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Economic, social and environmental spillovers decrease the benefits of a global dietary shift

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Dietary shifts are key for enhancing the sustainability of current food systems but need to account for potential economic, social and environmental indirect effects as well. By tracing physical quantities of biomass along supply chains in a global economic model, we investigate the benefits of adopting the EAT–*Lancet* diet and other social, economic and environmental spillovers in the wider economy. We find that decreased global food demand reduces global biomass production, food prices, trade, land use and food loss and waste but also reduces food affordability for low-income agricultural households. In sub-Saharan Africa, increased food demand and higher prices decrease food affordability also for non-agricultural households. Economic spillovers into non-food sectors limit agricultural land and greenhouse gas reductions as cheaper biomass is demanded more for non-food use. From an environmental perspective, economy-wide greenhouse gas emissions increase as lower global food demand at lower prices frees income subsequently spent on non-food items.

Transitioning to a more sustainable food system lies at the core of the Sustainable Development Goals[1]. Current food systems generate substantial environmental, social and health costs while failing to provide affordable healthy food to all[2]. Direct health and sustainability benefits of a diet shift are increasingly recognized following the publication of the EAT–*Lancet* diet[3,4], but economic, social and environmental goals need to be achieved in an integrated manner[5]. The EAT–*Lancet* diet requires substantial changes in consumption and production and therefore food prices, which, in turn, alter incentives for consumers and producers. Insight into these indirect or spillover effects on economic, social and environmental terms alongside direct impacts is thus key for steering the much-needed transformation of global food systems.

The EAT–*Lancet* diet is designed to simultaneously improve health and sustainability through a substantial transformation of current global food systems. In all but low-income regions with a substantial prevalence of hunger, calories need to be reduced, while increasing plant-based products and limiting animal-sourced foods (ASFs)[4]. This diet shift is designed to reduce mortality from weight and obesity, low fruit and vegetable consumption and high red meat consumption[6]. In addition, the EAT–*Lancet* diet simultaneously aims to improve sustainability by reducing global agricultural greenhouse gas (GHG) emissions, land and water use, biodiversity losses and nitrogen and phosphorus pollution[4,7,8]. In Willet et al.[4], the baseline scenario considered in the design of alternative diets is based on a partial equilibrium model[9], and the impacts of the proposed diet changes are derived from a static input–output model, ignoring any price impacts and therefore indirect effects.

Indirect effects—or spillovers—are likely to emerge given the extent of the food system transformation implied by the adoption of the EAT–*Lancet* diet. First, food affordability is key for social acceptance of the dietary shift and thus for reaching the intended health benefits associated with it. Affordability is determined by the combined impact of price and income changes[10]. Recent studies have outlined only first effects of dietary changes on food prices. Using empirical data of retail

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prices and income, Hirvonen et al.[11] found that the EAT–*Lancet* diet costs only a small fraction of income in high-income regions, while exceeding household per capita income for at least 1.6 billion of the world's poor. Springmann et al.[12] combined empirical data on food prices with current and simulated diet patterns looking at affordability compared to current diets and computing healthcare and climate damage costs. They found healthy diets to be cheaper in higher-income regions but more expensive than current diets in lower-income regions. While Hirvonen et al.[11] found limited food affordability for the poor, it did not capture income changes from a global shift in the food systems, which may alter conclusions on changing food affordability. Springmann et al.[12] did not address income nor price changes from a global shift in diets. While pointing to regionalized affordability concerns, these studies only partially captured social spillovers via food affordability.

Second, the food system transformation affects the wider economy as changing household spending patterns creates economic spillovers in non-food sectors. Reducing agricultural land area and emissions by reducing global food consumption are two key environmental benefits of the EAT–*Lancet* diet[4,6,13]. On the basis of static models without price changes or agricultural sector models, however, these studies could not account for changes in non-food demand—and thus production—under diet shifts. Non-food sectors use biomass and thus require land, which may reduce the impact of diet changes on land use. While agriculture is the main source of non-CO_2 emissions[14], total GHG emissions from the food system (including processing, retail, transport and consumption) are a third of global emissions[15]. Shifting consumption from food to non-food could thus generate more GHG emissions outside the food system. Economic spillovers to non-food sectors could alter the initial EAT–*Lancet* diet impacts in terms of non-food production, land use and GHG emissions.

Third, the substantial change in diet affects the composition and global flows of food loss and waste (FLW), creating environmental spillovers in terms of reuse possibilities. A reduction in total FLW generation is generally associated with a more sustainable diet[4,13]. Increased demand for plant-based foods commonly associated with high FLW shares[16] may increase FLW along global food supply chains (FSCs). These studies however provide no insight in changing composition (quality) nor geographical location of FLW when transitioning to a healthier diet. The dietary shift will induce changes in FLW composition and geographical production locations, creating environmental spillovers by affecting the scope for FLW reuse.

Here we investigate benefits and economic, social and environmental spillovers of a global transition towards a healthier and sustainable EAT–*Lancet* diet[4] in 2030. We address three main research questions focused on indirect effects or spillovers missing in existing studies, one for each of the domains integral to the Sustainable Development Goals. First, what are the economic spillovers into non-food sectors not targeted by the diet shift and do these thwart the environmental gains in terms of land use and GHG emissions? Second, what are social spillovers in terms of food affordability if we account for changes in food prices and wages that provide the main income for most and especially poor households? Third, what are environmental spillovers in terms of FLW amount, composition and location?

We contribute to the existing literature on moving within planetary boundaries through a diet shift by simultaneously addressing future non-food, income and FLW direct and indirect impacts through an enhanced economy-wide general equilibrium (GE) model. The GE model enhancements build a bridge between economic and technical modelling of biomass and FLW. It improves tracing of food and non-food use of biomass in physical quantities along global FSCs in a GE model, including behavioural responses of producers and consumers lacking in technical studies. Previous studies have extended global GE models with physical data on land use[17] and selected biomass flows[18,19], but none explicitly addressed the changes of physical biomass flows in the context of a global dietary transition and FLW. Our FLW amounts evolve with changing production and consumption patterns driven by the economic dynamics of the model and are based on best available estimates collected from literature, compiling a new global database to quantify lost or discarded food by region, commodity and supply chain stage. We align with the United Nations[1], defining FLW as 'food (including inedible parts) lost or discarded along the food supply chain, comprising pre-harvest losses, and excluding food diverted to animal feed, seed or to other non-food material uses such as bio-based products'.

We simulate the transition towards the EAT–*Lancet* diet by changing global consumption patterns in line with these healthy and sustainable dietary guidelines and compare it to a business-as-usual (BAU) scenario for 2030 without dietary shifts. While existing studies focus on the adoption of the EAT–*Lancet* diet, we also run separate scenarios for commodity targets and total calorie intake—which allows us to identify which components of the diet have the strongest impact. This decomposition also has policy relevance, providing guidance on which diet component to focus on if a complete diet shift is infeasible. We model a partial transition towards the EAT–*Lancet* diet in all regions, based on the unaffordability of a full diet shift for households in low-income regions[11]. Applying a homogeneous dietary shift across countries allows comparisons with existing global EAT–*Lancet* studies. The gap with the EAT–*Lancet* target is reduced by one-third in all regions.

The paper is structured in five main sections. The first provides an overview of how the diet scenario changes food demand compared to the BAU as this drives all other results. The second presents results for biomass production, trade, land use and GHG emissions—including economic spillovers in non-food sectors. The third section presents the implications of the diet change for food prices and wages, identifying negative social spillover effects for specific households and regions. In the fourth section, changes in FLW amounts, composition and geographical location are analysed to identify additional environmental spillovers from changes in FLW generation. We conclude with a discussion, placing our findings in context and deriving policy implications. The Methods and Supplementary Information provide our methodological contributions to simulate the EAT–*Lancet* diet in a global economic model and for tracing physical biomass flows and FLW across global supply chains in a more consistent manner.

Results

Consumption shifts towards a healthier and more sustainable diet

To analyse how a future healthy and sustainable diet may transform the food system, we use two scenarios. The BAU scenario provides a 'without' situation where diets are endogenously determined in response to two main drivers: population and gross domestic product (GDP) changes. The BAU scenario does not provide a forecast of the future but a plausible future state of the economy if past trends in these two main drivers continue, capturing the expected responses in terms of production, consumption and trade. The 'with' situation then simulates a counterfactual breaking with historical dietary developments by imposing a healthier and more sustainable diet on top of the BAU drivers. In addition to a complete diet scenario, we run scenarios for commodity group and calorie restriction separately. This provides insight in the contributions of different targets. It also offers a first insight into the effects of a diet better tailored to region-specific circumstances than the global EAT–*Lancet* reference diet as these commodity groups cover the items generally included in national food-based dietary guidelines. Instead of the BAU endogenous consumption, all diet scenarios consider (part of) consumption exogenous. We use an endogenous shifter variable modifying consumer food preferences such that they adhere to the imposed diet while still taking into account income and price changes.

