Exploring Regional Heterogeneity in Food Systems Transformation: A Multi-model Ensemble Perspective

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Abstract

Understanding the socioeconomic implications of food systems transformation requires exploring regional differences. Using a multi-model ensemble of nine global economic models, this paper investigates the socioeconomic implications of two different futures, a business-as-usual and the envisioned future food system. The transformation scenario is composed of dietary change, productivity growth, and halving food loss and waste. The advantage of the multi-model ensemble is to capture uncertainties of different food systems' futures. We find that food is becoming more affordable in all regions but with heterogeneity across food groups. The median price of agricultural products falls by 16% under the transformed food system compared to current trends, mostly driven by a 28% decline in prices of livestock products. The ensemble suggests uncertainties regarding the direction of change in prices of vegetables, fruits, and nuts across all regions. Ensuring a healthy diet for all brings about significant changes in food production and shifts the regional dynamics of trade, with a particular regional dominance in trading specific food groups. In such world, the agricultural sector reshapes and restructures, exposing land-abundant regions to potential socioeconomic implications, and environmental burdens of food systems transformation. A demand-side transformation is feasible but entails a political effort to ease the transition of the most vulnerable regions and target their vulnerable sectors. This analysis offers science-based insights to guide policymaking in food systems, especially to ensure a transition based on equity principles and actions whereby sustainable development can be achieved.

Keywords: dietary shifts; future food systems; global economic models; regional analysis; socioeconomic and environmental impacts

Introduction

The scientific community has shown a growing interest in the study of food systems, particularly faced by the challenge of feeding both the current and future global population under environmental constraints. While there is no universally agreed-upon definition for a food system (Béné et al., 2019), the general framework encompasses a set of interconnected activities from food production (and the underlying ecological systems) to processing, packaging, distribution, marketing and retail, and consumption of foods, with critical outcomes essential to sustainable development. These outcomes involve providing nutritious and healthy diets, supporting livelihoods, and promoting socioeconomic and environmental benefits (Fanzo et al., 2022).

However, current dietary patterns and food production have been closely associated with and affected by the degradation of terrestrial and aquatic ecosystems (Costa-Pierce et al., 2022), significant depletion of water resources (Ringler et al., 2022), biodiversity loss (Benton et al., 2021) and climate change (Clark et al., 2020; Holden et al., 2018), being food systems responsible for a third of global anthropogenic Greenhouse Gas (GHG) emissions (Crippa et al., 2021). Unsustainable food systems also refer to failures to nourish people adequately (Gonzalez Fischer & Garnett, 2016), with malnutrition in all its forms, and other dietary risks being a leading cause of poor health globally (Swinburn et al., 2019).

The call to reshape food systems towards more sustainable, inclusive of the poor and marginalized populations, healthy and climate-resilient futures is resonating more loudly than before (Gordon et al., 2017; Loboguerrero et al., 2020; Webb et al., 2020; Willett et al., 2019). Discussions on how to incorporate a food systems approach to sustainable governance have advanced in the policy arena, with food systems featuring negotiations at COP28 in Dubai and more than 130 countries committing to accelerating action towards sustainability and resilience in food systems nationwide. Actions to transform food systems have the potential to deliver multiple desirable benefits such as increased food quantity and quality, job creation and income growth and reduced negative externalities on the environment while improving health outcomes. We focus on dietary shift as a driver of food system transformation (Willett et al., 2019). However, while such transformation can help achieve sustainable development goals, it will likely redirect trajectories and realign enablers of change (Mason-D'Croz et al., 2016) across regions, resulting in a restructuring of food economics. A comprehensive economic analysis of such changes from a regional perspective is currently absent, particularly because most food systems transformation pathways featuring dietary shifts to date investigate the consequences at the global level. The global food systems agenda has not been widely established across regions, and thus, potential challenges costs and trade-offs have not yet been fully acknowledged (IPCC, 2023). This paper fills this gap by exploring how regional economies respond to achieving a healthy diet and to what extent such transition reshapes the future socioeconomic and environmental trajectories. The analysis sheds light on the various challenges and opportunities different regions face, exploring the distribution of socioeconomic implications while identifying vulnerabilities based on exposure to changes in affordability, production, and international trade in addition to land conversion and emissions.

This assessment advances the body of knowledge by adopting a regional approach to compare the potential of a transformed food system based on healthy diets and sustainable production (EL2) with a continuation of current trends 'business-as-usual' (BAU) using a multi-model ensemble of global economic models. The multi-model approach allows us to map drivers of change and navigate the complexities and uncertainties of the pathway towards achieving a healthy diet by 2050 based on dynamic responses in the food system. This is a key distinction from previous food systems transformation modelling efforts (Laderchi et al., 2024; Springmann et al., 2018) and has been adopted in AgMIP (Agricultural Model Intercomparison and Improvement Project) studies to explore uncertainty and comparability across various global economic models (Rosenzweig et al., 2018; Stehfest et al., 2019). Here the reporting protocol has been developed for the specific purpose of a series of papers, which includes this regional assessment in addition to a global and sectoral analysis. The analyses are based on preliminary runs and offer science-based insights to guide policymaking in food systems transformation. Our study uncovers key aspects of the future of food systems from a regional perspective, whereby it identifies changes in socioeconomic roles and burdens within the global food system.

Methods

Multi-model ensemble approach

We used a core group of nine global multiregional and multisectoral economic models to simulate scenarios for the 2020-2050 period. These include five Computable General Equilibrium (CGE) models (AIM, ENVISAGE, FARM, IMAGE, MAGNET) and four Partial Equilibrium (PE) models (CAPRI, GLOBIOM, IMPACT, MAgPIE). These are models regularly employed to inform policymakers about the economic implications of various policies. Although all contributing models are global in scope, they differ in their regional and sector representation of the global food system. We build on modelling protocols developed as a part of the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Nelson et al., 2014; Rosenzweig et al., 2018; Stehfest et al., 2019). For a summary of the participating models and the modelling protocol comparatively, refer to Section A in the Supplementary Information (SI).

Scenario settings

In this multi-model ensemble, exercise we explore three scenarios: a) the Business as Usual (BAU) and b) the EAT-Lancet 2.0 transformation (EL2). The pathways towards the EAT-Lancet 2.0 world account for population and income growth by 2050, with different representations of the change in demand, technological bundles, and price relationships across models, reflected in how the scenarios are implemented. All models can represent the global production and consumption of various sectors of each regional economy, featuring several socioeconomic and environmental indicators depending on the model's capabilities.

