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Exploring potential food self-sufficiency across alternative dietary futures

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ABSTRACT

Food self-sufficiency (FSS) and healthy diets are high on policy agendas to ensure food security under increasing global pressures. A global shift towards self-sufficient production of healthy diets would represent a radical departure from today's globalised food system. Representing such scenarios in a biophysically consistent way requires accounting for multiple resource constraints and feedback loops—including feed, fertiliser, and trade flows—while allowing flexible reallocation of crop areas, livestock numbers, and biomass streams. We use the global biophysical optimisation model CiFoS (Circular Food Systems) to evaluate the potential for self-sufficient production of multiple food groups and nutrients in 70 regions by 2050 under a business-as-usual diet (BAU-MinTrade) and a Planetary Health Diet (PHD-MinTrade). FSS is assessed by minimising biomass and nutrient trade while fulfilling dietary requirements, with trade only balancing shortages. Results show that total trade could fall by 62% to 618 million tonnes in BAU-MinTrade and by 79% to 343 million tonnes in PHD-MinTrade. Many regions—including Europe, the Americas, Oceania, and China—could be almost self-sufficient under both scenarios. Several African regions, India, and parts of Asia would still rely on imports, especially under BAU-MinTrade. Most food groups and nutrients show potential for increased FSS, though trade in some animal-source products and nutrients may rise. Self-sufficient systems can keep land use and GHG emissions within planetary boundaries, but nitrogen and phosphorus inputs remain high. PHD self-sufficiency is consistently more sustainable than BAU. Aligning production with dietary shifts towards a PHD supports self-sufficiency while reducing environmental trade-offs.

1. Introduction

The extent to which countries should pursue food self-sufficiency (FSS) has long been central to debates on food security (Lang and Barling, 2012). Motivations include ensuring a stable food supply amid international market disruptions, price volatility, and political embargoes, and protecting local producers and livelihoods (Clapp, 2017). Recent events, notably the Ukraine war and the COVID-19 pandemic, have renewed the policy interest in FSS by highlighting the fragility of international markets (Szajner et al., 2024; Van Zanten et al., 2025b). Ultimately, the goal of FSS ambitions is to ensure food security. Food security is defined as universal and continuous access to sufficient, safe, and nutritious food that meets dietary needs and preferences (FAO, 1996a) with agency and sustainability increasingly recognised as key dimensions (HLPE, 2020). In this study, FSS is understood as a country's capacity to meet those food needs through domestic production, focusing on availability, while recognising trade as an important source of resilience (Clapp, 2015).

The effects of FSS ambitions and international trade on food security vary across its dimensions—availability, access, affordability, utilisation, and stability—and depend on countries' resources, population, income, and position in global trade (Mamassi et al., 2025). Globally, trade generally improves food availability by redistributing calories, increasing dietary diversity in low-capacity countries, and reducing nutrient inequality (Aguiar et al., 2020; Dithmer and Abdulai, 2017; Wood et al., 2018). It also raises land productivity by concentrating production in resource-endowed regions (Kastner et al., 2021) and is expected to become more important as climate change shifts production patterns (Geyik et al., 2022; Janssens et al., 2020). However, trade does not optimise equitable nutrient distribution. Low- and lower-middle-income countries often import foods low in vitamin A and B12 (Geyik et al., 2022). Trade effects also differ by food group, reducing inequality in cereals and vegetables but increasing it in fruits, stimulants, and nuts, while also raising the availability of unhealthy foods (Carr et al., 2016; Springmann et al., 2023). The interaction of FSS with stability depends on trade-offs between exposure to international market disruptions and vulnerability to domestic production shocks (Grassia et al., 2022). Affordability generally declines under trade barriers but may improve in export-oriented countries, farming communities, or remote regions where local supply strongly influences prices (Aragie et al., 2023; Schiavo, 2025).

FSS policies have traditionally aimed to meet national calorie or

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cereal targets through domestic production (Clapp, 2015). However, nutrition and sustainability research increasingly emphasises healthy, sustainable diets rather than calorie adequacy alone (Rockström et al., 2025). A narrow focus on calories can miss deficiencies in other important macronutrients like protein, carbohydrates and fat, as well as micronutrient deficiencies, contributing to the global burden of hidden hunger (Yilmaz and Yilmaz, 2025), while overconsumption of unhealthy foods drives diet-related non-communicable diseases (Afshin et al., 2019). Prioritising cereal production may reduce short-term hunger but can promote monocultures and nutrient-poor diets (van Ittersum et al., 2025). From a nutrition perspective, cereals are partly substitutable with other staples, whereas fruits, vegetables, legumes, and nuts have minimum intake thresholds that are essential for healthy diets (Arimond et al., 2010; Rockström et al., 2025; Yilmaz and Yilmaz, 2025). Achieving healthy diets requires substantial shifts in production towards diverse, often perishable foods (Rockström et al., 2025). This may conflict with staple-focused FSS agendas. If FSS policies aim to ensure food security and healthy lives within planetary boundaries, they should therefore be assessed against the capacity to supply healthy and sufficient diets. A growing literature has begun to evaluate countries' FSS in producing healthy diets (Navarre et al., 2023; Stehl et al., 2025; Wassénius et al., 2023) though further work is needed to examine different dietary scenarios and the full alignment of production systems and biomass flows with this goal.

Shifting towards a Planetary Health Diet (PHD) is expected to lower environmental food system impacts, mainly through reduced meat consumption, though in regions lacking key foods or nutrients, impacts may rise (Rockström et al., 2025). The environmental impacts of self-sufficient production are less understood, but trade studies offer insights: trade generally benefits water use (Fader et al., 2011) and can reduce carbon and biodiversity impacts due to higher productivity in exporting regions (Bai et al., 2021; Wang et al., 2022), though export orientation often simplifies landscapes (Kastner et al., 2021) and shifts environmental pressures to poorer nations (Gu et al., 2024; Hong et al., 2022; Zhong et al., 2023). Optimised trade for minimal environmental impacts could further cut GHG, water, and fertiliser impacts, outweighing trade-related emissions (Bayer et al., 2023; Simon et al., 2024; Van Zanten et al., 2025a). Trade and FSS also shape consumption patterns, affecting environmental outcomes (Kastner et al., 2021). Yet interactions between FSS, dietary shift and environmental impacts remain largely unexplored.

Studies assessing FSS mostly focus on calories, cereals, or biomass (Beltrame et al., 2019; Pradhan et al., 2014), while a few consider multiple nutrients (Wassénius et al., 2023) or healthy intake levels per food group (Navarre et al., 2023; Stehl et al., 2025). Evaluating the counterfactual—how agricultural production and land use would look without trade—remains challenging (Kastner et al., 2021). Most studies stay close to current production patterns (Beltran-Peña et al., 2020; Pradhan et al., 2014). Some assume certain elements in the food system to be flexible, like the share of produced nutrients that is consumed (Wassénius et al., 2023), the area of sustainable irrigation and changes in yield due to climate change (Beltran-Peña et al., 2020), cropping patterns (Fader et al., 2011) and nationally specific environmental impacts of crop production (Kastner et al., 2021). Only a few studies allow for changes in crop production areas and trace the resulting changes in feed availability (Kaufmann et al., 2022; Navarre et al., 2023).

Despite this progress, a gap remains for counterfactual scenarios that (1) integrate detailed diet composition for nutrients and food groups, allowing evaluation of dietary shifts, (2) enable a flexible yet biophysically consistent redesign of the food system, while optimising biomass use for food, feed, and fertilizer, and (3) maintain international interdependencies by accounting for import needs. Considering population growth, tightening environmental boundaries, and the renewed interest in FSS, it is crucial to examine how dietary patterns, trade, and environmental factors interact with national FSS potential and production patterns. We contribute to the FSS debate by assessing national FSS under both business-as-usual and healthy dietary scenarios, accounting for a broad range of food groups and nutrients, and potential changes in agricultural land use, animal production, feeding, and fertilisation strategies. We use the detailed food system optimisation model CiFoS (Circular Food Systems) to evaluate potential FSS at the food group and nutrient levels of 70 countries and regional aggregates (covering 178 countries), comparing production patterns and highlighting environmental outcomes.

