Bodirsky, B. L., Chen, D.-M.-C., Weindl, I., Sörgel, B., Beier, F., Molina Bacca, E. J., Gaupp, F., Popp, A., Lotze-Campen, H. (2022): Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100. - Nature Food, 3, 5, 341-348.

DOI: https://doi.org/10.1038/s43016-022-00500-3

Supplementary Information for:

Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100

Authors: Benjamin Leon Bodirsky, David Meng-Chuen Chen, Isabelle Weindl, Bjoern Soergel, Felicitas Beier, Edna Molina Bacca, Franziska Gaupp, Alexander Popp, Hermann Lotze-Campen

Includes:

1. Supplementary Text S1-2
2. Supplementary Table 1.
3. Supplementary Figures 1-4.

Supplementary Text

S1. Detailed Model Variables and Scenario Outcomes

In the business-as-usual (BAU) world, based on the middle-of-the-road storyline of the Shared-Socioeconomic Pathways[1], the amount of people living in high-income countries (based on the World Bank threshold between middle- and high-income countries[2]) increases from 3370 million people to 6499 million people by 2050, with 2695 million people living in middle- and low-income countries by 2050. Based on empirically estimated income elasticities[3], the global per-capita demand for food in terms of total calories increases from 2985 kcal/capita/day to 3222 kcal/capita/day from 2020 - 2050, while the demand for resource-intensive livestock products increases to 703 kcal/capita/day from its 2020 level of 547 kcal/capita/day (see figure S2a). The demand for animal products rises most strongly in the lower-income world regions (LIW, see table S1) and the rest-of-world world regions (ROW), while it remains rather constant in the high-income world regions (HIW). This is reflected by the strong increase in livestock production to 515 Mt dry matter (dm) by 2050 (Figure S3) and feed demand for crop products (Figure S2b) that is most pronounced in these world regions. Pasture areas are not increasing substantially (Figure S3) as the increase of production is mainly achieved via intensification of livestock system with a substitution of roughage feed by concentrate feed. To satisfy increased demand, crop production increases to 7961 million tonnes of dry matter (Mt dm). Trade in the year 2010 mainly happens within and between HIW and ROW, while LICs have only a minor fraction in agricultural trade and are mainly importers. By 2050, LIW becomes a major importer, while

HIW increases exports, likely due to a rising demand in LIW with increasing land scarcity and a stagnant demand in HIW.
The model correspondingly projects cropland area expansion by 362 Mha to 2125 Mha. Cumulative greenhouse gas (GHG) emissions in the period 2020-2100 amount to 1229 in CO2 equivalents (CO2eq). They mainly occur in LIW and ROW, as area expansion mainly occurs in tropical world regions and the emission intensity of livestock production is also higher in these world regions. Economic activity in the agricultural sector, as quantified by the total costs of production and processing activities in the model, rises from 2684 billion USD_{05PPP} to 4980 billion USD_{05PPP} in 2100 (Fig. 1b).

Beginning in 2020, the GDP-CAP scenario limits the average per-capita income of all countries around the globe to the World Bank threshold of 12746 USD_{05PPP} by the year 2030, the threshold between a middle- and high-income country[2]. As a consequence of reduced income, the consumption of animal-source foods (601 kcal/capita/day), processed foods (786 kcal/capita/day compared to 879 kcal/capita/day in BAU), fruits, vegetables (216 kcal/capita/day compared to 224 kcal/capita/day in BAU) is moderately decreased by 2050, while the consumption of staple crops rises to guarantee an adequate caloric intake (1199 kcal/capita/day compared to 1116 kcal/capita/day). The demand reduction is most pronounced in HIW, but as several of the current LICs and MICs become high-income countries in the BAU scenario by 2100, the demand reduction is also visible in the consumption patterns of LIW and ROW. The reduced consumption leads to less cropland expansion compared to BAU (2031 Mha by 2050).

