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Hype or Accelerator of Sustainable Diets? Evaluating Global Land Use and Spillovers of Diet Shifts from Animal Products to Plant-Based Alternatives

Amelia Espey

amelia.espey@uni-hohenheim.de

University of Hohenheim https://orcid.org/0000-0002-2382-610X

Franziska Schuenemann

University of Hohenheim https://orcid.org/0000-0002-1311-0570

Yaghoob Jafari

University Hospital Bonn

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Hype or Accelerator of Sustainable Diets? Evaluating Global Land Use and Spillovers of Diet Shifts from Animal Products to Plant-Based Alternatives.

Amelia Espey[1], Franziska Schuenemann[1], Yaghoob Jafari[2]

[1] Chair of Bioeconomy, University of Hohenheim
[2] Global Economic Modelling of Food Systems Group, University of Bonn

Abstract

Interest in replacing animal-based proteins and reducing the environmental impacts of livestock production has driven research into plant-based alternatives (PBAs), which mimic the sensory and functional properties of animal products. By incorporating PBAs and livestock value chains into a global economic model, we assess how shifts in preferences towards PBAs could facilitate sustainable diet transitions in high- and upper-middle-income regions by 2040, after accounting for economy-wide feedback effects. Restructuring value chains lowers land rents and agricultural prices, raising food demand with minimal spillovers to other sectors. Even after price effects, all scenarios reduce on-farm emissions. Reduced pressure on unmanaged forests, particularly in Brazil, contributes to global carbon stocks, but more extensive agriculture limits these gains, especially in high-income regions. Technological change matters most in upper-middle-income regions. Milder technologies can offset higher CO_2 emissions from energy-intensive protein extraction as PBA consumption rises, albeit with trade-offs in protein content.

Keywords: plant-based alternatives, diet transition, computable general equilibrium, greenhouse gas emissions, land-use change

1 Introduction

Dietary changes are essential for a more sustainable food system as the consumption of animal products, especially red meat, is associated with substantial environmental degradation[1,2]. Livestock production tends to be more environmentally damaging than plant-based proteins due to inefficient feedstock-to-food conversion and emissions from enteric fermentation and manure management[3,4]. Given overconsumption of animal products in high- and upper-middle-income regions, research advocates for dietary shifts from dairy and meat towards plant-based foods[5].

Plant-based alternatives (PBAs) could facilitate dietary change. As most consumers do not follow vegan or vegetarian diets, the plant-based food industry increasingly targets meat and dairy consumers through 'next-generation' PBAs, such as burgers and plant-based milks[6]. These PBAs aim to replicate the sensory (e.g., taste, texture) and functional (e.g., behaviour during cooking) properties of animal-based foods[7] and, by providing a similar experience to animal products, have the potential to accelerate substitution towards plant-based diets rather than complete reliance on minimally processed plant-based foods (e.g., vegetables, fruits, legumes, and whole grains)[8]. The PBA sector has seen rapid growth over the last decade, with global sales increasing from $2.2 billion to $6.6 billion between 2015 and 2025, although growth has slowed in recent years and has declined across some regions and categories[9].

Sustainability impacts of PBAs remain uncertain. Their extensive processing increases energy requirements and feedstock inputs relative to minimally processed plant-based foods. Despite this, life-cycle analyses (LCAs) generally find PBAs outperform animal products in terms of GHG emissions and other environmental indicators[10,11]. Springmann[10] reports GHG emissions per serving of about 1% of beef for unprocessed legumes and 5–6% of beef for plant-based burgers.

Processing technologies influence the extent of this advantage. Proteins extracted from cereals and legumes are key ingredients in plant-based meat analogues, and extraction methods yielding higher protein content (e.g., wet fractionation) require more energy and crop inputs than less refined alternatives (e.g., air classification)[12]. Depending on the method, GHG emissions for plant-based meat analogues can approach those of relatively efficient livestock, such as poultry[13]. However,

LCAs evaluate technologies in isolation, overlooking price-mediated responses to shifts in consumer preferences, such as rebound effects[14]. Without accounting for price effects, it is not possible to capture supply-side feedbacks for land, intermediate demand, and spillover effects to food and non-food sectors that determine the actual sustainability of PBAs.

Capturing price-mediated effects requires economic simulation models that represent how markets and prices adjust to shocks such as new product adoption. Partial equilibrium (PE) models simulate a single market or sector in isolation, while computable general equilibrium (CGE) models simulate the whole economy, accounting for cross-sector and cross-market feedbacks. Previous studies have used global PE[15,16] and CGE[17,18] approaches, or both[19], to model global dietary shift scenarios based on the EAT-Lancet diet, typically adjusting crop demand exogenously. While recent work has improved the representation of agro-food value chains within CGE models, such as feed demand[20,21], food processing sectors remain highly aggregated. This remains a significant gap, since these sectors comprise both the processed plant-based and feed concentrate central to the dietary shifts under analysis. CGE studies on the bio-based economy (e.g., bioplastics[14] and biochemicals[22]) show that increased sectoral detail is needed to account for input requirements and spillover effects to agricultural and other sectors.

A few studies model PBA adoption directly, including a single-country CGE approach modelling substitution from beef towards PBAs in the United States[23] and a PE approach assessing global impacts of dietary shifts towards PBAs[24]. However, previous research on modelling global protein transitions does not incorporate PBA processing technologies or consider the environmental implications of price-mediated spillover effects following their adoption.

Our study thus makes several important contributions to the literature on the economic and environmental impacts of dietary change by jointly modelling PBA and livestock value chains within a detailed, recursive dynamic, global CGE model. First, we represent feedstock processing and other input requirements, such as electricity, natural gas, and chemicals, associated with PBA technologies through greater sectoral detail. Specifically, we define five PBA sectors, including three plant-based protein extraction technologies (based on wheat, soy, and starch-based legumes)

that serve as intermediate inputs into a plant-based meat analogue, and a separate plant-based dairy analogue based on soy, oat, and nuts. These sectors directly address the lack of modelling PBA processing technologies in prior work. Second, we capture price-mediated feedback effects arising from shifts in dietary preferences towards PBAs, alongside the resulting impacts on GHG emissions and land-use change, addressing the absence of an economy-wide environmental analysis in prior work. Third, we adjust the technologies to reflect improved feed- and energy-use efficiency and examine how processing technologies influence the environmental performance of PBAs, after accounting for price responses.

2 Results

2.1 Consumption shifts towards PBAs

Substantial uncertainty exists regarding the pace and regional extent of PBA adoption[25]. To capture this range of scenarios, we run six diet transitions: 20%, 40%, and 60% replacement of animal-based foods with PBAs in high-income countries, with the same levels extended to upper-middle-income countries, each benchmarked against the business-as-usual (BAU), which reflects continued population and gross domestic product (GDP) trends with moderate climate change mitigation and adaptation.

Consumer preferences in the diet scenarios are modified using a twist parameter that replaces household demand for animal-based foods with PBAs stepwise from 2017 to 2040. High-income diet shifts apply only to high-income regions, reflecting higher per capita livestock consumption[5] and concentration of PBA companies[25]. Extended diet shifts add upper-middle-income regions such as Brazil and China, where rising per capita meat consumption presents health and environmental concerns[24].