2. Methods

We used a refined version of the global CiFoS model (Simon et al., 2024, 2026; Van Zanten et al., 2023) to explore the extent to which the 70 countries and regions, including aggregates of 178 countries, could produce the projected food supply for 2050 self-sufficiently under two dietary scenarios.

2.1. The CiFoS model

CiFoS is a global biophysical food system optimisation model, representing flows between human dietary requirements, animal and plant production systems, fertilisation, capture fisheries, processing, and different waste streams from post-harvest to consumption waste (Van Zanten et al., 2023). The CiFoS model allows assessment of the potential for FSS, assuming a flexible redirection of biomass flows within the food system on a high level of detail in product and waste streams and their nutrient contents. The smallest unit of assessment is ~4000 agroecological soil-climate zones for crops, including 1.62 billion ha of cropland harvested area and 3.12 billion ha of grassland (Simon et al., 2024). Average yields of 46 crops were extracted from the SPAM maps 2020 (IFPRI, 2025) per zone, and it is assumed that crops can expand within each zone, limited by a rotation constraint with an equal yield when sufficient fertiliser is available (Simon et al., 2024). Sufficient fertilisers are conceptualised as enough phosphorus and nitrogen to cover the losses (IPCC, 2019a; Lun et al., 2018) as well as the plant removal. The animal production data is largely taken from the GLEAM model (FAO, 2022), including the animal numbers, the nutrient requirements and productivities. Processing fractions (FAO, 1996b) and losses (Gustavsson et al., 2011) are modelled according to the FAO standard assumptions. Human nutrient requirements of 34 macro and micronutrients are set according to EFSA recommendations (EFSA, 2017) and the food group requirements according to the EAT Lancet recommendations (Rockström et al., 2025).

The model is set to choose flexibly among optimisation functions and constraints. Optimisation functions include minimisation of environmental impacts like land use, CO_2 emissions, or nitrogen use, the approximation of the production of a certain diet or the maximisation of the number of diets produced. All these elements can be optimised, but also set as hard or soft constraints. For diets, for example, we can fix the product-level supply, the supply of protein or fresh matter per food group of a current or projected diet, or a combination of the food group ranges with the nutrient recommendations. Biomass flows are partly allocated through constraints such as the share of grass in an animal's diet. Within the range of the constraints, they are allocated in an optimised way. The model contains options to assess different degrees of circularity, like the feeding of by-products and waste or the avoidance of waste. A more detailed description of the model can be found in preceding publications (Simon et al., 2024; Van Zanten et al., 2023) as well as the model documentation (Simon et al., 2026).

2.2. Scenarios

The two scenarios modelled are called BAU-MinTrade (business-as-usual diet) and a PHD-MinTrade (Planetary Health Diet). For both scenarios, we enforce the respective dietary supply while minimising the trade between regions. In a second step, we fix the minimum trade volume reached in the first optimisation and minimise environmental impacts. Constraints and relationships of diets, crops, animals, and the environment are set as described in Table 1.

2.3. Diets and food supply

For estimating the demand of the scenarios, we use projections of an economic model, developed in the course of the newest modelling efforts around the PHD. The projections on the BAU food demand are based on income, population, demographics, physical activity levels, and age and gender structure of the population. For the PHD the food group limits as well as healthy intake levels of calories were used to adjust the dietary projections. The economic projections are reported on 26 food items (Beier et al., 2025). We mapped and applied the same trends to the 55 dietary product groups distinguished in CiFoS, largely overlapping with the food items from the FAO Food Balance Sheets (FAO, 2025). Where this factoring led to a crossing of the minimum or maximum PHD value of food supply per food group, we adjusted the value to fit within the range (Appendix A.2.3). We did not actively ensure that the PHD recommendation meets all nutrient requirements, but decided to keep the product level mix in combination with the economic projections. The advantage is that, like this, the BAU and PHD stay closer together and more comparable. The change in food supply is a combination of shifts in per-person demand and the population growth rate. The changes in the BAU and PHD diet, modelled for 2050 relative to the 2020 rate, are shown in Table 2.

2.4. Production patterns

Production patterns in CiFoS include the cropping and grassland areas, feeding and fertilisation practices, the number of animals and productivities of cropping and livestock production. In the reporting, we summarise the areas and biomasses of fruits, vegetables and nuts which are the product groups with a minimum recommended intake level according to the PHD. Oilseeds and pulses are included, because they are among the crops with the highest share in international trade and they play an important role in replacing animal protein. We look at staples, including cereals, tubers and starchy fruits and then at cereals alone to account for the fact that staples and cereals are usually the target of FSS policies. For each of these crop types we report the area covered as well as the biomass. Differences between yield and area changes arise if the model uses more or less of a higher yielding crop in a group. Animals are grouped in chicken, large ruminants, small ruminants and pigs as well as the production of animal sourced protein from eggs, meat, milk and in total animal sources protein. All these parameters are direct outputs of the CiFoS model and give an indication about the regional changes in production patterns implied in a redesign towards FSS (Simon et al., 2024; Van Zanten et al., 2023, 2025a).

2.5. Environmental impacts

The environmental impacts captured in the model include the total land use of cropland and grassland, the non-fossil fuel CO_2 emissions including direct and indirect N2O emissions from fertilisation, CH4 emission from cultivating organic soils (IPCC, 2019b), manure storage and enteric fermentation emissions from animals taken from the IPCC (IPCC, 2019c) as well as CO_2 emissions from transport (Li et al., 2022). The phosphorus and nitrogen fertiliser input considered crucial for water pollution are N input for manure, compost application and artificial fertilisers (de Vries et al., 2021; Schulte-Uebbing et al., 2022). The global boundaries for a safe and just food system are 5000 Mt CO_2 yr−1, 4.9 billion ha land, 134,000 kt N yr−1, and 12000 kt mineral P yr−1 (Te Wierik et al., 2025).

These environmental impacts are used as secondary objectives to make sure the counterfactual shows a food system which is as self-sufficient as possible while not using more resource than necessary to meet the primary objective. In the results section we are comparing the resulting global impacts of the food system with the planetary boundaries chosen.

2.6. Objective function

The new objective function applied within CiFoS minimises the trade of biomass, protein, and energy to equal weights. We are considering the trade of raw crop and animal products as well as processed food and feed products. Grass cannot be traded but needs to be sourced within the country. We do not include the trade of fertilisers or seed. The demand for artificial fertiliser is accounted for and quantified but without specifying source regions. Minimising trade is used as a helper function to enforce that each country's food supply is covered as much as possible from the countries own productive capacities and imports will only occur, when countries cannot produce enough food or feed with their

Table 1
Model assumptions per scenario.

	BAU-MinTrade	PHD-MinTrade
Diet	Business-as-usual 2050 factor per food group applied to FAO food balance sheet products and food group level protein supply.	Planetary Health Diet factor per food group for 2050 applied to FAO food balance sheet products and food group level protein supply, limited to minimum and maximum recommendations per food group.
Crops	Production zones can be chosen freely within rotation and land constraints. Yields increase according to projected trends until 2050; regional yields can additionally rise up to 5% by shifting to more productive zones within each country.	
Animals	Animal requirements for gross energy, metabolizable energy, crude protein, dry matter, and grass share in animal diets must be met. Meat demand is fixed based on projected trends for red meat and chicken; within red meat, the share of pork, beef, etc., is kept as current.	
Environment	Reference values: 134 Tg nitrogen, 12 Tg synthetic phosphorus, and 5000 Gt CO_2 eq. for a food system within planetary boundaries. Environmental impacts are secondary objectives; scenarios are assessed post-hoc for compliance with these boundaries.	
Objective	First, we minimise the trade biomass, protein, and energy between 70 regions, then fix the minimum value of trade, and subsequently, as a second and third objective, we minimise land use and other environmental impacts (greenhouse gas emissions, nitrogen, and phosphorus inputs) to make sure exports occur from regions with the highest environmental efficiencies.	

Table 2
Food intake in g/day per capita under the different dietary scenarios with the % change to the 2020 diet in brackets. The colors indicate the % change with red hinting at a higher supply, increasing production pressure and green hinting at a reduction.

