
# Impacts of changes towards more sustainable food production and consumption at the global level

by Kirsten Boysen-Urban, George Philippidis, Robert M'barek, and Emanuele Ferrari

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**Abstract**

With a focus on achieving the global sustainability goals as agreed under the United Nations Sustainable Development Goals, the aim of this study is to investigate the potential impacts of reducing food waste and losses and changing dietary habits on economic, social and environmental (emissions, land use change as well as water withdrawals) indicators.

For this purpose, this study uses an advanced neoclassical computable general equilibrium model which takes into account linkages and feedback mechanisms of upstream and downstream markets, factor markets and international trade.

The results show that all scenarios lead to an increase in food consumption at lower world prices compared to a baseline in 2050, thus could contribute to increasing food security in terms of food availability and affordability. The environmental impacts of all scenarios are predominantly positive, although the impacts of reducing food waste and losses are much smaller than those associated with dietary change.

**Keywords:**

Agricultural and food policy, computable general equilibrium, sustainability

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# Impacts of changes towards more sustainable food production and consumption at the global level

## 1 Introduction

With ever more mouths to feed worldwide, policy makers are engaging in ways to develop more sustainable and climate friendly systems of economic development that avoid further increases in harmful greenhouse gas emissions and reduce the burden on our natural biophysical planetary boundaries. One hot topic is the role of changing consumer behaviour and attitudes to food consumption. The FAO (2014) estimates that annually, the economic cost of food waste amounts to 2.6 trillion USD, equivalent to 3.3% of global GDP. Furthermore, non-market biophysical benefits arising from reductions in food waste in terms of land and water savings are to be expected. From an environmental perspective, also reducing activities in emissions intensive activities such as primary agriculture is expected to play a positive role in curbing greenhouse gas emissions. Countries committed to the 2030 targets agreed with the UN Sustainable Development Goals and the Paris Agreement, which includes a transformation of the food system towards more resilient and sustainable production and consumption of food and towards a more circular economy also including food loss reductions. Assessing the impact of such a transformation requires a holistic approach that involves all actors in and all stages of the food system and includes for example significantly reducing food waste and losses, but also ambitious changes in consumers' diets through the sourcing of e.g., protein from non-meat activities.

However, in our globalized world all regions, productions sectors and markets are linked through international trade so that the desired switching between food sources in the case of dietary changes as well as the reduction of food waste and loss will have repercussions on prices and thus influences upstream and downstream markets including consumer demand. Food could become cheaper by reducing food waste and losses; however, their relative prices could be affected differently. While consumers spend less of their income on food commodities, the above price changes affect their consumption decisions. Consequently, lower total food purchases by households does not automatically imply that food production and consumption of all different food commodities will also decrease. When considering the circular economy, questions such as how less food waste and loss affects the demand for biomass arise, and it also remains less clear what the circular effects are of reducing available waste as a source of biomass to produce market goods (e.g., energy). Finally, what is the impact of combining this with changes in diet (i.e., less meat consumption but significant increases in cereal and horticultural consumption)? What role does international trade and thus the possible leakage effects from virtual trading of land and emissions play in achieving the sustainability goals?

There is a growing body of literature that assesses the environmental impacts of diets (see Hallstroem et al. 2015 for a review on diet scenarios) and food waste and loss reductions along the supply chain (see Omolayo et al. 2021 for a review) using Life Cycle Assessment (LCA) models. However, such models do not take into account the linkages between markets within the economy as well as international markets.

Since reducing food waste and loss and changing dietary habits affect the economy at different levels, economic models such as Computable General Equilibrium (CGE) or Partial Equilibrium (PE) models would be well suited to account for such effects and could enrich the impact assessment of food waste and loss and diets by contributing to answer the questions raised.

In the recent literature (table A1 in the annex), there are only a limited number of quantitative studies using CGE and PE models that assess the global impact of either food waste (Jafari et al. 2020, Lopez Barreira and Hertel 2021, and for the EU: Britz et al. 2019, Philippidis et al. 2019, Campoy-Munoz et al. 2017), food loss (Kuiper and Cui, 2020), food waste and loss (Rutten et al. 2015) or dietary changes (Philippidis et al. 2021, for the EU: Latka et al. 2021 and Rutten et al. 2013a) as well as a combination of diets and food waste and loss (Springmann et al. 2018) that consider these interlinkages at regional and/or global levels. These studies differ not only in terms of the model chosen and thus extent to which they take these linkages into account, but also in terms of the approach to how food waste and loss as well as diets are considered, the model extensions and underlying databases, as well as the linkages with biophysical models to quantify environmental effects, the time horizon considered as well as assumptions made about the definition of food waste, what part of food waste they consider, and the definition of diets. Some of these papers quantify the impact of food security and employment, however, the impact on the social dimension of sustainability is often neglected.

To the best of our knowledge, only the study by Springmann et al. 2018 assesses the impacts of combined policies towards a healthier and sustainable food system at the global level using a food system model with a global partial equilibrium model at its core. In their analysis, they do not quantify the impacts for different stages of the supply chain, for different sectors, nor the costs associated with such a transformation.

Against this background, this study aims to assess the impact of global reductions of food waste and loss in combination with the associated compliance costs, dietary changes, and the introduction of a global tax on fossil energies on the economic, social and environmental dimensions of sustainability. The aim is to shed light on the linkages and possible repercussions that influence the expected outcome.

This paper therefore uses an advanced variant of a neoclassical CGE model to examine how changing consumer choice patterns, including changing dietary habits and food waste, together with food loss reduction, affect food consumption and environmental market indicators and the resulting trade-offs, for selected regions worldwide. Additional modelling innovations to consider food waste and loss reduction by region by 2030, while changing diets consider the impact of food substitutions under conditions of unchanged food balances compared to a baseline from 2020 to 2050. The modelling approach is also enhanced to compute the impact on biophysical/environmental indicators as well as to trace the virtual trade of resources.

This article is structured as follows. Section 2 introduces the model and data used to assess the impact of changes in consumer behaviour and describes the experimental design, while Section 3 presents the results focusing on economic, social and environmental indicators. The final section summarises the results.

# 2 Methods

## 2.1 Modeling Framework and aggregation

This study employs an advanced CGE neoclassical model known as the Modular Applied GeNeral Equilibrium Tool (MAGNET) (Woltjer et al., 2014), which is a recursive dynamic variant of the standard Global Trade Analysis Project model (Hertel 1997). This version of the model is benchmarked to version 9 GTAP database with base year 2011 (Aguiar et al. 2016) which covers 57 production sectors and 140 countries and regions. To enhance the analysis of the circularity of food waste and loss reductions, a biobased variant of the standard GTAP database consisting of numerous additional biobased activities splits including waste and recycling (Philippidis et al., 2019) is used. Furthermore, this study makes use of a nutrition module in MAGNET (Rutten et al., 2013b, 2014) in order to control the balance of food nutrients in the diet when changing consumer dietary patterns (i.e., red meat reductions).

To enable the tracing of food consumption on environmental impacts such as land use and emissions, the CGE model is extended by module that calculates footprints such as the average per capita per year land use related to household food consumption. These footprints consider all economy-wide inter- and intra-industry intermediate input purchases within and between food and non-food production chains, as well as the use of scarce resources. Furthermore, this module allows the tracking of non-tradable virtual commodities (land, water, emissions) along the food supply chain associated with household food consumption.

With a focus on food waste and loss as well as consumer diets, this study keeps all agricultural and food activities as disaggregated as possible. Furthermore, it includes a detailed depiction of bio-based activities and their non-biobased counterparts, while other sectors such as manufacturing and services are aggregated as shown in table 2.