The fair distribution GDP-FAIR scenario, which additionally increases the minimum per-capita income of people around the globe to 12746 USD_{05PPP} by 2030, results in a global GDP that is fixed roughly at current levels, but with an equal per-capita distribution. This redistribution of income results in a slight but rapid increase of total food demand as well as demand for animal source foods by 2030 (3212 kcal/capita/day and 645 kcal/capita/day by 2030 respectively, remaining roughly stable until 2100). By 2050, demand patterns in this scenario are again very similar to the GDP-CAP scenario as income redistribution has already moved per-capita incomes to the same level as the threshold of GDP-CAP the normal economic growth has moved per-capita incomes beyond the level where they would receive transfers (Figure S1). Crop production increases to 7666 Mt dm and 476 Mt dm for livestock products. Cropland area expands to 2123 Mha by 2050, values slightly higher than those of GDP-CAP given that the GDP-FAIR scenario is an accelerated convergence scenario. Yearly emissions increase rapidly during the redistribution phase, with emissions in 2030 in GDP-FAIR being higher than in any other scenario. However, as stated, cumulative emissions remain slightly below that of BAU by 2100. This can be explained by the accelerated income growth in lower-income countries in the time until 2030 combined with the Engel's Curve-shaped food demand functions, which show a steep increase of demand at lower-income levels that saturates with higher incomes[3].

The “Preference Change” (DIET) scenario illustrates the impacts that changes in food preferences could have. While per capita incomes remain the same as in BAU, the DIET scenario involves a shift in consumer demand by 2030 towards healthy and sustainable diets, as described by the EAT-Lancet commission[4]. The EAT Lancet diet contains much less demand for animal source foods (197 kcal/capita/day by 2030, remaining constant until 2100) and processed products (555 kcal/capita/day). Total food demand also decreases slightly to 2807 kcal/capita/day by 2050, reducing rates of overweight and obesity. Per-capita intake differs slightly by world regions depending on the metabolic needs of the population. LIW and ROW have a slightly lower per-capita demand due to a younger population and other demographic factors.

Our assumed preference change also extends to food waste, where we assume a per-capita reduction of 50% in high-income countries, resulting in a reduction of food waste from 25% wasted calories in BAU 2050 to 12% in DIET. As a consequence of altered food demand, the production of livestock and the demand for feed falls. Still, the demand for plant-based food does not strongly increase due to waste-reduction (fig S2b, S3). International trade is reduced substantially in the DIET scenarios, mostly due to a reduction of demand in ROW, while HIW is still a net-exporter of food and LIW a net-importer. The strongly reduced crop demand (Figure S2) results in a contraction of cropland area (1854 Mha by 2100).

The efficient allocation “EFF” scenario draws from the idea that without an internalization of the pollution damage of an activity, the information on the scarce absorption capacity of the Earth System is lost within markets or other social interactions, resulting in inefficient factor allocation. To reduce global warming, the internalized price-information and incentives can be restored through a CO2eq tax on GHGs. This increases production and land expansion costs according to the GHG intensity of the respective activity. The carbon tax incentives lead to the abstention from polluting activity such as deforestation, or the undertaking of afforestation and adopting pollution mitigation measures such as more efficient fertilization or livestock management. This is evidenced by the substantial reduction in emissions referenced above and in Fig. 1. Cropland also expands to only 1903 Mha by 2050, 225 Mha less than in BAU.

Our “sustainable transformation” (TRANS) scenario combines the fair redistribution, emissions taxation, and dietary change scenarios. Demand levels match those of the DIET scenario above, while income levels in lower- and middle-income countries are at 12746 USD/capita by 2050, compared to 6702 USD/capita. The TRANS scenario sees the highest environmental benefits as evidenced already by its emissions. Less cropland is expanded in the TRANS scenario than any other scenario, at 1717 Mha by 2050, and pasture land is reduced to 2433 Mha by 2050 compared to 3207 Mha in BAU. This is the combined effect of reduced demand and price-incentives for afforestation on unused pasturelands. Cumulative emissions from 2020 onwards are thus limited to 93 Gt by 2050 and 109 Gt by 2100. Methane emissions and nitrous oxide are even lower than in the DIET scenario due to efficiency improvements and the employment of mitigation technologies. Carbon sequestration through afforestation even leads to net-negative greenhouse gas emissions by the end of the century.

