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Exploring changing food attitudes to respect planetary boundaries

A global, model-based analysis

Boysen-Urban, K.

M'barek, R.

Philippidis, G.

Ferrer Pérez, H.

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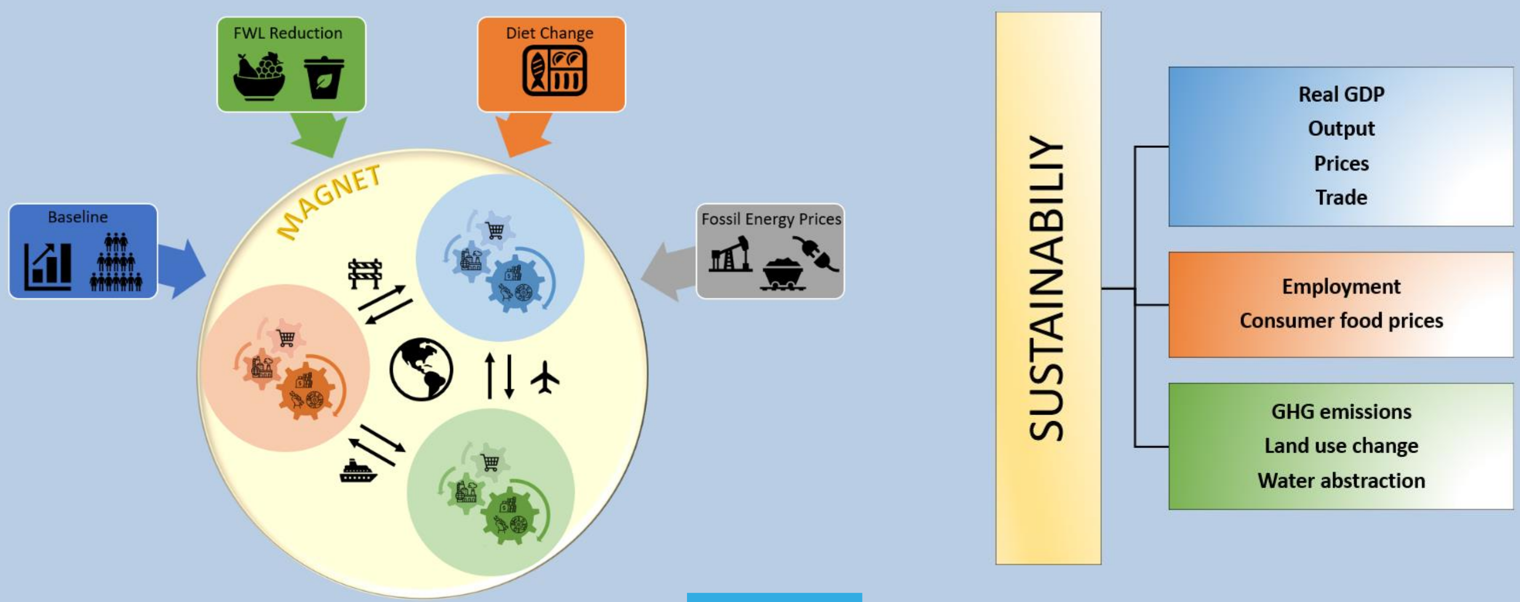

Joint
Research
Centre

EUR 30794 EN

Contact information
Name: Robert M'barek
Address:
Email: Robert.M'barek@ec.europa.eu
Tel.: +34 954 488 489

EU Science Hub
https://ec.europa.eu/jrc

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Contents

Abstract

Healthier, more sustainable and more equitable food systems have a key role to deliver progress on all 17 Sustainable Development Goals (SDGs). This study aims at assessing the impact of behavioural changes with regard to food consumption with a focus on the objectives of SDG target 12.3.