**Table 2: Overview commodity coverage**

| | |
|---|---|
| **Arable crops, horticulture** | rainfed paddy rice; rainfed wheat; rainfed other grains; rainfed oilseeds; rainfed raw sugar; rainfed vegetables, fruits and nuts; rainfed other crops; irrigated paddy rice; irrigated wheat; irrigated other grains; irrigated oilseeds; irrigated raw sugar; irrigated vegetables, fruits and nuts; irrigated other crops; crude vegetable oil |
| **Livestock, meat and fish** | cattle and sheep; pigs and poultry; raw milk; cattle meat; other meat; dairy; processed fish products |
| **Fertiliser** | fertiliser |
| **Other food and beverages** | sugar processing; vegetable oils and fats, processed rice, other food and beverages |
| **Other ‘traditional’ bio-based activities** | fishing; forestry; wood products; paper products; textiles & clothing |
| **Bio-mass supply** | energy crops; residue processing; pellets; by-product residues from rice; by-product residues from wheat; by-product residues from other grains; by-product residues from oilseeds; by-product residues from horticulture; by-product residues from other crops; by-product residues from forestry; Municipal waste |
| **Bio-based liquid energy** | 1st generation biodiesel; 1st generation bioethanol; 2nd generation thermochemical technology biofuel; 2nd generation biochemical technology biofuel; bio-kerosene |
| **Bio-based and non-bio-based animal feeds** | 1st generation bioethanol by-product distillers dried grains and solubles; crude vegetable oil by-product oilcake animal feed |
| **Renewable electricity generation** | bioelectricity; hydroelectric; solar and wind |
| **Fossil fuels and other energy markets** | crude oil; petroleum; gas; gas distribution; coal; coal-fired electricity; gas-fired electricity; nuclear electricity; electricity distribution; kerosene |
| **Other sectors** | chemicals, rubbers and plastics; other manufacturing; aviation; other transport; food services; services |

Source: Own elaboration.

The 140 countries and regions are aggregated to 13 regions: USA and Canada (USACAN); Brazil (Brazil); Rest of Latin America (RLatAme); Northern Africa (NoAfrica); Sub Saharan Africa (SSAfrica); European Union (EU); Rest of Europe (REurope); Russia (Russia); Middle

East (MidEast); India (India); China (China); Rest of Asia (RAsia); Oceania (Oceania). This regional coverage accounts for the major continents and players on world food and energy markets.

## 2.2 Baseline and scenario overview

A long run reference scenario transition pathway from 2011 to 2050 is designed and implemented based on the Global Energy and Climate Outlook (GECO) published by the Joint Research Centre of the European Commission (Keramidas et al., 2018, Weitzel et al., 2019). This baseline characterises a climate and energy pathway to 2050 by implementing detailed assumptions regarding real macroeconomic growth, population change, fossil fuel prices, energy usage and efficiency by types of activity and region, emissions changes, and land productivities (details in table 3).

**Table 3: Summary of key market driver implemented in the baseline**

| Exogenous driver | Description |
|---|---|
| **Region-wide productivity** | Region-wide productivity calibrated to regional real rates of GDP (Keramidas et al., 2018). |
| **Capital stock** | Baseline assumes a fixed capital-output ratio so that capital stock changes at the same percentage rate as GDP |
| **Population** | Reginal population changes are taken from Keramidis et al. 2018 |
| **Labour force** | Baseline assumes a fixed long-run employment rate so that labour force changes at the same percentage rate as regional population |
| **Carbon tax** | Global increases in the carbon tax ($/tonne) by time period on all activities (Weitzel et al., 2019). |
| **Energy input shifters** | Calibrated input-output technology shifters to mimic energy balance trends by energy type and usage (Keramidas et al., 2018). |
| **Land productivity** | Land productivity changes are taken from the Shared Socioeconomic Pathway 2 (SSP2) (O'Neill 2014) |
| **Energy final demands** | Exogenous final energy demand taste shifters to mimic pathway trends (Keramidas et al., 2018). |
| **Global fossil prices** | Fossil fuel price changes are taken from Keramidis et al. 2018 |
| **Biofuel mandates** | Exogenous mandates on first-generation and advanced-generation biofuels by region |

Source: Own elaboration.

A further refinement to the baseline was the recreation of a plausible food demand pathway consistent with the baseline narrative by implementing downward shifters on the income elasticities as per capita kilocalorie daily intake exceeded reasonable expectations, particularly in high-income and rapidly growing countries. Income elasticity shifters have also been used to ensure the same rates of catch-up in kilocalorie intake in emerging regions as observed in the initial baseline. In addition, we assume no dietary changes in the period 2030 to 2050 with regard to the shares of kilocalories of red meat, white meat, dairy and fish products in total daily per capita food consumption, to consistently account for the substitution effects of food commodities and the related effects on household budget and environmental indicators in the simulated scenarios and the baseline.

In addition to the baseline scenario to 2050, we simulate four additional scenarios assessing the impact of food waste and loss reductions, and combination of food waste and loss reductions with assumption about associated costs, dietary changes, and increased costs of fossil energies. The following paragraphs provide details about the four scenarios and the underlying data sources and assumption that are also summarized in table 4.

FAO (2011) provides estimates along five steps of the supply chain from food loss at the farm level to food waste at the consumer level for seven commodity groups and seven aggregated regions. Using this information, we calculated the food loss and waste rates weighted by agriculture and food production for the aggregation chosen in this study. Food waste and loss shares differ largely between regions, commodity groups as well as stages of the supply chain. The highest food waste shares are observed in high-income countries at the consumer level, while low-income countries tend to have the highest shares of food losses due to agricultural and production and post-harvest losses. Food waste and loss shares are the highest for horticultural commodities including fruit and vegetables as well as roots and tubers, and for cereals.

**Table 4: Scenario overview**

| Scenario | Description |
|---|---|
| **FWL** | All regions reduce their food waste and loss by 50% until 2030 along five steps of the supply chain (agricultural production, post-harvest, processing, retail, consumption) utilizing FAO estimates for 7 food groups and 7 global regions |
| **&cost** | Scenario FWL plus adding compliance cost associated with the reduction of food waste and loss equivalent to 5% of the sales value of the respective commodity incorporated in the cost function |
| **&diets** | Scenario FWL plus changing consumer diets. Regions gradually adopt from 2020 to 2050 a feasible reference diet as suggested by the Eat Lancet report (Willet et al. 2019) by changing the average daily dietary shares of red meat, white meat, dairy and fish. The feasible reference diet considers cultural, religious and affordability criteria/specificizes so that specific country and commodity pairs are exempted from dietary adjustments. Cultural and religious beliefs mainly affect meat and dairy consumption mainly in Asia and parts of Africa, while the diet is not introduced in sub-Saharan Africa due to affordability. |
| **&oil** | Scenario FWL plus the gradual introduction of a 25% global tax on fossil energies including crude oil, coal and petroleum until 2050. |

Source: Own elaboration.

The simulation of food waste reductions by commodity category is done using household budget share shifters that endogenously adjust to meet targeted household consumption reductions as applied by Philippidis et al. 2019 to assess food waste impacts. This approach considers food waste as a decrease in the quantity or quality of food resulting from decisions and actions of food services and consumers. A reduction in food waste thus corresponds to reduced expenditure on food as well as reduced input demand from the food service sector, represented by an increase in the input use efficiency of the food service sector. In addition, food waste generated at the retail level is introduced into the model as an input saving shock.

In line with Kuiper and Cui (2020), this study considers food loss as a decrease in the quantity or quality of food resulting from decisions and actions of food producers in the supply chain. Therefore, we assume that reducing food losses associated with agricultural production losses and post-harvest losses will lead to an increase in the productivity of primary agricultural commodities such as arable crops, horticulture, and livestock production, while reducing food losses associated with processing and packaging will lead to an increase in the input use efficiency of primary agricultural commodities used for food processing (e.g., meat and dairy production, vegetable oils, cereals and fruit and vegetable products (other food) imposed as an input saving productivity shock. Our first scenario (FWL) simulates a 50% reduction of food waste and loss until 2030 in line with the SDG target 12.3. In this scenario, we assume that the reduction of food waste and losses is cost-neutral.

This assumption is unrealistic as scientific evidence (Philippidis et al. 2019) clearly shows that reducing food waste and loss is not cost-neutral. However, to the best of our knowledge, there are no cost estimates at country or global scale, so we use an ad-hoc approach (Philippidis et al. 2019) to overcome this problem in our second scenario (&cost) that adds cost to the food waste and loss reductions. Assuming that compliance cost per unit of sales could trigger the required behavioural changes in food consumption and food production, we make a rough assumption about compliance cost equal to 5% of the value of production. Specifically, we assume that the costs arise on the supply side, e.g., through changes in production as wells as packaging processes, investments in improved storage facilities or means of transport. Implementing these determined costs into the cost function increases the unit costs of the inputs for each relevant agricultural and food commodity.