S2 Price elasticity of food demand

To our knowledge, there is no global scale database that estimates the price elasticity of physical quantities of food consumption to changes in the prices of agricultural raw-commodities. Global-scale models usually work with food expenditure elasticities relating food expenditure (quantity * price) with final consumer prices (see Valin et al. 2014[5], Latka et al. 2020[6] appendix B, Springmann et al. 2018[7]). They thereby attribute both quantity and quality substitution to a change in quantity, while in reality quality substitution plays an

important role, e.g. the shift from processed to unprocessed or from fresh to preserved ingredients, the selection of a cheaper brand, or the change from a more expensive to a cheaper retailer. This quality substitution does however not reduce the environmental impacts connected to the production of the raw ingredient. Bonnet et al (2018) consider quality adjustment by covering 28 product categories of different cuts of meat, resulting in a considerably lower demand elasticity than other models. Yet, also their study only covers part of the quality adjustment as they do not consider substitution between brands or store chains.
Secondly, they often do not, or not comprehensively, represent the value added in the food supply chain which makes up the difference between raw commodity prices and final consumer products. These post-farmgate value chains make up more than 60% of consumer food expenditures in India, and more than 75% in the United States[8]. Any price shock to agricultural markets is therefore strongly diluted by the value added before arriving at consumers, and therefore have a smaller impact on final food expenditures.

Quantity reactions to price shocks estimated with expenditure elasticities should therefore rather be considered high-end estimates. Nevertheless, already these studies find a very inelastic demand reaction to prices. Springmann et al (2018)[7] estimate that consumer prices for processed meat would need to more than double to achieve a reduction in expenditure by 25% in high-income countries. Latka et al (2020)[6], using three different food system models, estimate that red and processed meat prices would need to change by more than an order of magnitude (~1400-2600%) in the European Union to achieve a reduction of expenditure for red and processed meat by 50%. As the authors state[6], such high changes in prices and quantities also go beyond the domain at which measured price elasticities can be applied with confidence, as they only express the price elasticity at the current marginal consumption levels. Moreover, a recycling of tax revenues as income transfer would further reduce the income-effect of the price shock.

A practical example illustrates why the environmental footprint of food consumption is too small a tax basis for incentivizing diet change in the necessary magnitude in high-income countries. In Germany, the carbon footprint of a vegan diet is still roughly half that of an average consumer[9]. This difference of about 1.1t CO2eq per year translates into a diet-related mitigation of roughly 1 kg of CO2eq per meal. Our CO2 price trajectory estimates prices of 110 and 371 USD05/tCO2eq in 2025 and 2050, respectively, and thus results in a price difference of 0.11 and 0.37 USD per meal between a vegan and a vegetarian option in 2025 and 2050. The price difference would be even further reduced when mitigation reduces the emission intensity and therefore the tax basis. These price differences are unlikely to change consumption patterns in high-income countries in the order of magnitude that is sketched out in our DIET scenario. Roosen et al. (2022)[10] estimate that for a meat tax in Germany of 86 USD05/tCO2eq (100 USD/tCO2eq with unspecified base year, but likely 2012-2014) greenhouse gas emissions from meat products (not total diet emissions) fall by 8.9%. This estimate however does not include incomplete price transmission to consumers[11], the effects of supply-side mitigation, increased greenhouse gas emissions through substitution with e.g. dairy products or plant-based products, quality substitution, and tax recycling - all of which would reduce the mitigation potential of tax-induced diet change. For France[12], a consumption taxation of 20% on all animal products (corresponding roughly to our 110 USD05/tCO2eq taxation scenario) would result in a reduction of diet-related GHG emissions by 7.5%, again with similar limitations. Bonnet et al (2018)[13], considering different consumption taxation and including quality substitution between different cuts of meat with a CO2 price of 40 and 200 EUR/tCO2eq (46 and 230 USD05/tCO2eq, again including no dampening by supply-side mitigation) find a reduction of greenhouse gases of only 2% and 6%.