All scenarios are implemented using the latest SSP2 data (version 3 released in January 2024, REF) for population and GDP projections. BAU uses the Shared Socioeconomic Pathway (SSP2) scenario for population and Gross Domestic Product (GDP) projections (Riahi et al., 2017). This scenario assumes minimal mitigation efforts in climate and land, consequently anticipating higher impacts, as indicated by the representative concentration pathways (RCP) 7.0. The BAU scenario considers the current trends in diet along with assumptions on crop, livestock and labor productivity and food loss and waste (FLW).

The EL2 scenario is a food systems transformation scenario consistent with the EAT-Lancet reference diet (Willett et al., 2019). Compared to some previous efforts to model dietary shifts using global economic models (Eker et al., 2019), this is a more comprehensive scenario and transcends the common emphasis on reducing consumption of animal-based foods. The diet implementation requires data on food consumption categorized by food group and region for both the benchmark and flexitarian diet, provided by Springmann et al. (2018). We assume that healthy diets will be achieved in all regions by 2050, enhancing health and well-being.

Additionally, the EL2 scenario includes agricultural productivity consistent with the more optimistic and sustainable SSP1 (Riahi et al., 2017), and reductions in FLW. Supply-side productivity trends are based on a set of data inputs, which are harmonized for consistency across scenarios of the multi-model ensemble. To cover climate-related impacts on crops, we used IPSL GCM average of the GGCMI crop model ensemble for soybean, maize, wheat and rice from Jägermeyr et al. (2021). For livestock productivity changes, we used changes in the value of milk and meat production from heat-stress-induced losses in Thornton et al. (2022). Agricultural labor productivity trends are based on Nelson et al. (2024) and reflect global reductions in manual agricultural work capacity due to climate change. EL2 and BAU scenarios diverge in the growth trends for diet, productivity and FLW. However, both scenarios align climate and land policies with minimal mitigation efforts, thus accounting for climate impacts based on RCP 7.0. Table YY in the SI details the scenario specification.

Results

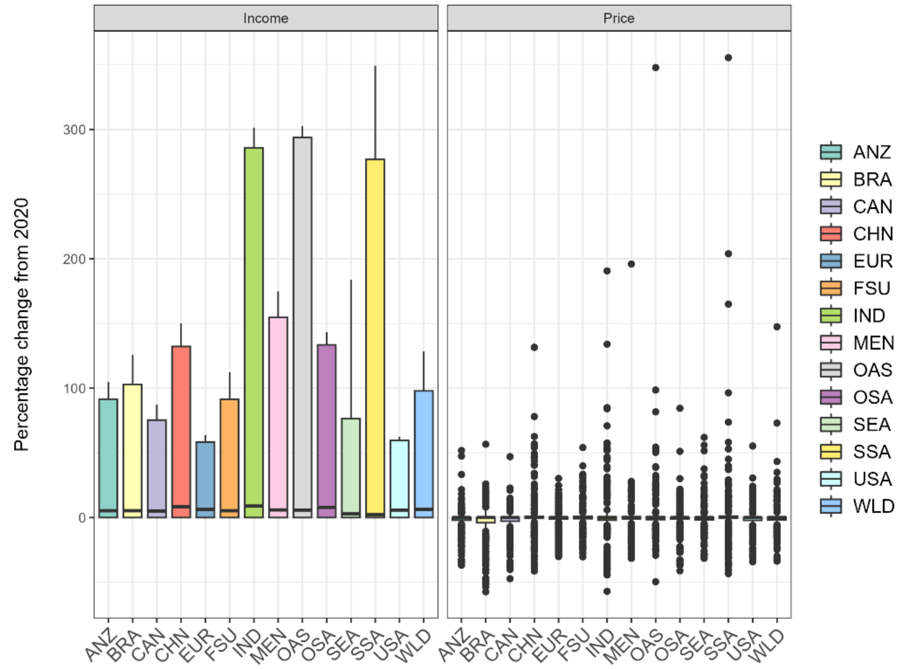
A continuation of current food system trends implies a larger agricultural production and trade in all regions but threatens to exceed planetary boundaries in different magnitudes.

We evaluate three food systems' futures to compare the effects of the EAT-Lancet transformation by 2050, starting with the BAU food system scenario and comparing it with current levels. The BAU scenario is based on an SSP2 world in which the global population reaches 9.6 billion by 2050, an increase of 21% from 2020. The global GDP is projected to grow at a faster rate than the population and double by 2050, especially in Low-and-Middle Income (LMI) regions (this is detailed in Table XX of the SI). The growth disparities between the High-Income (HI) and LMI regions (Figure 1a) are reflected across all dimensions of the BAU scenario. Sub-Saharan Africa (SSA) [+240 to +425%], India (IND) [+231 to +301%] and Other Asia (OAS) [+150 to +302%] experience a more optimistic income increase compared to Europe (EUR) [+52 to +63%] and the United States (USA) [+57 to +62%], with higher model agreement on these changes. Although only reported by two models [ENVISAGE and MAgPIE], increases in agricultural wages in these regions more than double in 2050, despite uncertainties in the magnitude for SSA [+27% to +244%].

Changes in income, typically represented by the average GDP per capita, and prices determine food affordability; they are key drivers of food choices as they reflect the financial resources of households available to purchase food and the corresponding costs (Bijl et al., 2017). In 2050, global food prices decrease by 4%. Some regions, like Canada (CAN) (-10%), Southeast Asia (SEA) (-7%), BRA (-7%) and Other South, and Central America & Caribbean (including Mexico) (OSA) (-7%), experience a median reduction in food prices while others see an increase compared to current levels, such as SSA (+16%) and OAS (+12%). The relative price increases in SSA (+17%) and OAS (+4%) follow income increases and are primarily driven by a rise in the price of livestock products (ruminant and non-ruminant meat, dairy, and other animal products), a comparable trend for the median price of livestock products projected to IND (+12%).