As a stylised representation of our finite planetary resources, the study employs a recursive dynamic global computable general equilibrium simulation model known as MAGNET, which is ideally suited to examining forward-looking medium- to long-term scenarios. The MAGNET model is macroeconomic in scope with fully internalised gross bilateral trade flows between regions and a full accounting system of global virtual flows for assessing footprints. Moreover, the model has a broad array of economic, social and environmental indicators to fully explore the sustainability implications arising from demand driven changes in the state and potential future evolution of the global food system within the wider bioeconomy.

The first scenario investigate the impact of global food waste and loss (FWL) reductions at different points along the supply chain, implemented by 2030 and maintained until 2050. The remaining scenarios build upon the FWL scenario through four sets of experiments: (i) a dual decomposition of the FWL scenario to examine waste and loss reductions in isolation, (ii), variations in associated food supply chain compliance costs to meet the assumed FWL reduction, (iii), an exploration of the resilience of food demand systems to rising fossil energy prices, and (iv) a transformation toward healthier plant-based diets over the period 2020 to 2050 inspired by the EAT-Lancet report. To facilitate the comparison of the diet scenario and FWL scenarios, the share of red meat, white meat and dairy consumption is kept constant in the baseline and all FWL scenarios.

Box 1. Key messages from the study

Due to improved production efficiency in the food chain arising from food loss reductions, global food prices decrease, and therefore lead to a higher food consumption, indicating a positive impact of all scenarios on food affordability.

The region-wide reduction in food prices is a significant benefit for the most vulnerable members of society, particularly poor households in developing countries and could thus contribute to reducing food insecurity.

While trade-offs exist and have to be carefully analysed and addressed, the scenarios show a strong positive message regarding the reduction of the environmental impact in the depicted scenarios. The global food footprints are reduced throughout all scenarios for land and emissions, with the FWL scenario combined with a healthy diet having the largest impact. The smaller impact from the FWL scenario on the emissions is due to the strong improvement of productivity and related consumption increase. Water abstraction shows a more mixed picture as it increases in many regions compared to the baseline, with the highest effects relating to the diet shift. While livestock production declines, water-intensive and irrigation-based horticulture production significantly increases.

From a macroeconomic perspective, the results indicate that GDP increases in all regions as a result of the FWL scenario, with strongest relative impacts in regions such as Sub-Saharan Africa, which have a large agricultural sector share of the total GDP and, accordingly, benefit the most from the efficiency gains.

Adding the costs associated with of food loss and waste reductions, lowers these GDP gains in all regions. The higher the assumed costs, the stronger the downturn on real GDP, but the extent to which GDP gains reduce varies across regions. Moreover, a global fossil fuel tax drives energy prices up and consequently leads to lower GDP gains or even losses in regions heavily dependent on fossil energy production.

Finally, although beyond the scope of this study, it should be recognised that more sustainable and healthier diets offer additional benefits to biodiversity and related ecosystem services, as well as improved health of the population, greater labour productivity and reductions in associated public health expenditures.

The scenarios selected represent important targeted synergetic directions for tackling the most pressing challenges of today and the future, put in place on a global policy agenda with the SDGs and the Paris agreement. From a European perspective, within the context of the European Green Deal and related strategies, the market driven dynamics explored in this report constitute a relevant building block toward the realisation of a sustainable 21st century vision of European agriculture. For example, there is a clear complementarity in pairing the attitudinal changes toward more sustainable food consumption examined in this report, with environmentally friendly and, albeit, potentially productivity reducing farming practises. The implications for food affordability, sustainable usage of resources and the protection of rural livelihoods through payments

linked to efficient and socially responsible agricultural production practises, offers great promise and should constitute a line of inquiry for further research.

It should be noted that the report does not constitute an impact assessment. The work in this report began back in 2019, inspired by the Sustainable Development Goals related to the reduction of food waste and losses (SDG 12.3) and healthier diets (SDG 2). As in any other ex-ante modelling exercise, the results provided are contingent upon, and bounded by, assumptions and model capacities.

Acknowledgements

We would like to thank colleagues from the JRC and DG SANTE for their helpful comments and suggestions. We acknowledge the scientific support for the MAGNET model from the team at Wageningen Economic Research, under the leadership of Hans van Meijl.