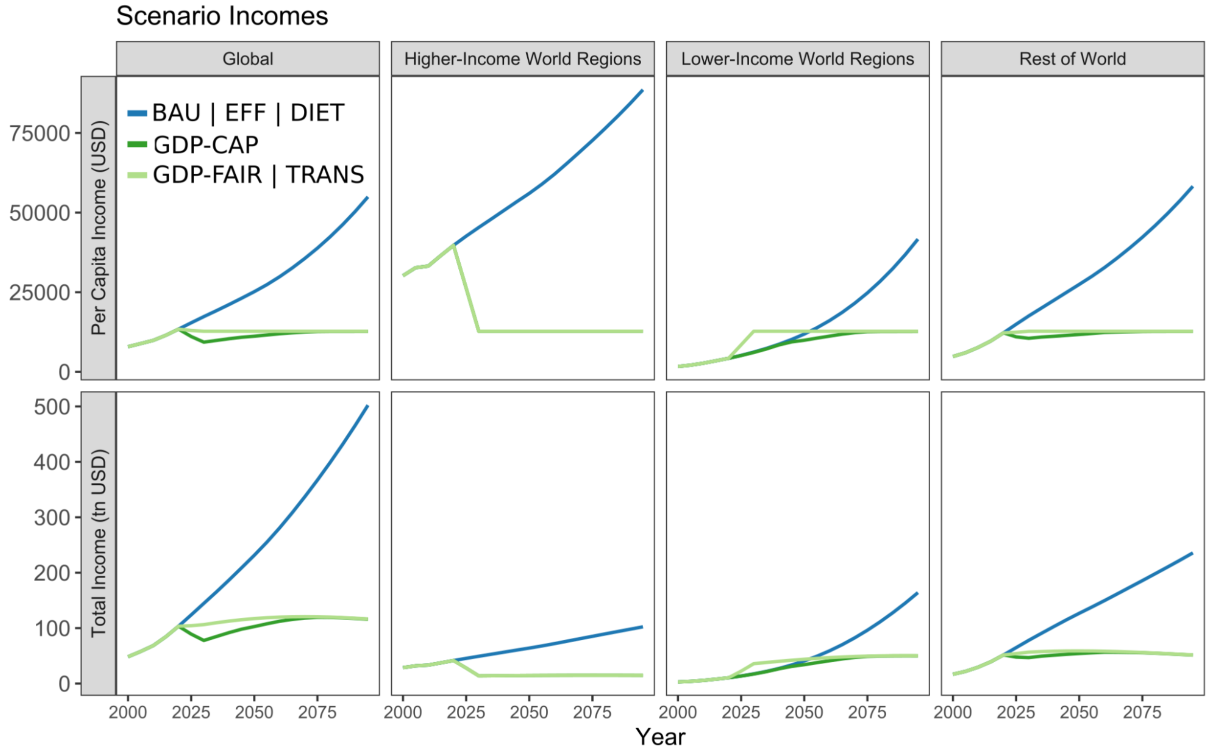
In low- and lower-middle income countries the price differences would matter more, but can also not induce major dietary shifts given the already low consumption levels. As we point out in our discussion, dietary shifts may still be achieved despite price-inelastic demand patterns if policy interventions target the preferences and food environmentsrather than the prices. Moreover, price elasticities may become more elastic with the appearance of novel plant-based substitutes of animal products with comparable sensory properties[14].

Supplementary Table

Supplementary Table 1. Region Mapping based on current GDP. Lower-income world regions (LIW) includes the two MAgPIE world regions with the lowest per-capita income, higher income world regions (HIW) includes the five MAgPIE world regions with the highest per-capita income. To point out the difference between our world region mapping and the Worldbank definition for lower-income countries (LICs) (according to which India and several Sub-Saharan countries are classified as medium-income countries), we name the regions LIW instead of LICs.