Table 1 | Overview of investigated dietary scenarios and magnitude of implemented regional diet shocks in net consumption

		Region-specific shock (% change in driver or final net consumption)							
		EU27	**SEA**	**INDA**	**NAMO**	**LAC**	**REUCA**	**MENA**	**SSA**
Macro drivers (% change from 2020–2030)[a]	Population	1.2	8.4	−3.9	8.3	11.4	3.4	21.8	39.1
	BAU GDP	24.7	69.7	18.6	26.3	30.5	17.9	42.5	48.6
	Towards EAT–*Lancet* GDP	24.7	70.6	18.4	26.7	30.8	17.9	42.4	48.4
Agricultural share in GDP in 2030 (%)	BAU	1.4	5.0	0.6	0.9	5.1	1.9	3.4	14.7
	Towards EAT–*Lancet*	1.3	4.6	0.9	0.7	4.5	1.4	3.0	18.9
EAT–*Lancet* targets (grams per capita per day)	Diet scenarios towards the EAT–*Lancet* (reducing the gap with targets by a third):								
232	Cereals	−26.2	−22.3	−25.8	−28	−21.7	−22.9	−24.6	−15.2
675	Horticulture[b]	−4.1	−1.4	0.7	9.2	13.9	−3.0	3.6	−9.3
51.8	Fats	−26.9	−26.1	−24.8	−23.5	−24.1	−22.7	−20.7	−14.8
31	Sugars	−31.4	−30.3	−30.5	−31.5	−32.6	−30.7	−30.6	−27.7
7	Meat—ruminants[c]	−24.8	−12.4	−23.8	−29.7	−29.1	−27.3	−23.5	−15.7
49	Meat—non- ruminants[d]	−21.6	−5.6	−23.6	−24.6	−22.2	−21.0	−10.3	57.3
250	Dairies	−20.7	24.1	15.3	−17.4	−3.6	−17.3	6.9	93.9
28	Fish	−9.0	−20.0	−24.9	−11.1	−16.2	−11.2	3.7	42.5
2,500 (kcal per capita per day)	Calories	−23.1	−13.0	−20.9	−24.4	−18.4	−18.9	−18.2	−1.7
Towards EAT–*Lancet*			Combination of all shocks reported above for each region						

[a] Population and BAU GDP projections from International Monetary Fund[49] covering the period between 2020 and 2030. These are used to calibrate a BAU total factor productivity change that replicates the IMF GDP growth. In the diet scenarios, this BAU factor productivity is maintained while GDP can adjust, reflecting the average income effects of the diet change. Population growth is exogenous and identical in BAU and diet scenarios. EU27 = European Union-27; SEA = Southeast Asia; INDA=industrialized Asia; NAMO = North America and Oceania; LAC = Latin America and Caribbean; REUCA = rest of Europe and Central Asia; MENA = Middle East and North Africa; SSA = sub-Saharan Africa. [b] Horticulture includes fruits, vegetables, roots, tubers, pulses, starchy vegetables and nuts. [c] Red meat (ruminant meat, mostly beef). [d] Other meats and animal products (mostly pork and poultry).

A summary of our scenario assumptions and impacts on GDP is provided in Table 1 to support interpretation of results. Details on scenario implementation and limitations posed by the commodity detail in our model are provided in the methods section and Supplementary Information. For all regions, GDP growth from 2020 to 2030 exceeds population growth so income per capita rises. Moving towards the EAT–*Lancet* diet only marginally changes GDP. Our preference shifts do not impose any cost on the economies while reducing the size of the agricultural sector which, in most regions, receives substantial subsidies. As a result, economies restructure in response to the diet shift but do not change in size. In general, our results show that the EAT–*Lancet* diet reduces intake substantially in most high-income regions. For low-income regions such as sub-Saharan Africa (SSA) and to a lesser extent Southeast Asia (SEA), changes in the intake of some commodities have to decrease less or even have to increase substantially (for example, non-ruminant meat and dairy consumption in SSA).

Transitioning to a healthier and sustainable diet results in reduced global food consumption (and thus production) by one-fifth in 2030 compared to BAU developments (Fig. 1). The per capita income increase projected for 2030 results in higher global average food intake when past trends continue as in the BAU. Given the scenario set-up detailed in Table 1, global intake across all commodity groups decreases in the EAT–*Lancet* scenario. Total intake is 20% lower than in the BAU and 17% lower than in 2020, implying a substantial global reduction in food production. This global average hides regional differences such as the increase in food intake in low-income regions such as SSA (11.4%).

The reduction in quantities consumed is not proportional across commodities with diets transitioning towards horticultural products and away from cereals, sugars, meat and dairy. Compared with the BAU, horticultural intake in 2030 remains the same. Whereas fruit and vegetable consumption needs to increase globally, the horticultural commodity in the MAGNET (Modular Applied General Equilibrium Tool) model also includes roots and tubers that need to decrease. These opposing shifts cancel each other at the global level and lead to targeted reductions for horticultural products in several regions (Table 1). Consumption of other crops decreases substantially compared to the BAU, ranging from −26% for cereals to −34% for sugar crops. ASFs also decrease substantially, ranging from a 32% reduction for red meat to a 10% reduction in dairy intake. The dietary shift brings intakes below 2020 levels for all but horticultural products, implying a contraction of current food production instead of the BAU expansion.

Although total food intake reduction can be reached by targeting calories alone, the resulting diet would have too much meat and sugar while lacking in horticultural products and dairy. Targeting calories without side constraints on the composition of the diet about matches the total intake measured in grams (2,261 versus 2,233 grams per capita per day). But the composition only matches for other meat (85 grams, includes eggs as well). Intake of horticultural products would be much lower (525 grams per capita per day, 22% lower than in the EAT–*Lancet* diet), as would dairy (16% lower). All other commodity groups would be higher, most notably sugar crops (45%) and red meat (11%).

Economic spillovers into non-food sectors increase GHG emissions

To analyse economic spillover effects we investigate how changes in global biomass production, trade and non-agricultural sectors affect global land use and GHG emissions.

By reducing food demand, the transition towards the EAT–*Lancet* diet reduces global biomass production for food, but there is no one-to-one link for all commodities. While still increasing from 2020 levels, total biomass production is 79% lower than in the BAU (Fig. 2a). The diet transformation reduces cereal, oil seed, sugar crop, meat and

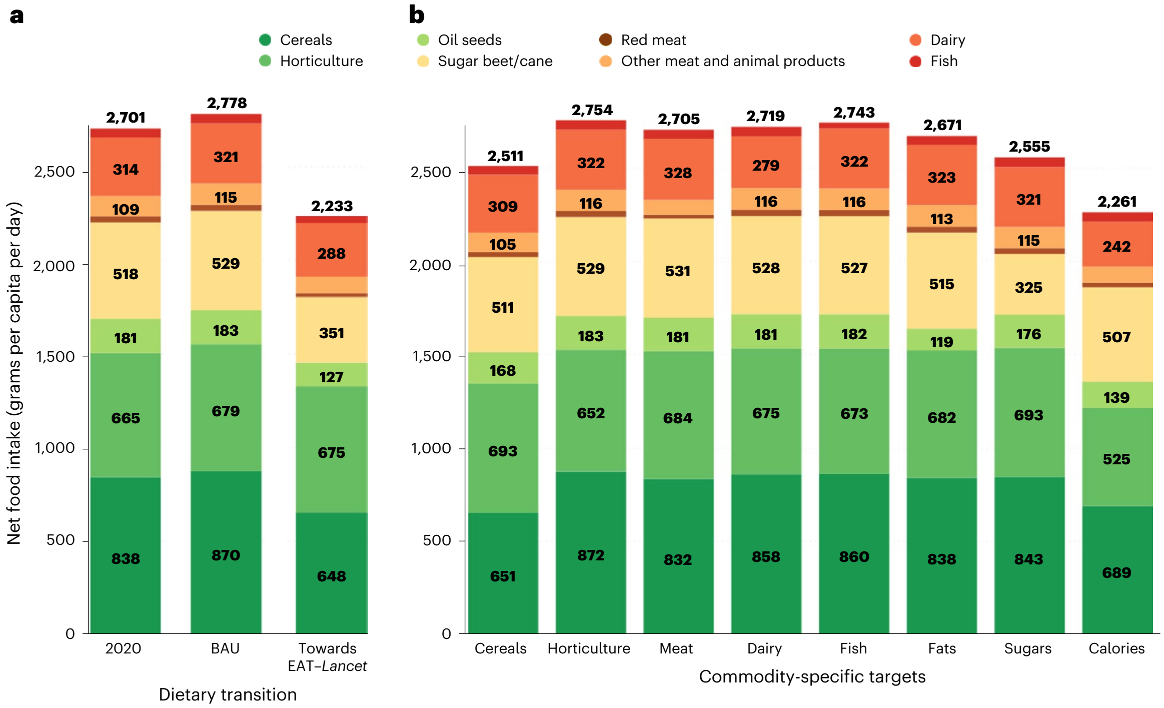

Fig. 1 | Average global net food intakes in 2020 and in 2030 with BAU and diet scenarios. a, Average net food intake in 2020 (starting point of our simulation) and in 2030 for the BAU and transition towards the EAT–*Lancet* diets. **b**, The impact of commodity group and calorie targets constituting the EAT–*Lancet* diet. Table 1 provides a description of the scenario set-up by region. Intake estimates exclude FLW discussed in more detail in the last results section. The reported global averages hide impacts on single supply chain stages and regional variation. Units are grams per capita per day.

