (2022) highlight that education (Garcia-Gonzalez and Eakin 2019) and health-promoting policies (Muller et al. 2009) are considered powerful incentivizes for mobilizing major changes in food consumption choices. Increasing cross-sector dialogue and collaboration can also help. A review of integrated planning initiatives in South and Central America showed that bringing diverse stakeholder groups in a landscape or community together to discuss priorities, identify conflicts, and co-develop a shared vision for a sustainable future increases the likelihood of positive outcomes (Estrada-Carmona et al. 2014). In interdisciplinary research projects, even spontaneous, low levels of stakeholder engagement can be enough to achieve impact and is sometimes actually more effective than organized, regular engagement (Huzzard 2021).

Engaging stakeholders in finding solutions

The FABLE approach involves multi-sector stakeholder engagement to ensure that the pathways tested are of interest to relevant stakeholders and are thus more likely to be implemented. This engagement takes place via a 'Scenathon', or scenario marathon, which is an iterative series of stakeholder consultations that progressively develops the pathways for testing with the integrated assessment tool. The engagement focuses on bringing together both researchers and policy stakeholders from multiple sectors to remove communication, methodological, knowledge, and political barriers and build consensus around a shared vision for a sustainable future.

Papers in this special feature show that there are multiple methods of effectively engaging national stakeholders; that doing so helps increase the policy relevance of the developed pathways, and including multiple sectors and disciplines helps identify priorities for action to create a shared vision and incentives for change. For example, in the UK, three pathways were co-created with 27 relevant stakeholders through a series of workshops and consultations (Smith and Harrison et al. 2022). This iterative and transparent engagement throughout the process ensured the pathways fit well with current government policy and future policy aspirations. Stakeholders felt that the integrated modeling of land-use taking account of trade and global environmental targets was a major strength of FABLE, as it emphasizes links between the UK and other countries' emission reduction ambitions. It also enabled exploration of the trade-offs and challenges associated with the major land-use change needed to deliver the UK's net-zero target, while simultaneously meeting our biodiversity and other environmental commitments (FABLE 2020).

In Germany, Rasche et al (2022) engaged stakeholders from 25 organizations ranging from national and local governments, civil society, academia and the private sector, primarily through an online survey. Some of the survey questions aimed at gathering stakeholder perspectives about the feasible range of changes that Germany could make to its food and land-use systems, which were then used to design the country's pathways. With the respective responses, the authors defined four pathways which symbolized the preferences of each of the respondents' types: the common vision of all stakeholders, and specific preferences of academic, public sector, and private sector actors. An important finding was the heterogeneity of responses across stakeholder groups highlighting where additional effort is needed to build consensus.

Cross-country collaboration and consistency

The FABLE consortium itself is one of the world's largest multidisciplinary collaborations focused on tackling the challenge of achieving a sustainable future in the existing national policy contexts. Researchers involved in the FABLE Consortium are specialists in every aspect of the food system and regularly share information, guidance, and resources on research, stakeholder engagement strategies, and methodological advances with the entire group. This gives each country team easy access to the latest data and science on FABLE-related topics and a go-to person to ask about topics that lie outside their area of expertise. The consortium members work together to agree on global targets, develop methodologies to apply consistently across countries to quantify impacts of food and land-use scenarios, and iteratively adjust assumptions to ensure global trade balance. This exercise produces nationally and globally relevant research outputs, but its less tangible value lies in fostering cross-country understanding and learning, knowledge sharing, collaborations, and momentum, to strive to achieve our collective vision of a sustainable future.

Conclusion

Globally, a shift to sustainable food and land-use systems is needed to meet nutritional, agricultural, and environmental targets. FABLE is the only bottom–up initiative for exploring food and land-use pathways at the global scale that takes account the national context through stakeholder engagement, while factoring in international trade and fostering understanding of the collective responsibility across countries for meeting global targets. Work on the FABLE initiative presented in this special feature explains the FABLE methodology and demonstrates how applying it pinpoints leverage points that can secure sustainable food and land-use futures nationally and globally. The major leverage points, in terms of their cross-country importance and magnitude of progress that can be made for achieving single and multiple food security, biodiversity conservation, freshwater use, and climate mitigation targets, include shifting diets, raising crop and livestock productivity, and restoring natural land where biodiversity thrives and carbon sequestration increases. Other important levers include reducing food losses and waste, shrinking per capita resource consumption, and filling nutritional gaps through international trade. Minor changes in each of these areas will be insufficient to get countries and the planet on track; only major changes, made in many countries, will enable us to achieve holistic sustainability targets. Stronger policies and incentives will help enable all stakeholder groups to participate and support the transformative change process. These and other mechanisms for applying sustainability levers need to be implemented with care and tailored to each country's local context to ensure that benefits and trade-offs are fairly and equitably distributed.

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