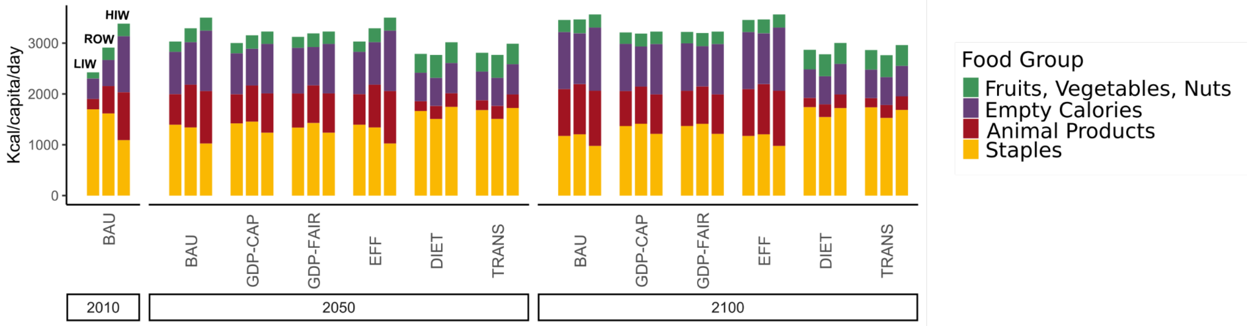
Income-aggregated Region	Countries/Regions
Current High-Income World Regions (HIW)	USA, Europe, Canada, Australia, New Zealand, Japan
Rest of World (ROW)	All world regions excluding HIW and LIW
Current lower-income world Regions (LIW)	India, Sub-Saharan Africa

Supplementary Figures

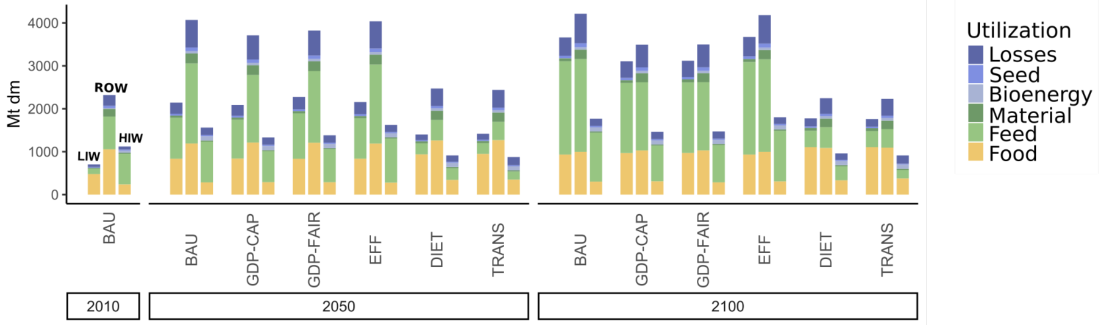


Supplementary Figure S1. Per capita and total income (in USD05PPP) for the six modeled scenarios. Regions are aggregated according to Table S1 Region Mapping

