Paper Title: Comparative analysis of historical changes with multi-model scenarios of food systems transformation to 2050

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Abstract

Food systems must transform in pursuit of health, sustainability, and justice goals. The scale and distribution of these profound changes across different food sectors is underexplored. We examine possible impacts on food sectors, contextualised with historical data, of a global food systems transformation by 2050. We do this through modelling a transformation scenario composed of dietary change, productivity growth, and reduction of food loss and waste using a multi-model ensemble of 8 global economic models. Preliminary results show substantial food sector restructuring, including a decline in the economic value of agricultural production (-$1.4tn) by 2050 under a transformation scenario versus current trends. Within this, the value of livestock production collapses (-$1tn) with declines also in cereal and sugar crop values of $800bn, partially offset by increases in the value of vegetable, fruit, and nut production ($700bn). Preliminary results also show changes to growth rates of agricultural land expansion from 0.56%/year on average for grazing land over the last 250 years to -0.87%/year from 2020 to 2050 in a food systems transformation scenario, compared to 0.12%/year under business-as-usual trends. The restructuring of global agriculture and food systems suggests a critical role for food policy to both catalyse such a transformation, as well as navigate the political economic consequences of its impacts.

Keywords: food systems transformation, scenario analysis, global economic modelling, historical analysis

Introduction

Food systems contribute around one third of all anthropogenic greenhouse gas (GHG) emissions globally (Crippa et al., 2021) and are a leading factor in the destabilization of several planetary boundaries (Campbell et al., 2017), including the largest driver of habitat and biodiversity loss around the world (Kehoe et al., 2017). Additionally, current food systems outcomes leave 3 billion globally unable to afford healthy diets (FAO, 2023), contributing to poor quality diets being among the leading mortality risks globally (GBD 2019 Risk Factors Collaborators, 2020). In response to these multiple intersecting crises, there is an urgent need to transform food systems (Fanzo et al., 2021; Singh et al., 2021; Webb et al., 2020; Willett et al., 2019), which, following previous definitions (Patterson et al., 2017; Sonnino, 2023) we consider as processes of radical change in the structural, functional and relational aspects of food systems that lead to more just socio-ecological relationships, patterns of interactions and outcomes.

Modelling and scenario analysis of food systems transformation has included the EAT-Lancet Commission (Willett et al., 2019) that employed static input-output modelling to assess the feasibility of feeding everyone healthy diets within planetary boundaries, and more recently, the Food Systems Economics Commission (Ruggeri Laderchi, C et al., 2024) that employed an integrated assessment framework to explore future food systems pathways. We build off and extend these previous analyses in three main ways. First, rather than single model analyses, we employ a multi-model ensemble of 8 dynamic global economic models running two food systems scenarios. In futures-oriented scenario exercises, ensemble analyses, which incorporates model diversity, offers advantages over single model assessment (Stehfest, van Zeist, et al., 2019). We focus on two scenarios: a continuation of current trends ‘business-as-usual’ (BAU) to 2050 and a food systems transformation scenario (EL2) that combines EAT-Lancet diet recommendations, supply-side productivity increases, and reductions to food loss and waste (FLW). The ensemble comprises a mix of computational general equilibrium (CGE) and partial equilibrium (PE) models that have all previously participated in multi-model exercises through the Agricultural Model Intercomparison and Improvement Project

(AgMIP) (Rosenzweig et al., 2013; Valin et al., 2014; von Lampe et al., 2014). Second, data inputs to the modelling ensemble include the latest update to the Shared Socioeconomic Pathway (SSP) projections (version 3). Note, preliminary results use model runs with SSP version 2 data. Final results will incorporate the latest version 3 release.

Finally, we provided a granular focus on the socio-economic, justice and environmental impacts of transformation across different food sectors (e.g. livestock products; cereals; vegetables, fruits, and nuts) by exploring the reallocation of resources and economic value. This is complemented by a novel historical lens that compares agricultural land changes over the last 250 years with possible future trajectories, and 21st century food production trends with future paths from 2020 to 2050, responding to literature calling for greater attention to historical food systems transformation (van Bers et al., 2019).

Through this we aimed to 1) identify the global magnitude and direction of change between BAU and EL2 scenarios in 2050 of different agri-food sectors across several food systems dimensions (calorie availability, price, production, area, emissions, end use, economic value), 2) historically contextualise a subset of these results to understand the scale and precedence of such a transformation, and 3) discuss the possible implications in terms of the restructuring of global agriculture, the trade-offs inherent in such a change, and the need for a fundamental shift in the intentionality of food systems decision-making.