Our third and fourth scenarios are based on the recognition that achieving the SDG targets cannot be solved by one policy alone. Therefore, these scenarios aim to assess the linkages between food waste and loss reduction in combination with changes in dietary habits and policy-driven changes in fossil energy prices.

Scenario three (&diet) gradually introduces a feasible reference diet over the period 2020 to 2050, in addition to reducing food waste and loss by 2030, to change consumption patterns towards a more sustainable and healthier diet. The adopted feasible reference diet is inspired by the Eat Lancet report (Willet et al. 2019), which proposes to reduce consumption of red and white meat and dairy products and increase consumption of fish, fruits and vegetables. In addition, some region-commodity pairs are excluded from these changes, as such dietary changes need to consider specificities such as religiously prescribed diets (e.g., limited pork consumption in predominantly Islamic regions, and limited beef consumption in predominantly Buddhist regions), as well as cultural specificities or intolerances such as those related to milk consumption in Asia. The affordability of the diet is also an important factor to be considered, as for example incomes in many poorer countries are not sufficient, which is why for example no dietary changes are introduced in SSAFRICA. Philippidis et al. (2021) provides further insights into the assessment on different dietary assumptions on biophysical indicators. In this scenario, we fixed the kilocalories consumed per capita per day to the value obtained in the FWL scenario and also fixed the sugar consumption.

Our last scenario (&oil) simulates in addition to reducing food waste and losses, the gradual introduction of a global tax of 25% on crude oil, coal and petroleum until 2050.

## 3 Results

Before digging deeper into the impacts of changing consumer pattern on the social and environmental dimension of sustainability, figures 1 to 3 show the effects of the four scenarios on agricultural and food production and consumption in selected regions as well as global price changes compared to the baseline in 2050.

### 3.1 Economic impact

Reducing food loss at agricultural production, post-harvest and processing levels leads to an increase in the quantity of agricultural and food commodities which decreases market prices and thus reducing input costs further for food processing and driving up demand for now cheaper agricultural and food commodities. Reducing food waste at consumer, food service and retail at the same time counteracts these effects as now the household food expenditure for certain products is reduced, however, the rules of supply and demand equalized by market prices still apply so that in the end consumers might consume more kilocalories than in the baseline as food in general becomes cheaper so that they can consume more for less.

According to figure 1 the highest effects on agricultural and food output are in low-income and emerging regions such as SSAFRICA, Latin America (LATAME including Brazil and rest of Latin America) and ASIA (including China, India and rest of Asia) as agricultural productivity increases are highest in these regions due to reducing food loss which leads to a significant fall of market prices. In addition, food waste reductions lead to a decrease of household demand for agricultural and food commodities as well as input demand of food services, which enhances the fall of markets prices. The latter effect is higher in high-income countries as waste rates tend to be higher in these regions. A fall in market prices drives up the consumption of agricultural and food products (figure 2) as well as the consumption for non-food uses.

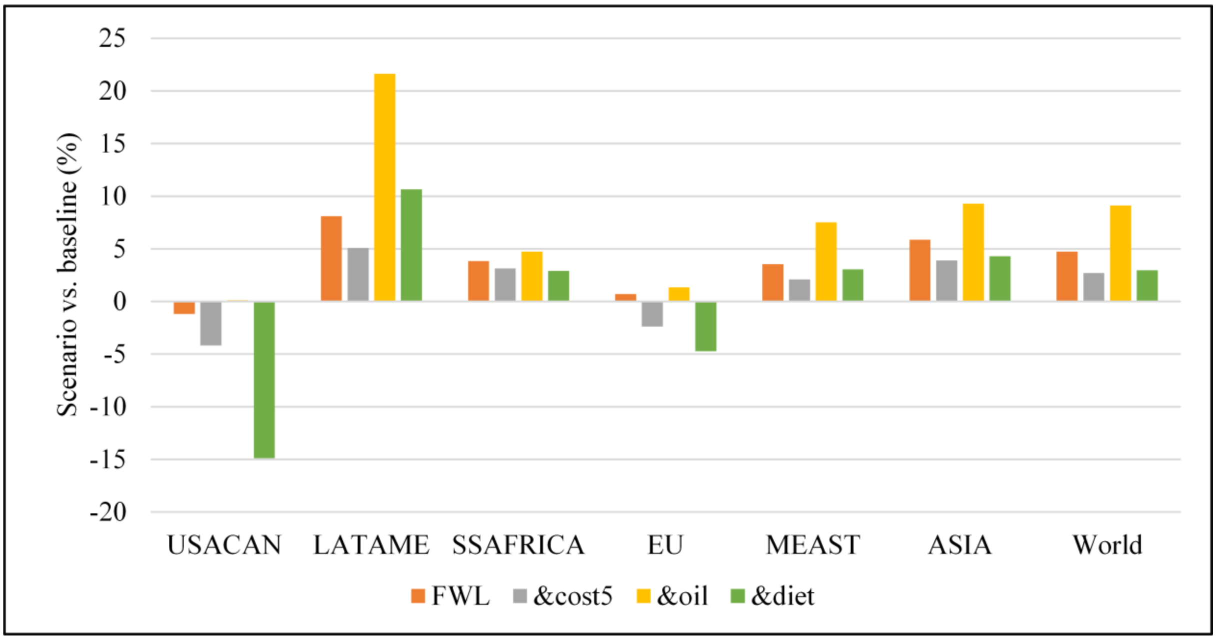


**Figure 1: Output quantity changes (%) of agricultural and food commodities of selected regions compared to the baseline in 2050**

Source: MAGNET simulation results.

At world level, agricultural and food prices decline by more than 5% in scenario FWL and by 7% in scenario &diet, while they only fall by 1% in scenario &cost5 and 5% in scenario &oil (figure 3). Hence, food waste and loss reductions contribute to increasing the availability as well as the affordability of agricultural and food commodities and results in higher agricultural and food production and consumption at the global level, however, production in high income countries decreases while consumption increases, even more than in low-income or emerging countries compared to the baseline.

Considering cost associated with food waste and loss reductions tends to have mixed impacts such as reducing the production and consumption increases in low-income and emerging regions, it further decreases production reductions USACAN and turns a production increase in the EU into a decrease. By contrast, the fossil energy tax leads overall to a higher increase in agricultural and food production and consumptions. However, the diet scenario is the scenario that leads to the highest impact on the results with boosting agricultural and food consumption in high-income countries and world average, however, also leading to a slight reduction of agricultural and food consumption in SSAFRICA and ASIA. These developments lead to a further reduction of the production agricultural and food commodities in most regions, except for Latin America compared to the food waste and loss only scenario.

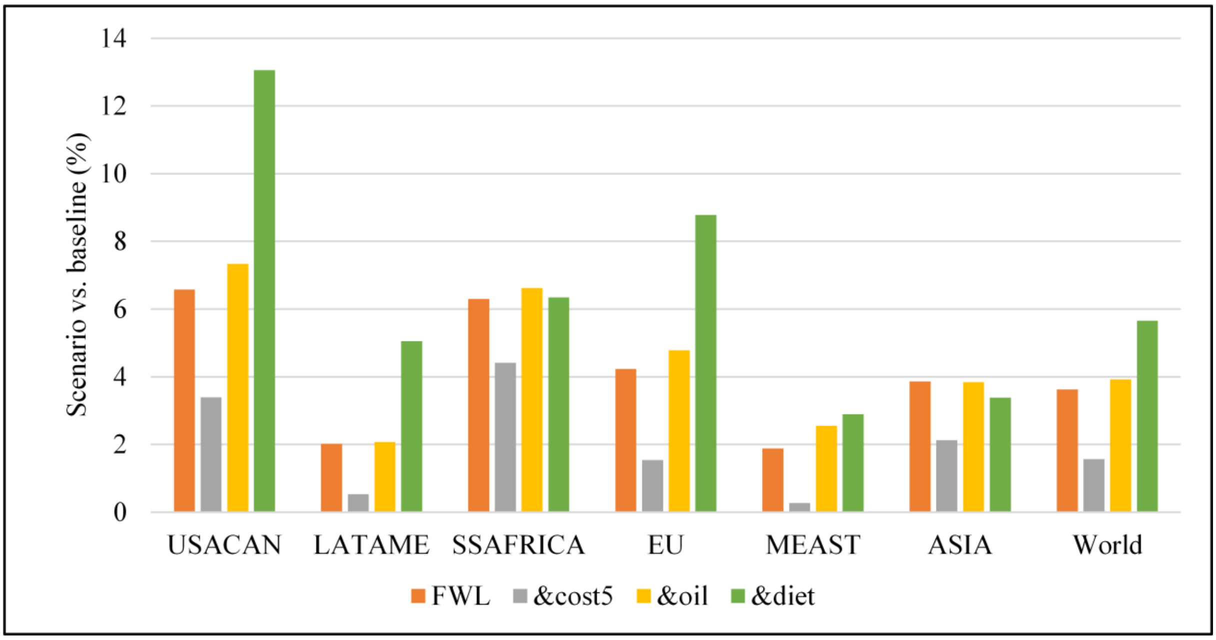


**Figure 2: Consumption changes (%) of agricultural and food commodities of selected regions compared to the baseline in 2050**

Source: MAGNET simulation results.