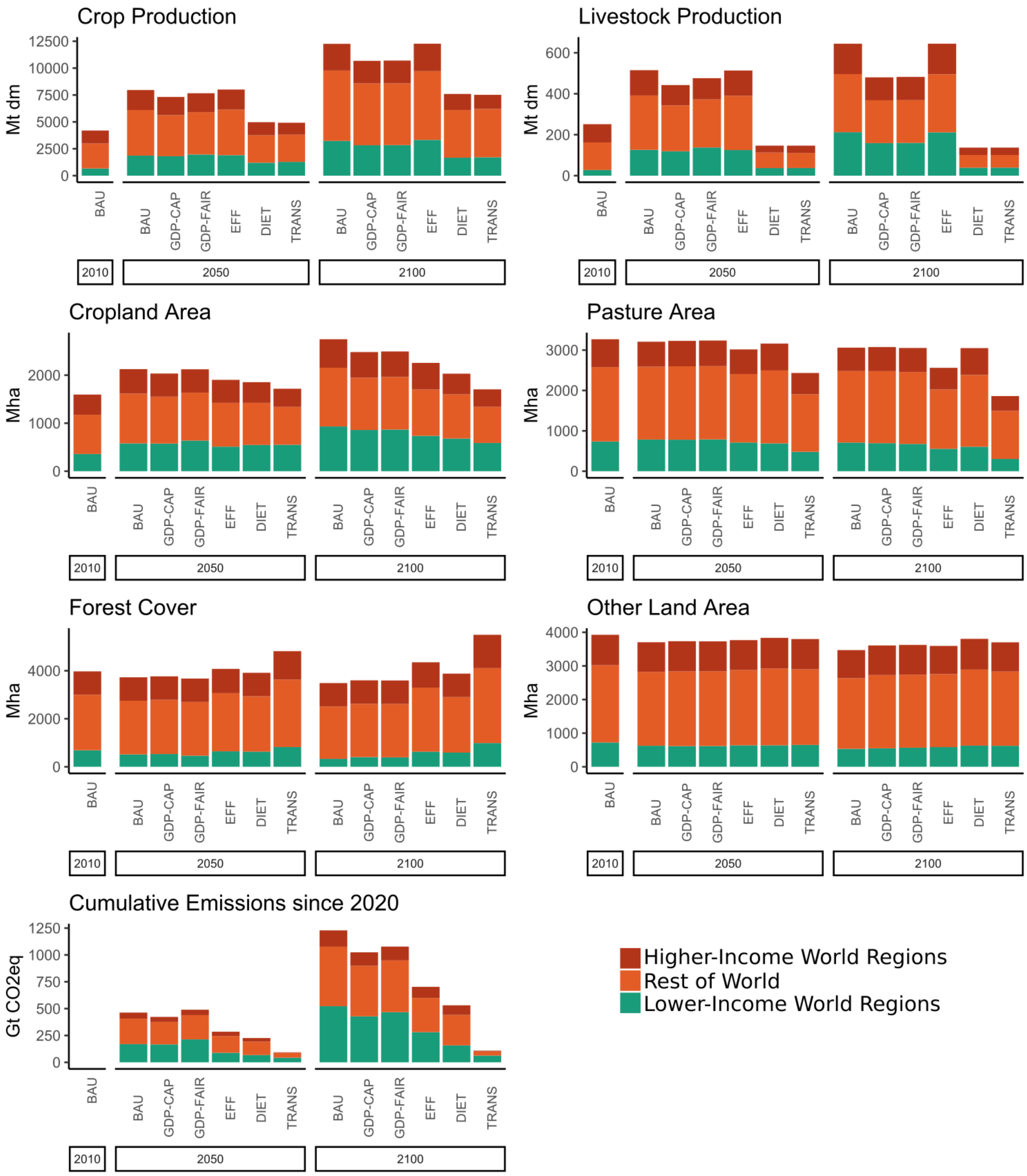
a) Per Capita Food Demand



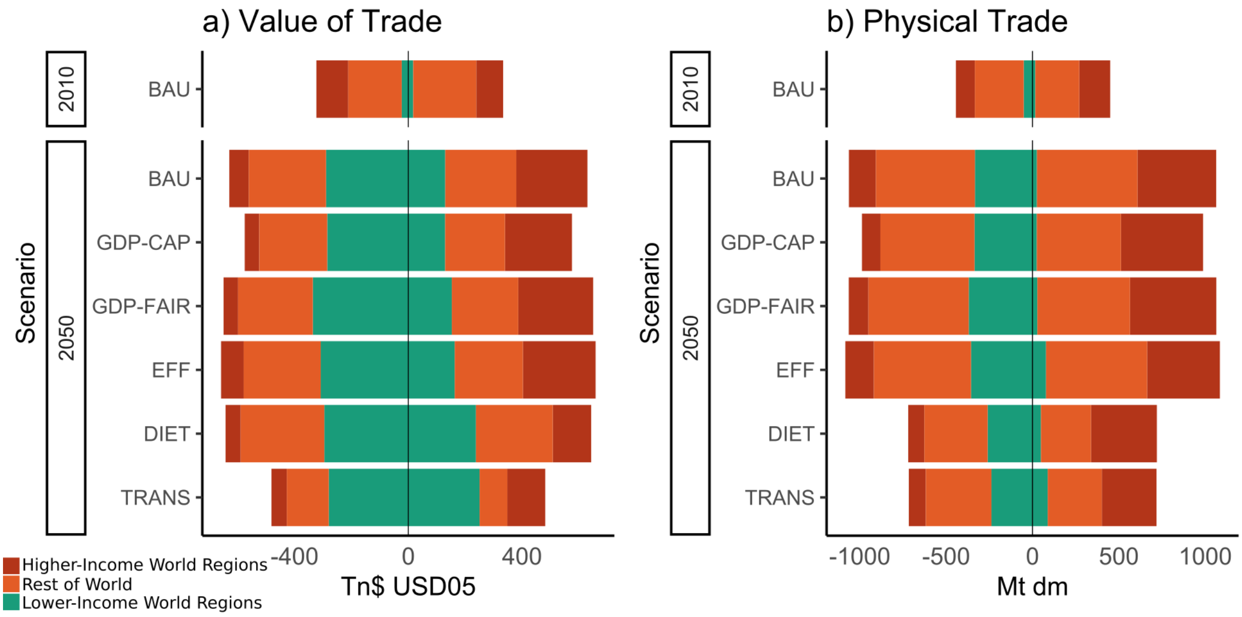
b) Crop-Based Product Demand



Supplementary Figure S2. Demand dynamics across scenarios and years. Three columns in each scenario represent the MAgPIE world regions grouped by income from left to right (see Table S1 Region Mapping). a) Per-capita food demand in kilocalories per capita per day by food groups. b) Demand for crop-based products by utilization category in million tons dry matter.



Supplementary Figure S3. Model projections for agricultural production, land use and emissions estimates grouped by scenario and by MAgPIE world region income groups (see Table S1). Year 2010 is historical data.



Supplementary Figure S4. Balance of trade by scenario and income grouping (Table S1). Positive values indicate exports and negative values indicate imports. Trade flows are estimated based on commodity-specific net-trade between MAgPIE world regions; trade within world regions is not included, and bi-directional trade flows of the same commodity groups are only considered in their net-flow. a) Balance of trade indicated in trillion dollars USD05, using constant prices as weight. b) Balance of trade indicated in million tonnes dry matter of agricultural products.

Supplementary References

1. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Change* **42**, 153–168 (2017).
2. High-Income Countries. in *The World Bank Group A to Z 2016* 83b–83b (The World Bank, 2015). doi:10.1596/978-1-4648-0484-7_high_income_countries.
3. Bodirsky, B. L. *et al.* The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. *Sci. Rep.* **10**, 19778 (2020).
4. Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447–492 (2019).