This suggests that by 2050 food will become more affordable as regional incomes rise faster than prices across all regions. As a result, global and regional median per capita caloric intake is higher than in 2020, especially in SSA (+16%) and OSA (+10%), reflecting the relative increases in per capita calorie availability in those regions. In a future BAU scenario, animal-sourced products are the main driver behind increases in caloric intake in these regions, with non-ruminant (NRM) products showing the largest increase in SSA (+43%) and OSA (+35%). Projections show a similar trend for IND, where the median caloric intake of non-ruminants and ruminants increases by 96% and 24%, respectively, compared to current levels.

a) regional changes in income and prices in BAU 2050 compared to BAU 2020



b) regional changes in income and prices in EL2 2050 compared to BAU 2050

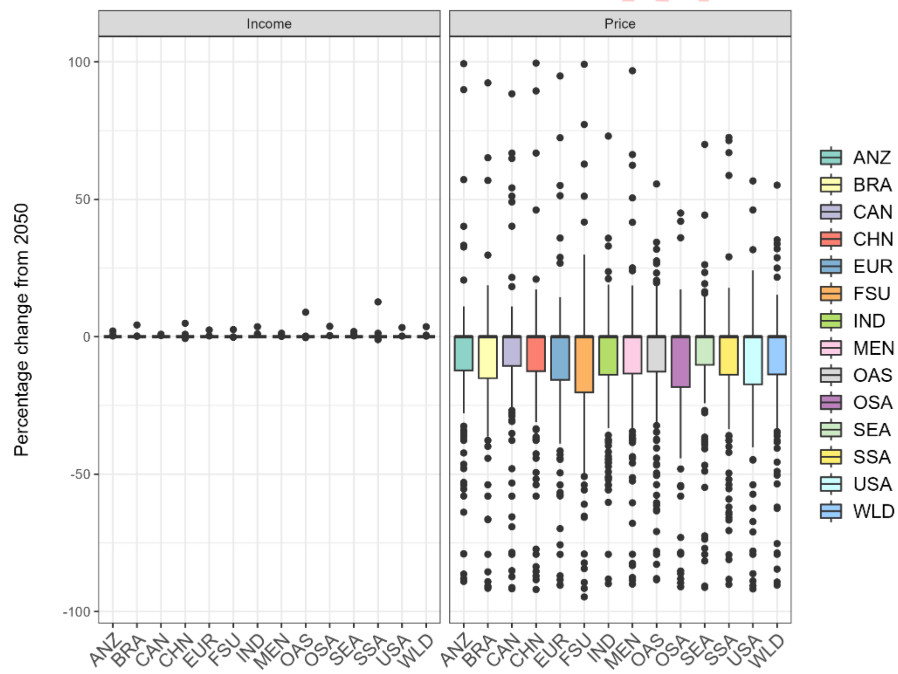


Figure 1: Regional results from the multi-model ensemble showing a) percentage change between the BAU scenario in 2050 versus 2020; b) EL2 scenario in 2050 versus BAU 2050. Results exhibit changes in income and prices across 13 regions: Australia/New Zealand (ANZ), Brazil (BRA), Canada (CAN), China (CHN), Europe (EUR), Former Soviet Union (FSU), India (IND), Middle East/North Africa (including Turkey) (MEN), Other Asia (OAS), Other South, Central America & Caribbean (including Mexico) (OSA), South-East Asia (including Japan and Taiwan) (SEA), Sub-Saharan Africa (SSA), the United States (USA) and the world.

Globally, increased demand translates into a rise in global agricultural production by 35% [+22 to +44%], increasing the median economic value of agriculture from USD 4.7 trillion in 2020 to USD 7.3 trillion in 2050. This absolute increase is distributed across regions, with SSA (+111%), the Middle East/North Africa (including Turkey) (MEN) (+81%), and OAS (+80%) benefiting economically the most from this positive shift. In the BAU scenario, SSA trends are driven by increases in crops (+70 to +136%) and livestock production (+63 to +152%) and result from productivity increases of similar magnitudes in the sectors. This boosts agricultural production in SSA, increasing its share of global production from 8% to 13%.

There is a low agreement regarding changes in agricultural production for China (CHN) (-12 to +20%), EUR (-6 to +26%) and the USA (-2 to +25%), with the median of the ensemble suggesting a small increase in both production and productivity growth. Accounting for 32% of global agricultural production in 2050, these regions experience the smallest increases in the economic value of production, but with varying production structures and relative competitiveness in the international market. Agricultural domestic production exported from EUR (+24%) and the USA (+17%) constitutes a relatively small share of their total production compared to CHN (+3%), which has a considerably large domestic market (approximately 1.5 billion people in 2050). Other LMIs present a comparable economic structure where exports play a relatively low economic role, such as IND (+5%), OAS (+6%) and MEN (+8%), representing 10% of the global exports. With high agreement across models, global trade is projected to increase by a third of its 2020 size, expanding across all regions and suggesting a more interconnected food system by 2050. This trend particularly enhances the availability of animal-sources products for consumption. The top exporting regions are OSA (+17%), BRA (+15%), EUR (+13%), USA (+11%) and Former Soviet Union (FSU) (+10%).

However, a larger global food system comes with environmental consequences as a result of harvested area expansion [+5% -13%] (Sundiang et al., 202X), especially in SSA [+10% to +48%], SEA [-2% to +29%], OSA [+7 to +20%] and OAS [+1 to +33%], and therefore, the total land dedicated to the agricultural sector [+3%-13%], increasing the median greenhouse gas emissions by +37% [+19%

to +107%] globally. There is a high agreement on the loss of forest cover across all regions under the BAU scenario. Regionally, models agree that the largest increases in emissions originate from LMICs and align in showing that the primary driver is livestock production, although with uncertainties in terms of magnitude. For instance, in SSA agricultural land use increases by a median of 17% at the costs of forests and other natural vegetation, which decrease between 25% and 10%. Under this BAU scenario, agricultural emissions in SSA increase between 24% and 227%, with the rise of crop-related emissions varying from 51% to 118% due to intensified use of fertilizer [+60% to +192%]. On the other hand, BAU projections show a more moderate increase in emissions for BRA [-2% to +83%] and a decline for USA [-21% to +38%], aligning with reduced fertilizer usage and therefore, nitrogen emissions. Despite showing relatively lower emissions, agricultural production in BRA (+11%) and USA (+11%) under the BAU scenario demands more water. This upward trend is also projected for SSA (+46%), Canada (CAN) (+27%) and OSA (+14%). The multi-model ensemble indicates a rise in the overall use of natural resources to sustain the expanding food system in the BAU scenario, potentially placing an environmental burden on people and the planet.