fish production below 2020 levels. Despite a comparable intake of horticultural products (Fig. 1), the increase in horticultural production with the diet transformation is 14% less than in the BAU. By contrast, average dairy intake decreases below 2020 levels with the dietary transition (Fig. 1), while dairy production increases compared to 2020 levels (Fig. 2a), showing the increase in dairy production in locations (mainly low-income regions) associated with higher rates of FLW. As with food intake, restricting calories is the main driver of decreasing food biomass production, which also shifts production towards meat and sugar crop production. Commodity-specific targets have limited impact on the biomass production pattern, apart from a change in the targeted commodities.

In addition to reducing biomass demand and therefore production for food, we find that the lower food demand imposed with the EAT–*Lancet* diet induces the economic adjustments leading to lower agricultural prices, which stimulates biomass demand and therefore production for non-food use. Production of other crops used as non-food (including, for example, products such as natural rubber, forage plants and plants used primarily in perfumery, pharmacy or textiles) increases substantially compared to 2020 levels (191%), while increases are negligible in the BAU. In our model simulations, the production of non-food crops and non-food use of all biomass is stimulated by lower agricultural prices, resulting from the decreased demand for food. Lower prices make food biomass more competitive relative to non-biomass-based alternatives (for example, fossil sources) in non-food sectors. Single commodity-specific targets nor calorie reduction have a strong impact on non-food biomass production.

Similar to production, global biomass trade shows a more moderate increase in volume with a changing diet than in the BAU, but the non-food shift is much stronger with trade for food use declining below 2020 levels (Fig. 2b). Biomass traded for use as food in primary, processed or service products decreases compared to 2020 by 234 million tonnes (−15%). This is more than compensated by the increase in trade for non-food use of 243 million tonnes (117%). As food biomass production increases (Fig. 2a) and especially trade for processed food declines, this signals shorter supply chains (that is, fewer stages) oriented towards fresh products. Trade of non-food biomass increases under all single commodity-specific targets but most with the calorie target. The 158 million tonnes (or 28%) reduction in biomass trade for processed foods compared to 2020 levels with the EAT–*Lancet* is principally due to targets on calories, sugars, cereals and fats. Only the calorie target also leads to a decrease in primary food and food service biomass trade, making it the main driver of changing global biomass trade.

Our results illustrate that transitioning to the EAT–*Lancet* diet generates an economic spillover effect in non-food sectors, visible in biomass production and trade and by a declining share of agriculture in GDP. The production and trade patterns in Fig. 2 already show the stimulus of non-food sectors by the diet transition. The impact of the diet extends beyond biomass as shown by lower shares of agriculture in GDP than in the BAU, while GDP growth remains the same (Table 1). With the global transition to a healthier and sustainable diet thus comes a shift towards consumption of non-food commodities made possible by the combined effect of lower food prices (Fig. 4a,b) and lower food consumption levels (Fig. 1). The notable exception is sub-Saharan Africa, where food consumption does not need to decrease and shifts to higher cost for animal-sourced foods (diet shocks in Table 1). As a result, here the already high share of agriculture in GDP in the BAU (15%) increases to 19% with the diet transition.

In our simulations, the economic spillovers into non-food sectors reduce the benefits of the EAT–*Lancet* diet by mitigating the reduction in global agricultural land use compared to the BAU (Fig. 2c). Globally transitioning to the EAT–*Lancet* diet still mitigates the BAU trend of increasing agricultural land use, reducing the 3.8% expansion in the BAU to 3.2%. While rising consumption of primary fresh plant-based

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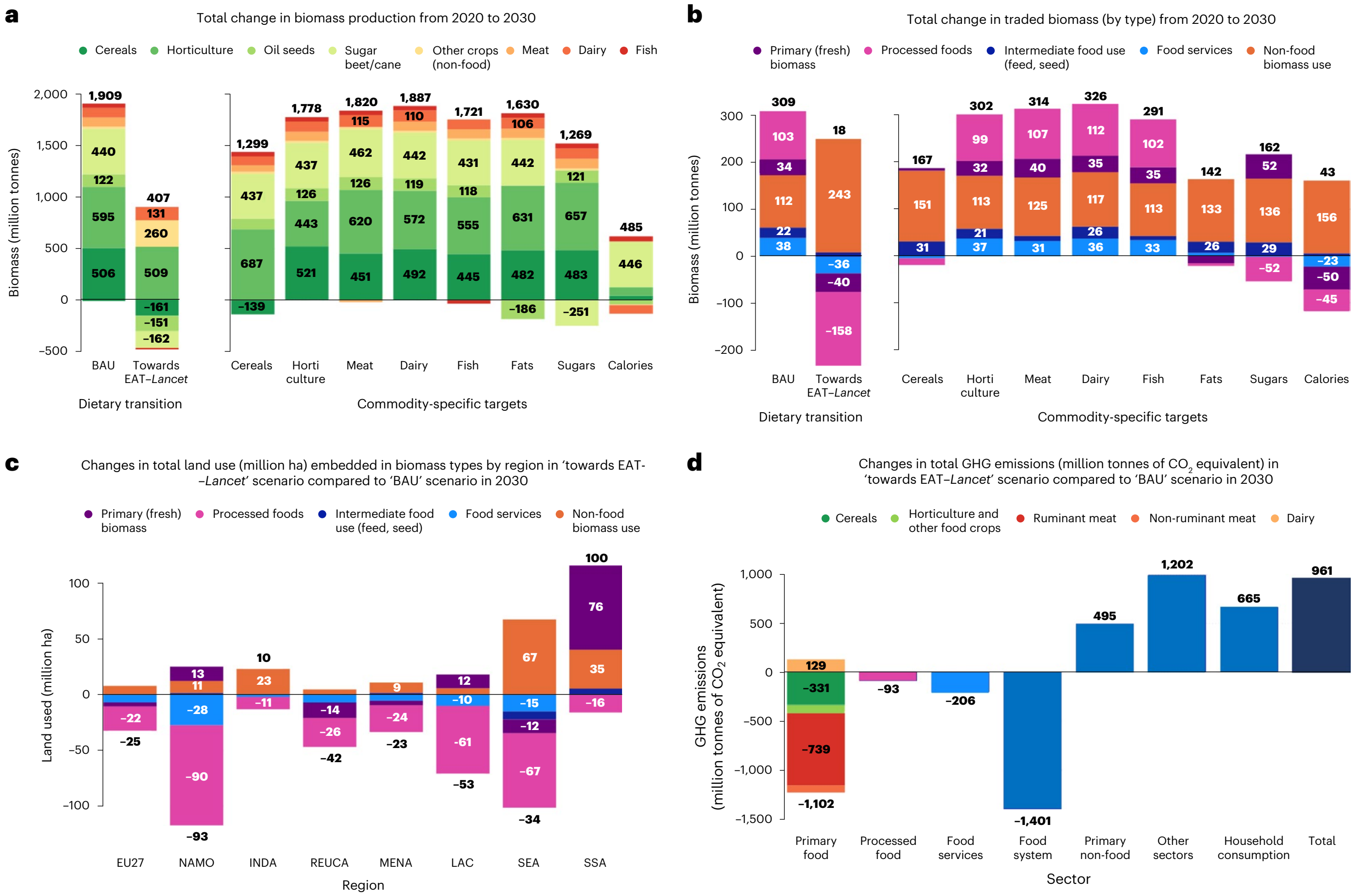