Changes in agricultural and food production as well as price changes affect the total output of economies. On the one hand, prices decrease and, in some regions, (USACAN and EU) also agri-food production decreases compared to the baseline, at least in some scenarios. On the other hand, the reduction of food waste and losses improves the efficiency of the agri-food sector, so that factors of production and inputs are used in other sectors and have become cheaper, so that the output of these sectors increases, while the overall impact of the &diet scenario is less clear. Figure 4 shows the impact of the four scenarios on the regions' GDP compared to the baseline. While the results show that GDP increases in all regions as a result of the FWL scenario, this effect is strongest in regions such as SSAFRICA, which have a large agricultural sector share of total GDP and accordingly benefit most from the efficiency gains. Adding costs reduces these GDP gains in all regions, but the extent to which GDP gains decrease varies. In contrast, a global tax on fossil energy drives up energy prices and consequently leads to lower GDP gains or even losses, as the increase in energy costs can only be partially compensated by the growth of the bioeconomy. GDP in MEAST is most affected by these developments, as the region is heavily dependent on fossil energy production.

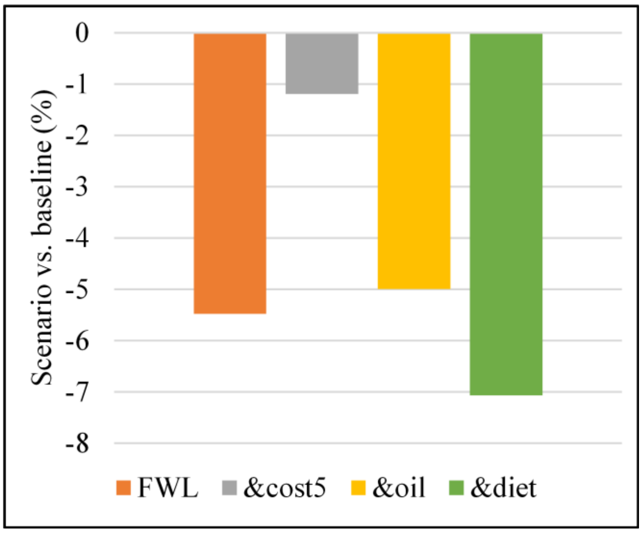


**Figure 3: World agricultural and food prices (%) compared to the baseline in 2050**

Source: MAGNET simulation results.

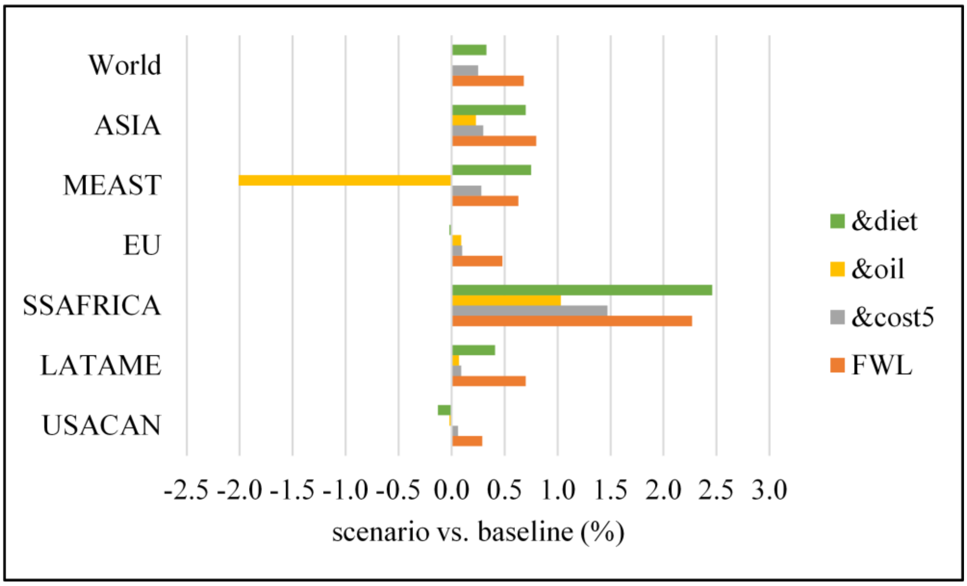


**Figure 4: Impact on GDP compared to the baseline in 2050 (%)**

Source: MAGNET simulation results

The introduction of dietary changes leads to a remarkable reduction in GDP gains compared to the FWL scenario and, especially in high-income regions, even to a decrease in GDP compared to the baseline. Regions that are at least partially exempt from dietary changes seem to experience the smallest GDP losses compared to the FWL scenario, or even an increase in GDP in the case of SSAFRICA.

## 3.2 Social impact

This sub-section first focuses on employment in the agri-food sector (Figure 5), followed by food affordability (Figure 6), to provide some insights into the social sustainability implications of the four scenarios.

The reduction in agri-food production, combined with the reduction in food waste and loss, results in a global employment loss in the agricultural sectors of 31 million full-time equivalents (FTEs). Decomposition of this result shows that this decline in agricultural employment is mainly driven by changes in the horticulture sector and, to a lesser extent, by changes in the livestock sector (Figure 5).

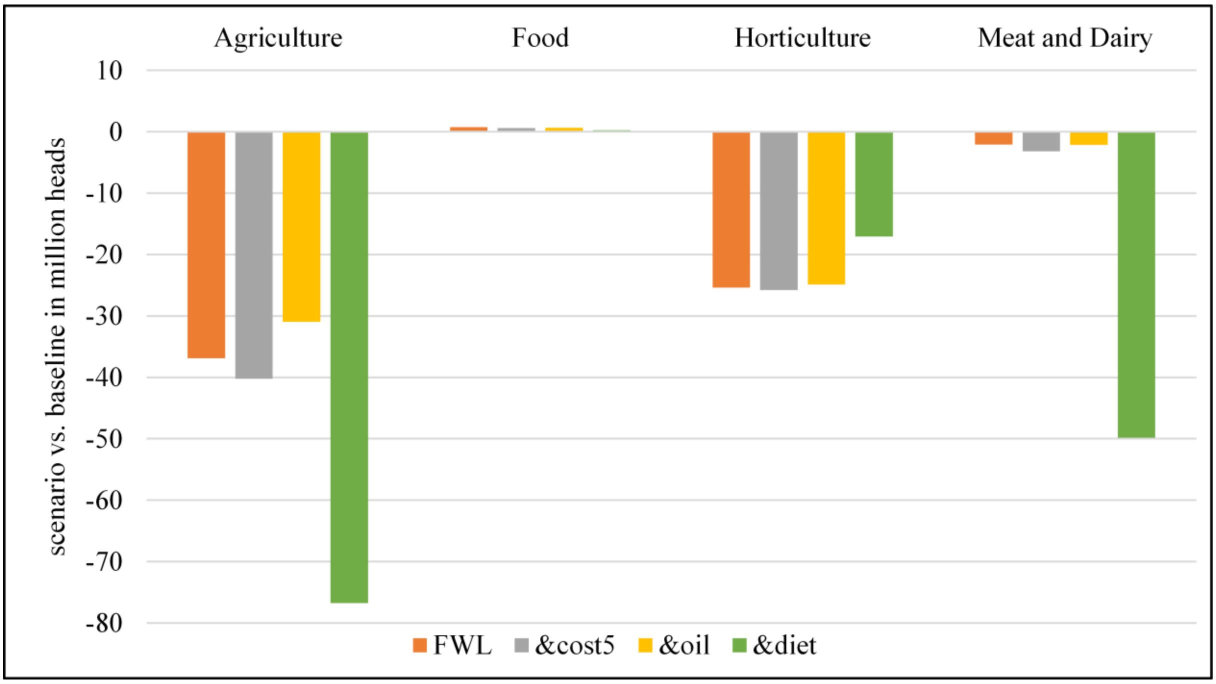


**Figure 5: Impact on employment compared to the baseline in 2050**

Source: MAGNET simulation results

While the addition of costs or a global tax on fossil energy does not have a large impact on agricultural employment, the change in global dietary habits almost doubles the number of FTEs lost in the agricultural sector. However, in this case, the sharp decline in meat and dairy consumption drives FTE losses, while the increase in fruit and vegetable consumption has a positive impact on employment in this production sector. In contrast, the impact of all scenarios on employment in the food sector is small but positive with 0.27 million additional FTEs in the &Diet scenario and 0.75 million additional FTEs in the FWL scenario.