Ensuring a healthy diet for all brings about significant changes in food production and shifts the regional dynamics of trade

As an alternative future, we compare the EL2 and the BAU scenarios to understand how regions respond to food systems transformation based on changes in diet, productivity, and reduced waste. Models agree on the direction of change in GDP, revealing that transforming food systems improves global [+1%-4%] and regional incomes. From three models that reported GDP trends [AIM, ENVISAGE and MAGNET], economic benefits are larger for LMI regions, such as SSA (+1.3%) and IND (+1%), with uncertainties in the magnitude. The rising incomes coupled with declining median food prices across all regions substantially increase food affordability, but especially in HI regions, such as EUR (-26%), the USA (-22%), and Australia/New Zealand (ANZ) (-20%) (Figure 1b). Among LMI regions of the ensemble, SSA (-18%), OSA (-18%), CHN (-15%) and BRA (-14%) observe the largest food price reductions. The decline in global median food prices (-12%) compared to BAU in 2050 is mostly driven by reductions in the median prices of livestock products (-25%), with high agreement across models. Regionally, the largest declines in livestock prices are observed in BRA [-85% to -11%], OSA [-79% to -10%], USA [-77% to -7%] and SSA [-71% to -10%]. Due to their relatively large consumption and exports of livestock products, a global shift away from livestock results in a more substantial decline in prices.

Falling prices potentially make healthy diets more affordable. Although the EAT-Lancet transformation scenario projects a median decrease of 9% in the global price of vegetables, fruits, and nuts (VFN), two [CAPRI and IMPACT] of five models suggest positive changes across all regions. VFN is the only food group with a lower model agreement on the direction and magnitude of price changes. Notably, in regions like OAS (+16%), SEA (+16%) and IND (+1%), the EL2 scenario exhibits higher median prices compared to the BAU scenario. OAS stands out as the only region where four of five models agree on increased food prices under EL2. This highlights the substantial challenges that certain regions will encounter in their efforts to ensure access to healthy diets for all by 2050.

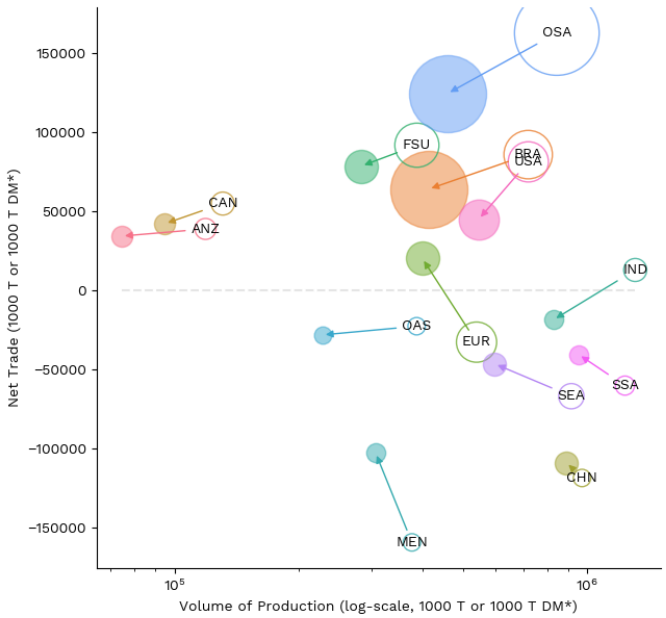
The dietary shift is one component of the EAT-Lancet transformation scenario leading to average reductions in food availability and per capita food intake across all regions compared to BAU in 2050. To meet the reduced food demand, the volume of global food production will fall by 27%, reducing the total value of production from USD 7.3 trillion in 2050 in BAU 2050 to USD 6.3 trillion in EL2 2050. The EL2 scenario embodies sustainable production and is characterized by increased productivity for both crops and livestock combined, affecting the changes observed. While all regions experience a reduction in agricultural production, such declines are particularly substantial for HI regions, including USA (-38%), EUR (-33%), CAN (-30%) and ANZ (-27%).

Projections also show significant production declines for BRA (-29%) and OSA (-25%). These changes result in a slight reduction in their contribution to global food production, counterbalanced by increases in other regions. However, the top three producers with the largest production share remain unchanged, CHN (+16%), SSA (+14%) and IND (+12%) as changes in the food systems are taking place simultaneously worldwide. These regions are important food producers and possess 58% of the global production of VFN under the EL2 scenario, despite the lower share of VFN production of SSA in the EL2 scenario (from 20% in BAU 2050 to 16% in EL2 2050). A reallocation of production from consolidated agricultural producers like EUR and the USA occurs, mainly driven by a substantial reduction in livestock production relative to crop products. This leads to a global median decrease in livestock employment from 114 million to 51 million, as indicated by the only model of the ensemble reporting this indicator [MAgPIE]. Although the workforce in the livestock sector is at least halved in most regions, workers most affected are in CHN (-78%), OSA (-65%), BRA (-65%), FSU (-65%) and ANZ (-62%). The lowest reduction in employment takes place in IND (-32%) and SSA (-48%), with a drop from 11 million to 8 million, and from 31 million to 16 million, respectively. Overall, food systems transformation affects approximately 49 million people employed in the global agricultural sector who need to move to other economic activities. The EL2 scenario suggests that CHN (-52%) followed by OSA (-34%) and BRA (34%) are the regions most vulnerable to those changes.

By 2050, global agricultural exported volumes decline in the EL2 scenario by 23% compared to BAU 2050. In this smaller export market, certain regions become more dominant. Global Food systems transformation offers trade opportunities to CHN, SEA, MEN and SSA by reducing trade deficits while for EUR it implies a shift towards increased exports that leads to a trade surplus. Figure 2a presents the relationship between production and trade patterns at a regional level to highlight the economic dynamics associated with these changes from a regional perspective. Under EL2 2050, CHN holds the largest share of the global volume of food production in the ensemble (Table 1), with a median of 28%, and accounts for approximately 5% of global agricultural exports, a 2-percentage point (pp) increase from BAU 2050. SSA and SEA are also key agricultural producers worldwide, responding to 25% of the global agricultural production but only contributing to 9% of global agricultural exports. Food systems transformation represents a median gain in the international food market for BRA, increasing from 14% in BAU 2050 to 19% in EL2 its global share. The relatively small changes in inter-trade suggest a potential intra-trade effect not captured by the current regional aggregation.