Figure 1 summarizes changes in household consumption. Because baseline consumption of PBAs is low, the preference shift expands global production dramatically: plant-based meat rises by 1,460–4,890% (high-income) and 4,370–14,560% (extended) and plant-based dairy by 210–760%

and 450–1,600%, respectively, the smaller increase reflects that plant-based dairy currently has a higher market share.

In the high-income scenarios, the global decline in animal product consumption is most pronounced for other meat (e.g., pork and chicken) at 3.61–12.13%, then ruminant meat at 2.89–9.80%, and least for dairy at 2.47–8.91%. The extended scenarios follow a similar pattern, with other meat at 11.26–37.90%, ruminant meat at 8.50–29.02%, and dairy at 5.20–18.99%. Household demand for minimally processed vegetables, fruits, legumes, and whole grains rises modestly under the high-income scenarios (0.15–0.60%) and more substantially under the extended scenarios (0.68–2.65%), with smaller gains for other processed foods.

2.2 Economic effects of PBA diet shifts

Diet shifts reshape input demand across the food system, leading to changes in output (Figure 2a) and prices (Figure 2b). Tracing the high-income scenarios, a decline in livestock production (2.61–9.02%) reduces demand for labour, capital, land, and feed across these sectors, while growth in PBAs increases input demand along these value chains. Livestock and PBA sectors draw on overlapping ingredients and feedstocks. For instance, as soy is a central feedstock for both, net production changes depend on how reduced feed demand compares to increased PBA input requirements. Globally, PBA feedstocks (e.g., wheat, oats, starch-based legumes, soy, other oilseeds, and nuts) experience an overall production increase (0.85–3.00%). In contrast, other cereal grains, a key feed input, decrease (0.82–2.81%).

Despite this reallocation, land rents in shocked regions decrease, as agricultural production shrinks with the decline in livestock production exceeding the expansion of crop production (0.12–0.46%). Falling land rents reduce production costs and crop prices (0.15–0.57%), incentivizing substitution from other inputs towards land, lowering crop prices and raising final and intermediate crop demand. As PBA value chains are more electricity- and gas-intensive, shifts towards PBAs raise their relative prices (0.01–0.03%). Since capital, labour, and land are region-specific endowments, factor price effects occur locally. Stronger reductions in land rents than prices

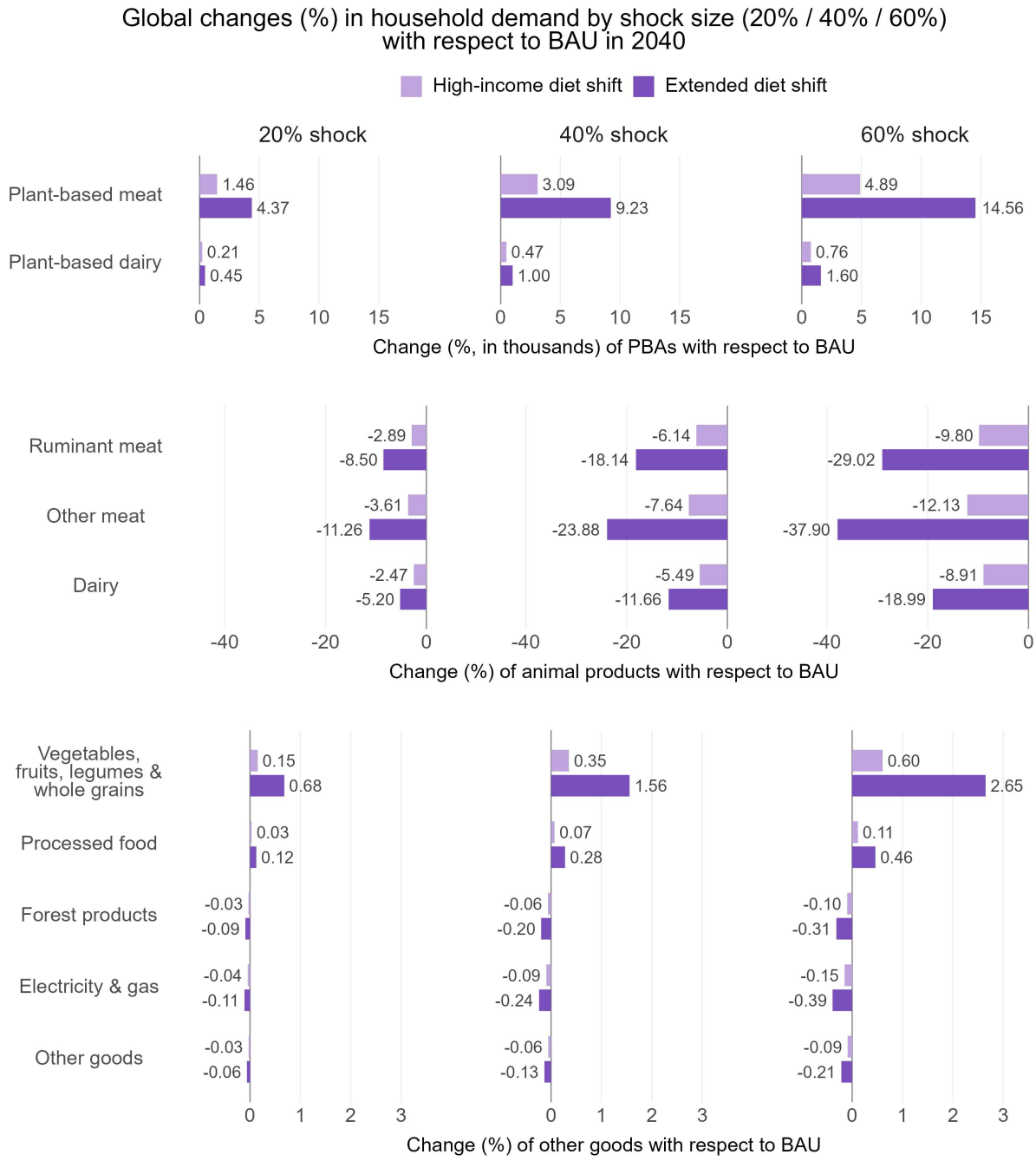


Figure 1: Change in household consumption following diet shifts towards PBAs.