Fig. 2 | Changes in biomass production and international trade with a healthy and sustainable diet. a, Changes in biomass production. Estimates refer to changing production of total global biomass (million tonnes) suitable as food summed over all uses (food, feed, seed and other non-food) and all sectors (primary sectors, manufacturing and services) from 2020 to 2030 by scenario. To highlight the shift towards non-food use, we report biomass from non-food crops (such as plant-based fibres) that are easily substituted with food crops. 'BAU' refers to the baseline business-as-usual scenario. 'Towards EAT–*Lancet*' scenario refers to a combination of all commodity-specific scenarios and the 'Calories' scenario. **b**, Changes in global biomass trade volumes by type of biomass from 2020 to 2030 by scenario. Estimates refer to change in trade of biomass categorized through different channels of use. Intermediate food use refers to primary food biomass serving as intermediate input (in the form of feed or seed) to produce other food commodities (such as meat). Non-food biomass use refers to food biomass used for non-food purposes such as industrial and non-food services. **c**, Changes in land use (hectares) by region and biomass types comparing the 'Towards EAT–*Lancet*' scenario with our BAU scenario (baseline) in 2030. **d**, Finally, total changes in GHG emissions (million tonnes of carbon-dioxide (CO$_2$) equivalents) in the 'Towards EAT–*Lancet*' scenario compared to our BAU scenario (baseline) in 2030. The first column of **d** is split by food categories to illustrate the major impact of the dietary transition in reducing GHG emissions from ruminant meat and cereals (mainly rice) production. 'Primary non-food' refers to GHG emissions related to non-food agricultural sectors. The sum of GHG emissions in the 'Primary food' and 'Processed food' columns constitutes the 'Food system' column, illustrating changes in GHG for the entire food system (that is, primary food, processed food and food services). 'Other sectors' refer to changes in GHG emissions produced by non-agricultural sectors. 'Household consumption' refers to emissions related to purchases of food and non-food products by households. Finally, the last column of **d** reports the total changes in GHG emissions in the whole economy.

products increases global land use for primary biomass by 66 million hectares (4%), reductions from lower consumption of processed foods (317 million hectares) and food services (74 million hectares) result in substantially less land used for food (325 million hectares globally). Lower demand for food reduces land prices, inducing both extensification and land taken out of production. Lower land prices also reduce biomass prices, increasing their competitiveness in non-food use, which also keeps land in production; land use for non-food biomass increases by 163 million hectares (+38%). Globally, this implies that the benefit of the EAT–*Lancet* diet in terms of reducing land use is halved from 325 million hectares from reduced food use to 162 million when accounting for increased non-food land use as well. Linked to this, the global use of chemical fertilizers declines only by 2% as the decrease in the application of chemical fertilizers for food crops (−20.5%) is almost erased by a parallel increase in fertilizer use for non-food crops (+128.1%).

Regional developments differ from the global pattern with land use in sub-Saharan Africa and industrialized Asia, increasing more than in the BAU, and similar trends in land use being driven by different commodity targets in high- and mid-income regions. In sub-Saharan Africa, the EAT–*Lancet* diet increases land demand by 100 million hectares (2.4%) due to a combination of additional land for food (fresh biomass 76, seed and feed 5 million hectares) and non-food biomass (35 million hectares). Given that sub-Saharan Africa is relatively land abundant, land prices in sub-Saharan Africa are also relatively low, stimulating land expansion. Land for non-food biomass production drives the 10 million additional hectares brought into production in industrialized Asia compared to the BAU. In all other regions, land use decreases compared to the BAU, dominated by reductions in land use for processed foods. In high-income regions, this is linked to commodity targets on meat and dairy, and thus reductions are mainly pasture land. In mid-income regions, targets for cereals and sugars result in less land for processed food, thus reducing land used for crops. Even with similar trends, there are thus differences in drivers and types of land hidden in these aggregate numbers.

Economic spillovers into non-food sectors reverse lower food system emissions when transitioning to the EAT–*Lancet* diet (1,195 million tonnes of CO_2 equivalents), resulting in a net increase of GHG emissions by 1.7% compared to the BAU (equal to 961 million tonnes of CO_2 equivalents; Fig. 2d). The total reduction in food system emissions is dominated by lower consumption of ruminant meat (739 million tonnes of CO_2 equivalents) and cereals (notably rice, 331 million tonnes of CO_2 equivalents). The stimulus of non-food consumption as a smaller share of income is spent on food due to lower quantities and prices, the diet transition increases emissions compared to the BAU from non-food primary sectors food (135%), industrial and service sectors (2.3%) and from household consumption (9.9%). Despite lower percentage changes, higher 2020 emissions levels have adjustments outside of the agricultural sector (industrial and service sectors, household consumption) that drive the net increase in GHG emissions when transitioning to the EAT–*Lancet* diet.

Social spillovers enlarge the income gap among workers

To analyse social spillovers we investigate how the dietary transition affects food affordability through changes in food prices and low-skilled wages that provide the main source of income for low-income households in all regions. We analyse prices of two types of food baskets. First, we analyse a healthy food basket defined in accordance with the EAT–*Lancet* dietary targets to assess if the imposed diet would be affordable and thus more likely to be adopted. Second, we analyse staple foods composed of different cereals that provide the main source of calories for the poor[20]. Decreased staple food affordability signals that hunger among the poorest households may increase when transitioning to an EAT–*Lancet* diet. Prices tell only half the story of affordability and are therefore compared to changes in income for two types of low-skilled workers, those in agriculture and non-agriculture. This distinction is relevant due to the persistent much lower wages in agriculture and because of the stimulus from economic spillovers to non-agricultural sectors.

We find the diet transition improves affordability of an EAT–*Lancet* diet for all non-agricultural low-skilled workers except those in sub-Saharan Africa but only for agricultural workers in high-income regions and Southeast Asia (Fig. 3a,b). Prices of an EAT–*Lancet* diet decrease in all regions apart from sub-Saharan Africa (Fig. 4a). The reduced affordability of an EAT–*Lancet* diet for low-skilled agricultural workers in all but high-income regions and Southeast Asia is thus due to their wages decreasing even more than the drop in food prices (Fig. 4c). While affordability of an EAT–*Lancet* diet for non-agricultural workers in Latin America, the European Union and industrialized Asia increases, our results show that the gain is mitigated by a decrease in non-agricultural low-skilled wages (Fig. 4d), despite the boost of the non-food economy. In sub-Saharan Africa, EAT–*Lancet* targets imply an increase in food demand. Although consumers benefit from lower world market prices and sub-Saharan Africa turns into a net food importer, part of the food is still produced domestically at a higher cost. However, the higher food prices also increase wages of agricultural unskilled workers (8.8%; Fig. 4c), mitigating most of the 10.1% food price increase for agricultural low-income households. Low-skilled workers in non-agricultural sectors benefit much less from the boost of the non-food sectors; their wages increase by only 0.2% (Fig. 4d).