However, there are sectoral changes in production towards more crop-produced food, also leading to changes in the composition of the food export basket, as Figure 2b suggests. For BRA, this results in a 5-pp increase in the export share of OSD and VFN under EL2 compared to BAU 2050, offsetting the drop in the cereal's share from 29% to 22%. OSD serve as an important nutritional source, also used in animal feed. Despite decreased demand for livestock production and subsequently production that reduces the need for animal feed, healthy diets include a daily consumption of oilseeds. Although all regions consistently show a growth in the median exports of VFN, CHN is the region responding for the largest VFN share of the export food basket across all regions. Food system transformation creates opportunity costs in producing more VFN in IND (Table 1) and exporting to the international market, increasing the share from 8% to 12%. The increase in production results from a median increase in harvested area (29%) and a median decrease in yields (-2%).

a) Relationship between net trade and value of production



b) Exports composition

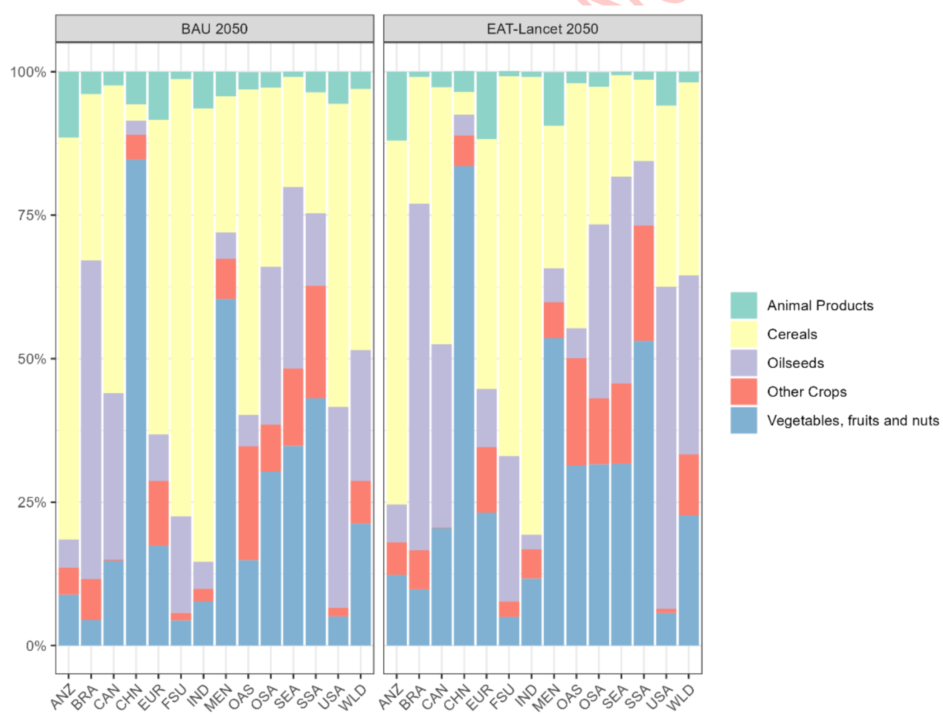


Figure 2: a) Relationship between net trade (exports minus imports) and volume of production in BAU and EL2 2050. Arrows indicate the direction of change whereas circle sizes reflect the region's share of global food export. Scenarios are differentiated by the filling, where the EL2 scenario is filled with the color of the region. The volume of production is reducing in all regions. Some regions experience improvements in net trade even if their share of global exports is reducing, such as EUR. For others, imports increase and lead to a negative net trade (e.g., IND), or exports increase and reduce the negative net trade (e.g., MEN, SSA, SEA). The future food system of a group of regions implies a continuation of positive net trade despite a reduced share in global food production (e.g., CAN and OSA). b) Exports composition by region shows changes in the export food basket, which includes cereals (rice, wheat and coarse grains), animal products (ruminant and non-ruminant meats, dairy and other animal products), oilseeds, other crops (including sugar crops), and vegetables, fruits and nuts.

Changes in the share of global exports for three major food groups are driving the redistribution observed in EL2 compared to BAU 2050: cereals (median reduction from 46% to 34%), oilseeds (median rise from 23% to 31%) and vegetables, fruits, and nuts (median rise from 21% to 23%). These changes result from shifts in sector sizes in response to dietary changes, which alter international trade compositional dynamics. Trade moves away from cereals products towards other crops, with animal-sourced products playing a smaller role and vegetables, fruits and nuts contributing more globally (Gibson et al. XX), with similar restructuring across regions depending on the economic structure. Regions in the multi-model ensemble are highly aggregated, allowing them to produce all food groups and export if production is less costly and potentially more efficient. Many regions primarily produce for local consumption while others have a more export-oriented economic profile, with certain regions dominating the trade of specific food groups. Table 1 illustrates this pattern by showing the regional reliance on exports as a proportion of the overall production or on imports as a proportion of demand.

Under EL2, EUR, ANZ, and OSA predominantly export livestock products, while BRA and USA remain important exporters but with a lower share. Except for ANZ, these regions retain a significant portion of agricultural and particularly livestock production to be consumed within the domestic market. For example, BRA exports slightly less of total domestic agricultural production than in BAU 2050 but mostly because production is also decreasing, particularly from the livestock sector, which is supplied to domestic consumers. Comparatively, the share of livestock production that is exported slightly increases in EUR, ANZ and USA compared to BAU 2050. By changing demand for livestock products, reductions in production and consequently prices increase competitiveness and lead to trade. By changing demand for livestock products, reductions in production and consequently prices increase competitiveness and lead to trade. The dynamics of livestock production and trade are consistent in all regions, signalizing a future food system less livestock-oriented, from which sectoral restructuring generates winners and losers within regions.

Various countries exhibit differing degrees of dependence on exports and imports for crop commodities. In several cases, the proportion of these products being traded is relatively higher, as seen in CAN (68%), ANZ (55%) and OSA (40% of production). In both IND (93% of production) and CHN (95% of production), crop production is mainly consumed locally given the projected large size of their population. The global importance of sugar-based food items significantly decreases in EL2 resulting from the dietary pattern achieved that entails a lower daily sugar intake per capita, with economic implications for BRA, the major producer and exporter of SGC which holds 34% of the trade market.

Producing healthy diets more sustainably modifies the land use dynamics in all regions and reduces agricultural emissions while increasing forest cover.

Producing healthy diets from sustainable production, with higher productivity and less food loss and waste alters the dynamics of land use. Models agree on the direction of change in global harvested area, showing a decrease between -45% and -3% compared to BAU 2050. Projections for BRA in the EL2 scenario indicate a substantial and the largest median decrease in harvested area (-39%), with changes from BAU in 2050 ranging from -63% to -2%, mostly driven by higher crop yields [-22% to 58%] from lower fertilizer use. In OSA, there is a similar downward trend in the total area used for agricultural production, with variations across models ranging from -52% and -4%. There is an overall agreement regarding the changes in the total area occupied by agricultural production in IND, with a median decrease of 5%. Lower usage of fertilizer input decreases the median yields by 14% while reducing total nitrogen emissions by -25%. In the EL2 scenario, the cultivated agricultural area in MEN decreases by 6% compared to the BAU 2050 scenario. This reduction is accompanied by declining yields due to the decreased use of fertilizers. The lower median reduction in the agricultural harvested area occurs in CHN (-4%).