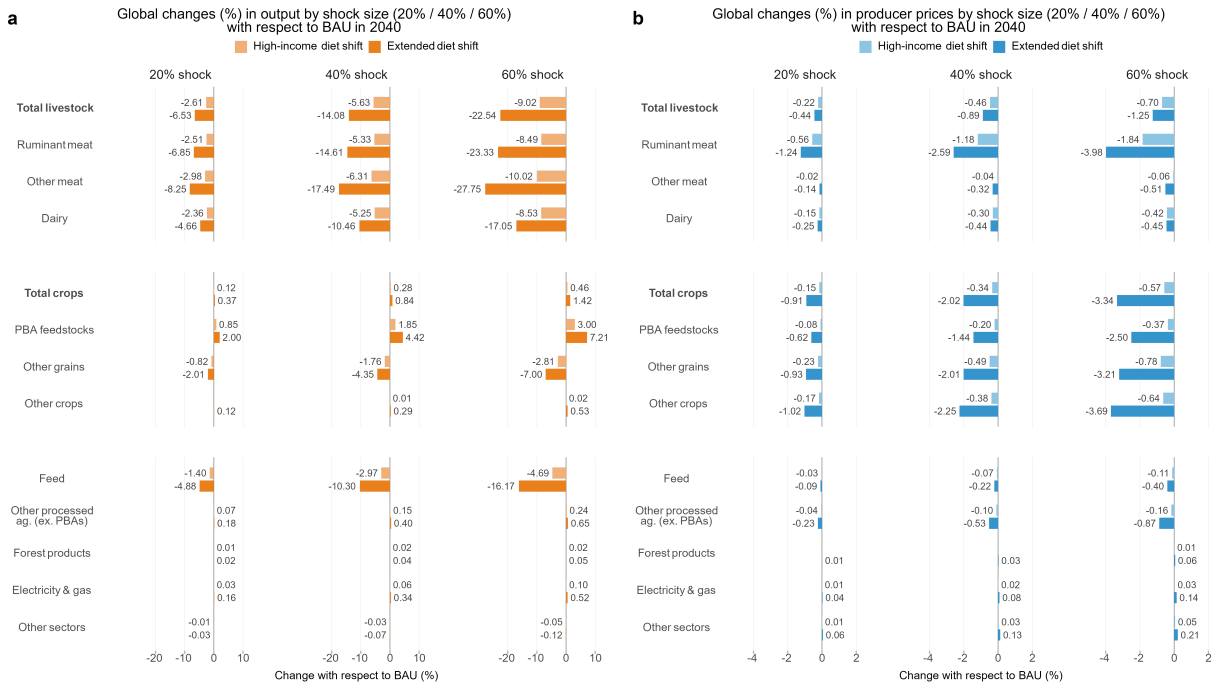


Figure 2: Changes in sectoral output and prices following diet shifts towards PBAs.

for other factors and energy raise costs for non-food relative to agricultural products. As a result, household demand (Figure 1) for forest products (0.03–0.10%), electricity and gas (0.04–0.15%) and other goods (0.03–0.09%) falls slightly. Extending the shock amplifies these effects (Figure 2). PBA feedstock production expands further (2.00–7.21%) while other grains contract more sharply (2.01–7.00%). Greater downward pressure on land rents decreases crop (0.91–3.34%) and processed food prices (0.23–0.87%) relative to other sectors, and further lowers final demand for forest products (0.09–0.31%), electricity and natural gas (0.11–0.39%) and other goods (0.06–0.21%).

Output effects vary regionally (Figure 3a–d; Supplementary notes, Table 1). Under the 40% high-income shock, livestock production shrinks across all regions, most sharply where shocked (7.52–19.51%), with smaller spillovers elsewhere (0.21–3.05%). Crop production expands in most shocked regions (0.74–7.43%) as the growing PBA industry and increased demand from falling agricultural prices offset losses in feed crops. Extending the shock deepens the livestock decline everywhere (0.42–24.99%). Crop responses are more mixed, rising sharply in high-income (9.75%) and upper-middle-income (5.85%) Latin America, falling in high-income Europe and Central Asia (1.61%), and rising only slightly in Brazil (0.94%) and North America (0.14%).

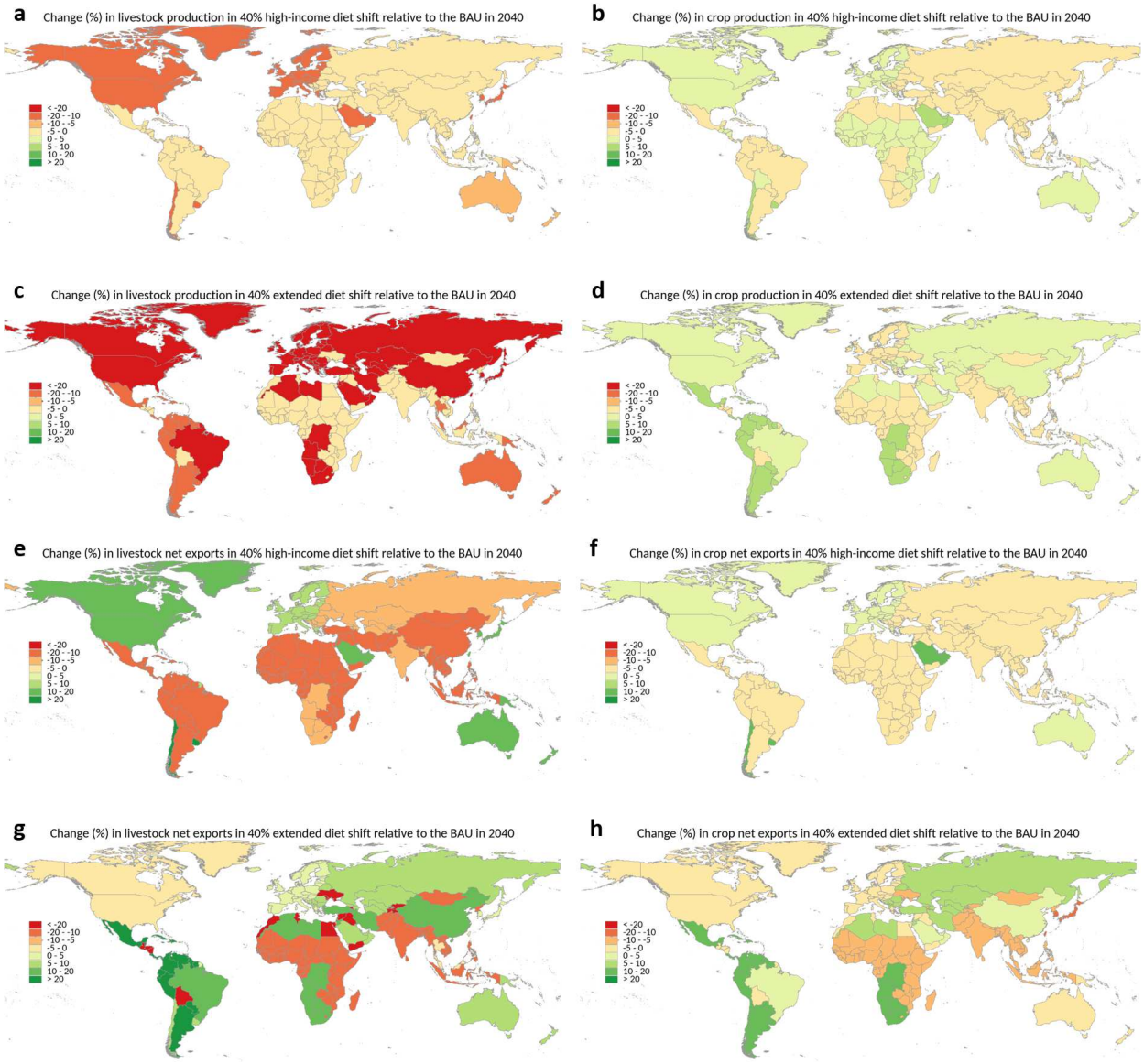


Figure 3: Changes in regional production and net exports under the 40% high-income and extended scenarios.