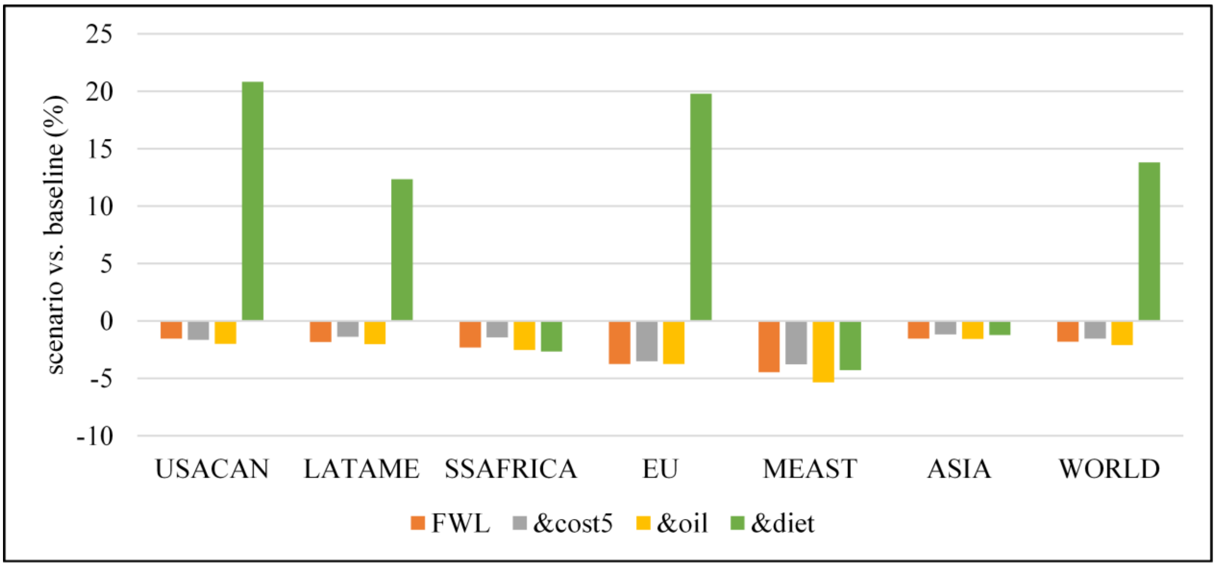


**Figure 6: Impact on share of food expenditure compared to the baseline in 2050**

Source: MAGNET simulation results

As previously shown, agricultural and food consumption increases in all regions, while global agricultural and food prices decrease, indicating a positive impact of all scenarios on food affordability. To further assess this, Figure 6 shows the impact of the four scenarios on the share of expenditure spent on food compared to the baseline. This figure highlights the positive impact of reducing food waste and loss, including costs, and fossil fuel taxes on affordability, as despite increasing food consumption, consumers in all regions spent less on food on average compared to the baseline. However, adopting more sustainable and healthier diets increases the budget share spent on food in high-income and emerging regions by 21% in USACAN, 20% in the EU and 12% in LATAME compared to baseline. In low-income regions or regions partially excluded from the nutrition transition, the results show a rather small increase in food expenditure compared to the FWL scenario and even a further decrease in the expenditure share in SSAFRICA.

### 3.3 Environmental impact

How do these developments now affect the use of our scarce resources and environmental impact? Figure 7 provides an overview of the absolute changes in water withdrawal, land use and emissions compared to the baseline in 2050. While the FWL, &cost5 and &oil scenarios lead to global water savings of about 30 to 40 km$^3$, mainly due to efficiency gains in agriculture and food production, the &diet scenario leads to an increase in water withdrawals of more than 70 km$^3$ compared to the baseline, due to a significant increase in production and consumption of horticultural products, which are often grown on irrigated land.

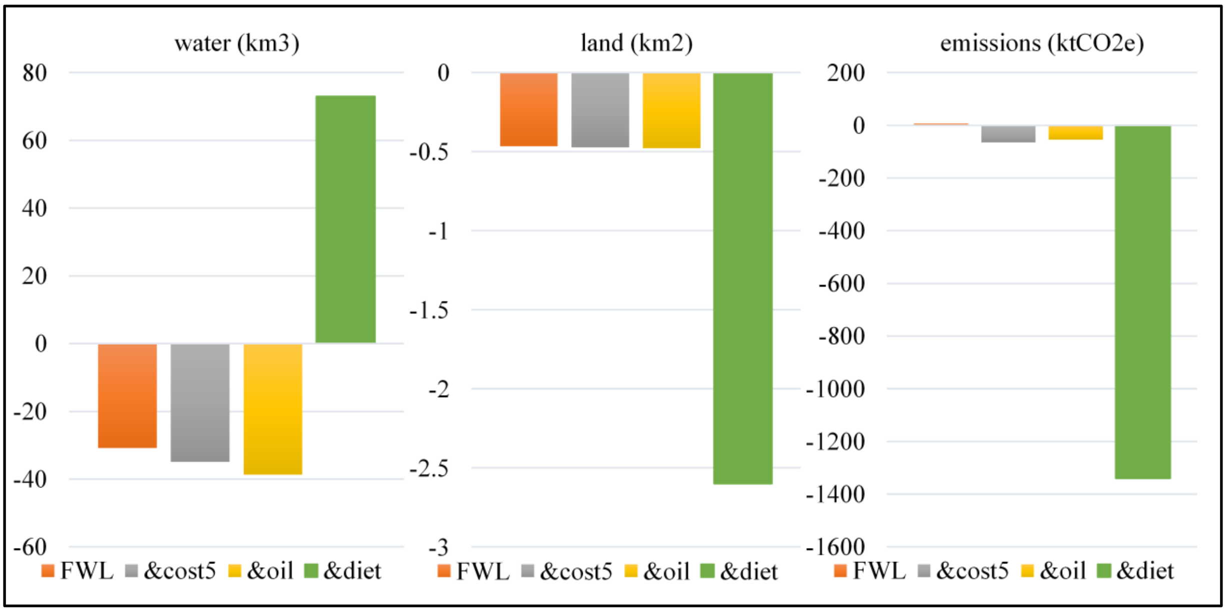


**Figure 7: Global impact on water abstraction, land use and emission compared to the baseline in 2050**

Source: MAGNET simulation results.

Land use savings at the global level are low in terms of FWL, &cost5 and &oil, while these savings are more than five times higher for the &diet scenario. Land use changes are driven by increasing the efficiency of agricultural production, so that less land is needed to produce the same amount of output, and agricultural production in high-income countries is replaced by production in low-income countries and emerging economies. With regard to the &diet scenario, the dramatic decrease in meat consumption is worth mentioning here, which is produced in a very land-intensive way in many regions, while horticulture is labour- and water-intensive but requires relatively little land. Finally, the impact on emissions reduction is clearly dominated by the significant reduction in meat production from ruminants. The impact of FWL and &cost is negligible and rather small, here market price reductions that make processed food and meat and dairy products relatively cheaper contribute to an increase in the consumption and this production of meat and dairy products that cancels out almost all efficiency gains and thus emission savings of these scenarios. Surprisingly, the impact of fossil energy taxes is also rather small at the global level.

Figures 8 and 9 present the land and emission footprint based on household food consumption measured as average m$^2$ of land consumed per capita per year and average emissions in kg CO2 equivalents consumed per capita per year. Land and emission footprints differ largely between regions in the baseline in 2050, and also the effect of the scenarios is uniform. While the impact of the FWL and &cost5 scenario reduces the land footprint in emerging and low-income regions, it has hardly an effect in high-income regions such as the EU and USACAN.