Table 1 - Regional median contributions in percentage change (%)

Regions	Share of production for exports	Share of imports for domestic consumption	Global share of production						Global share of food demand					
BAU 2050														
			CGR	*NRM*	*RUM*	*RIC*	*SGC*	*VFN*	*CGR*	*NRM*	*RUM*	*RIC*	*SGC*	*VFN*
ANZ	51	7	1	1	4	0	2	0	0	1	1	0	1	0
BRA	25	2	6	6	11	2	33	2	3	5	9	2	4	2
CAN	54	20	2	1	1	0	0	0	0	1	1	0	1	0
CHN	3	13	16	25	11	20	5	27	10	28	12	20	6	26
EUR	24	19	10	13	8	0	5	7	7	11	7	1	7	5
FSU	25	9	6	4	5	0	3	5	3	5	5	0	5	3
IND	4	4	5	4	5	26	15	13	10	4	3	27	22	13
MEN	8	39	3	6	7	2	4	7	5	6	9	3	8	7
OAS	6	16	1	2	6	12	5	3	2	2	6	11	6	4
OSA	27	17	8	8	11	2	11	6	10	8	9	3	9	4
SEA	17	28	3	10	3	29	9	7	5	11	5	23	8	6
SSA	5	19	12	4	15	6	7	20	41	7	19	9	8	23
USA	17	8	25	13	11	1	4	2	4	11	11	1	6	3
EL2 2050														
Regions	**Share of production for exports**	**Share of imports for domestic consumption**	**Global share of production**						**Global share of food demand**					
			CGR	*NRM*	*RUM*	*RIC*	*SGC*	*VFN*	*CGR*	*NRM*	*RUM*	*RIC*	*SGC*	*VFN*
ANZ	55	9	1	1	4	0	2	0	0	1	0	0	1	0
BRA	23	3	6	4	7	2	34	3	4	3	3	2	2	2
CAN	63	24	2	1	1	0	0	1	1	1	0	0	1	0
CHN	5	14	17	23	15	21	5	28	9	21	8	25	7	23
EUR	26	29	9	9	8	0	4	7	7	7	4	1	5	6

FSU	29	12	6	4	4	0	2	4	3	4	3	0	3	3
IND	6	7	4	7	8	26	16	15	9	9	13	24	18	16
MEN	10	37	3	7	9	1	3	8	4	8	13	4	8	7
OAS	7	22	2	5	7	11	5	5	2	5	8	10	8	6
OSA	37	18	8	7	9	2	10	6	11	7	6	3	6	5
SEA	17	25	3	10	4	26	10	7	4	12	5	16	10	8
SSA	6	13	13	8	15	6	7	16	39	14	24	9	17	19
USA	23	13	23	9	9	2	3	3	6	4	3	1	4	4

Table 2 – Regional changes in harvested area and GHG emissions in EL2 compared to BAU 2050 (%)

Regions	**Harvested area**									**Total GHG emissions**		
	Agricultural			Cropland			Livestock					
	Min	*Median*	*Max*	*Min*	*Median*	*Max*	*Min*	*Median*	*Max*	*Min*	*Median*	*Max*
ANZ	-64	-3	-1	-51	-6	26	-68	-14	3	-48	-49	-76
BRA	-63	-39	-2	-53	-12	-2	-75	-51	-7	-78	-62	-68
CAN	-39	-7	0	-33	-4	10	-64	-49	84	-46	-42	-58
CHN	-48	-4	1	-50	-2	7	-63	-10	8	-35	-36	-50
EUR	-54	-14	21	-63	-4	21	-62	-36	-2	-53	-46	-42
FSU	-44	-8	3	-62	-2	13	-57	-15	6	-38	-23	-27
IND	-19	-5	-1	-19	-4	8	-31	-11	15	-26	-48	-27
MEN	-37	-6	-2	-29	0	9	-49	-6	-2	-27	-46	-43
OAS	-21	-5	-2	-37	-4	8	-45	-3	5	-32	-32	-39
OSA	-52	-29	-3	-60	-4	-1	-64	-40	3	-70	-58	-59
SEA	-47	-11	-5	-38	-13	-2	-60	-18	21	-14	-40	-60
SSA	-46	-17	-2	-35	-9	13	-55	-18	3	-21	-51	-56
USA	-55	-16	-4	-60	-7	32	-73	-43	0	-47	-56	-37
WLD	-46	-9	-3	-38	-5	3	-61	-22	3	-40	-43	-53

Table 2 exhibits the changes in the harvested area by the main food sectors for all regions and the corresponding total GHG emissions for that region. Models overall agree on the direction of change, showing a median decrease in agricultural harvest areas across all regions, varying according to the sector. The largest reductions in harvested area in the EL2 scenario are in BRA (-39%), OSA (-29%) and SSA (-17%) due to a decline in the area used for livestock production. This result suggests that food systems transformation releases land for other uses in all regions compared to BAU by 2050, with some uncertainties in the magnitude of change especially in BRA [-63% to -2%) and ANZ [-64% to -1%). The area for cultivating SGC, WHT and RIC falls in virtually all regions while for VFN and OCR, it increases consistently across regions. However, four models project an expansion in cultivated areas for OSD, particularly with a median increase in SSA (+23%), CHN (+10%), FSU (+9%), OAS (+8%), MEN (+6%) and IND (+2%), as they include peanuts and soybeans in this sector.

The EL2 scenario underscores the importance of food systems transformation to avoid future land use conversion and create space for afforestation with a median increase of 8% of global land use for forests. SSA contributes to approximately 18% of the global median land share and is the region with the second-largest land cover area in 2050 (3816 Mha), trailing only behind FSU (4527Mha). Under EL2, the median afforested land in SSA increases compared to BAU 2050, despite uncertainties in the magnitude [-1% to 38%]. Regions abundant in forests also see increases in forest cover. For instance, BRA, which occupies 11% of the global land area, is projected to convert 14 pp of the median land use from grasslands to forests by 2050 under the EL2 scenario. Forests are projected to cover about 80% of the land area in BRA, resulting in significant reductions in emissions. This includes a median decrease of 110% from forest conversion and a median fall of 62% in total agricultural emissions. Transforming food systems contributes to emission reductions across all regions, with OSA (-58%) and USA (-56%) playing important roles. In OSA, the future EL2 food system represents a reduction in emissions from SGC (-69%), NRM (-55%) and RUM (-46%). Meanwhile, in the USA, reductions from DRY (-46%), NRM (-45%) and WHT (-43%) are prominent. The only food group whose production increases emissions in all regions is VFN, varying from -10% to 247% across models. This overall increase is driven by higher nitrogen emissions from increased fertilizer use, increasing irrigation and water demands. Reported by two models [GLOBIOM and IMPACT], exceptions to this trend in water use include OSA (-16%), CHN (-7%) and BRA (-3%). The multi-model ensemble suggests that it is possible to have smaller and more sustainable food systems with a lower burden on people and the planet.