	BAU-MinTrade								PHD-MinTrade							
Food Group	Africa	Americas	Asia	China	Europe	India	Oceania	World	Africa	Americas	Asia	China	Europe	India	Oceania	World
Chicken	37 (365%)	139 (36%)	71 (81%)	68 (42%)	68 (6%)	30 (233%)	41 (-11%)	50 (89%)	25 (216%)	43 (-58%)	30 (-24%)	14 (-70%)	24 (-63%)	20 (126%)	15 (-67%)	26 (-1%)
Dairy	150 (94%)	372 (12%)	446 (134%)	102 (19%)	559 (5%)	387 (72%)	400 (154%)	236 (56%)	110 (41%)	233 (-30%)	206 (8%)	90 (5%)	224 (-58%)	168 (-25%)	189 (20%)	139 (-8%)
Eggs	13 (190%)	50 (60%)	36 (106%)	87 (42%)	37 (5%)	38 (233%)	18 (106%)	23 (63%)	9 (97%)	16 (-50%)	15 (-16%)	18 (-70%)	13 (-63%)	26 (126%)	8 (-13%)	11 (-20%)
Fish	50 (142%)	30 (27%)	68 (69%)	63 (3%)	57 (38%)	69 (233%)	48 (-7%)	54 (88%)	66 (220%)	61 (154%)	73 (82%)	55 (-11%)	62 (51%)	65 (216%)	54 (5%)	67 (134%)
Fruits	296 (77%)	346 (-2%)	308 (67%)	252 (-12%)	341 (18%)	240 (38%)	168 (-63%)	298 (50%)	343 (105%)	343 (-2%)	337 (83%)	224 (-22%)	339 (17%)	343 (97%)	299 (-34%)	338 (70%)
Grains	261 (-13%)	287 (7%)	320 (14%)	198 (-13%)	325 (-14%)	188 (-12%)	212 (42%)	270 (-6%)	198 (-34%)	285 (6%)	267 (-5%)	171 (-25%)	333 (-12%)	164 (-24%)	179 (20%)	217 (-25%)
Legumes	63 (55%)	27 (-3%)	18 (-15%)	18 (-12%)	10 (12%)	55 (38%)	28 (333%)	49 (52%)	131 (225%)	42 (55%)	26 (25%)	16 (-22%)	13 (48%)	89 (124%)	53 (718%)	98 (203%)
Nuts Seeds	10 (65%)	13 (6%)	35 (137%)	6 (-12%)	47 (43%)	8 (38%)	10 (4%)	15 (59%)	19 (236%)	20 (59%)	44 (201%)	6 (-22%)	61 (87%)	13 (124%)	15 (64%)	24 (155%)
OilFat	42 (46%)	65 (-5%)	75 (63%)	37 (14%)	89 (16%)	66 (28%)	60 (-68%)	51 (28%)	82 (185%)	82 (19%)	82 (79%)	82 (154%)	82 (7%)	82 (59%)	82 (-56%)	82 (105%)
Other	7 (-7%)	15 (-5%)	17 (8%)	2 (-8%)	21 (-27%)	7 (-22%)	11 (-37%)	10 (-11%)	6 (-31%)	25 (62%)	37 (135%)	2 (1%)	43 (53%)	16 (72%)	23 (34%)	14 (25%)
RedMeat	51 (67%)	97 (-6%)	99 (145%)	135 (7%)	150 (4%)	8 (-12%)	63 (-58%)	66 (37%)	12 (-60%)	13 (-87%)	15 (-64%)	8 (-94%)	15 (-89%)	8 (-15%)	11 (-92%)	12 (-74%)
Sugars	50 (67%)	100 (6%)	92 (70%)	21 (28%)	89 (11%)	73 (51%)	70 (43%)	62 (44%)	30 (-1%)	26 (-72%)	29 (-46%)	19 (14%)	30 (-62%)	23 (-52%)	25 (-48%)	29 (-32%)
Tubers	832 (92%)	153 (11%)	174 (64%)	157 (-12%)	222 (20%)	112 (38%)	144 (-65%)	605 (104%)	110 (-75%)	110 (-20%)	110 (4%)	110 (-39%)	110 (-41%)	110 (35%)	110 (-73%)	110 (-63%)
Vegetables	241 (58%)	210 (5%)	394 (42%)	927 (-12%)	416 (6%)	339 (38%)	212 (21%)	298 (19%)	497 (226%)	331 (65%)	525 (89%)	686 (-35%)	550 (40%)	550 (124%)	381 (118%)	502 (101%)

own land. Normalization is done by dividing the trade of each nutrient by the average current nutrient content in traded biomass. The objective equation is specified as

$$\mathrm{vObjectiveMinTrade} = \frac{\sum_{C,C1,p} \mathrm{vFromToProduct(C, C1, p)}}{\mathrm{CurrentBiomassTrade}}$$
$$+Weight_{CP} * \frac{\sum((C, C1, p), vFromToProduct(C, C1, p).NutrCont(p, 'CP'))}{CurrentNutrTrade('CP')}$$
$$+Weight_{GE} * \frac{\sum((C, C1, p), vFromToProduct(C, C1, p).NutrCont(p, 'GE'))}{CurrentNutrTrade('GE')}$$

Where *vObjectiveMinTrade* is the objective variable, depending on the weights assigned to minimise the trade of protein (*WeightCP*) and energy (*WeightGE*). *C* is the source country, *C1* is the consuming country, and *p* is the product. *vFromToProduct(C, C1, p)* represents the quantity of the traded product from *C* to *C1*. *NutrCont (p,Nutr)* is the nutrient contest of the product and *CurrentBiomassTrade* and *CurrentNutrTrade (Nutr)* refer to the sum of the current biomass respectively the sum of a nutrient traded currently, used for normalization. We then fix the trade volume to that minimum value and minimise land use. Therefore, the remaining exports are taken from the countries which have the highest yields and productivities per land area as well as additional capacities after producing for their own population. As a third step, we optimise GHG emissions, nitrogen and phosphorus input in a normalized multi-objective function (Van Zanten et al., 2025a). This makes sure that fertilisers, land areas and animal feeding are allocated in the most environmentally friendly way within the options space that remains after minimising trade and land use.

2.7. Food self-sufficiency indicators

FSS measures the extent to which a country meets its food needs through domestic production. It does not imply isolation from trade but reflects the proportion of total supply covered by local production. The Food Self-Sufficiency Ratio (SSR) is defined as (FAO, 1999)

$$SSR = \frac{Production}{Production + Imports - Exports}$$

An SSR of 1 indicates full FSS, values below 1 indicate net import dependence, and values above 1 indicate net export surplus. While in real-world policy contexts desirable SSRs are considered within a range of 0.85 and 1.15 (Clapp, 2017) many modelling studies are using this value as a cutoff point to distinguish between net importers and exporters (Beltran-Peña et al., 2020; Stehl et al., 2025).

To assess the differences in FSS between scenarios on a global level, reports usually choose the number or share of self-sufficient countries, or the share of the global population living in self-sufficient countries (Navarre et al., 2023; Stehl et al., 2025). To show the severity of the FSS gap, we adopt a second indicator, which averages the self-sufficiency rate of the countries below the threshold of 1. The average across all countries would always be 1. Since self-sufficiency questions are especially relevant to resource-scarce countries, we are putting the focus on countries below the threshold and investigating further how severe the scarcity is. This allows us to see, e.g., if any countries have averages below the politically relevant threshold of 0.85 (Clapp, 2017). Two indicators, which capture both the extent and severity of trade dependence across food groups and nutrients, describe results:

- **Self-sufficient population share (SSRPop):** share of global population in self-sufficient countries (SSR ≥ 1).
- **Average self-sufficiency in deficit countries (AvgSSRDef):** population-weighted mean SSR among countries with SSR <1.

Baseline SSRs are derived from FAO Food Balance Sheet for biomass and product groups (FAO, 2025). Scenario SSRs are computed similarly using CiFoS outputs at the product-trade level. Baseline interregional trade uses outcomes from the Multi-Region-Input-Output Model FABIO (Bruckner et al., 2019), as this data excludes intermediary trade flows and is therefore most comparable to CiFoS trade flows. The baseline nutrient self-sufficiency is calculated by adding the data on 42 nutrients to the FAO Baseline data to FAO Supply and Utilisation Accounts as processed by GCAM FAOstat (Zhao et al., 2025). For the scenarios, we used the CiFoS nutrient sheet, which is mainly based on USDA (USDA and Agricultural Research Service, 2024). For both, we calculate the sum of imports, exports and production per nutrient for each region. Then, we calculate the same indicators as for the food groups (Appendix A.2.5).