This regional variation also reflects a price-driven redistribution of agricultural production: the diet shift lowers relative prices in shocked regions, increasing their price competitiveness and raising net exports (Figure 3e–h; Supplementary notes, Table 2). Under the high-income shock, livestock and crop net exports rise in high-income regions, most strongly in Latin America (26.27%), and fall elsewhere (6.77–19.26%). Extending the shock produces a more extreme reallocation. Livestock net exports rise sharply in upper-middle-income Latin America (27.29%) but change little in high-income Europe and Central Asia (1.24%) or North America. Crop net exports rise strongly in high-income (15.87%) and upper-middle-income (14.94%) Latin America, marginally in Brazil (0.17%), and fall in North America (3.98%) and high-income Europe and Central Asia (3.93%).

2.3 Environmental effects of PBA diet shifts

Given these economic effects, we examine the environmental implications of PBA-driven diet shifts (Figure 4). In the high-income scenarios, global annual non-LUC GHG emissions fall (63.59–219.72 Mt CO_2eq), driven by lower N_2O (18.70–64.37 Mt) and CH_4 (43.08–149.18 Mt). CO_2 contributes only modestly to emission reductions (1.72–5.83 Mt): lower emissions from livestock rearing (1.23–4.21 Mt) and processing (1.16–4.05 Mt), and household demand (2.46–8.42 Mt) are partially offset by PBA processing (1.99–6.76 Mt) and electricity and gas (2.42–8.14 Mt).

In the extended scenario, non-LUC reductions are 148.63–527.08 Mt CO_2eq with lower N_2O (64.56–224.93 Mt) and CH_4 (123.15–432.51 Mt) compensating for an overall increase in CO_2 (38.93–130.12 Mt). For CO_2, growing emissions from PBA processing (22.55–74.70 Mt) and electricity and natural gas (30.66–101.54 Mt) exceed reductions from livestock rearing (4.08–14.04 Mt) and processing (3.47–12.03 Mt), and household consumption (8.28–28.04 Mt).

Land conversion also reflects these price changes (Table 3, Supplementary notes). In the BAU, cropland expansion follows FAO projections. In the counterfactuals, managed-land stocks adjust in response to land rents, with conversion occurring across managed land types (cropland, pastureland, and managed forest) and between managed and natural land. In the high-income scenarios, falling land rents ease conversion pressure and managed land falls (5.10–18.40 Mha). As PBA growth

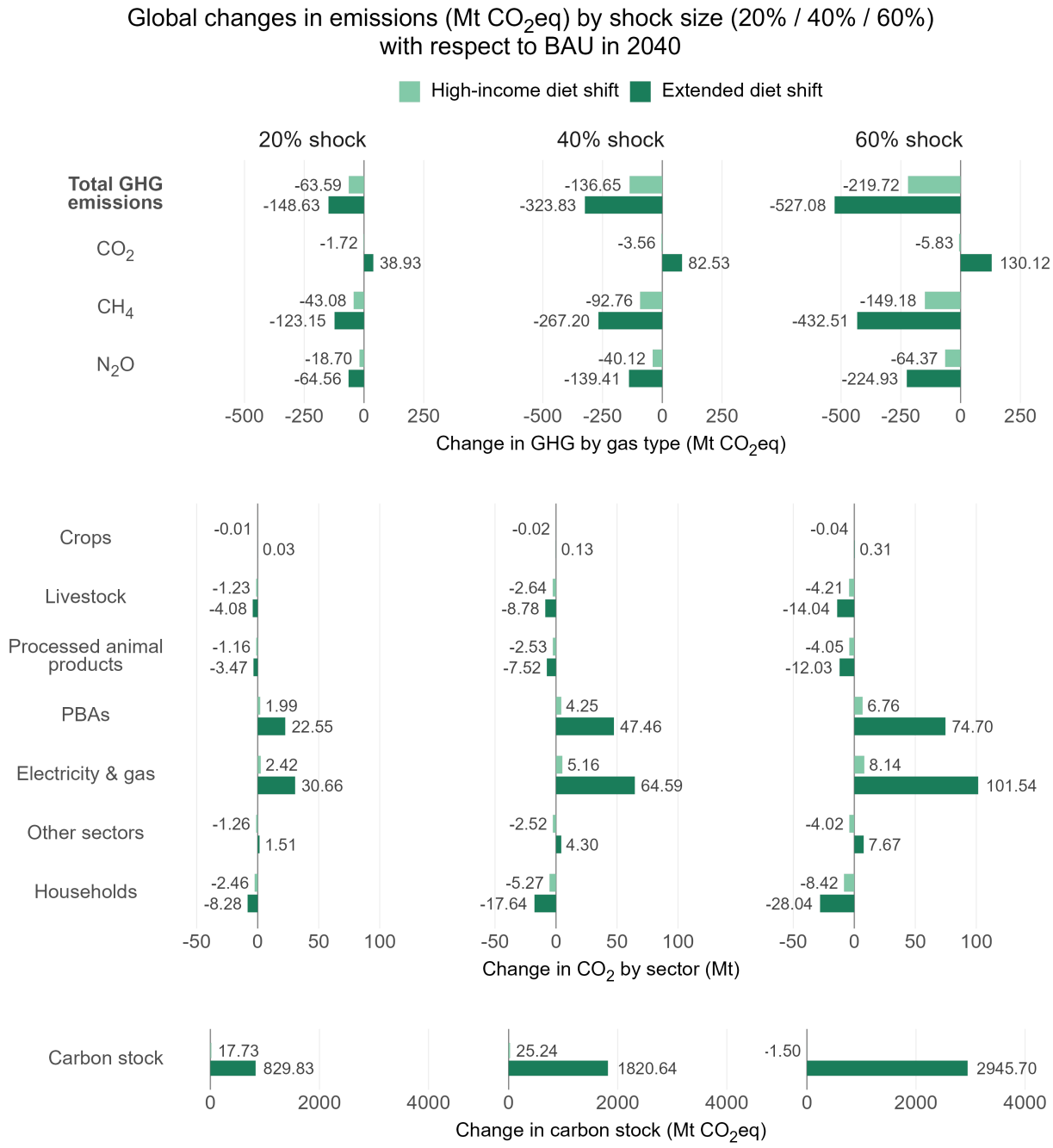


Figure 4: Changes in environmental impacts following diet shifts towards PBAs.

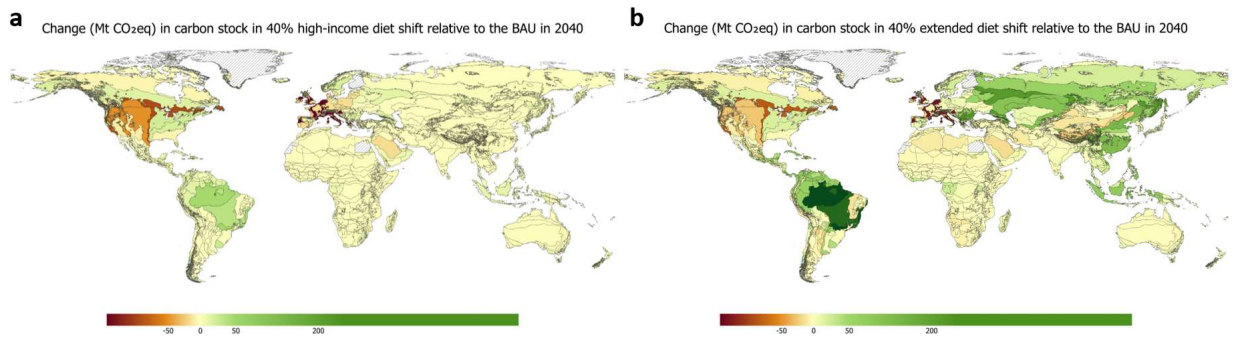


Figure 5: Changes to regional carbon stocks under the 40% high-income and extended scenarios.

lowers livestock returns relative to crops, and pastureland rents relative to cropland, global pastureland contracts (11.42–42.89 Mha) while cropland expands (6.39–24.70 Mha). Managed forest also declines slightly (0.79–2.16 Mha), as returns to forest products fall compared to crops. The extended scenarios strengthen these effects, with greater declines in managed land (20.79–75.09 Mha), pastureland (40.15–156.70 Mha), and managed forest (0.96–3.38 Mha), alongside greater cropland expansion (20.32–84.99 Mha).