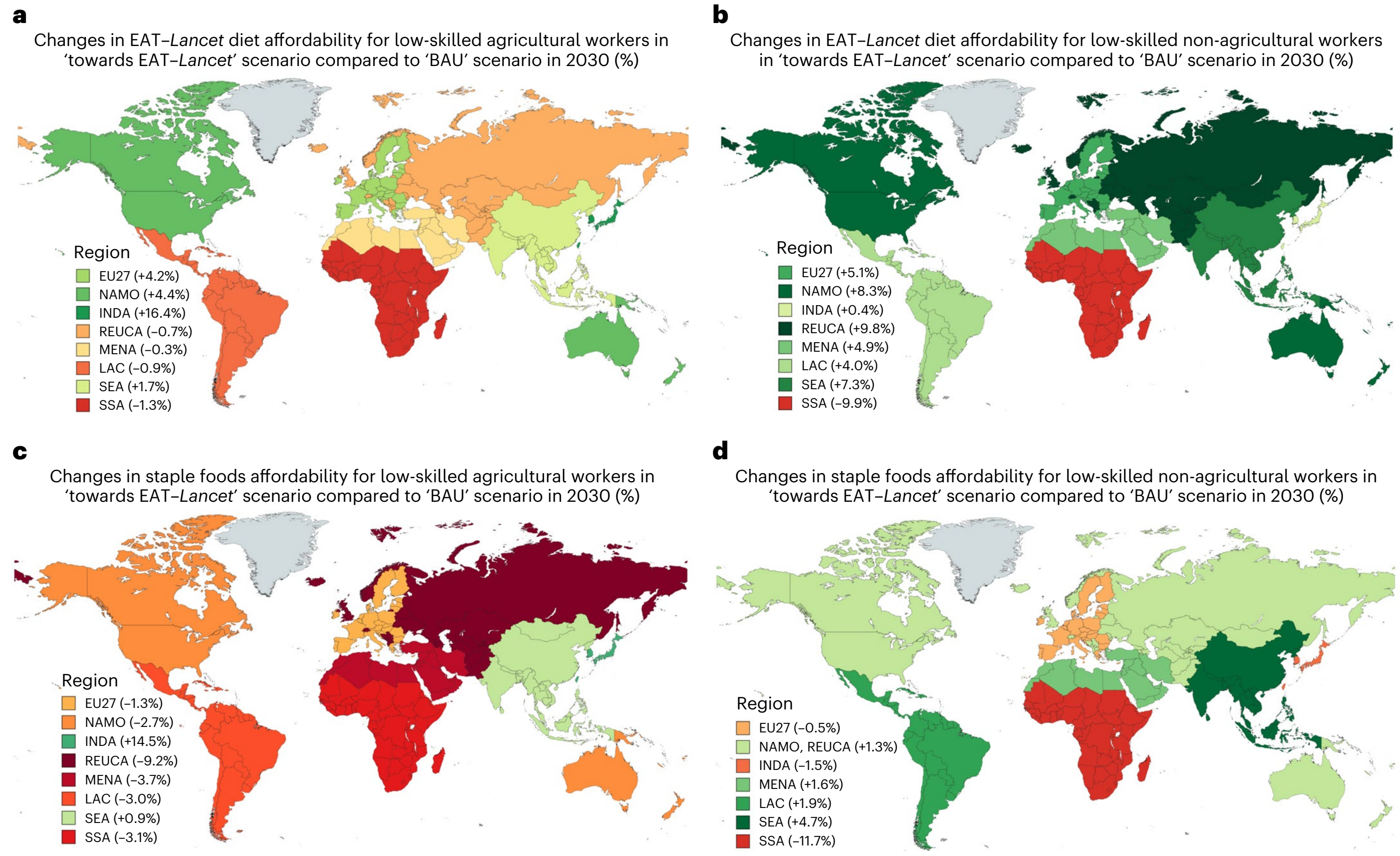
Staple food affordability worsens for all low-skilled agricultural workers apart from those in industrialized Asia and Southeast Asia, while improving for non-agricultural households apart from those in sub-Saharan Africa and the European Union. Staple foods are key for the lowest-income households, making the worsening for both agricultural (−3.1%) and non-agricultural households (−11.7%) in sub-Saharan Africa a concern. As with the price of an EAT–*Lancet* diet, the increase in staple food prices of 11.9% is mostly buffered by agricultural wage increases (8.8%), while non-agricultural households get a minimal increase income from the economic spillovers to non-food sectors (0.2%). Our results show that the global shift towards healthier and sustainable diets may increase hunger in a region where it is already a major worry. For the other regions, except industrialized Asia and Southeast Asia, there is a clear dichotomy. Staple foods become less affordable for poor agricultural households as wages drop more than prices. By contrast, non-agricultural poor households benefit from the economic spillover effects to non-food with their wages increasing (most regions) or decreasing less than staple food prices (notably Latin America).

Environmental spillovers indicate a link between food loss and waste and consumption across countries

We find, moving towards the EAT–*Lancet* diet decreases average global food demand, reducing FLW to 1.8 billion tonnes (−18.9%; Fig. 5a). With a global shift from processed foods to fresh plant-based products, manufacturing losses have the highest relative decrease (−29.2%). But in absolute terms, lower food demand and decreasing trade reduces farm-level losses (around −249.5 million tonnes) and consumption waste (around −94.1 million tonnes) most. The calorie reduction is crucial for the global FLW reduction as most individual targets provide very minor FLW reductions. Apart from calories, a lower demand for cereals, sugar beet/cane and oil seeds decreases FLW in the Middle East and North Africa (MENA, 17.1%), Latin America (LAC, 23.8%) and the rest of Europe and Central Asia (REUCA, 19.2%), mostly at the agricultural production and post-harvest handling and storage stages. At the other end of the supply chain, a reduction in ASF consumption is key for decreasing total FLW in high-income North America and Oceania (NAMO, 20.2%), European Union (EU27, 20.5%) and industrialized Asia (INDA, 18.6%). The same meat and dairy targets increase agricultural production losses in sub-Saharan Africa (SSA), resulting in an overall rise in FLW generation with the diet (3.9%).

Our results illustrate that shifting consumption towards the EAT–*Lancet* diet enlarges the global share of plant-based products within global FLW (6.3%; Fig. 4b). This primarily occurs in higher-income regions (1.3%) and in REUCA (0.3%), where current ASF overconsumption decreases in favour of increasing plant-based product consumption. By contrast, a shift towards ASF in lower-income regions results in lower amounts of plant-based products embedded in total FLW. Plant-based FLW decreases mainly in SSA (10.6%) and Southeast Asia (SEA, 2.3%), where cereals and horticulture are replaced by dairy and meat products. Similarly, lower exports of plant-based foods result in lower amounts of plant-based FLW in LAC (0.7%) and MENA (1.2%). Overall dairy targets increase shares of dairy FLW by an average +2.8%, while targets on fats and sugars reduce shares of oil seeds (−1.6%) and sugar beet/cane (−4.4%). In NAMO and EU27, lower ASF intakes reduce shares of meat FLW at the last stages of the FSC (−1.4%). Dairy shares expand particularly in SEA and SSA (4.7%) at agricultural production and consumption production stages, replacing decreasing shares of sugar crops (−3.5%) and oil seeds (−2.9%).

Decreasing global food trade with the EAT–*Lancet* diet in our model simulations reduces amounts of food losses related to food imports (that is, generated outside of the region where final food consumption occurs) by an average 21.2% (Fig. 5c). Main reductions are observed in SEA (−33.2%), INDA (−29.5%) and NAMO (−31.1%) and to a lesser extent in MENA (−18.7%) and EU27 (−25.8%). By contrast, the increasing food demand observed in SSA results in higher food imports, increasing losses generated abroad (16.4%). Despite import-related food losses decreasing on average across regions, our results show that large shares of losses generated abroad remain, mainly located in lower-income regions (Fig. 4d). Such environmental spillover effects are largest in SSA, SEA and LAC, where exports of perishable fresh foods generate considerable losses at agricultural production and



a Changes in EAT–*Lancet* diet affordability for low-skilled agricultural workers in 'towards EAT–*Lancet*' scenario compared to 'BAU' scenario in 2030 (%)

b Changes in EAT–*Lancet* diet affordability for low-skilled non-agricultural workers in 'towards EAT–*Lancet*' scenario compared to 'BAU' scenario in 2030 (%)

c Changes in staple foods affordability for low-skilled agricultural workers in 'towards EAT–*Lancet*' scenario compared to 'BAU' scenario in 2030 (%)

d Changes in staple foods affordability for low-skilled non-agricultural workers in 'towards EAT–*Lancet*' scenario compared to 'BAU' scenario in 2030 (%)

Fig. 3 | Change in healthy food and staple food affordability for low-skilled workers employed in agricultural and non-agricultural sectors. **a**–**d**, Estimates refer to a comparison of the 'Towards EAT–*Lancet*' scenario with the 'BAU' scenario in 2030. Affordability is defined as comparing prices of food commodities with labour wages of low-skilled workers. **a**, Percentage changes in affordability of a 'healthy foods' basket defined in accordance with the EAT–*Lancet* dietary targets for low-skilled workers employed in agricultural sectors across global regions in 2030. **b**, Percentage changes in affordability of 'healthy foods' for low-skilled workers employed in non-agricultural sectors across global regions in 2030. **c**, Percentage changes in 'staple foods' affordability for low-skilled agricultural workers across global regions in 2030. **d**, Finally, percentage changes in 'staple foods' affordability for low-skilled workers employed outside the agriculture sector across global regions in 2030.

post-harvest handling and storage. Around 67.5% (50 million tonnes) of food losses generated abroad by consumption in higher-income regions (NAMO, EU27 and INDA) are located in lower-income regions. This share is significantly lower for mid- and lower-income regions, where shares of losses generated abroad are more equally distributed between higher-income and lower-income regions. Despite the EAT–*Lancet* diet decreasing the environmental impact in terms of total amount of FLW, food consumption in high-income regions represents a main driver of FLW at early stages of the supply chain in low-income regions.