5. Valin, H. *et al.* The future of food demand: understanding differences in global economic models. *Agric. Econ.* **45**, 51–67 (2014).

6. Latka, C. *et al.* Paying the price for environmentally sustainable and healthy EU diets. *Glob. Food Secur.* **28**, 100437 (2021).
7. Springmann, M., Godfray, H. C. J., Rayner, M. & Scarborough, P. Analysis and valuation of the health and climate change cobenefits of dietary change. *Proc. Natl. Acad. Sci.* **113**, 4146–4151 (2016).
8. Yi, J. *et al.* Post-farmgate food value chains make up most of consumer food expenditures globally. *Nat. Food* **2**, 417–425 (2021).
9. Meier, T. & Christen, O. Environmental impacts of dietary recommendations and dietary styles: Germany as an example. *Environ. Sci. Technol.* **47**, 877–888 (2013).
10. Roosen, J., Staudigel, M. & Rahbauer, S. Demand elasticities for fresh meat and welfare effects of meat taxes in Germany. *Food Policy* **106**, 102194 (2022).
11. Viren, M. Does the Value-Added Tax Shift to Consumption Prices? *Czech Economic Review* **3**, 123–142 (2009).
12. Caillavet, F., Fadhuile, A. & Nichèle, V. Taxing animal-based foods for sustainability: environmental, nutritional and social perspectives in France. *European Review of Agricultural Economics* **43**, 537–560 (2016).
13. Bonnet, C., Bouamra-Mechemache, Z. & Corre, T. An Environmental Tax Towards More Sustainable Food: Empirical Evidence of the Consumption of Animal Products in France. *Ecological Economics* **147**, 48–61 (2018).
14. Tziva, M., Negro, S. O., Kalfagianni, A. & Hekkert, M. P. Understanding the protein transition: The rise of plant-based meat substitutes. *Environ. Innov. Soc. Transit.* **35**, 217–231 (2020).