Carbon stocks vary regionally with changes in natural land area and conversion between managed land types. In the high-income scenario, carbon stocks change only modestly, rising 17.73–25.24 Mt under the 20–40% shocks but falling 1.50 Mt at 60% (Figure 4). Under 40% substitution, carbon stock losses are 129.08 Mt in high-income Europe and Central Asia and 77.39 Mt in North America (Figure 5a, Table 4, Supplementary notes), as gains in carbon stock from lower natural land conversion cannot compensate for the lower carbon sequestration per hectare of cropland compared to pastureland and losses from managed forests (Table 5, Supplementary notes). Under the extended scenarios, LUC emissions fall more substantially (829.83–2945.70 Mt; Figure 4). Looking at the 40% shock, Brazil (750.51 Mt) and upper-middle-income Europe and Central Asia (422.98 Mt) lead this carbon stock increase (Figure 5b; Table 4, Supplementary notes). Losses are smaller in high-income Europe and Central Asia (88.94 Mt) and North America (54.28 Mt), where less production eases pressure on managed land. In Brazil, lower land prices slow deforestation of carbon-rich unmanaged forest.

2.4 Impacts of technological change

Our main scenarios assume intensive processing technologies with high feed and energy inputs. Additional technology scenarios retain the same diet shifts but adopt milder refining techniques (Table 6, Supplementary notes) with a 10% reduction in feedstock and 60% reduction in energy use for plant-based protein extraction.

The technology change raises average energy prices slightly via higher capital rents, so there is no incentive to substitute towards energy, and the reduction in PBA energy intensity translates directly into lower CO_2 emissions (Figure 6). In the high-income scenarios, milder extraction further reduces non-LUC CO_2eq by 2.06–6.83 Mt, mainly from PBA processing and electricity and gas. Reductions are starker in the extended scenario (31.67–103.74 Mt), where technological change cuts the original 38.93–130.12 Mt CO_2 increase by 30.22–98.66 Mt, leaving a net increase of only 8.71–31.46 Mt.

LUC emissions decline slightly in both scenarios as greater feedstock efficiency lowers land prices and slows land expansion, although, consistent with Jevons paradox[26], cheaper land is partly substituted for other inputs, dampening land savings. Reduced land expansion increases unmanaged forest area, driving a 7.45–25.51 Mt gain in carbon stock (Figure 6; Table 7, Supplementary notes). In the high-income scenario at 60% substitution, this increase reverses the net loss seen under the main scenario. The extended scenarios have 22.46–80.54 Mt carbon stock growth, driven by afforestation (unmanaged forest expansion) in North America and reduced deforestation in Brazil.

3 Discussion

Our results indicate that PBAs can contribute to more sustainable food systems, even after accounting for economy-wide feedback effects, through both lower farm-level emissions and increased carbon sequestration from reduced deforestation and land restoration. However, the overall environmental gains from restructuring livestock into PBA value chains depend on feedback effects from lower agricultural and land prices and the energy intensity of PBA processing.

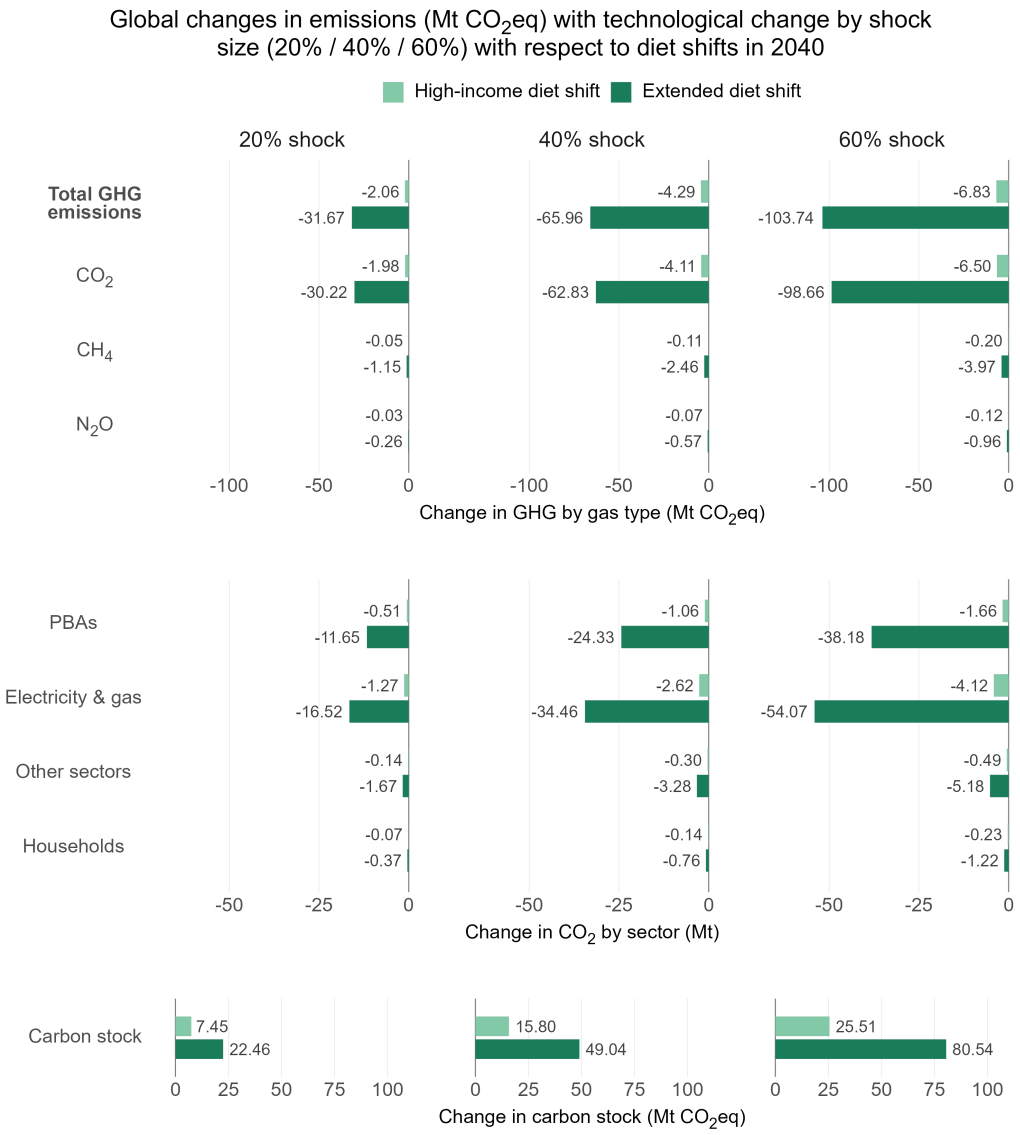


Figure 6: Changes in environmental impacts following technological change (milder protein extraction).