Authors

Kirsten Boysen-Urban

Robert M'barek

George Philippidis

Hugo Ferrer Pérez

Executive summary

Policy context

Globally, the Sustainable Development Goals (SDGs) set the agenda for advancing towards an economically, socially and environmentally sustainable planet in 2030 and beyond. The UN Food Systems Summit in September 2021 discussed actions, solutions and strategies to deliver progress on all 17 SDGs, which are relying on healthier, more sustainable and more equitable food systems. Sustainable food systems that deliver health and nutrition are defined in von Braun et al. (2021) with the following three objectives, used as a broad guideline for the analysis of the scenarios: Objective 1 - End hunger and achieve healthy diets for all; Objective 2 - Sustainable use of biodiversity and natural resources, the protection of ecosystems and the safeguarding of land, oceans, forests, freshwater and climate; Objective 3 - Eliminate poverty and increase income and wealth.

The European Union (EU) has developed a comprehensive approach, embedding its policies and strategies into the SDGs as an overall framework. The European Green Deal sets the compass for Europe's transition to a climate-neutral economy, as 'our current levels of consumption of raw materials, energy, water, food and land use are not sustainable' (SOTEU 2020). This quote also points to the central role of the food system, being an integral part of the circular and sustainable bioeconomy. Several policies and initiatives under the umbrella of the European Green Deal – aiming at a circular, sustainable and transformative EU economy – emphasise the key role of waste and diets, together with the importance of the oil (carbon) price.

It should be noted that the report does not constitute an impact assessment. The work in this report began back in 2019, inspired by the Sustainable Development Goals related to the reduction of food waste and losses (SDG 12.3) and healthier diets (SDG 2). As in any other ex-ante modelling exercise, the results provided are contingent upon, and bounded by, assumptions and model capacities.

Methodology

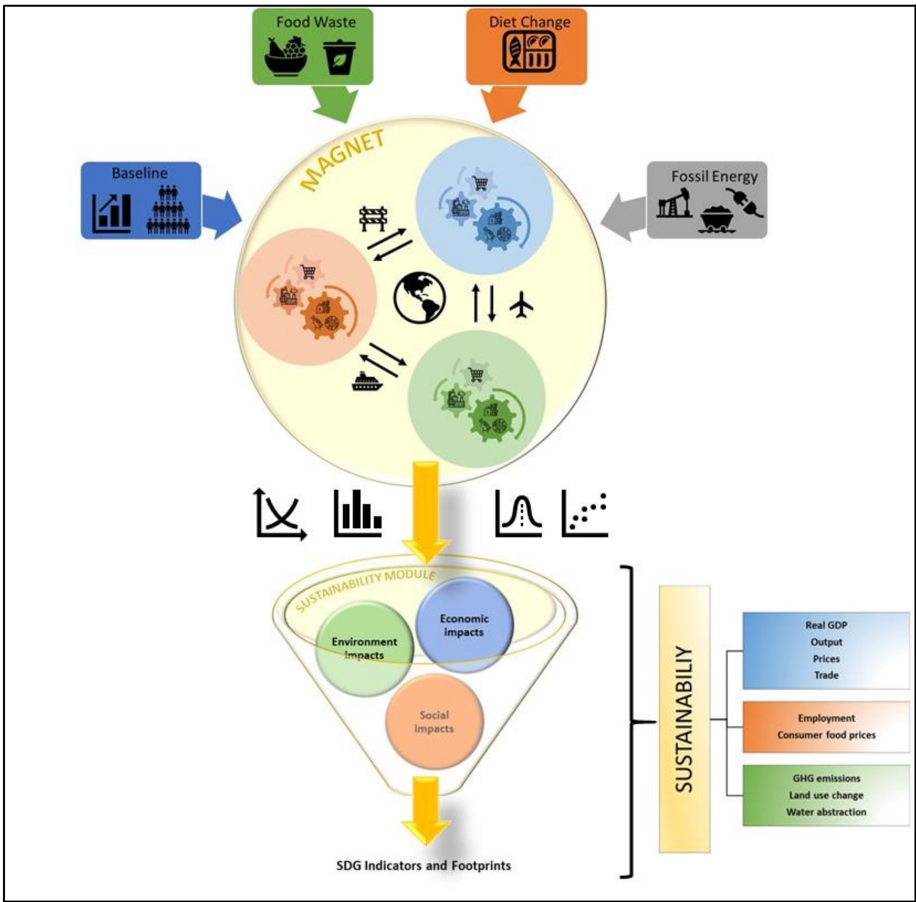
Exploring pathways for a more sustainable future of the global food system can be done from many different sectorial, geographical and methodological angles. The complexity of the food system and its multiple connections will necessarily render all approaches incomplete, since not all drivers can be addressed simultaneously.