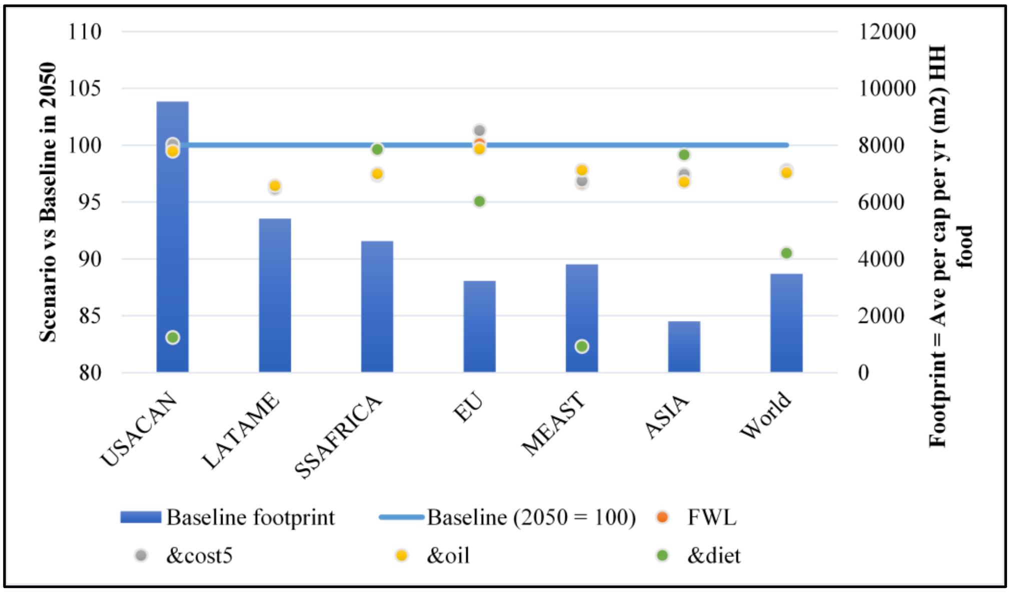


**Figure 8: Household food consumption land footprint in 2050 for selected regions**

Source: MAGNET simulation results.

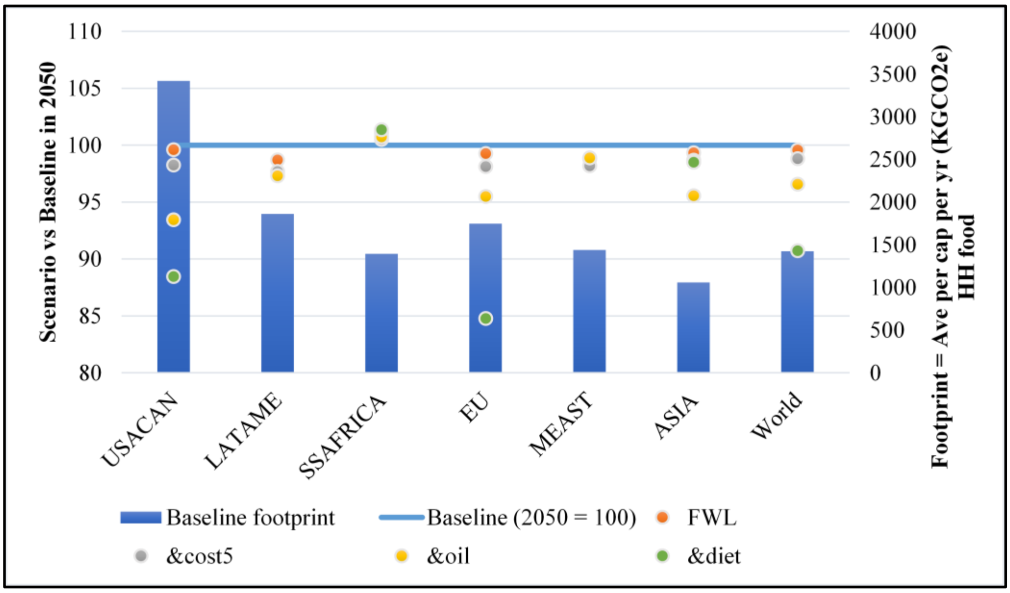


**Figure 9: Household food consumption emission footprint in 2050 for selected regions**

Source: MAGNET simulation results.

Furthermore, the &oil scenario lead in these regions even to an increase in the land footprint. By contrast, the &diet scenario has hardly an impact on the land footprint in SSAFRICA and Asia as these regions are to a large extent exempted from the feasible reference diet. While the effect of this scenario is still small in the EU and Latin America with a decrease of up to 5% compared to the baseline, the land footprint in the Middle East and USACAN decrease by more than 15% compared to the baseline.

Overall, the world emission footprint decreases in all scenarios compared to the baseline, with the lowest effect in scenario FWL (1.2%) and highest in scenario &diet (9.7%). While SSAFRICA shows an increase of the emission footprint in all scenarios compared to the baseline, the footprint in regions such as Latin America and Asia are the most affected by the implementation of a tax on fossil energy and less by dietary changes. While the impact of FWL and &cost5 on the footprint are rather low in USACAN and the EU, the impact of &oil and &diet is significant with -6.5% and -11.5% in USACAN and -4.5% and -15.2% in the EU.

In most regions, the results of the model show a decrease in land use and emissions footprints of consumers, while at the global level, absolute land use and emissions also decrease in all scenarios. But what about international trade? How much do the scenarios affect import and export flows and thus virtual trade in emissions and land? Figures 10 and 11 show the amount of land and emissions, respectively, that are virtually imported and exported via trade in agricultural and food products for household consumption in the base year and in the four scenarios in 2050.

In terms of land use and emissions, regions such as USACAN, the EU and ASIA are net importers, as shown by the trade balance in the baseline, which shows that their amount of land and emissions indirectly imported via food imports exceeds the amount of land and emissions indirectly exported. In contrast, LATAME is a net exporter of land and emissions, as indirect exports of land and emissions via food exports exceed indirect imports. In the baseline scenario, LATAME's trade balance is 400,000 $km^2$ of net land exports and net emissions exports worth 91 million tonnes of $CO_2$ equivalents, while the EU, for example, has net land imports of just under 200,000 $km^2$ and net emissions imports of 18 million tonnes of $CO_2$ equivalents.

While reducing food waste and losses helps to worsen the virtual land and emissions trade balance for agricultural and food commodities compared to the baseline in high-income regions such as USACAN and the EU, it reduces net virtual imports in low-income regions and emerging economies. Less food waste and loss, on the other hand, increases net exports of emissions but decreases net exports of land from LATAME. The &cost5 and &oil scenarios tend to slightly amplify the effect observed in FWL. In contrast, a change in consumer behaviour towards a more sustainable and healthier diet significantly improves the virtual land trade balance in USACAN, EU and MEAST compared to the baseline and even offsets the negative effect of FWL. The EU even becomes a net exporter of emissions under the &diet scenario. However, in SSAFRICA the virtual trade balance of land and emissions deteriorates compared to the baseline, while in ASIA the virtual trade balance for land deteriorates and for emissions improves. The virtual trade balance of land and emissions in LATAME decreases significantly, indicating that LATAME reduces its virtual exports more than imports.