On-farm CH_4 and N_2O reductions drive non-LUC emissions savings, indicating that substitution away from livestock is crucial for reducing food system emissions. This result is consistent with studies of PBA substitution of beef in the US[23] and of livestock globally[24]. Falling livestock production reduces enteric fermentation and manure, key sources of CH_4[27]. Less manure and synthetic fertilizer application reduce N_2O[28], with falling land prices driving the latter by shifting input use away from chemical inputs and towards cropland. These mechanisms also reduce emissions in non-shocked regions, though less strongly, as livestock falls indirectly through reduced net exports while crop production shifts toward shocked regions.

We endogenize the conversion between natural and managed land, bringing natural land into production as land rents rise or removing hectares from production as rents fall. The downward pressure on land rents observed in our scenarios slows land-use expansion relative to the baseline, and the increase in unmanaged forests, especially tropical forests in Brazil, drives carbon-sequestration gains in the extended scenarios. However, cheaper land partially substitutes other inputs, limiting land savings through more extensive agricultural production. Land rents are only one of many factors influencing the complex dynamics of land-use conversion, including conservation and land restoration measures[24] and regulatory compliance and effectiveness[29].

Preference shifts towards PBAs free up land, lowering agricultural prices and generating price-driven feedback effects for agricultural products. As in other general equilibrium studies of plant-based diet transitions[17,23], these effects make it difficult to discern how much lower prices influence crop demand compared with the relative efficiency of converting feedstock into PBAs rather than animal feed. Similarly, technological change has rebound effects: greater feedstock efficiency lowers crop prices and cuts costs for PBAs and other agricultural products, raising demand and partially offsetting crop savings. Shifting preferences towards fewer calories, already emphasized by healthy and sustainable diet guidelines[5], could offset price-driven increases in crop demand by curbing food consumption. However, freed income may shift consumption towards emissions-intensive goods[17].

Production technologies for livestock rearing and processing value chains vary considerably

across regions[25], which shapes how PBA substitution influences regional emissions. More efficient protein extraction technologies could have a greater mitigating effect in upper-middle-income regions, where technological change offsets much of the non-LUC CO_2 emissions increase from economic restructuring towards PBA value chains. However, milder extraction techniques yield a lower protein content[30]. Moreover, replicating the functional and sensory properties of animal-based products is often considered crucial for PBA adoption[31], likely creating a trade-off between formulations that best mimic animal-based foods and emissions savings, as closer replication may require more intensive processing.

Our study has limitations stemming from our modelling assumptions. First, although our PBA technologies draw on the most common PBA feedstocks, they are highly stylized, and the ingredients are not country-specific. This contributes to large production shocks in some regions (e.g., high-income South and East Asia) that do not typically produce or consume certain crops, such as starch-based legumes or nuts. Widespread adoption likely requires a PBA offering that reflects regional and cultural preferences. Second, due to data limitations, we assume that increased PBA consumption is accompanied by the development of value-added processing capacity within the same region. In reality, PBA manufacturing is currently concentrated in high-income regions, and expanding regional consumption may not translate into regional growth in PBA value chains.

Despite these limitations, our results have several policy implications. PBAs can foster sustainable food systems alongside other measures for sustainable and healthy food systems (e.g., cutting food waste and calorie intake and substitution toward minimally processed legumes, vegetables, fruits, nuts, and whole grains[5]). In the model, we force preferences to change without assuming any interventions, as do many approaches to modelling diet transitions[17,23,24], but in practice, substituting meat and dairy with PBAs likely depends on a supportive policy environment.

Given often low substitution elasticities between animal-based foods and PBAs[32], combining information-based policies with fiscal measures is likely more effective than any single intervention. Information campaigns can promote moderate PBA consumption within a balanced diet. Clear emissions labels, such as carbon footprint labels[33], could encourage consumers to purchase PBAs

and less energy-intensive formulations, although labelling has had mixed success in promoting environmentally friendly purchases[34]. Fiscal instruments, such as restructuring livestock subsidies[35] and reducing value-added taxes on PBAs[36], can make PBAs and other plant-based foods relatively more affordable. If calorie consumption declines in line with dietary guidelines, greenhouse gas emission taxes may help prevent expenditure from shifting toward emissions-intensive non-food products[17,32]. Land conservation and forest restoration measures implemented alongside PBA adoption policies can help secure carbon sequestration gains. For PBA technologies, a greener energy mix and investments in lower-energy processing technologies that still replicate animal-based foods would reduce PBA emissions, particularly in upper-middle-income regions.

Our study provides a starting point for incorporating food technologies into analyses of the global economic impacts of dietary transitions. Future research should include more detailed nutritional data and a wider range of PBA ingredients to better reflect the caloric and nutritional consequences of these transitions. It should also assess the environmental effects of substituting specific animal products, as targeting high-impact products such as beef is likely more efficient than replacing products with lower impacts, such as chicken. Finally, greater attention should be given to the distributional and equity implications of PBA transitions across different household groups and in regions reliant on livestock production to better understand how costs and benefits are distributed and to inform policies that support more just dietary transformations.

4 Method

4.1 Data processing

We adapt the GTAP-Power Database (v.11)[37] to explicitly represent PBA and livestock value chains and capture their input requirements, specifying additional sub-sectors using the split utility approach[14] (Table 8, Supplementary notes). Following Britz[38], we introduce crops central to PBAs (e.g., oats, starch-based legumes, nuts, and soybeans), a soy-crushing activity co-producing soy cake and soy oil, and feed concentrate with region-specific crop demands. In addition, we establish

five new sub-sectors to represent PBA products explicitly. We split these from the 'other food processing' sector, which includes PBA-related products such as protein concentrates and food preparations from soy flour[39]. Table 9 (Supplementary notes) shows the production technologies for our plant-based protein sectors, expressed as the cost of each input per US$1 of output.

First, we add three plant-protein extraction sectors based on the most common feedstocks[40]: soy, starch-based legumes, and wheat. We assume the current industry standard for protein-extraction technologies, 'wet fractionation', which suspends the milled feedstock in water, chemically precipitates and then dries the protein, with drying contributing most to energy use[12]. To calculate the cost shares for our plant-based proteins, we combine LCAs and other food science publications to derive the physical quantities of raw materials, energy (natural gas and electricity) and chemicals required to produce one kg of protein isolate (Tables 10–13, Supplementary notes). For wheat and starch-based legume proteins, the cost shares include milling the crop into flour. For soy protein, the soy crushing activity captures the oil extraction (defatting) step, and soy cake enters the technology as a proxy for defatted soy flour, the typical industry starting point for soy protein extraction. We then multiply the physical quantities of these inputs by average US prices and divide by the market price of the protein per kg to convert them into cost shares. Protein isolates are both feedstock- and energy-intensive to produce, with feedstock accounting for roughly 30–31% and energy for 26–27% of input costs (i.e., 30–31¢ and 26–27¢ per US$1 of output).