The positive economic outcomes of transitioning to healthier diets, e.g. stemming from reduced healthcare costs, are not included in the analysis. Estimations by Hendriks et al. (2021) attribute a value of almost 20 trillion USD to global food consumption externalities, including 11 trillion USD of estimated costs relating to increased mortality related to diseases. This is compared to the value of total global food consumption of around 9 trillion USD.

The scope of this study also does not include the impact on and of climate change; thus, it does not investigate the costs of inaction to limit climate change and biodiversity needs. Latest research shows possible options of aligning the climate action narrative with one of increasing welfare and sustainable development (Koeberle et al., 2021).

In this study, we look at the food system with a global perspective and scenarios mainly targeting changes in attitudes towards food waste and diets.

Overview of modelling approach



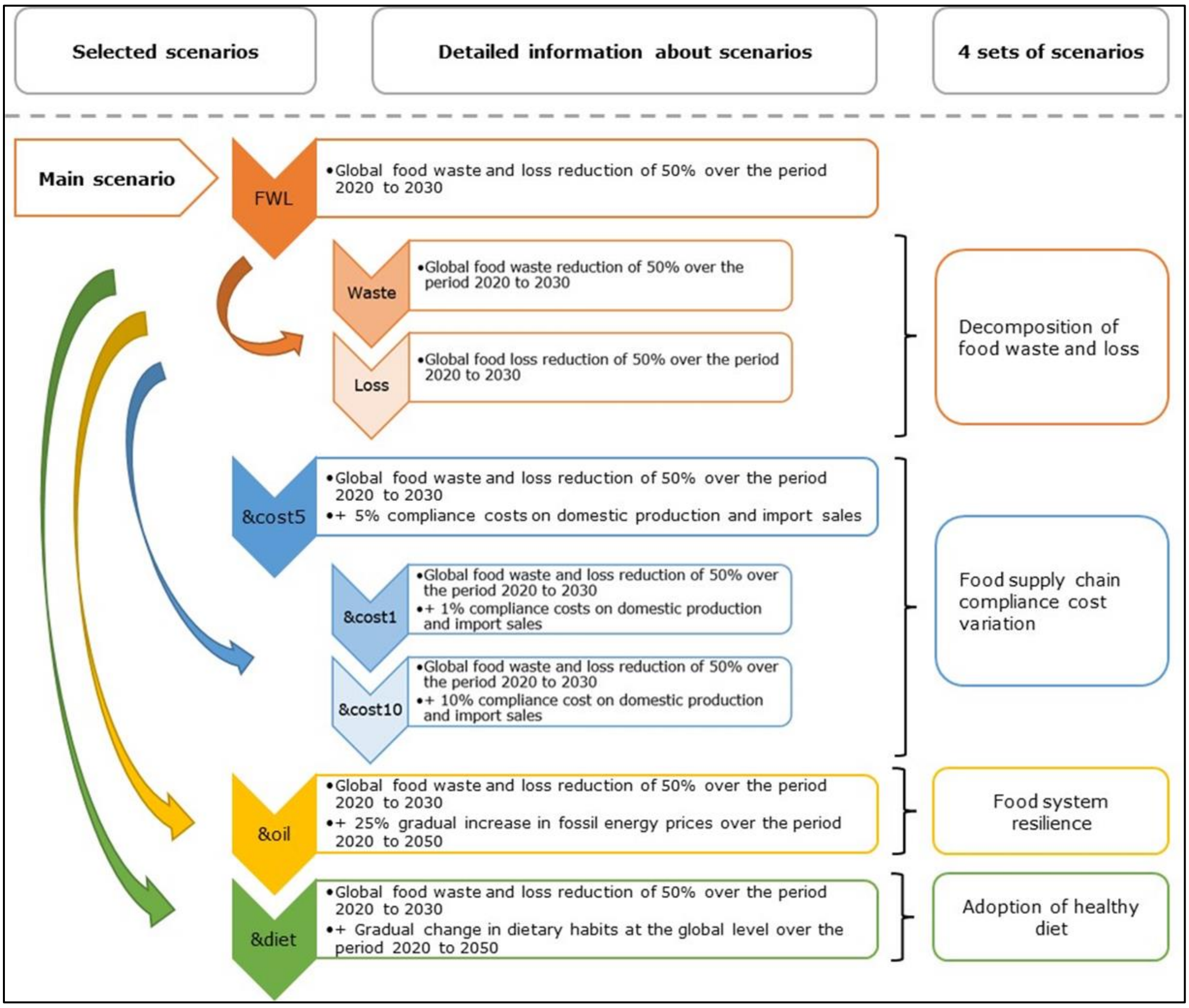
As a stylised representation of our finite planetary resources, the study employs a global computable general equilibrium simulation model known as MAGNET, which is ideally suited to examining forward-looking medium- to long-term scenarios, analysing the results from a social, environmental and economic perspective.