Methods

Global economic model ensemble

We simulated scenarios using a multi-model ensemble, building on AgMIP food system modelling efforts that have developed modelling protocols to explore future uncertainty and increase the comparability across various economic models (Nelson et al., 2014; Rosenzweig et al., 2018; Stehfest, Zeist, et al., 2019). The ensemble includes 8 global economic models, which have featured in a wide range of high-level science-policy reports (Cointe et al., 2019). While all models are global in scope, they have varying levels of detail in representing parts of global food systems including food production, processing, trade, and demand, as well as environmental and socioeconomic outcomes of these activities.

Scenarios and data inputs

Two scenarios are modelled by the ensemble. The first is a 'business-as-usual' (BAU) scenario based on current trends that model BAU assumptions on diets, crop and livestock productivity, and food loss and waste (FLW). The second makes use of the core EAT-Lancet reference diet whereby the diet is achieved globally by 2050 driven by consumer preference shifts, along with higher productivity growth rates similar to trends associated with SSP1, and a reduction of FLW. Both scenarios have BAU assumptions of global climate mitigation and land-use change policies to 2050 (assume Representative Concentration Pathway (RCP) 7.0) and include climate-related impacts to crops (using IPSL GCM average of the GGCMI crop model ensemble for soybean, maize, wheat, and rice), livestock (based on data from Thornton et al., 2022), and agricultural labour (based on data from Nelson et al., 2024).

Historical data and analysis

We obtain long-run historic agricultural land and population from the History database of the Global Environment (HYDE) (version 3.3) (Klein Goldewijk et al., 2017). HYDE gives data at global and country level from -10,000CE to present. FAO Food Balance Sheet (FBS) data (FAO, 2001) are used to compare global production from 1960 to 2020 with projected production under BAU and EL2 scenarios out to 2050. FAO food items were aggregated into broader food sector categories (e.g. ruminants; vegetables, fruit, and nuts). For consistency and effective comparison, the relative (percent) change for modelled scenarios in 2050 versus model 2020 values were applied to FAO 2020 values.

Results

Food system transformation scenario leads to relative decreases compared to BAU but sectoral results show much heterogeneity

Table 1 shows the percentage change in 2050 across food groups for key food systems outcomes between a future transformed food system and one that follows current trends (BAU). Crops include rice, wheat, coarse grains, vegetables, fruits and nuts, oilseeds, sugar crops and other crops (not shown). Livestock products is broken down into ruminants, non-ruminants, dairy, and other animal products (not shown). With the exception of vegetables, fruits and nuts (VFN) and oilseeds, all other food groups show reductions in an EL2 scenario compared to BAU by 2050.

Overall, global food sector results under an EL2 scenario show declines relative to BAU by 2050 but with different levels of model agreement and uncertainty across key food system dimensions – per capita calorie availability, producer prices, production, area, emissions. There is high agreement (all models) of relative decreases for ruminant meat across per capita calorie availability (-72% on average), producer prices (-38% on average), production (-55% on average), grazing area (-33% on average), and total GHG emissions (-36% on average). Dairy also shows high agreement in decreases, although of smaller magnitude on average, for calorie availability (-31% on average), producer prices (-21% on average), production (-38% on average), while total GHG emissions changes are comparable (-38% on average) and there is lower agreement for grazing area with three of five models showing decreases (-5% on average). Non-ruminant meat (and eggs) shows broadly comparable percentage declines on average to ruminant meat for calories, production, and emissions, however, there is lower agreement for prices and area.

Cereals also show high agreement in the direction of change with decrease across per capita calorie availability (-35% on average across rice, wheat and coarse grains), producer prices (-32% on average), production (-36% on average), harvested area (-29% on average), and total GHG emissions (-46% on average). Similarly, sugar crops show high agreement (all models) in the direction of change in an EL2 scenario versus BAU with decrease across capita calorie availability (-46% on average), producer prices (-26%

on average), production (-40% on average), harvested area (-36% on average), and total GHG emissions (-58% on average).