Second, we introduce two activities producing PBA products for household consumption: a plant-based meat analogue and a plant-based dairy analogue. In the split utility approach, output split shares allocate production from the original sector to each new activity according to the sub-sector's value share in each region. Assuming households consume PBAs directly, we approximate these shares as retail sales of PBAs at cost (https://www.euromonitor.com/), divided by the production value of 'other food processing'. Table 9 includes the cost shares of key inputs (cost breakdown in Tables 13–15, Supplementary notes).

The representative plant-based meat analogue uses the operating expenses of a conventional extrusion technology to estimate cost shares for raw materials and electricity. We then allocate the

raw materials cost share across individual ingredients (vegetable oils and soy, legume, and wheat protein) in proportion to their projected demand in the plant-based meat sector, valued at benchmark prices. We assume that the extracted proteins are used exclusively in the plant-based meat analogue, so the production value of extracted proteins equals this intermediate input demand.

The plant-based dairy aggregate includes the most common milk types based on global market share: soy (0.65%), oat (0.20%), and nut-based milks (0.15%) (https://www.euromonitor.com/). For each milk type, we calculate the cost shares of the corresponding production technology using LCAs. We first derive the physical quantities of key intermediate inputs required per litre, convert these quantities into input costs using benchmark prices, and divide these costs by the total production cost per litre. Finally, we then weight the resulting cost shares by each milk type's global market share to derive the final cost shares.

For ease of interpretation and to maintain consistency across data sources, we use US prices and apply the resulting cost shares across high- and upper-middle-income regions. For factor demand, and where information on intermediate inputs is unavailable, we apply the proportionality assumption (see Britz[38]) to ensure production value equals total cost.

For the technological change scenarios, we introduce a 'dry fractionation' technology, which uses air classification or electrostatics to separate flour into a protein-rich fraction (around 40-60%) and a starch-rich fraction, avoiding the energy-intensive drying process but yielding a lower protein content than the at least 80% typical of 'wet fractionation'[30]. Based on a comparison of wet and dry fractionation for yellow peas, we estimate that switching from a wet to dry fractionation method can produce 1 kg of ingredient with around 60% less energy and 10% less feedstock (Table 6, Supplementary notes).

4.2 Modelling framework

We set up a recursive dynamic CGE model in the flexible, modular, and open-source platform CGEBox[41]. CGEBox is built on the GTAP standard model and includes modules for database disaggregation, flexible nesting, and baseline construction. We use its G-RDEM module[42] to

construct the BAU baseline by calibrating total factor productivity to exogenous GDP and population projections from the Shared Socioeconomic Pathway 2 (SSP2), while accounting for structural change processes consistent with this narrative (see Goebel and Britz[43]). Our model setup includes a MAIDADS final demand system estimated by Britz[44], which is particularly suited to modelling long-run food expenditure as budget shares adjust with rising incomes. We also incorporate GTAP-E[45] to allow substitution between capital and energy, and an extended version of GTAP-AEZ[46], which enables conversion between cropland, pastureland, and managed forest within the same agro-ecological zone (AEZ) and lets the stock of managed land adjust to land rents using regionally estimated AEZ elasticities, with a default of 0.05 where estimates are unavailable[47].

We modify the final demand structure by adding lower-level CES sub-nests for the agro-food sector to reflect substitution between similar commodities, drawing on the structure of GTAP-AGR[48]. We extend the existing CES structure for composite meat and dairy commodities by nesting conventional meat with the plant-based meat analogue and conventional dairy products with the plant-based dairy analogue. Both composites are assigned a substitution elasticity of 0.5, consistent with within-group elasticities for meat and dairy products reflecting findings that elasticities between plant-based and animal-based products are similar to those between different animal-based foods[49].

We aggregate the GTAP-Power v.11 regions by income level, using World Bank income classification and geographic region, into high-, upper-middle-, lower-middle-, and low-income categories (Table 16, Supplementary Notes). China and Brazil (both upper-middle-income) and India (lower-middle-income) remain disaggregated as major agricultural producers. To improve computational efficiency, we combine all electricity-generating technologies (11) into one electricity-generating sector (ely). All other sectors are kept disaggregated, resulting in 66 sectors pre-split. The final database comprises 19 countries or regions, a non-diagonal make with 78 commodities, 77 production activities, and five production factors.

To implement the dietary shocks, we use a twist parameter (see van der Mensbrugghe[50]) to update preferences towards plant-based and conventional animal foods, while preserving aggregate utility. We calibrate the twist parameter from baseline final consumption quantities to achieve 20:80,

40:60 and 60:40 splits between plant-based and conventional animal foods by 2040, corresponding to the 20%, 40% and 60% shock sizes (Tables 17–19, Supplementary notes). The shock is introduced in a stepwise fashion, accounting for changes in the relative prices of conventional animal products and PBAs.

For the technology scenario, we also use twist parameters to lower feedstock requirements by 10% and energy requirements by 60% while holding initial production costs constant, relative to the extended and high-income diet-shift scenarios in each period. The twist updates the non-neutral productivity shifters in the capital–energy bundle to reduce energy requirements while increasing capital use, and in the intermediate input bundle to reduce feedstock requirements while increasing the use of other inputs. We calibrate these technology shocks using prices from the extended and high-income diet-shift scenarios, allowing the model to still capture endogenous responses to changes in feedstock and energy prices (Tables 20–22, Supplementary notes).

References

[1] Clark, M. *et al.* Estimating the environmental impacts of 57,000 food products. *Proceedings of the National Academy of Sciences of the United States of America* **119** (2022).

[2] Williams, D., Buchanan, G., Ficetola, G. & Rondinini, C. Proactive conservation to prevent habitat losses to agricultural expansion. *Nature Sustainability* **4** (2021).

[3] Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).

[4] Shepon, A., Eshel, G., Noor, E. & Milo, R. Energy and protein feed-to-food conversion efficiencies in the us and potential food security gains from dietary changes. *Environmental Research Letters* **11**, 105002 (2016).

[5] Rockström, J. *et al.* The eat-lancet commission on healthy, sustainable, and just food systems. *The Lancet* **406** (2025).

[6] McClements, D. & Grossmann, L. Next-generation plant-based foods: Challenges and

opportunities. *Annual Review of Food Science and Technology* **15** (2024).

[7] McClements, D. & Grossmann, L. The science of plant-based foods: Constructing next-generation meat, fish, milk, and egg analogs. *Comprehensive Reviews in Food Science and Food Safety* **20** (2021).

[8] Bryant, C. Plant-based animal product alternatives are healthier and more environmentally sustainable than animal products. *Future Foods* **6** (2022).

[9] Battle, M. *et al.* State of the industry report: Plant-based meat, seafood, eggs, dairy, and ingredients. Tech. Rep., The Good Food Institute (2026). Available at https://gfi.org/wp-content/uploads/2026/05/GFI_2026_State-of-the-Industry-Plant-based-meat-seafood-eggs-dairy-and-ingredients.pdf.

[10] Springmann, M. A multicriteria analysis of meat and milk alternatives from nutritional, health, environmental, and cost perspectives. *Proceedings of the National Academy of Sciences* **121** (2024).