3. Results

3.1. *Trading patterns in a self-sufficient world*

The results show the minimum trade required to ensure sufficient food supply given the respective diet, while maximising national productive capacities. Global trade volumes decline by 62% to 618 million tons in BAU-MinTrade and by 79% to 343 million tons in PHD-MinTrade. Under BAU-MinTrade, total imports drop substantially across most regions: Europe and the Americas reduce imports by about 87–88%, Oceania by 76% and Asia (China and India excluded) by 50% and Africa's imports decline moderately (−19%). China would be able to eliminate net imports (−100%), whereas India's imports show the largest increase (+620%) as compared to today's imports to meet rising

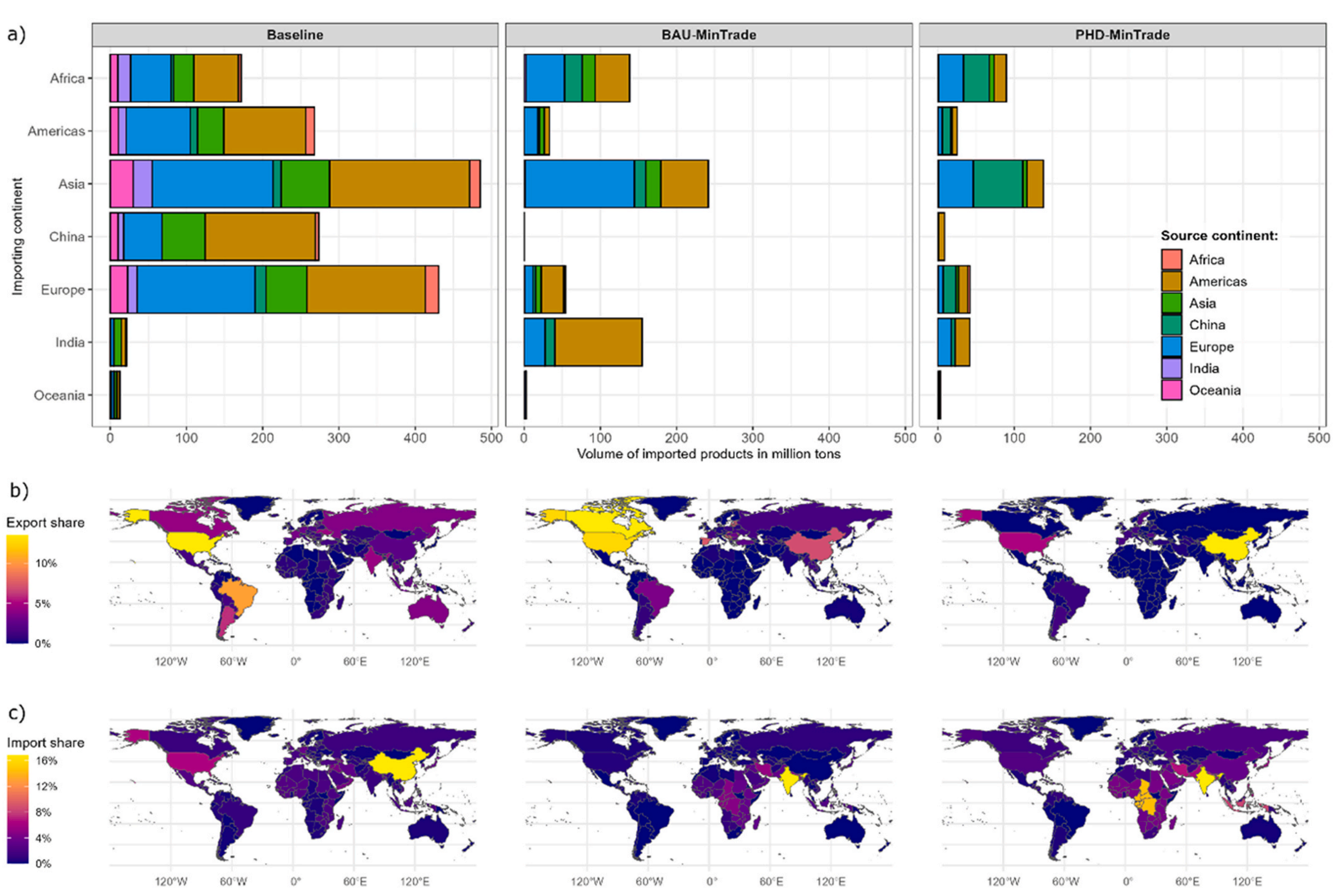

Fig. 1. Global food trade volumes and regional import and export shares. Panel a) shows total import volumes (million tons fresh matter) by importing continent and source continent. Bars also include intracontinental trade between different regions within the same continent. Panel b) shows the share of a country or region in total exports and panel c) the share of a country or region in total imports per scenario.

dietary demands especially for meat and the expected population growth by 2050. Under PHD-MinTrade, imports decline even further: Africa (−48%), the Americas (−91%), Asia (−71%), Europe (−90%), China (−97%), and Oceania (−74%), and increase less for India (+94%). These patterns highlight that if production patterns were optimised to maximise FSS, global trade volumes could be substantially lower; however, persistent import dependencies remain, particularly in Africa and India. A shift towards a PHD could reduce the minimum required international trade volume as compared to the BAU diet (Fig. 1a).

At the regional level, in the Baseline scenario, the largest exporters of biomass are the United States and Brazil, while the leading importers are China and the United States. In the BAU-MinTrade scenario, the top exporters shift to Canada (18%) and the United States (17%), while India (25%), the Rest of South Asia (8%), and Rest of Central Africa (7%) dominate imports. In PHD-MinTrade, China (39%) and the United States (15%) are the main exporters, with imports concentrated in India (12%), Rest of Central Africa (10%), and Indonesia (6%). Since trade is minimised and optimised for environmental impacts, importers are primarily regions with limited productive capacity, while exporters are regions that can supply deficits at minimal environmental cost (Fig. 1b and c).

Cereal trade volume declines by −88% in BAU-MinTrade and by −94% in PHD-MinTrade. The trade of tubers, vegetables, fruits, and fish are all sinking by more than −80%. Only eggs (+200%) and milk (+205%) increase trade volumes in BAU-MinTrade, and nuts (+33%) in the PHD-MinTrade scenario (Appendix A.1.2.3).

3.2. Self-sufficiency of food groups

Both BAU-MinTrade and PHD-MinTrade strongly increase self-sufficiency, with particularly large gains in staples and horticulture. Under BAU-MinTrade, cereals reach an SSRPop of 0.65 (AvgSSRDef 0.87), rising further to 0.71 (0.92) under PHD-MinTrade; tubers increase from 0.43 to 0.50 SSRPop, with near-complete AvgSSRDef (0.99) in both scenarios. Fruits and vegetables achieve very high population coverage in both scenarios—fruits: SSRPop 0.81 (BAU) and 0.80 (PHD), AvgSSRDef 0.97 in both; vegetables: SSRPop 0.95 (BAU) and 0.94 (PHD), AvgSSRDef 0.94–0.96. Animal-sourced foods diverge: chicken and eggs become almost fully population-self-sufficient under both scenarios (SSRPop 0.98–0.99 for chicken and 0.89–0.96 for eggs), but with very low AvgSSRDef in the remaining deficit countries—especially under PHD-MinTrade (0.14 for chicken and ~0.00 for eggs), indicating that only a few countries remain non-self-sufficient, and these rely almost entirely on imports. Fish also shows high SSRPop (0.91 BAU, 0.88 PHD). In contrast, meat and milk remain only moderately self-sufficient (SSRPop 0.36–0.41 for meat and ~0.37 for milk). Nuts, pulses, and oilseeds continue to show the largest deficits, with extremely low AvgSSRDef for nuts (0.03–0.05) and modest SSRPop for oilseeds (0.23–0.32), indicating persistent structural gaps.