The MAGNET model is macroeconomic in scope with fully internalised gross bilateral trade flows between regions and a full accounting system of global virtual flows for assessing footprints.

Source: Authors' elaboration.

The first group of scenarios (Waste, Loss and its combination labelled FWL) investigates the impact of food waste and loss reductions along the supply chain. All the following scenarios add to the FWL scenario i) a sensitivity analysis of the impact of different assumptions with regard to the associated costs of FWL reductions (1, 5, and 10%), ii) higher fossil energy prices, and iii) a dietary transformation over the period 2030 to 2050 based on the EAT-Lancet report. To facilitate the comparison of the diet scenario and FWL scenarios, the share of red meat, white meat and dairy consumption is kept constant in the baseline and all FWL scenarios.

Scenarios overview



Source: Authors' elaboration.

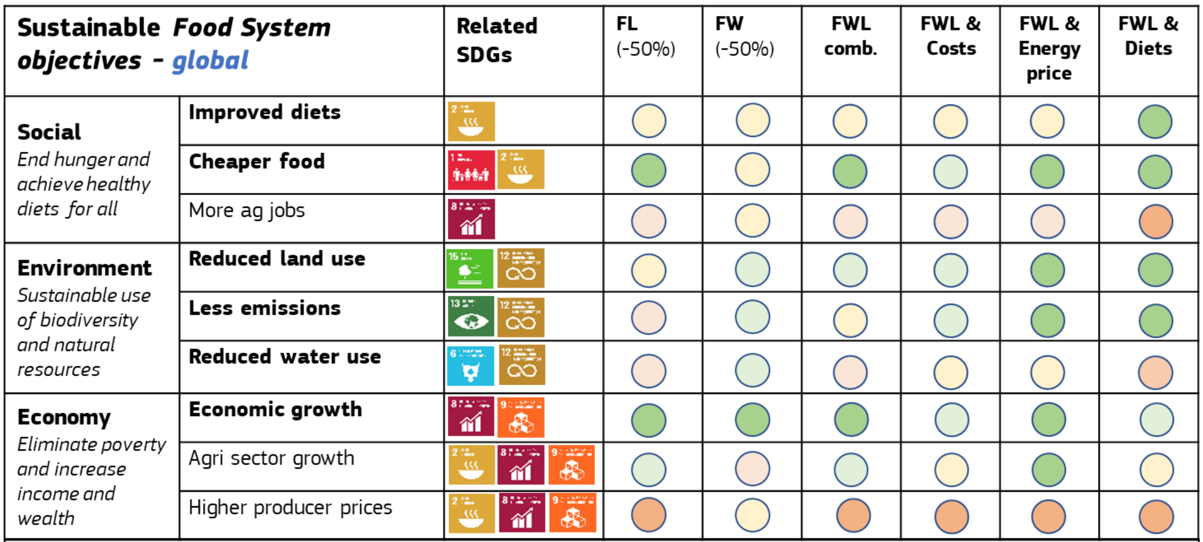
The results are presented from a global viewpoint and, in some more detail, for the European Union. It should be noted, that the regional food systems in poorer and richer countries face the global challenges of climate change and biodiversity loss. Each class of country, however, exhibits very different socio-economic conditions and therefore seek different goals. For instance, while food systems in developing countries still have to overcome hunger, i.e. increase in kcal per capita, those food systems in richer countries are more firmly prioritising mitigation measures to tackle environmental deterioration.