Discussion (1000-1500 words) - TBD

The following topics are planned to be covered in this discussion:

- Heterogeneity across regions and models leading to uncertainties.
- Compositional effect: a) in food consumption b) a large part of the socioeconomic effects are compositional and based on an intra-region reallocation/redistribution.
- Adopting a more diversified diet, combined with a moderate intake of animal-source foods and low sugar, increases the vulnerability of certain regions to change.
- The effect of food systems transformation from dietary shifts is heterogeneous. Overall, food is more affordable, but prices of VFN are uncertain.
- Winners and losers? Distribution of socioeconomics and environmental burdens and benefits in food systems transformation.
- Identify challenges, opportunities and trade-offs digging into the literature for more exposed/vulnerable regions to discuss how to ease the transition.
- Food system transformation is a demand-side issue, with political challenges.
- Policy implications.
- Future research: case studies and other emergent themes (e.g. development of regional studies)

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Supplementary Information

Section A

Model-based scenarios are often used to explore possible environmental trends in relation to uncertain development of driving forces. These driving forces include population and income development, technology development, lifestyle change and evolving production and consumption patterns (see for an overview Van Vuuren et al., 2012).

A1. Model description

Table 1 - Participating models

Model	Full name	Model type	Institution	Country
AIM	Asia-Pacific Integrated Model	CGE	National Institute for Environmental Studies & Kyoto University	Japan
CAPRI	Common Agricultural Policy Regional Impact	PE	European Commission Joint Research Centre	EU
ENVISAGE	Environmental Impact and Sustainability Applied General Equilibrium	CGE	Purdue University	USA
FARM	Future Agricultural Resources Model	CGE	U.S. Department of Agriculture	USA
GLOBIOM	Global Biosphere Management Model	PE	International Institute for Applied Systems Analysis (IIASA)	Austria
IMAGE	Integrated Model to Assess the Global Environment	CGE	Netherlands Environmental Assessment Agency (PBL)	Netherlands
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade	PE	International Food Policy Research Institute (IFPRI)	USA
MAGNET	Modular Applied General Equilibrium Tool	CGE	Wageningen University	Netherlands
MAgPIE	Model of Agricultural Production and its Impact on the Environment	PE	Potsdam Institute for Climate Impact Research (PIK)	Germany

The multi-model ensemble protocol breaks down the global economy into 13 regions, including five individual countries, and 17 sectors, as described in Table 2 and Table 3.

FoodMIP code	MAPPING Country
ANZ	Australia
ANZ	New Zealand
BRA	Brazil
CAN	Canada
CHN	China
CHN	Hong Kong
CHN	Macao, China
EUR	Albania
EUR	Andorra
EUR	Austria
EUR	Belgium
EUR	Bosnia and Herzegovina
EUR	Bulgaria
EUR	Croatia
EUR	Cyprus
EUR	Czech Republic
EUR	Denmark
EUR	Estonia
EUR	Finland
EUR	France
EUR	Germany
EUR	Gibraltar
EUR	Greece
EUR	Holy See
EUR	Hungary
EUR	Iceland
EUR	Ireland
EUR	Italy
EUR	Latvia
EUR	Liechtenstein
EUR	Lithuania
EUR	Luxembourg
EUR	Malta
EUR	Monaco
EUR	Montenegro
EUR	Netherlands
EUR	Norway
EUR	Poland

EUR	Portugal
EUR	Romania
EUR	San Marino
EUR	Serbia
EUR	Slovakia
EUR	Slovenia
EUR	Spain
EUR	Sweden
EUR	Switzerland
EUR	Macedonia
EUR	United Kingdom
EUR	Greenland
EUR	Svalbard and Jan Mayen
EUR	Isle of Man
EUR	Jersey
EUR	Guernsey
FSU	Armenia
FSU	Azerbaijan
FSU	Belarus
FSU	Georgia
FSU	Kazakhstan
FSU	Kyrgyzstan
FSU	Rep. of Moldova
FSU	Russian Federation
FSU	Tajikistan
FSU	Turkmenistan
FSU	Ukraine
FSU	Uzbekistan
IND	India
MEN	Algeria
MEN	Bahrain
MEN	Egypt
MEN	Iran
MEN	Iraq
MEN	Israel
MEN	Jordan
MEN	Kuwait
MEN	Lebanon
MEN	Libyan Arab Jamahiriya
MEN	Morocco
MEN	Oman
MEN	Palestinian Territories
MEN	Qatar
MEN	Saudi Arabia

MEN	Syrian Arab Republic
MEN	Tunisia
MEN	Turkey
MEN	United Arab Emirates
MEN	Yemen
MEN	Western Sahara
OAS	Afghanistan
OAS	Bangladesh
OAS	Bhutan
OAS	Cook Islands
OAS	Fiji
OAS	French Polynesia
OAS	Kiribati
OAS	Maldives
OAS	Marshall Islands
OAS	Micronesia (Federated States of)
OAS	Mongolia
OAS	Nauru
OAS	Nepal
OAS	New Caledonia
OAS	Niue
OAS	Pakistan
OAS	Palau
OAS	Papua New Guinea
OAS	Samoa
OAS	Solomon Islands
OAS	Sri Lanka
OAS	Tokelau
OAS	Tonga
OAS	Tuvalu
OAS	Vanuatu
OSA	Anguilla
OSA	Antigua and Barbuda
OSA	Argentina
OSA	Aruba
OSA	Bahamas
OSA	Barbados
OSA	Belize
OSA	Bermuda
OSA	Bolivia
OSA	British Virgin Islands
OSA	Cayman Islands
OSA	Chile
OSA	Colombia