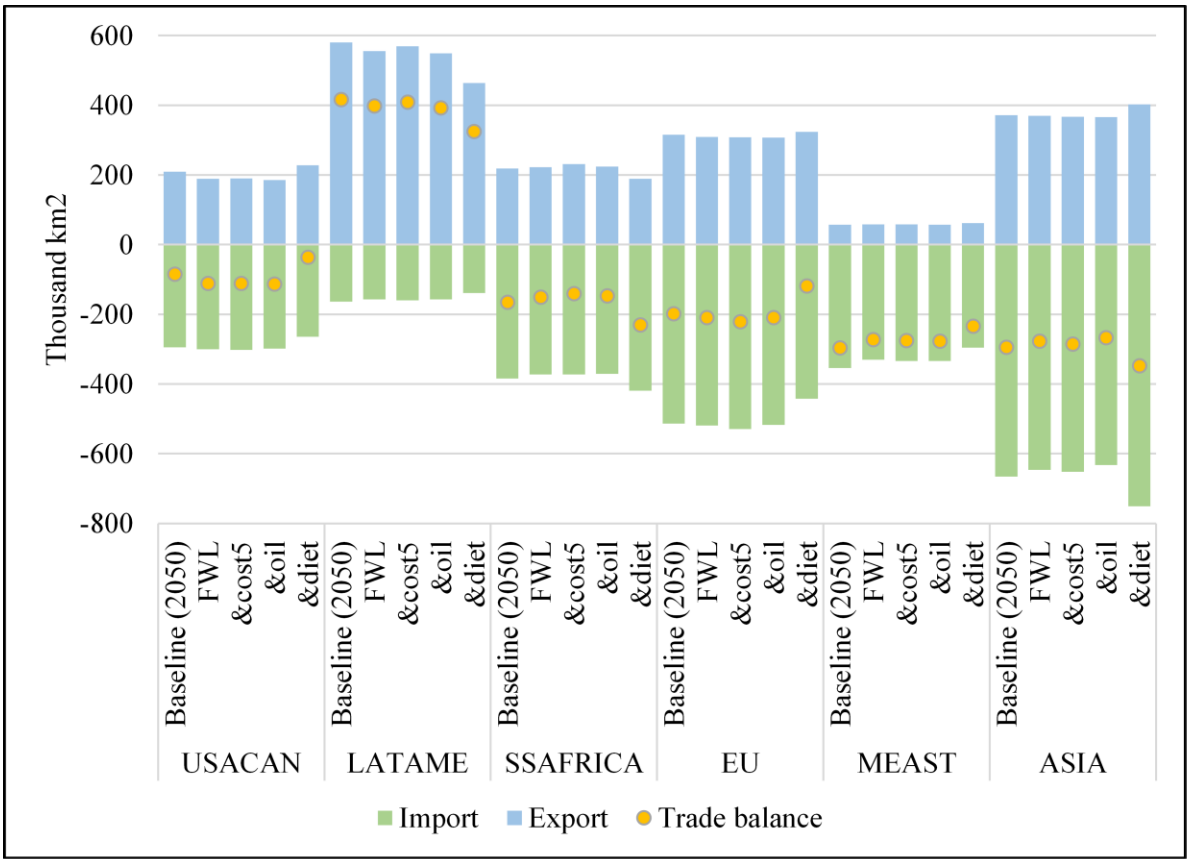


**Figure 10: Virtual land trade in 2050**

Source: MAGNET simulation results.

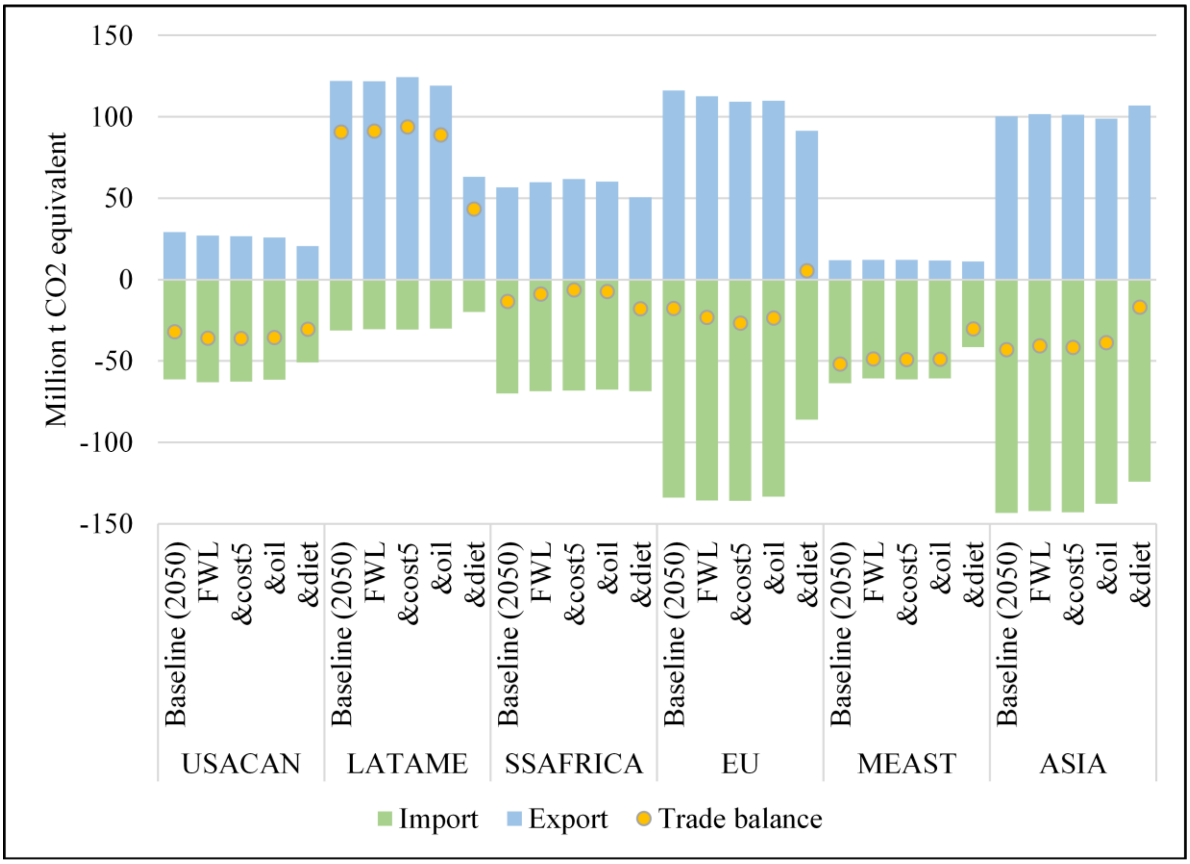


**Figure 11: Virtual emission trade in 2050**

Source: MAGNET simulation results.

## 4 Discussion and conclusion

This study aims to assess the impact of changes in consumer behaviour on economic, social and environmental sustainability, such as a 50% global reduction in food waste and loss by 2030, impact of costs associated with food waste and loss reductions, changes in dietary habits through the adoption of a feasible reference diet as proposed in the Eat Lancet report as well as the impact of a 25% global tax on fossil energies. By using a global computable general equilibrium model, the study takes into account linkages and feedback mechanisms of upstream and downstream markets, factor markets and international trade.

The results show that all four scenarios lead to an increase in food consumption at lower world prices compared to a baseline in 2050, thus could contribute to increasing food security in terms of food availability and affordability. However, food consumption increases most in high-income regions such as USACAN and the EU. While dietary change improves the average diet of consumers in these regions in the form of less meat and more vegetable and fruit consumption, reductions in food waste and losses and increased energy prices make agricultural and food products generally cheaper and thus increase food consumption in line with existing consumption patterns, so that consumption of meat, dairy products and fish increases most in these regions, while consumption of cereals and horticulture in particular tends to decline.

As a result, the focus on reducing food waste and losses and taxing fossil fuels, without providing guidance to consumers on diet composition, could lead to a worsening in dietary habits, both in terms of health impacts and environmental impacts, especially in high-income countries. The same trend towards more meat and dairy-based diets can also be observed in lower-income regions and emerging economies but starting from a lower consumption share of meat and dairy products and lower percentage increases. For example, falling meat prices lead to rising protein consumption in sub-Saharan Africa in all scenarios, which is particularly pronounced when the feasible reference diet is introduced. Such effects in lower-income regions could help reduce malnutrition and thus improve health. Despite the observed increase in food consumption when food waste and losses are reduced, the efficiency gains offset the negative environmental impacts, so that overall the environmental impacts of all scenarios are predominantly positive, although the impacts of reducing food waste and losses are much smaller than those associated with dietary change.

At global level, land use and emissions are decreasing, with the biggest impact coming from changing diets. In particular, the huge decrease in meat and dairy consumption contributed to the reduction of GHG emissions as well as the saving of pasture land. Reductions in food waste and losses lead to lower consumption of cereals and horticultural products, the latter of which in particular are often produced on irrigated land, thus showing a decrease in water withdrawals on a global scale. The opposite effect becomes evident when changes in diet are added, as the introduced feasible reference diet mainly increases kilocalories consumption of cereals and horticultural products, which leads to an expansion of land and water consumption for the production of these products. However, a drawback of our approach is that the water consumption of livestock is not captured by the model.