Discussion

This study investigates benefits and economic, social and environmental spillover effects of a global transition towards a healthier and more sustainable diet using a global GE model enhanced to trace material flows along global supply chains. Calibrated on national statistics, the model captures the response of the current global economy, accounting for presence of trade barriers, regional patterns and volumes of global trade along food supply chains and responses of producers and consumers to price changes. Our improved tracing of physical biomass and FLW material flows in a monetary GE model addresses one of the key weaknesses of these models[21]. Methods for preserving physical quantities in model simulations have been previously developed[22,23]. We present an alternative that respects initial material balances in physical units in the model database and shows only minor violations of material balances in counterfactual simulations. Our approach maintains constant elasticities of substitution functions typical of GE models easing joint economic and biophysical analyses. It permits analysis of the impact of the EAT–*Lancet* diet on global physical biomass flows while accounting for economic variables key to assess the affordability of dietary shifts. Covering global FSC while collecting best available physical FLW estimates from literature, we expand existing monetary analyses of FLW[24–26], providing a quantification of physical FLW in a global GE framework. The large reduction in total food demand and shift between food groups induced by a shift towards the EAT–*Lancet* diet induces price changes that impact sectoral demand and supply in the rest of the economy and result in land rent, wage and income changes. Our method complements other studies, such as Willet et al.[4], by offering estimates of direct and indirect (price-induced) effects associated with the adoption of the EAT–*Lancet* diet.

Transitioning towards the EAT–*Lancet* diet improves the sustainability of global food systems, decreasing global food demand and thus global biomass production mostly by reducing calorie intakes in all but the poorest countries. Reduced global land use in 2030 confirms the positive impact of dietary changes in previous studies[4,7,27]. Less land use is crucial to support biodiversity[28]. The EAT–*Lancet* diet additionally reduces GHG emissions from global food systems. We model the transition towards the EAT–*Lancet* diet imposing one-third of the dietary targets outlined in Willet et al.[4], and our food-related GHG emissions decrease by 16.1%. A three times higher full dietary

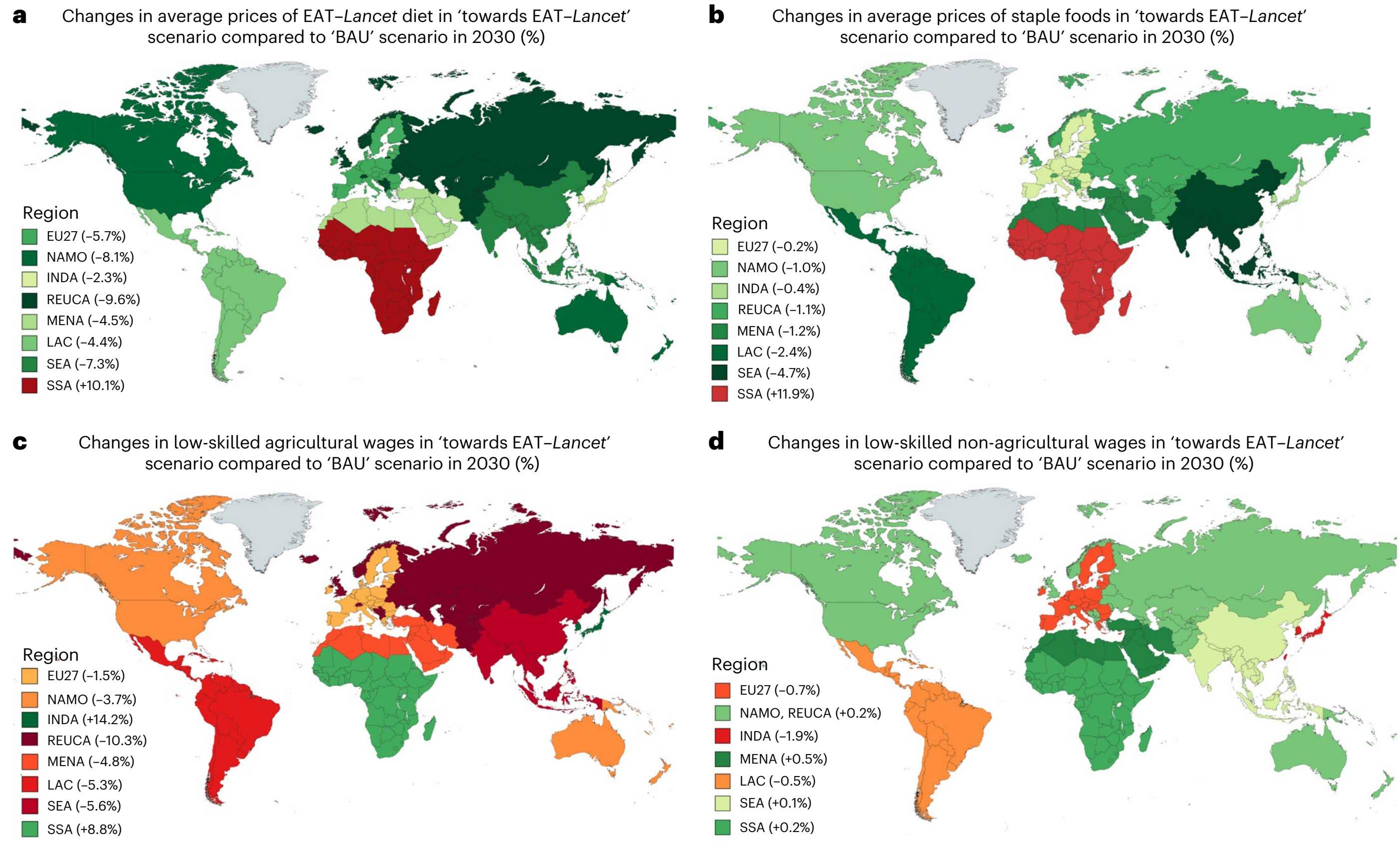


Fig. 4 | Drivers of changes in affordability of healthy foods and staple foods. **a**–**d**, Estimates refer to a comparison of the 'Towards EAT–*Lancet*' scenario with the 'BAU' scenario in 2030. **a**, Percentage changes in average prices of a healthy food basket defined as the EAT–*Lancet* dietary targets across global regions. **b**, The percentage change in average staple food prices across global regions in 2030. **c**, Percentage changes in low-skilled agricultural wages across global regions. **d**, Percentage changes in low-skilled non-agricultural wages (that is, wages of unskilled workers employed in sectors outside agriculture) across global regions in 2030.

transition is projected to decrease food-related GHG emissions by 29–54% (refs. 3,4,7,13), placing our finding within the expected range. Reduced biomass production also reduces global FLW. Agricultural production and consumption stages are current global hotspots for FLW generation[29,30]. We find the EAT–*Lancet* diet reduces losses at both these stages, benefitting mainly high-income regions where reduced ASF intakes decrease FLW. The focus on fresh and plant-based foods reduces losses from food manufacturing and reduces shares of sugar crops and ASF in total FLW. The change in composition also reduces calorie losses embedded in FLW, as decreasing ASF lowers nutrient losses along each stage of global FSC. Lower ASF shares in high-income regions additionally increase reuse potential of FLW, as plant-based losses have more reuse possibilities as feed[31,32] or fertilizer[31].

While benefits of the EAT–*Lancet* diet from other studies are confirmed, we find several spillover effects related to a global dietary change missing from previous static and partial equilibrium studies. Economic spillovers to non-food sectors alter the initial EAT–*Lancet* diet impact in terms of non-food production, land use and GHG emissions. A first negative economic spillover effect occurs through reduced demand for food, reducing biomass prices and increasing its competitiveness relative to non-biomass substitutes in non-food use. This mitigates the initial biomass production and thus land-use reduction from the diet shift. A second negative economic spillover effect of the reduced food demand is lower demand for land, reducing land prices. This, in turn, promotes extensification. Using more land for the same amount of biomass further mitigates the reduction in land use. This extensification process also reduces demand for relatively more expensive labour and capital in production, generating a third negative spillover in the shape of lower wages. Land, however, can also be substituted for fertilizers (and other chemicals) in production. This generates a positive spillover effect by reducing chemical input-related emissions (for example, N_2O) and pollution. In contrast to the global pattern, land use in sub-Saharan Africa increases due to rising demand for fresh biomass. The resulting higher land prices result in intensification with a negative spillover in terms of increased chemical inputs and a positive externality in terms of rising wages.

Economic spillovers into non-food sectors have major implications for total GHG emissions, with increased emissions linked to non-food demand outweighing decreased GHG emissions from the food system. The increase in biomass production for non-food use erases almost half of the reduction in emissions achieved by the reduction in biomass demand for food with the diet. Following, reduced food expenditures free income for non-food commodities. Consumers, especially in higher-income regions, consume less food, which is available at lower prices, hence expenditures on non-food items increase. This is a strong stimulus for non-food sectors given the zero-cost consumer preference shift combined with a constant GDP per capita. The resulting stimulus of the non-food sectors increases global economy-wide emissions in 2030 compared to the BAU scenario with no diet shifts.