The regions with the highest number of deficient food groups are Japan and Korea, Rep. with 13 food groups and Saudi Arabia and Israel with 12 food groups under BAU-MinTrade. Under PHD-MinTrade, Korea, Rep., and Saudi Arabia are deficient in 13 food groups, and Israel, the Middle East, and the Rest of Central Africa in 10. For all 12 food groups shown in Fig. 2b only 2% of the global population could achieve full FSS (Brazil and Other America), increasing to 16% under PHD-MinTrade, due to China becoming self-sufficient additionally.

3.3. Self-sufficiency of nutrients

For nutrient self-sufficiency, Baseline SSRPop for macronutrients is low: Energy 0.19, Protein 0.31, and total Fat 0.17. Under BAU- and PHD-

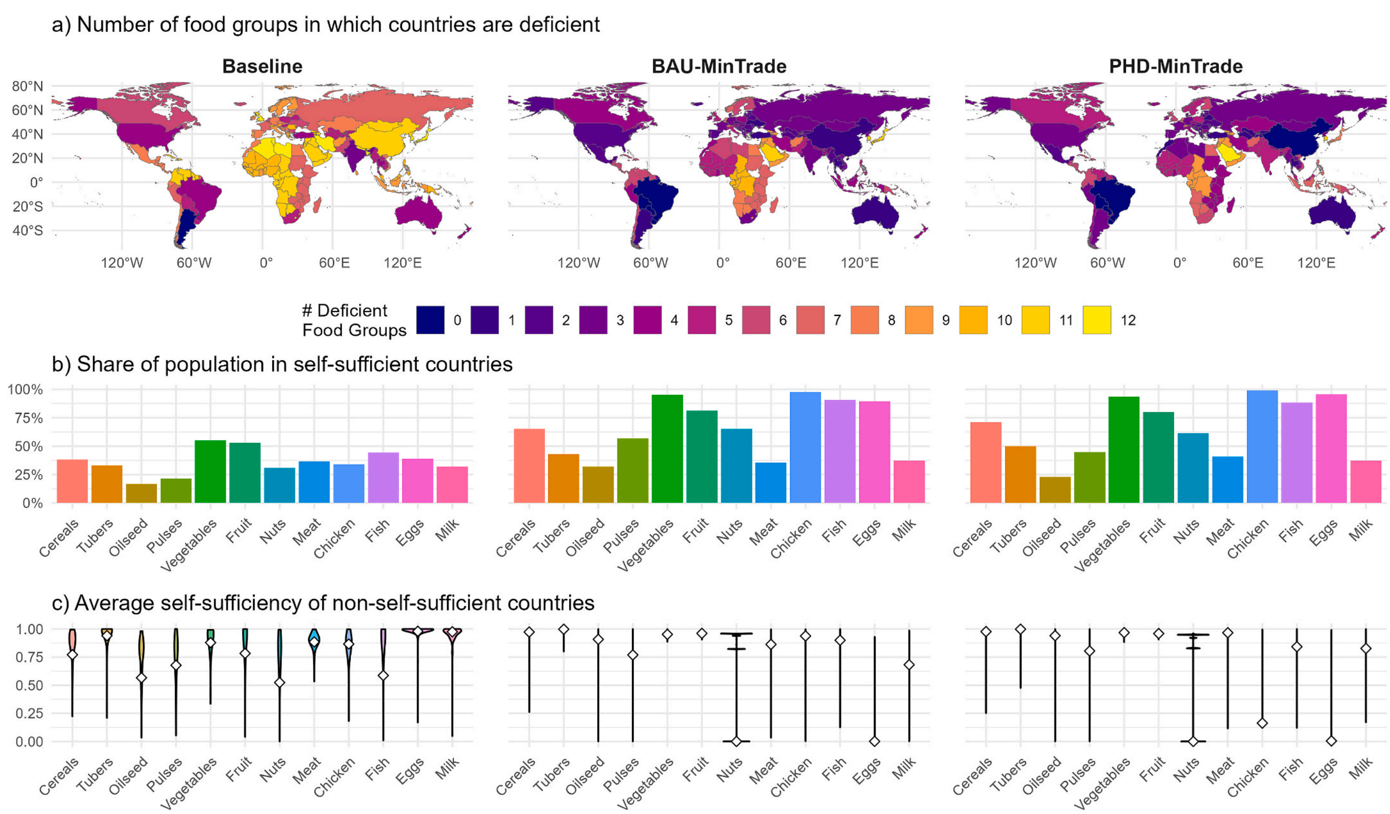

Fig. 2. Current and modelled regional FSS in different food groups, expressed as the share of domestic production in domestic supply (production plus imports minus exports). Panel (a) shows the number of food groups in which each country is deficient under the Baseline, BAU-MinTrade, and PHD-MinTrade scenarios. Panel (b) presents the share of the global population living in countries that are self-sufficient for each food group. Panel (c) depicts the average self-sufficiency ratio (domestic production divided by total domestic demand) among countries that are not self-sufficient.