Conversely, the general trend for vegetables, fruits, and nuts (VFN) are increases relative to BAU, but with less agreement (in direction and magnitude) across models. Five of six models show increased per capita calorie availability (+44% on average), two of four models show increased producer prices (+6% on average), five of six models show increased production (+29% on average), four of six models show increased harvested area (+29% on average), while all models show increased total GHG emissions (+40% on average). Oilseeds similarly display mixed model agreement regarding the direction of change between EL2 and BAU scenarios.

Table 1: Global results from the model ensemble showing percentage change (median, maximum, minimum) between an EL2 scenario versus a BAU scenario in 2050. Results are shown for food group sectors across five food systems dimensions (calorie availability per capita, agricultural producer prices, production, area (harvested area for crops, grazing area for livestock), and total GHG emissions (CO2e). All agriculture includes all crops and all livestock products. All crops includes cereals (wheat, rice, coarse grains); vegetables, fruits and nuts; oilseeds; and sugar crops (all shown) and other minor food crops and non-food crops (energy crops and plant-based fibres) which are not shown. All livestock products includes ruminant meat (mainly cattle, sheep, and goats), non-ruminants (mainly pork and poultry meat and eggs), and dairy (all shown) and also includes a category of other animal products (e.g. wool) which is not shown.

Sector	Calorie availability			Price			Production			Area			Emissions		
% change	Med.	Max	Min	Med.	Max	Min	Med.	Max	Min	Med.	Max	Min	Med.	Max	Min
All agriculture	-16	-9	-54	-12	29	-32	-27	-5	-45	-9	-3	-46	-40	-15	-49
All crops	-13	-1	-57	-5	55	-27	-20	-3	-45	-5	2	-38	-27	-12	-49
Rice	-36	-22	-59	-36	-6	-54	-34	-16	-54	-29	-15	-53	-40	-16	-58
Wheat	-27	-12	-66	-33	-8	-41	-34	-15	-59	-26	-5	-50	-48	-22	-57
Coarse grains	-35	-7	-60	-29	-8	-38	-39	-6	-49	-30	-11	-46	-46	-13	-55
Veg., fruit, nuts	44	54	-27	6	136	-12	29	50	-22	29	73	-33	40	42	37
Oilseeds	16	76	-14	-4	34	-15	0	32	-17	3	61	-45	3	15	-8
Sugar crops	-46	-42	-71	-26	-7	-35	-40	-20	-59	-36	-21	-46	-58	-50	-66
All livestock products	-57	-22	-62	-25	-8	-75	-42	-17	-58	-22	3	-61	-35	-16	-55
Ruminant meat	-72	-15	-87	-38	-13	-89	-55	-14	-80	-33	-5	-83	-36	-15	-57
Non-ruminants (meat and eggs)	-57	-29	-74	-18	13	-90	-44	-28	-61	38	125	-49	-41	-27	-49
Dairy	-31	-15	-51	-21	-8	-62	-38	-6	-53	-5	14	-32	-38	-15	-39

Restructuring of global agriculture

Overall, all models show a decline in the economic value of agriculture by 2050 in a EL2 scenario (-17% on average, from $8.4tn under a BAU world to $7tn). The livestock sector (meat, dairy, eggs, other livestock products) faces a substantial reduction in the value of production (high agreement, -$1tn on average). Within this, ruminant meat not only faces a $400bn decline on average (72% to 94% reduction in value) compared with a BAU 2050 but shows an absolute reduction on 2020 levels (Table 2). Major commodity crops – sugar (-58% on average) and cereals (-46% on average) – together on average show declines in value of around $800bn. Some of this reduction in agricultural value is offset by growth of vegetables, fruits, and nuts (VFN) (high model agreement, around $700bn on average). Oilseeds also show an increase on average, but there is less agreement, with two of five models showing declines. Globally, this amounts to a substantial restructuring of agriculture, with the livestock sector declining from around 40% to 25% of agricultural output by value on average in EL2 compared to BAU by 2050, while VFN increases its share from around 30% to 50% on average.

Table 2: Economic value of global production of food sectors in billion USD across current (2020), BAU and EL2 scenarios (2050). Median values of the model ensemble are given.