As a consequence, our results do not take into account, firstly, the increased water consumption of livestock caused by increased meat consumption and production when reducing food waste and losses which would have resulted in much lower water savings, and secondly, more importantly, the likely large water savings from the reduction in meat and dairy consumption when the feasible reference diet was introduced.

Average per capita per year footprints of land use and emissions related to household food consumption show that these footprints improve in more or less all regions compared to the baseline. Only the diet scenario leads to a clear reduction of this footprint compared to the baseline in high-income countries, while food waste and loss reductions tend to have only a small impact. Virtual trade balances show that food waste and loss reductions as well as increasing fossil energy prices tend to worsen the virtual trade balances of the net-importing countries of land emissions while only changing dietary habits contributes to improving virtual trade balances of net-importing countries.

While the overall, economic impact of our scenarios is mixed with clear GDP increases associated with the efficiency gains in the agricultural and food sector due to reducing food loss and waste in all regions, more expensive fossil energy reduces these gains in all regions or even leads to GDP decreases, particularly in regions that produce oil. Changing diets clearly offsets all macro-economic benefits from reducing food waste and loss in high-income countries, but it tends to strengthen the positive impact on GDP in low-income regions. Effects on GDP are the highest for regions in which agriculture constitutes a high share of GDP.

The revealed socioeconomic impacts are less desirable on the global as well as regional level as all scenarios are associated with reduced employment in the agricultural, and only a small employment increase in the food production sectors. This is particularly important for low-income regions, in which many, often small scale, farmers could be affected by this development. These agricultural employment falls affect household incomes of particularly poor people. Furthermore, the observed fall in agricultural and food prices is on the one hand beneficial for poor people as it increases food affordability, however, on the other hand it negatively impacts on farm income and thus contributing to a possible increase in poverty.

Since modelling approaches are not able to perfectly represent reality and therefore several assumptions were made that influence the model result, the following paragraphs list the caveats of our approach that mainly affect the results of our analysis.

First, the modelling framework only models water withdrawal for arable crops and neglects water used in livestock production. Only indirect water withdrawal through feeding (cereals and other crops) is captured by the model. According to Mekonnen et al. (2012), additional water services account for about 2% of water consumption. Furthermore, households are represented in terms of one representative household per region, so our approach cannot help assess the impact of reducing food waste and losses on different households and income distributions, i.e., it does not quantify the impact on poverty, food accessibility and food affordability for specific households.

Secondly, different assumptions have also influenced the results of the simulated baseline and the scenarios. The underlying baseline covers the time horizon until 2050, so that the assumed development of the economy, resource availability and energy prices are likely to change over this period in the future. In addition, there is a high degree of uncertainty about the costs associated with reducing food waste and loss. In this study, we have assumed costs equal to 5% of sales value (Figure A1 in the appendix gives an insight into the impact of different assumptions regarding these costs on production). Furthermore, our approach does not take into account the evolution of food waste as a function of wealth, as discussed in Verma et al. (2020), thus our impact assessment most likely underestimates the impact of food waste. Another assumption that may have led to an overestimation of the effects is that the kilocalorie shares from red meat, white meat, dairy and fish consumption are held constant in the baseline and food waste and loss scenarios to allow for the assessment of substitution effects in the diet scenario. However, under this assumption, this study neglects changes in dietary habits caused by the reduction of food waste and losses and the associated price changes.

While our model indeed takes into account all forward and backward linkages including manufacturing and services, and furthermore includes a detailed representation of the bioeconomy including circular flows covering biomass use and waste treatment as well as the production of bio-based products, this study only tracks the economic, environmental and social impacts related to food consumption. Consequently, the results shown in this article ignore the impacts on e.g., jobs and emissions in non-food sectors.

As this work shows that a more holistic view is essential to understand the impact of changing consumer behaviour patterns on economic, social and environmental sustainability, future research should also focus the assessment of the impact of non-food responses in the analysis, including the impact on the production and consumption of bio-based products.

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## Annex

**Table A1: Overview on quantitative impact assessments of food waste and loss and diets accounting for market interlinkages (could be moved to appendix)**

| Reference | Economic model | Time horizon | Regional depiction for policy shock | Impact coverage | Food waste | Food loss | Dietary habits | Costs |
|---|---|---|---|---|---|---|---|---|
| Britz et al. 2019 | Global CGE with sub-regional detail | - | EU, NUTS2 level | Global economic and environmental impacts | X | | | X |
| Campoy-Munoz et al. 2017 | Social accounting matrices | - | EU | Economic impacts | X | | | |
| Jafari et al. 2020 | Global CGE | - | EU | Global impact on food availability and planetary boundaries | X | | | X |
| Kuiper and Cui, 2020 | Global CGE | - | Global | Impact on markets, food security, GHG emission and land use | | X | | |
| Latka et al. 2021 | Global CGE model linked to PE model and biophysical model | 2050 | EU | Economic and emission impacts | | | | |
| Lopez Barreira and Hertel 2021 | Global PE model | 2050 | Global | Impact on food security and environmental indicators | X | | | |
| Philippidis et al. 2019 | Global CGE | 2050 | EU | Impact on market, food security, environmental indicators | X | | | X |
| Philippidis et al. 2021 | Global CGE | 2030 | Global | Planetary boundaries | | | X | |
| Rutten et al. 2013a | Global CGE | 2020 | EU | Economic, food security and land use impacts | X | | X | |
| Rutten et al. 2015 | Global CGE | 2020 | EU | Food prices, impacts on SSA | X | X | | |
| Springmann et al. 2018 | Global food system model with a global partial equilibrium model based on the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model and database at its core linked with biophysical models | 2050 | Global | Planetary boundaries | X | X | X | |

Source: Authors' elaboration.

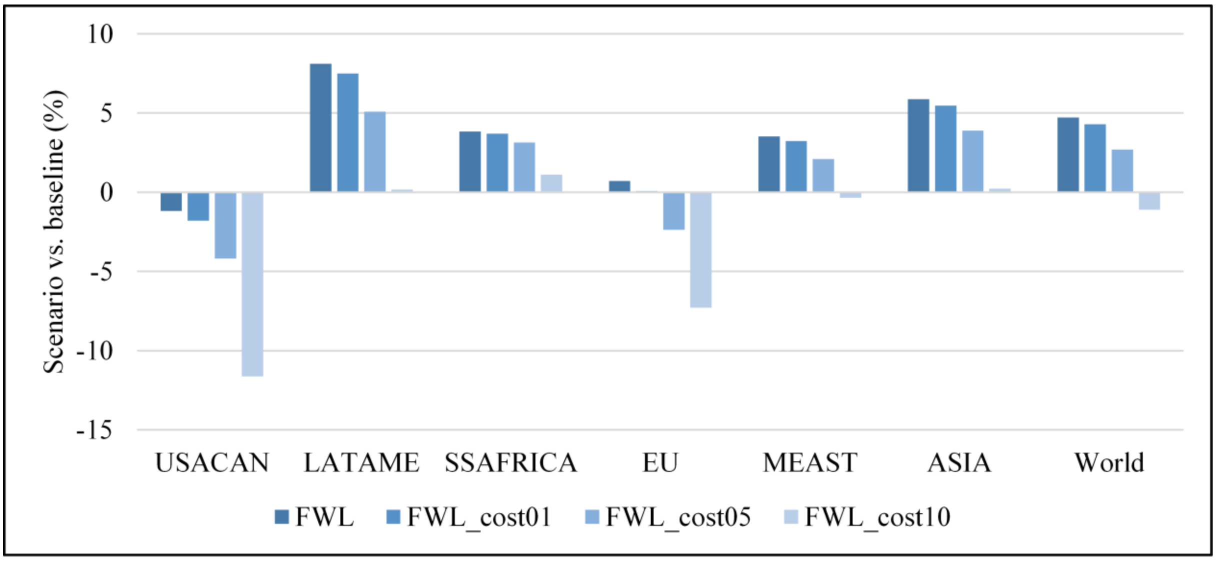


**Figure A1: Sensitivity analysis of costs associated with reducing food waste and loss**

Source: MAGNET simulation results.

Note: FWL_cost01, FWL_cost05 and FWL_cost10 account for the assumption of 1%, 5% and 10% compliance cost associated with reducing food waste and losses, respectively.