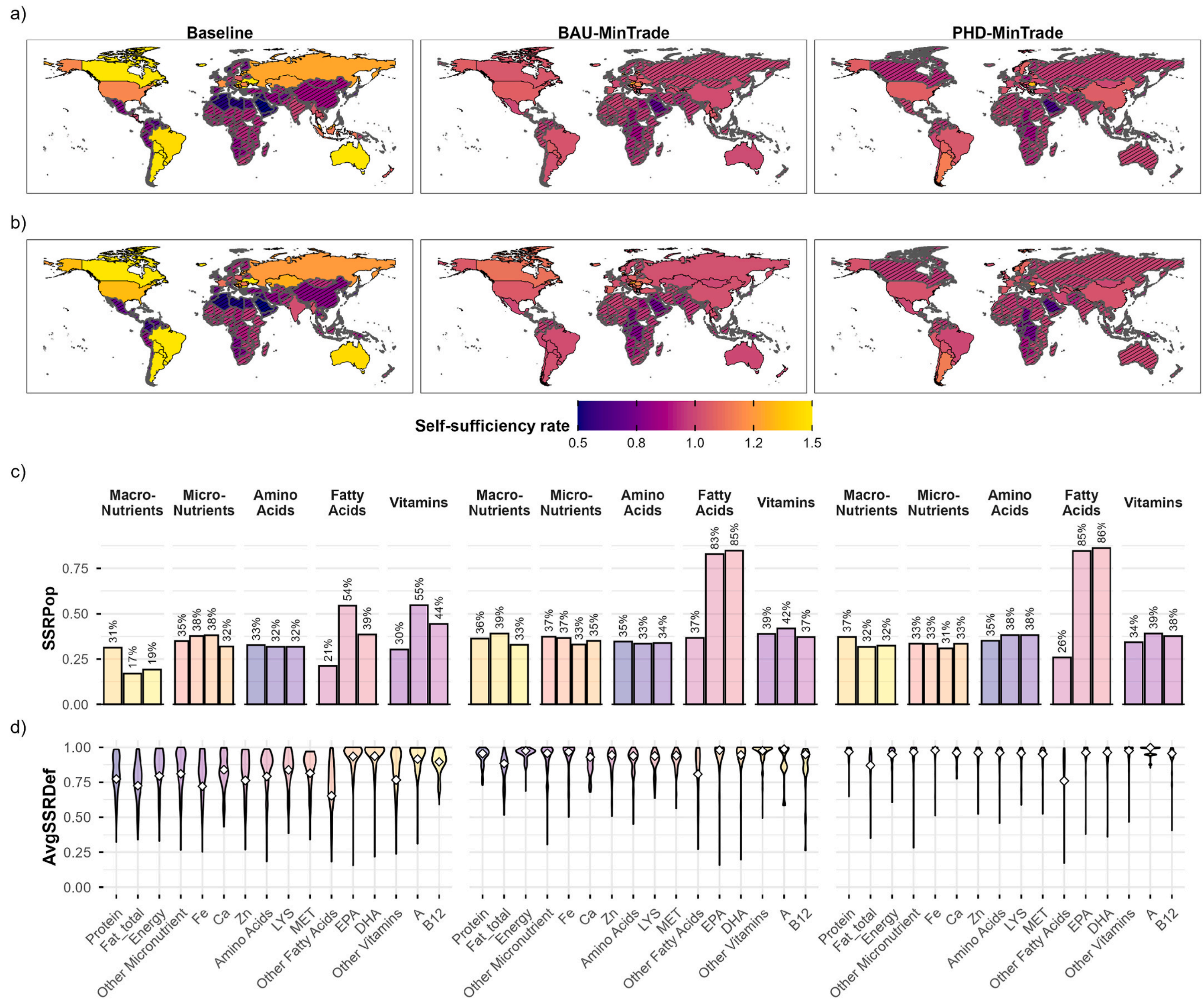

Fig. 3. Nutrient self-sufficiency. For all graphs, column 1 shows the Baseline scenario, column 2 BAU-MinTrade and column 3 PHD-MinTrade. Panel a) shows the SSR of energy for all 70 regions. Panel b) shows the SSR of protein. Panel c) shows the SSRPop, the share of the world population living in a country which is fully sufficient in different nutrients. Amino acids include Lysine (LYS) and Methionine (MET) an average of Histidine (HIS), Isoleucine (ILE), Leucine (LEU), Phenylalanine (PHE), Threonine (THR), Tryptophan (TRP), and Valine (VAL); Fatty Acids include DHA and EPA and aggregate other fatty acids, which are an average of Alpha-Linolenic Acid (ALA) and Linoleic Acid (LA); Besides Calcium (Ca), Iron (Fe) and Zinc (Zn) micronutrients include an average of Sodium (Na), Potassium (K), Phosphorus (P), Magnesium (Mg), Copper (Cu), Selenium (Se), and Iodine (I); Vitamins include Vitamin A (A) and Vitamin B12 (B12) as well as other vitamins include an average of Thiamine (Vitamin B1/B1), Riboflavin (Vitamin B2/B2), Niacin (Vitamin B3/B3), Vitamin B6 (B6), Folate (Vitamin B9/B9), Vitamin C (C), Vitamin D (D), Vitamin E (E), and Vitamin K (VitK). Panel d) shows the average self-sufficiency in the population share below a SSR of 1 for the same nutrients.

MinTrade, SSRPop rises only moderately (Energy 0.32–0.33, Protein 0.36–0.37, Fat 0.32–0.39), while AvgSSRDef increases markedly (Protein 0.81 → 0.94–0.95, Fat 0.77 → 0.85–0.86, Energy 0.86 → 0.95), showing that import-dependent countries are producing more domestically, with fat remaining the most geographically constrained (Fig. 3c and d).

At the country level, the lowest energy self-sufficiency remaining under trade minimisation occurs in land- and water-constrained countries such as Saudi Arabia, Israel, and Korea, Rep., Japan, and Switzerland, reaching 0.69–0.87 as well as Egypt and the Rest of the Middle East reaching 0.86–0.88 under BAU and 0.92–0.93 under PHD. Some regions' SSR declines due to population growth and dietary change like in the Rest of Oceania −11% to 0.85, Rest of Central Africa −8% to 0.85 and South Africa −5% to 0.93 (Fig. 3a). For protein results (Fig. 3b) see Appendix A.1.5.1.

Other nutrients vary widely. At Baseline, marine omega-3s (DHA 0.39, EPA 0.54), essential fatty acids (LA 0.17, ALA 0.25, total fat 0.17), B9 (0.21), B3 (0.32), Cu (0.31), and fibre (0.32) are lowest. Under the scenarios, DHA shows the largest SSRPop gain (0.71 → 0.84) due to aquaculture potential. AvgSSRDef improves for most nutrients, but gaps persist for DHA, EPA, LA, ALA, fat, fibre, and vitamin C (~0.68–0.78). Extreme deficits remain in some regions: Belgium (EPA 0.16, DHA 0.20), the Middle East (B12 0.26), and under PHD-MinTrade, Saudi Arabia, and Afghanistan (ALA 0.17–0.19, LA 0.18) (Fig. 3c and d).

3.4. *Production patterns*

In the following, we describe shifts in crop production, tracked through biomass and harvested area, and changes in animal production, summarised via animal numbers as well as eggs, meat, milk, and total

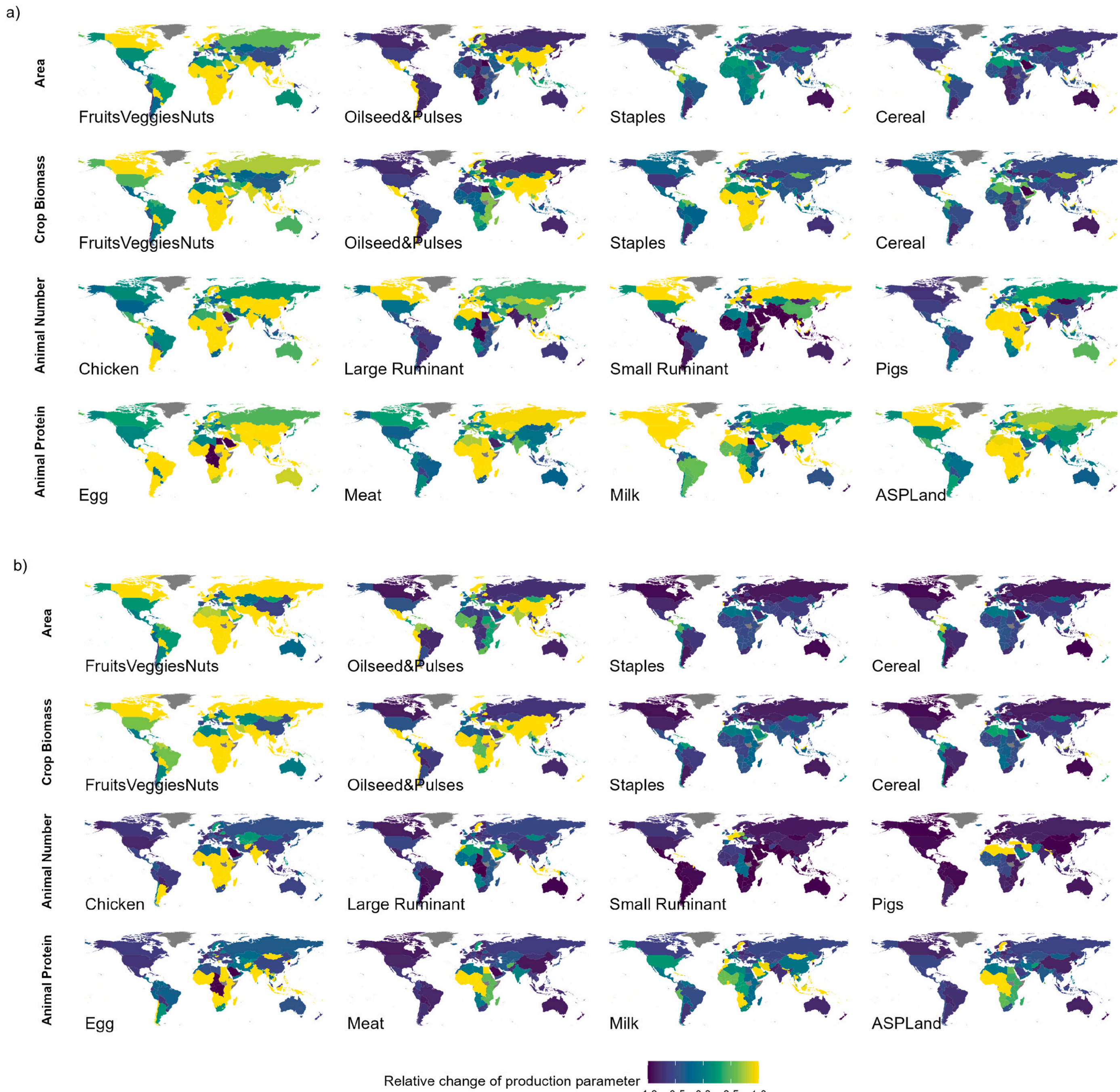

Fig. 4. Relative production changes across agronomic indicators — crop area, produced crop biomass, animal numbers, and animal product protein yield — under two scenarios compared to baseline data. Panel a) BAU-MinTrade scenario. Panel b) PHD-MinTrade scenario.