Sectors	BAU 2020	BAU 2050	EL2 2050	BAU 2050 - BAU 2020	EL2 2050 - BAU 2020	EL2 2050 - BAU 2050
All agriculture	4225	8437	7034	4212	2809	-1403
Rice	209	569	214	360	5	-355
Wheat	172	256	139	85	-33	-118
Coarse grains	246	406	246	160	-1	-160
Veg., fruit, nuts	1924	1808	2466	-117	542	659
Oilseeds	323	530	716	207	392	186
Sugar crops	111	246	104	135	-7	-142
Ruminant meat	296	494	86	199	-209	-408
Non-ruminants (meat and eggs)	480	1089	637	609	157	-452
Dairy	331	756	562	425	231	-194

Historical context for the Great Food Transformation

Compound annual growth rates (CAGR) show an expansion in cropland under an EL2 scenario to 2050, but at a slower rate than observed historically over the last 250 years or under a BAU scenario. In stark contrast, grazing land under an EL2 scenario shrinks at -0.87% per year (on average) compared with a historic rate of 0.56% per year and 0.12% per year (on average) under a BAU scenario. Ruminant meat and vegetables, fruits, and nuts are key sectors that drive crop and grazing land change in a EL2 scenario to 2050. From a production perspective, ruminant meat marks a distinct break with the past going from a CAGR of 1.6% between 1960 and 2020, to a CAGR of -1.2% (on average) in EL2 versus 1.2% (on average) under BAU. In contrast, the required rates of growth in vegetables, fruits and nut production are more comparable to recent history, but higher than under a BAU scenario.

Table 3: Compound annual growth rates of land and production change for select historical periods, BAU and EL2 future scenarios. Historical crop and grazing land rates are shown for 1750-2020 and production rates are shown for ruminant meat, and vegetables, fruits, and nuts over 1960-2020.

Sector	Dimension	Historical	BAU	EL2
Cropland	Land	1750-2020 0.52%/yr	2020-2050 0.48%/yr	2020-2050 0.45%/yr
Grazing land	Land	1750-2020 0.56%/yr	2020-2050 0.12%/yr	2020-2050 -0.87%/yr
Ruminant meat	Production	1960-2020 1.6%/yr	2020-2050 1.2%/yr	2020-2050 -1.2%/yr
Vegetables, fruits, nuts	Production	1960-2020 1.8%/yr	2020-2050 1.1%/yr	2020-2050 1.9%/yr

Discussion

Model ensemble results highlight agreement and uncertainty in food systems transformation

There are three main reasons for differences across model ensemble results. First, there are model composition effects whereby varying numbers of models report results across food sectors and food system variables. The second reason is differing interpretation and implementation of scenarios. Key scenario dimensions, for example SSP projections on population and economic growth, were harmonized across models. However, within broadly defined scenario specifications, modelling groups were free to follow individual assumptions, based on a priori knowledge and assessment, on productivity changes, 50% reduction in food loss and waste, and transitions to EAT-Lancet aligned diets. The third reason for differences in model results is model design, parameterization, and representation. The ensemble comprised 4 partial equilibrium (i.e. agricultural sector only) and 4 general equilibrium (i.e. whole economy) models which have different foci of analysis. Models also have varying detail and representation of land, flexibility in the response and type of land-use change (e.g. protected areas, forestry, biofuels) and spatial constraints on different crop and livestock production. Socio-economically, there are model differences in the responsiveness of producers to commodity price signals. We view this diversity as a strength when conducting scenario modelling studies of complex systems, such as food, which enhances our understanding of the range of possible outcomes from uncertain futures.

Substantial restructuring of global agriculture sector

A future transformed food system delivering improved global dietary health and sustainability outcomes compared to BAU but with a smaller agricultural sector economically, represents a reorientation of what is valued. This change in economic value is unevenly distributed across agricultural sectors. Chiefly, ruminants and non-ruminants see an absolute decline compared to 2020 levels, which would have serious ramifications for production practices, labour, and the prospect of consolidation. Substantial economic contraction and the possibility of consolidation poses potentially sizable negative consequences for livestock oriented rural economies and livelihoods, and the agenda of the “renaissance of rural territories” (Caron et al., 2018). Alternatively, a shrinking global livestock market could disincentivise consolidation due to the prohibitive capital costs.

The transformation of food production would likely have gender implications, even as predicting these outcomes is challenging. One possible outcome is increasing crop diversification from reduced livestock and cereal production and increases in vegetables, fruits, and nuts. While the relationship between crop diversification and gender equality is not settled (Feliciano, 2019), there is evidence that this can lead to greater women’s empowerment among some groups e.g. low-income agricultural households (Connors et al., 2023; Tavenner et al., 2019; Valencia et al., 2021). Conversely, the restructuring of the global agriculture sector may further entrench existing gender inequalities. Another possible outcome is that livestock ceases to be seen as a viable development pathway for poor rural populations (Herrero et al., 2013), with gender implications from how the rearing of small and large livestock animals is distributed among women and men.