Our use of a global GE model captures substitutions in food production between land and other production factors (for example, labour, capital) and inputs (for example, chemicals) also accounted for in partial equilibrium (PE) assessments[12], while adding an assessment of the changes in non-food sectors. The economic spillovers

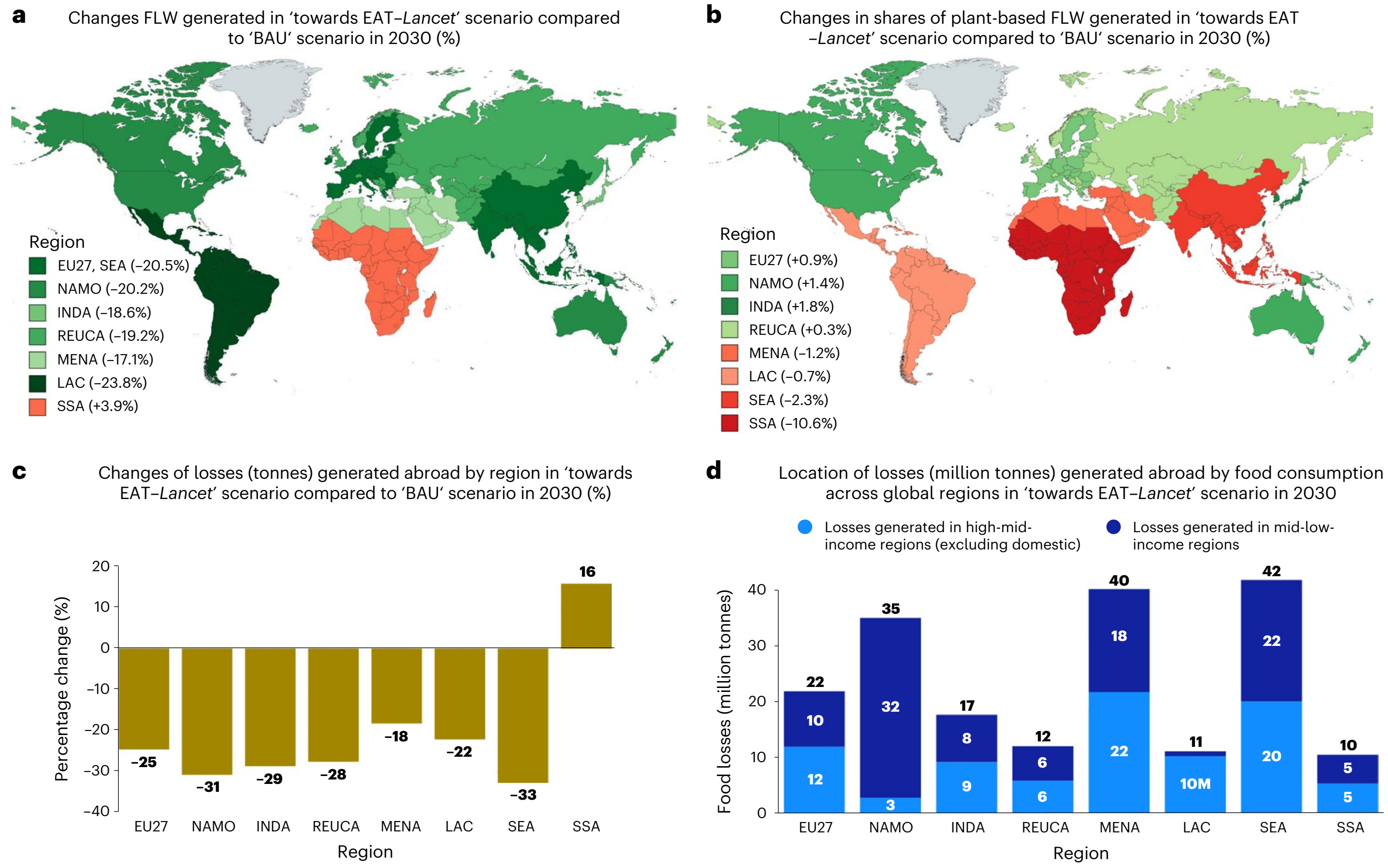


Fig. 5 | Magnitude, composition and geographical location of global FLW generation in the transition towards the EAT–*Lancet* diet. a, Changes (%) in total FLW amounts generated by region in the 'Towards the EAT–*Lancet*' scenario compared to a 'BAU' scenario in 2030. **b**, An overview of the changing composition of FLW with the EAT–*Lancet* diet, illustrating changing shares of plant-based FLW by regions in comparison to a 'BAU' scenario in 2030. **c**, Changes (%) in total amounts (tonnes) of food losses generated abroad by region in the 'Towards the EAT–*Lancet*' scenario compared to a 'BAU' scenario in 2030. **d**, Finally, the total amount of food losses (million tonnes) generated abroad in the 'Towards the EAT–*Lancet*' scenario by source, enlarging the information reported in **c**.

in non-food sectors dampen the benefits of the diet shift in terms of global biomass production and land use found in previous studies[4,27,33]. Our economy-wide perspective reverses the impact in terms of GHG emissions. While GHG reductions in the food system are comparable to those in earlier PE assessments, increased non-agricultural emissions result in a net increase in GHG emissions when diets shift.

Social spillovers enlarge the income gap between agricultural and non-agricultural low-skilled workers, while decreasing food affordability for workers employed in agricultural sectors. The first negative social spillover results from lower global food demand with the EAT–*Lancet* diet exerting different impacts on agricultural and non-agricultural wages. Labour markets are modelled as segmented between agricultural and non-agricultural sectors to capture observed persistent lower agricultural wages (for example, Gollin et al.[34]), signalling the presence of barriers for lower-paid agricultural workers to move to higher-paid non-agricultural jobs. Less demand for agricultural products then leads to lower wages in agriculture relative to the rest of the economy as the skills of agricultural workers are not in line with those demanded by other sectors. This forces workers to remain in agriculture and accept a lower wage. The stimulus of non-food production simultaneously increases non-agricultural wages. The diets shift, thereby increasing the existing income inequality between agricultural and non-agricultural workers.

Social spillover effects on affordability of a healthy food basket derived from the EAT–*Lancet* diet recommendations vary across regions and nuance the findings of Hirvonen et al.[11] and Springmann et al.[12]. Our economy-wide results capturing income and price effects not accounted for in these studies confirm positive impacts in high-income regions. Here healthy diet affordability improves for both agricultural and non-agricultural workers, suggesting that the affordability at currently observed prices is further improved. For non-agricultural workers in all regions but sub-Saharan Africa, affordability of healthy diets also improves. This may reduce concerns on the affordability of healthy diets in lower-income regions expressed in these previous studies for at least part of the population. At the same time, the negative impact on agricultural wages in lower-income regions worsens healthy food affordability for those employed in agriculture despite lower food prices. For these households, current unaffordability of healthy food thus becomes worse. Sub-Saharan Africa is the negative exception with the strongest decrease in healthy food affordability for both agricultural and non-agricultural workers. Here non-agricultural workers are worse off as they do not benefit as much from higher wages.

A third negative social spillover not addressed in Hirvonen et al.[11] and Springmann et al.[12] is on staple food affordability in all regions but industrialized Asia, resulting from the combination of diverging wage developments and lower staple prices. Globally for non-agricultural workers, gains from the lower staple prices are amplified by the income gains from higher wages, making staples more affordable. While agricultural workers benefit from the lower staple prices as well, the negative income effect from lower agricultural wages reduces affordability of staple foods. Sub-Saharan Africa stands out as the EAT–*Lancet* diet induces higher consumption levels and thus food prices. While this generates a positive income effect from rising agricultural low-skilled wages, it does not compensate the negative price effect from rising food prices. This region with high hunger and malnutrition rates thus faces decreasing affordability of a main source of cheap calories for both agricultural and non-agricultural low-skilled workers.

Finally, although the transition towards the EAT–*Lancet* diet decreases FLW by decreasing both biomass production and traded volumes, our findings illustrate that high-income food consumption continues to generate large primary losses in mid- to lower-income regions. This not only continues local environmental pressures. It also hampers FLW reuse due to lack of proper infrastructure and technologies in mid- to low-income regions[35]. Environmental impacts of the EAT–*Lancet* diet in terms of changes in FLW are thus mixed. On the one hand, lower levels of FLW mean fewer calorie and nutrient losses, while increasing shares of fresh plant-based FLW increases options for reuse. On the other hand, increasing plant-based FLW shares can lead to higher pollution rates[36]. Given the geographical mismatch between the location of FLW and recycling facilities, this may reduce anticipated environmental benefits of a dietary transition.