[11] Smetana, S. *et al.* Meat substitutes: Resource demands and environmental footprints. *Resources, Conservation and Recycling* **190**, 106831 (2023).

[12] Lie-Piang, A., Braconi, N., Boom, R. & van der Padt, A. Less refined ingredients have lower environmental impact – a life cycle assessment of protein-rich ingredients from oil- and starch-bearing crops. *Journal of Cleaner Production* **292** (2021).

[13] Schutyser, M., Pelgrom, P., van der Goot, A. & Boom, R. Dry fractionation for sustainable production of functional legume protein concentrates. *Trends in Food Science & Technology* **45** (2015).

[14] Escobar, N. & Britz, W. Metrics on the sustainability of region-specific bioplastics production, considering global land use change effects. *Resources, Conservation and Recycling* **167** (2021).

[15] Springmann, M. *et al.* Options for keeping the food system within environmental limits. *Nature* **562** (2018).

[16] Mishra, A. *et al.* Affordability and nutritional challenges for the future of eat diets: an economic modelling analysis (2025).

[17] Gatto, A., Kuiper, M. & Van Meijl, H. Economic, social and environmental spillovers decrease the benefits of a global dietary shift. *Nature Food* **4**, 496–507 (2023).

[18] Kuiper, M., De Lange, T., Van Zeist, W.-J. & Van Meijl, H. Exploring environmental and distributional impacts of different transition pathways for healthier and sustainable diets: an economic modelling study. *The Lancet Planetary Health* **9** (2025).

[19] Gibson, M. *et al.* Food systems transformation would reshape global agriculture. *Nature* (2026).

[20] Haddad, S., Escobar, N., Bruckner, M. & Britz, W. Subsidizing extensive cattle production in the european union has major implications for global agricultural trade and climate change. *Journal of Cleaner Production* **448** (2024).

[21] Gatto, A., Kuiper, M., van Middelaar, C. & van Meijl, H. Unveiling the economic and environmental impact of policies to promote animal feed for a circular food system. *Resources, Conservation and Recycling* **200** (2024).

[22] van Meijl, H. *et al.* On the macro-economic impact of bioenergy and biochemicals – introducing advanced bioeconomy sectors into an economic modelling framework with a case study for the netherlands. *Biomass and Bioenergy* **108** (2018).

[23] Mason-D'Croz, D. *et al.* Ethical and economic implications of the adoption of novel plant-based beef substitutes in the usa: a general equilibrium modelling study. *The Lancet Planetary Health* **6** (2022).

[24] Kozicka, M. *et al.* Feeding climate and biodiversity goals with novel plant-based meat and milk alternatives. *Nature Communications* **14** (2023).

[25] Qaim, M., Barrangou, R. & Ronald, P. C. Sustainability of animal-sourced foods and plant-based alternatives (2024).

[26] Alcott, B. Jevons' paradox. *Ecological Economics* **54** (2005).

[27] Ocko, I. *et al.* Acting rapidly to deploy readily available methane mitigation measures by

sector can immediately slow global warming. *Environmental Research Letters* **16** (2021).

[28] Ivanovich, C., Sun, T., Gordon, D. & Ocko, I. Future warming from global food consumption. *Nature Climate Change* **13** (2023).

[29] Börner, J., Schulz, D., Wunder, S. & Pfaff, A. The effectiveness of forest conservation policies and programs. *Annual Review of Resource Economics* **12**, 45–64 (2020).

[30] Lie-Piang, A., Yang, J., Schutyser, M., Nikiforidis, C. & Boom, R. Mild fractionation for more sustainable food ingredients. *Annual Review of Food Science and Technology* **14** (2023).

[31] Espey, A., Schuenemann, F. & Weinrich, R. Just another food fad? expert insights and future scenarios for the plant-based alternative sector. *Technological Forecasting and Social Change* **223** (2026).

[32] Caputo, V., Lusk, J. & Blaustein-Rejto, D. Plant-based versus conventional meat in food away from home settings: substitution, complementarity, and market impacts. *Agricultural Economics* **56** (2025).

[33] Taufique, K. *et al.* Revisiting the promise of carbon labelling. *Nature Climate Change* **12** (2022).

[34] Majcher, S. Consumers' perspective of plant-based meat alternatives—a systematic literature review and future research agenda. *International Journal of Consumer Studies* **49** (2025).

[35] Siegrist, M., Michel, F. & Hartmann, C. The shift from meat to plant-based proteins: consumers and public policy. *Current Opinion in Food Science* **58** (2024).

[36] Springmann, M., Dinivitzer, E., Freund, F., Jensen, J. & Bouyssou, C. A reform of value-added taxes on foods can have health, environmental and economic benefits in europe. *Nature Food* **6** (2025).

[37] Chepeliev, M. Gtap-power data base: Version 11. *Journal of Global Economic Analysis* **8** (2023).

[38] Britz, W. Disaggregating agro-food sectors in the gtap data base. *Journal of Global Economic Analysis* **7**, 44–75 (2022).

[39] United Nations. Central product classification (CPC) version 2.1. Statistical Papers, Series

M 77, Ver.2.1, United Nations, Department of Economic and Social Affairs, Statistics Division, New York (2015). Available at https://unstats.un.org/unsd/classifications/unsdclassifications/cpcv21.pdf. Accessed 6 October 2026.

[40] Troya, M., Kurawadwala, H., Byrne, B., Dowdy, R. & Weston, Z. Plant based meat: Anticipating 2030 production requirements (2022).

[41] van der Mensbrugghe, D. Cgebox: A flexible, modular and extendable framework for cge analysis in gams. *Journal of Global Economic Analysis* **3** (2018).

[42] Britz, W. & Roson, R. Exploring long run structural change with a dynamic general equilibrium model. *SSRN Electronic Journal* (2018).

[43] Goebel, T. & Britz, W. Global land use and land cover projections under the shared socio-economic pathways: An integrated computable general equilibrium analysis with sub-national resolution for europe. *Global Environmental Change Advances* **5** (2025).

[44] Britz, W. Estimating a global maidads demand system considering demography, climate and norms. *Bio-based and Applied Economics* **10** (2022).

[45] Burniaux, J.-M. & Truong, T. Gtap technical paper series (2002).

[46] Lee, H.-L., Hertel, T., Sohngen, B. & Ramankutty, N. Gtap technical paper series (2005).

[47] Miranda, J., Britz, W. & Börner, J. Impacts of commodity prices and governance on the expansion of tropical agricultural frontiers. *Scientific Reports* **14**, 9209 (2024).

[48] Wilts, R. & Britz, W. Distribution matters: Long-term quantification of the sustainable development goals with household detail for different socio-economic pathways. *Global Transitions* **6** (2024).

[49] Tonsor, G., Lusk, J. & Schroeder, T. Market potential of new plant-based protein alternatives: Insights from four us consumer experiments. *Applied Economic Perspectives and Policy* **45** (2023).

[50] van der Mensbrugghe, D. The constant elasticity of substitution function (2019). Available at https://www.gtap.agecon.purdue.edu/models/envisage/2019ENVISAGEWrkshp_2_CES-CETFunctions.pdf. Accessed 6 October 2026.

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