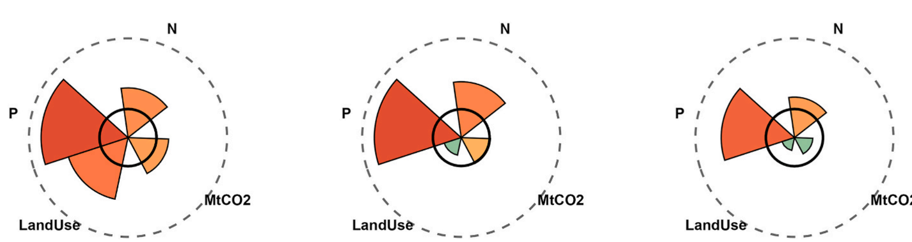

Fig. 5. Planetary boundaries for greenhouse gas emissions (GHG), land use, nitrogen (N), and phosphorus (P) per scenario. Each radar plot shows the extent of breaching relative to the food system's allocated share of the planetary boundaries (black circle): 5000 Mt CO_2 yr−1, 4.9 billion ha land, 134,000 kt N yr−1, and 12000 kt mineral P yr−1. Values beyond the circle indicate breaching of the planetary boundary, while values within indicate operation within safe limits.

animal-sourced protein (ASP). Globally, under BAU-MinTrade, fruits, vegetables, and nuts increase by ~16% in biomass and 35% in area, while oilseeds and pulses decline by 15% in biomass and 17% in area. Staple crops also see a reduction in biomass of 15% and a 38% decrease in area. Under PHD-MinTrade, fruits, vegetables, and nuts surge by 52% in biomass and 101% in area, oilseeds and pulses grow by 24–31%, and staple biomass drops by 57% with a 65% reduction in area. While total production shows differing trends, average area productivity (biomass per unit area) decreases for fruits, vegetables, and nuts, but increases for cereals.

Changes in ASP from land animals differ by continent and scenario. In Africa, total ASP increases by 156% under BAU-MinTrade and 45% under PHD-MinTrade relative to the baseline. Asia shows a small increase of 10% (BAU) and a decrease of −63% (PHD). Americas see an increase of 17% under BAU-MinTrade but a large decline of −62% under PHD-MinTrade. Europe shows an increase of 36% under BAU-MinTrade, but declines by −54% under PHD-MinTrade, and Oceania declines in both scenarios −55% under BAU-MinTrade and by −88% under PHD-MinTrade. For results on other indicators and regional disaggregation, see Fig. 4 and Appendix A.1.6.

3.5. Environmental impacts

After minimising trade, environmental impacts were minimised, starting with land use and followed by a combined objective function for nitrogen (N) input, phosphorus (P), and greenhouse gas (GHG) emissions to see the remaining option space for improved environmental outcomes. Current land use is 4.8 billion hectares (100% of the boundary level, assuming zero land use change is the planetary boundary target). BAU-MinTrade reduces this to 3 billion ha (60% of the boundary level) and PHD-MinTrade to 2 billion ha (40%), both well within the planetary boundary. GHG emissions fall from 7100 Mt CO_2 (142%) to 5151 Mt CO_2 (103%) under BAU-MinTrade and 3213 Mt CO_2 (64%) under PHD-MinTrade, with the latter scenario falling within the planetary boundary. For phosphorus all scenarios exceed the planetary boundary: current 36,500 kt (304%), BAU-MinTrade 36,787 kt (307%), and PHD-MinTrade 30,784 kt (257%). Nitrogen also remains above safe levels, rising from 233,000 kt (174%) currently to 263,910 kt (197%) in BAU-MinTrade and falling to 189,833 kt (142%) in PHD-MinTrade (Fig. 5). Overall, current levels exceed safe boundaries, but both scenarios reduce environmental pressures as compared to the current case, particularly PHD-MinTrade, except for phosphorus and nitrogen in the case of BAU-MinTrade. The decline in land use alongside continued high N and P inputs reflects the fact that reductions occur primarily in rangelands and pastures, which require little to no fertilisation, while more fertiliser-intensive croplands remain largely unchanged in the model.

4. Discussion

4.1. Potential self-sufficiency

We assessed the potential FSS of 70 regions across food groups and nutrients, accounting for both food and feed requirements. Under BAU-MinTrade, only 2% of the global population could achieve full FSS across 12 food groups, increasing to 16% under PHD-MinTrade, largely due to China becoming self-sufficient. For energy supply, potential self-sufficiency reaches 32–33% across scenarios. At the same time, both scenarios improve average self-sufficiency across most food groups and nutrients among regions that remain below full self-sufficiency. Applying a more permissive cutoff of 0.85 (Clapp, 2017), around 30% of the global population could be considered self-sufficient across all 12 food groups, and 99% for energy in both scenarios, compared to only 78% energy self-sufficiency at baseline (Appendix A.1.3 & A.1.4). These diverging results across indicators reflect a reduction of severe deficiencies and a reduction in specialization of product groups, while small imports remain in most and substantial FSS gaps in a few regions.

Due to the optimisation approach, our results are not directly comparable to most existing studies (Fader et al., 2013; Navarre et al., 2023; Stehl et al., 2025; Wassénius et al., 2023), which assume current or economically projected production patterns or treat countries independently. Based on current production, only one country has been found to be fully self-sufficient in seven food groups, while over one-third can meet self-sufficiency in only two essential food groups, often lacking fruit and vegetable production (Stehl et al., 2025). We found that, when we optimise for self-sufficiency, most regions can locally supply fruits and vegetables even under the EAT-Lancet diet (200 g/day vegetables, 100 g/day fruits). Cereal demand, traditionally central to self-sufficiency, declines under healthy diet scenarios because less grain is needed for animal feed and unhealthy processed products, whole grains replace refined cereals, and cereal calories are substituted by more nutritious foods. In contrast, the production of fruits, vegetables, tubers, pulses, and nuts increases substantially, consistent with the EAT Lancet Commission 2025 (Rockström et al., 2025). Local provision of these foods is particularly important given their perishability, high transport CO_2 emissions and limited affordability and availability in remote areas when imported (Li et al., 2022).

Navarre et al. (2023) estimate that about half of the global population could meet the full EAT-Lancet diet based on national land availability. We find a much smaller share achieving full self-sufficiency across all food groups because we base diets on consumed product shares rather than nationally produced shares, including foods that may not be locally producible due to climatic constraints. This highlights the relevance of place-based healthy diets as an alternative pathway (Alharbi et al., 2025). Our partially spatially explicit approach further restricts crop expansion to suitable areas within countries, and trade minimisation can still imply small imports to enable efficient exports (e.g. of animal products), even where domestic capacities would be enough, when treating the country in isolation.

Several constraints are not fully captured in our assessment, including future water availability, cropland management options, economic conditions, and behavioural responses of farmers (Mamassi et al., 2025). Moreover, many major producing regions—including South America, Asia, Europe, and under-fertilised regions such as Sub-Saharan Africa—remain highly dependent on fertilisers, pesticides, and commercial feeds (Sandström et al., 2024). Evidence suggests that scarcity of these inputs may pose a greater food security risk than food trade itself (Alexander et al., 2023). While we account for fertilisers in environmental terms, extending the analysis to explicitly include trade dependencies for agricultural inputs and nutrients would be a valuable direction for future research.

4.2. Implications of trade reduction

While previous studies have assessed self-sufficiency potential, to our knowledge, none have done so by explicitly minimising trade within an otherwise interconnected global food system. Our results show which trade flows would persist if international exchange were driven only by imports of food groups and nutrients that cannot be produced domestically, with cropping patterns, animal feed, and fertilisation optimised to minimise biomass and nutrient trade. Under this approach, global trade declines by 62% under a business-as-usual demand scenario by 2050 and by 79% with a shift to a PHD.