OSA	Costa Rica
OSA	Cuba
OSA	Dominica
OSA	Dominican Republic
OSA	Ecuador
OSA	El Salvador
OSA	Falkland Islands
OSA	Grenada
OSA	Guadeloupe
OSA	Guatemala
OSA	Guyana
OSA	Haiti
OSA	Honduras
OSA	Jamaica
OSA	Mexico
OSA	Montserrat
OSA	Netherlands Antilles
OSA	Nicaragua
OSA	Panama
OSA	Paraguay
OSA	Peru
OSA	Saint Kitts and Nevis
OSA	Saint Lucia
OSA	Saint Vincent and the Grenadines
OSA	Suriname
OSA	Trinidad and Tobago
OSA	Turks and Caicos Islands
OSA	Uruguay
OSA	Venezuela
OSA	French Guiana
OSA	Puerto Rico
OSA	US Virgin Islands
SEA	Brunei Darussalam
SEA	Cambodia
SEA	People's Republic of Korea
SEA	Indonesia
SEA	Japan
SEA	Lao People's Dem. Rep.
SEA	Malaysia
SEA	Myanmar (Burma)
SEA	Philippines
SEA	Rep. of Korea
SEA	Singapore
SEA	Thailand

SEA	Timor-Leste
SEA	Vietnam
SEA	Taiwan
SSA	Angola
SSA	Benin
SSA	Botswana
SSA	Burkina Faso
SSA	Burundi
SSA	Cameroon
SSA	Cape Verde
SSA	Cent African Rep
SSA	Chad
SSA	Comoros
SSA	Congo
SSA	Côte d'Ivoire
SSA	Dem. Rep. of Congo
SSA	Djibouti
SSA	Equatorial Guinea
SSA	Eritrea
SSA	Ethiopia
SSA	Gabon
SSA	Gambia
SSA	Ghana
SSA	Guinea
SSA	Guinea-Bissau
SSA	Kenya
SSA	Lesotho
SSA	Liberia
SSA	Madagascar
SSA	Malawi
SSA	Mali
SSA	Mauritania
SSA	Mauritius
SSA	Mozambique
SSA	Namibia
SSA	Niger
SSA	Nigeria
SSA	Reunion
SSA	Rwanda
SSA	São Tomé and Principe
SSA	Senegal
SSA	Seychelles
SSA	Sierra Leone
SSA	Somalia

SSA	South Africa
SSA	Sudan
SSA	Swaziland
SSA	Togo
SSA	Uganda
SSA	Tanzania
SSA	Zambia
SSA	Zimbabwe
USA	United States

For example, only CGE models can capture interactions across markets since PE models limit their scope to a single market, generally agriculture. Other distinctions dependent on model structure include production technology and producer supply behavior, treatment of technical change, specification of commodity demand and treatment of foreign trade (Robinson et al., 2014). Most CGE models can explicitly represent trade flows using the Armington approach while most PE models consider only net-trade.

A2. Modelling protocol

Scenario Code	Description	Climate				EL2.0 Dimensions			Climate Mitigation and Land-use Policies
		RCP	**Crop Model**	**Livestock**	**Labor**	**Diet**	**Productivity Assumptions**	**Waste**	
BAU	Business as usual scenario based on **SSP2** with a higher climate impact reflected by **RCP 7.0**	7.0	Using **IPSL** GCM Average of GGCMI crop model ensemble (**RCP 7.0**) for soybean, maize, wheat, and rice.	Livestock productivity shocks (**RCP 7.0**) from Thornton et al. (2022) based on changes in higher temperatures.	Labor productivity shocks (**RCP 7.0**) for agricultural labor from Nelson et al. (2024)	Model BAU assumptions on diets to 2050	Model BAU assumptions on crop and livestock productivity. (Exogenous yield trends from IMPACT have been shared)	Model BAU assumptions on FLW	Model BAU assumptions on climate mitigation and LUC policies based on **NPi assumptions** if possible
EL2	**Full EAT-Lancet Scenario** (diet, productivity, FLW) **without mitigation** and higher climate	7.0	Using **IPSL** GCM Average of GGCMI crop model ensemble (**RCP 7.0**) for soybean,	Livestock productivity shocks (**RCP 7.0**) from Thornton et al. (2022) based on changes in	Labor productivity shocks (**RCP 7.0**) for agricultural labor from	Globally achieves EL2 diet by 2050	High productivity growth rate consistent with SSP1 productivity trends (e.g.,	Reduction of FLW	Model BAU assumptions on climate mitigation and LUC policies based on NPi

	impacts based on **RCP 7.0**		maize, wheat, and rice.	higher temperatures.	Nelson et al. (2024)		PRD 1 in Stehfest et al.)		assumptions if possible

A3. Regional changes in food demand under the EL2 scenario compared to BAU 2020 and 2050

A3.1. Changes in food demand in EL2 compared to BAU 2020

	VFN	OSD	RIC	SGC	RUM	NRM	CGR	DRY
ANZ	↑	↑	↑	↓	↓	↓	↑	↓
BRA	↑	↑	↓	↓	↓	↓	↑	↓
CAN	↑	↑	↑	↓	↓	↓	↓	↓
CHN	↑	↑	↓	↓	↓	↓	↓	↓
EUR	↑	↑	↑	↓	↓	↓	↓	↓
FSU	↑	↑	↓	↓	↓	↓	↓	↓
IND	↑	↑	↓	↓	↑	↑	↓	↓
MEN	↑	↑	↓	↓	↓	↑	↓	↑
OAS	↑	↑	↓	↓	↑	↑	↓	↑
OSA	↑	↑	↓	↓	↓	↓	↓	↑
SEA	↑	↑	↓	↓	↓	↓	↓	↑
SSA	↑	↑	↑	↑	↑	↑	↑	↑
USA	↑	↑	↑	↓	↓	↓	↓	↓

A3.1. Changes in food demand in EL2 compared to BAU 2050

	VFN	OSD	RIC	SGC	RUM	NRM	CGR	DRY
ANZ	↑	↑	↑	↓	↓	↓	↓	↓
BRA	↑	↓	↓	↓	↓	↓	↓	↓
CAN	↑	↑	↓	↓	↓	↓	↓	↓
CHN	↑	↑	↓	↓	↓	↓	↓	↓
EUR	↑	↑	↓	↓	↓	↓	↓	↓
FSU	↑	↑	↓	↓	↓	↓	↓	↓
IND	↑	↑	↓	↓	↓	↑	↓	↓
MEN	↑	↑	↓	↓	↓	↓	↓	↓
OAS	↑	↑	↓	↓	↓	↓	↓	↓
OSA	↑	↑	↓	↓	↓	↓	↓	↓
SEA	↑	↑	↓	↓	↓	↓	↓	↓
SSA	↑	↑	↓	↓	↓	↓	↓	↓
USA	↑	↑	↓	↓	↓	↓	↓	↓