Our findings have several policy implications. First, the findings for high-income regions suggest that the adoption of healthy and sustainable diets can help consumers in those countries reduce food expenditures while making a positive environmental impact by decreasing land use and FLW generation both domestically and abroad. However, food affordability for workers within agriculture might deteriorate as wages within agriculture decline due to lower demand and segmented factor markets affecting especially large food-exporting countries such as Latin America and Central Asia. To prevent an increase in rural poverty when shifting to a healthier diet, low-paid agricultural workers could be temporarily compensated by income support while lowering barriers to better paid non-agricultural jobs through education or retraining programmes. Second, we find the target on calories as most effective in reducing biomass production, notably in reducing ruminant livestock biomass. However, steering consumer behaviour in terms of calorie content is difficult as calories cannot be directly observed. A focus on calories alone may also result in an unbalanced diet from a nutritional point of view. Steering consumption in terms of food items, easily observable by consumers, may be a more feasible option despite a less clear link to total calorie intake. By using a preference shift to implement the diet, we dodge the question on the policy instruments used to reach the diet. Consumers are assumed to change their preference to the EAT–*Lancet* diet overnight with no effort or cost explicitly modelled. This preference-shift approach is similar to key publications of EAT–*Lancet*[4,13]. Shifting preferences also resemble the revealed policy preferences for education and information campaigns: most countries have national dietary guidelines and require labelling of foods so consumers can make informed food consumption decisions with more stringent regulation (such as expiration dates) limited to food safety concerns. While appealing for policymakers, our results show that even if information alone would succeed in shifting preferences, health objectives would be reached but total GHG emissions would increase. This rebound effect through the non-food sectors may be (partially) avoided by taxing consumption in line with the diet recommendations. Measures such as health- or environmentally related taxes might redirect consumer behaviour, decreasing overconsumption and health-related problems while reducing domestic FLW and farm-level losses in exporting mid- and low-income regions. However, using taxes to steer food consumption can have regressive effects as lower-income households spend a relatively large share on food[37]. Alternatively, the diet transition could be accompanied by economy-wide GHG taxes to reduce the rebound effect.

The assessment of individual diet components cautions against selective focus on a few food items in the EAT–*Lancet* diet when designing policy interventions, as several components have little to no impact on biomass production nor FLW generation. Rising staple and healthy food prices limiting food affordability in sub-Saharan Africa remain a major concern in transitioning to a healthier and sustainable diet. Subsidies could assist dietary affordability, but our analysis points to the need to not only target healthy food items as staple food affordability declines as well. Supporting access to cheap calories for the poorest households should thus not be abandoned when shifting policies towards supporting healthy diets. In terms of FLW, policies should continue to focus on decreasing farm-level losses through improvements in agricultural production efficiency while simultaneously facilitating the reuse of FLW as feed aiming at lower ASF food production costs and hence food prices.

As always, findings are subject to the uncertainties and limitations of our study. Tracing material flows in a global economy remains a complex and challenging task. In the absence of better data, we used value-based shares to split physical flows of biomass across global supply chains, implicitly ignoring product quality differences along the supply chains that would be reflected in different prices (and thus different quantity shares). Our method thus serves as a step towards integrating physical and economic data in a multidisciplinary modelling framework that closely mirrors real-world economic dynamics and provides key insights for exploring global dietary transitions. Additionally, we model a partial transition towards the EAT–*Lancet* diet, obtaining relatively moderate effects in comparison to a full transition where dietary targets are fully met. Moreover, the high sectoral aggregation chosen because of FLW data availability impedes a proper match of the commodity-specific dietary recommendations of the EAT–*Lancet* diet with our modelling framework. This is particularly evident in the case of horticulture. By considering a single horticultural sector comprised of fruit and vegetables, pulses, nuts, roots and tubers, we omit dietary directions concerning specific commodities. For certain regions, the general increase in fruit and vegetables is outweighed by a decrease in consumption of starchy vegetables. An additional limitation concerns our modelling of FLW. FLW data are rather weak at a global scale but remain key for devising trade-offs when changing global dietary patterns towards a more sustainable consumption. Monitoring FLW remains a priority to enhance the empirical models. As we keep FLW rates constant over time, we do not investigate how FLW rates may respond to changes in economic structure or income across our scenarios.

This study may represent a starting point for bridging economic and technical models, supporting future multidisciplinary investigations on global biomass, interlinked food and non-food demand and FLW in support of policies towards a more sustainable and more inclusive global food system. Future work could enhance non-FLW aspects of the EAT–*Lancet* diet by including additional detail on fruit and vegetable sectors. Expanding the modelling framework with within-country income distributions and purchasing power differences, related social and fiscal policies could be introduced to further enrich distributional analyses. The scope of the environmental impact could be enhanced by including water and more detailed modelling of fertilizer and other chemical use. Finally, the economy-wide spillover effects in this study not only show unintended effects, most notably on GHG emissions, but also highlight the importance of policy design as spillovers could be less when the diet shift is achieved through taxes instead of a costless preference shift. Simultaneously addressing economic, social and environmental economy-wide impacts is key when designing operational policies to steer the food system towards a healthier and more sustainable future.

Methods

Methodology and scenarios

To assess the benefits and spillover effects of the diet change, we use the global GE model called MAGNET (Modular Applied GeNeral Equilibrium Tool; www.magnet-model.eu), developed with a focus on agri-food sectors, land use and on non-food biomass demand by the rest of the bioeconomy[17,38], implications on food security including food affordability[39], GHG emissions[40] and biodiversity[28]. It is an advanced recursive dynamic variant of the well-known Global Trade Analysis Project (GTAP) model[41]. MAGNET cooperates with the integrated assessment model called IMAGE to enhance the representation of the land market[17] and quantifies, for example, the Intergovernmental Panel on Climate Change scenarios in an integrated MAGNET–IMAGE modelling approach[42], identifying the trade-off effects of afforestation for climate change mitigation[43]. Food, biomass and related FLW and production-factor (various types of labour, capital, land) demand is endogenously determined by income changes, relative prices, preference shifts and dynamic income elasticities. As factor markets are segmented between agricultural and non-agriculture markets for two types of labour (skilled and unskilled), wage developments will differ between the types and sectorial use of labour. Food affordability relates to people's food purchasing power and therefore to food prices, dietary patterns and income developments[39,44]. We use a food affordability indicator relating price developments of a specific food consumption basket to income developments of a particular income group. For the food basket, we use consumption of cereals (including paddy rice, wheat and 'other grains') as a proxy for the diet of people potentially in poverty, as rice is an important food component for poor people in Asia, while grains are important in Africa. We use changes in the wages of unskilled workers as a proxy for the income component of poor people working in different sectors of the economy. In this study, we improve on existing value-based tracing in GTAP-based GE models[19,45,46] by enhancing the standard GTAP 10 database[47] with regionalized material balances to get closer to material flows. Furthermore, we integrate primary food biomass flows in tonnes derived from FAOSTAT into MAGNET using weight-based FLW estimates to compute the biomass amounts contained in final demand, respecting material balances in both monetary and physical units. These material balances have a regional dimension with each stage (production, processing, consumption), possibly located in a different region. Deriving the Leontief Inverse[48] from the regionalized material balances, we can trace all direct and indirect material flows throughout the entire global economic system. This tracing is key for processed and imported goods where biomass from various locations can be combined through multiple processing and trading steps before finally being consumed. Additional model details are available in the Supplementary Information.

Healthier and more sustainable dietary scenario

We analyse how a transition to a healthier and more sustainable diet affects global biomass production, economy and FLW generation. Starting from 2020, we define our business-as-usual (BAU) scenario from the IMF-World Economic Outlook projections[49] for GDP and population to project the global economy and associated biomass flows in 2030. As a counterfactual, we define a set of diet scenarios moving towards the EAT–*Lancet* dietary recommendations by 2030 (Willett et al.[4]). We decompose the EAT–*Lancet* diet in (sub-)diet scenarios linked to nutritional targets for commodity groups as available in the MAGNET model. A summary of our scenario assumptions is provided in Table 1.

Data availability

The FLW database and results data are available in the Supplementary Information.

Code availability

The code used for the analysis is described in the Supplementary Information.

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Author contributions

A.G., M.K. and H.v.M. conceived and designed the experiments, performed the experiments, analysed the data, contributed materials/analysis tools and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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