Most reductions stem from cutting non-essential imports to Europe, Oceania, and the Americas, while Africa and India remain substantially import-dependent even when production is fully aligned with self-sufficiency goals. This reflects population growth and rising demand for animal products, fruits, vegetables, and nuts, and underscores the importance of closing yield gaps in low-productivity regions (Baker et al., 2020; Tian and Yu, 2019). The large trade reductions achievable even under BAU-MinTrade indicate that current trade patterns are not primarily driven by the need to equitably redistribute food. Consistent with the literature on unequal exchange, poorer countries often act as net exporters of land and production capacity embedded in agricultural commodities (Dorninger et al., 2021). While our results are based on annual averages, diversified trade networks remain essential to manage seasonal variability and climate shocks (Aguiar et al., 2020).

While increased self-sufficiency could reduce such unequal exchange, neoclassical trade theory predicts lower food affordability due to reduced comparative advantages and economies of scale (Krugman and Obstfeld, 2000). Empirical evidence, however, points to heterogeneous effects: export promotion can raise food prices and weaken food security for urban consumers while benefiting rural producers (Aragie et al., 2023). In terms of stability, strengthening domestic production lowers exposure to international market disruptions, whereas diversified trade networks help buffer local shocks such as poor harvests—benefits that low-income and food-insecure countries often capture least (Grassia et al., 2022). Policies promoting self-sufficiency should therefore focus on building productive capacity to feed national populations, while maintaining international trade networks for flexibility (Lang and Barling, 2012). International trade policies should aim at redirecting trade flows towards regions with the greatest resource needs (van Berkum, 2021; Wynn Mitscherlich et al., 2021).

4.3. Environmental trade-offs

Our results show that prioritising national FSS still allows for environmental improvements through circularity and relocation of resources, especially for land use and GHG emissions, although nitrogen and phosphorus remain above safe limits. Outcomes are consistently better under a Planetary Health Diet (PHD) than under business-as-usual (BAU), even in self-sufficiency scenarios. Earlier CiFoS studies have shown that prioritising environmental goals over FSS can keep nitrogen and phosphorus below safe limits (Van Zanten et al., 2025a), mainly due to greater potential to relocate production globally, although assumptions about improved circularity and coarser diet-level resolution may also have contributed to more favourable outcomes.

Some trade-offs are expected, as international trade can lower global environmental footprints by reallocating production to more efficient regions (Fader et al., 2013; Liao et al., 2023), but current trading patterns often fail to fully exploit this potential. Global effects are estimated to be positive to neutral (Fader et al., 2013; Wang et al., 2022; Zhong et al., 2023), but regionally poorer countries may bear environmental costs of the consumption elsewhere (Dorninger et al., 2021). Export-oriented systems also tend to reduce cropping diversity, undermining agroecosystem resilience, whereas a shift towards self-sufficiency can support more diversified agricultural landscapes (Kastner et al., 2021; Kummu et al., 2020).

Self-sufficiency further increases the potential for national-scale nutrient circularity. CiFoS allocates manure and by-products efficiently within regions. The minimisation of nutrient trade results in a markedly different configuration of global nitrogen and phosphorus flows compared to today. Current trade-driven nutrient redistribution contributes to deficits in some regions and surpluses—and associated pollution—in others (Houlton et al., 2019). Relocalizing nutrient cycles could therefore generate synergies for both production and environmental outcomes (Kahiluoto et al., 2024), particularly when implemented in nested, agroecological systems that minimise nutrient losses and enhance resilience (Harder et al., 2021; Koppelmäki et al., 2021).

Beyond production patterns, self-sufficiency also reduces the decoupling between consumption and environmental impacts, potentially influencing what and how much is consumed (Kastner et al., 2021). Theories reaching from environmental psychology, to agroecology, to degrowth theory suggest that beyond what can be quantified in our modelling work, localizing production may benefit landscapes, reduce commodification of food and overconsumption, and promote behavioural change (Gibson et al., 2025; Rasmussen et al., 2024; Zhang, 2025). Such a consumption shift might counter the potentially negative rebound effects from circularity (Gatto et al., 2023). Overall, balancing national resilience and production diversity with global cooperation remains key to leveraging trade while lowering environmental pressures.

4.4. Synergies for food security and FSS

Recent reviews highlight that many factors interact with FSS and food security, and trade-offs often outweigh synergies. Land and water availability are primary determinants of FSS, with potential synergies from cropland expansion, yield gap closure, crop diversification, integrated management, and urban agriculture (Mamassi et al., 2025). Trade-offs also arise from infrastructure, climate, water, population density, and economic margins, affecting both production and consumption patterns. Studies are thus encouraged to integrate production and consumption dimensions and their systemic links (Mamassi et al., 2026).

Our study captures both production and consumption, showing that potential FSS is largely constrained by land availability. Synergies emerge between a PHD, circular biomass use, and environmental objectives. We assume no water constraints, potentially yielding optimistic estimates. Modelled FSS potential would be higher if we allowed for cropland expansion or accounted for potential yield gains from diversification. In CiFoS, cropping diversity is driven only by current supply diversity, and yield gains from diversification are not considered. Population growth further shapes projected supply-demand balances.

In our scenarios, circular redesign improves food availability and FSS potential while reducing land requirements in some regions. A fully aligned national circular food system, as we modelled it, would require substantial coordination, infrastructure, and behavioural change, which can hardly be implemented (De Bernardi et al., 2022). Steps towards such a system are best imagined by farm-level and local efforts to close agricultural loops (Koppelmäki et al., 2021; Wichern et al., 2024). At a local spatial scale that allows interaction between actors, circularity in food systems can emerge through planned and strategic efforts, as well as experimentation with and habituation to new forms of engagement with locally available waste (Schütz de Rivera et al., 2025). Fostering on-farm circularity and regional initiatives can support FSS and food security.

Lastly, our scenarios show an ideal nutrition-sensitive food system where agricultural production is aligned with the provision of healthy foods from national sources, and food is prioritised over other uses of agricultural biomass. Policies fostering nutrition-sensitive agricultural and agroecology can stir towards this direction and reconcile trade-offs between food security, health, FSS, and environmental targets (Geyik et al., 2022). These strategies increase domestic production of healthy foods (legumes, vegetables, biofortified staples) and reduce reliance on resource-intensive meats in line with our findings and the direction indicated in the EAT Lancet report (Rockström et al., 2025). For smallholders and remote or subsistence settings, agroecology and nutrition-sensitive agricultural interventions enhance food availability and dietary diversity, while impacts on affordability and utilisation need to be carefully considered to make policies effective (Bezner Kerr et al., 2021; Sharma et al., 2021). Agroecological practices also restore soil health, enhance biodiversity, and build resilience, thereby supporting the stability dimension of food security (Bezner Kerr et al., 2021). Embedding nutritional metrics into FSS goals and fostering nutrition-sensitive agroecological production thus complements national FSS efforts and strengthens both dietary quality and system sustainability.

5. Conclusion

We found that circularity and a shift towards a sufficient PHD demonstrate synergies with national FSS ambitions. While there are trade-offs between environmental outcomes and self-sufficiency when compared to globalised environmental optimisation using the CiFoS model, these are smaller under a PHD compared to a BAU diet. Policies aimed at enhancing self-sufficiency would benefit from adopting a more holistic definition of the concept and coordinating with measures that promote healthier diets. Such policies should focus on building and diversifying national capacities to produce a healthy diet while maintaining diversified trade networks to ensure resilience. If international trade were guided solely by the goals of fair nutrient distribution and minimising environmental impacts, global trading patterns would look very different. Trade dependencies of poorer regions are projected to persist by 2050, while current trade flows largely benefit wealthier regions. International trade policies should therefore aim to guide flows in ways that promote environmental sustainability and a fair distribution of nutritional and environmental outcomes.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT 4.0 in order to solve problems when generating the R code to generate figures from the model output and to suggest options to shorten paragraphs of the text and improve the grammar of the work. After using this tool/service, the authors reviewed and edited the content and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Laura Gerwien: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft. **Wolfram Simon:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – review & editing. **Adrian Muller:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Anita Frehner:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Elise F. Talsma:** Conceptualization, Supervision, Writing – review & editing. **Hannah van Zanten:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hannah van Zanten reports a relationship with AVINA Foundation that includes: funding grants. Adrian Muller reports a relationship with AVINA Foundation that includes: funding grants. Hannah van Zanten reports a relationship with European Union that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2026.100908.

Data availability

The authors do not have permission to share data.

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