Navigating land use change

Land reallocation occurs from livestock grazing to agricultural crops, but a significant proportion of grazing land (up to 65% globally, mostly rangeland for small ruminants) will likely exit the agricultural sector altogether as it is unsuitable for crops (Mottet et al., 2017). We see three likely categories of sectoral land reallocation: reallocation between crop land (e.g. from cereals to vegetables), grazing to cropland conversion, and conversion of grazing to non-agricultural use, of which forestry is a likely beneficiary. This poses opportunities and challenges to maximise socio-ecological benefits while minimising trade-offs where possible. For example, the scale of the decline in livestock value and area could exert downward pressure on grazing land prices. The consequences of these changes are hard to predict but one outcome could be the furthering of land-grabs undertaken by agri-capital, high wealth individuals, and state actors (Oliveira et al., 2021; Wolford et al., 2024). Alternatively, depressed grazing land prices and constrained market opportunities may result in land abandonment, as observed after the breakdown of the Soviet Union in which cattle production declined precipitously (Schierhorn et al., 2016) and 30-60Mha of agricultural land was abandoned (Lambin & Meyfroidt, 2011; Schierhorn et al., 2013; Wuepper et al., 2020).

The contraction of livestock sector production and reallocation among crops will likely result in sizeable land-use change, which rarely produces “win-win” outcomes (Lambin et al., 2013; Meyfroidt et al., 2022). These changes occur against a backdrop of currently unequal agricultural land distribution – where, globally, 70% of farmland is operated by 1% of farms (Lowder et al., 2021) – power asymmetries, unequal capture of benefits, and contested land tenure and rights (Meyfroidt et al., 2022). These current realities are contingent and may change, but nevertheless, the land-use change triggered by food systems transformation may advance health and sustainability goals, while risking reinforcing or replicating existing injustices.

Future research

How such a transformation might unfold and its possible impacts in 2050 is dependent on what we believe the future could or should be, and the core assumptions and worldviews that underpin this. Any exercise that poses questions of the future engages, consciously or not, with assumptions, representations, and worldviews of how the world works and how it might work in the future. All of which have bearing on the imaginaries and possibilities examined in futures-oriented research (Cork et al., 2023). The ensemble of models in this study are founded on neo-classical economic theory and are calibrated, to the extent possible, on historic trends and stylised representations of observed empirical relationships. This extends to model inputs, with the SSPs providing population and GDP growth scenarios which inform model results. The scenarios and modelling results here are a function of assumptions and perspectives that, while well established, do not, and are not intended to, represent the entire possibility space of future global socio-economic or food systems. More work is needed to develop, integrate, and critically examine radical and fundamentally different scenarios of the future, including post-growth and degrowth (e.g. Bodirsky et al., 2022). Future research should also consider questions of strategy and pathways for *how* to achieve food systems transformation, and linked to this, assessments of the costs (economic, material, opportunity) of transformation and how this might be distributed both socio-economically and geographically.

Policy implications

This study shows several dimensions of the 'Great Food Transformation' (Willett et al., 2019) are ahistorical. The scale of agricultural land reduction is likely without precedent, and the decline in livestock value and reduced meat consumption marks a paradigm shift in our relationship with farmed animals. And although the rate of increased production of vegetables, fruits and nuts under a transformed food system future is comparable to trends from the 1960s, the absolute scale of this increase will necessitate substantial investment. Historical comparisons make stark the scale of change across land, production, and consumption, and underline the challenge of how to achieve food systems transformation and mitigate the trade-offs among its impacts. Moreover, *how* this transformation plays out will determine how the benefits and trade-offs between health, sustainability, and justice are distributed.

The implications for policy are significant. First, the scale of change, as shown here, would require commensurate policy ambition. Existing types of intervention for healthy diets and sustainable food systems will not deliver the magnitude of change required. Second, the sectoral restructuring of such a transformation will yield winners and losers, and the consequences of how the impacts are distributed is inherently political. The dual challenge of engendering a substantial transformation and then navigating its impacts calls for a renaissance in national and international governance and with it, a radical shift toward greater intentionality of food systems decision-making.

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