Key conclusions

In an ever more populous world, an important contribution from the global food system to foster sustainable human development and alleviate malnutrition (in all its forms) within our finite planetary boundaries, is through coordinated efforts to reduce food waste and loss (FWL) and the adoption of healthier diets, as prescribed in SDG target 12.3. In addition to improving the availability and affordability of calories in poorer areas, there are accompanying desirable environmental benefits through demand-driven reductions in less emissions-intensive agricultural practises. Investigating the food footprints for land, water, emissions and energy in more detail, we observe a spatial, sectoral and time-wise heterogeneous picture, which undergoes further transformation under the different scenarios. These deviations in outcomes also indicate the importance of global trade exchange for a more resource-efficient food system.

The following figure gives an overview of the scenario impacts on food system objectives and indicators globally. While some trade-offs exist, the overall picture for the society, environment and economy is positive. The socioeconomic impacts on the farming sector need special attention.

Overview of scenario impacts on food system objectives and indicators globally



Important remarks:

- Indicators in bold are those relevant for the **whole society** and not a specific sector.
- Coloured circles indicate the direction towards reaching an objective.
- The expected reduced productivity due to environmental oriented policies such as in EU's Farm to Fork strategy could be counterbalanced with the increased efficiency as shown in the FWL scenario. Consequently, **the impacts on the agricultural sector** would look differently.
- Not creating more agricultural jobs while producing more, means a higher labour productivity.
- The reduced use of natural resources improves **biodiversity** and thus creates additional (socioeconomic) values.
- General **health benefits** through a better diet and better environment create enormous socioeconomic benefits, not included in this study.

Scenarios:
FL (-50%): Food loss reduction by 50%
FW (-50&): Food waste reduction by 50%
FWL comb.: Food loss and waste reduction combined
FWL & Costs: as FWL with 5% costs for reduction
FWL & Energy price: as FWL with a 25% higher oil price
FWL & Diets: as FWL with a healthier diet (EAT-Lancet)

Source: MAGNET model, transformation of results into more qualitative statements.

Food waste and loss reductions are almost perfectly complementary measures. Food loss reductions can be achieved through sustainable productivity growth, optimising the input-output relation on the supply side. Food waste reduction requires a shift in social attitudes towards a more sustainable food demand system. In reality, both measures are associated with costs, research and innovation for productivity growth on the one hand, and different costs along the food chain on the other. The sensitivity analysis with different costs for food waste reduction dampens the effects.

While the analysed (diet) scenario is clearly a simplified approach and would have to be accompanied by long-term transitional measures, the objective of improving the sustainability of production and consumption – mainly emissions reduction – is fulfilled. From a holistic point of view, adding a multiple indicator perspective along the lines of selected SDGs objectives, a multitude of synergies and trade-offs can be identified.

An important impact of the more efficient and less meat-oriented production and consumption model are reduced prices, which trigger a demand increase in some sectors. This supply and demand equilibrating function of the price is the central mechanism of the global economic system and will therefore always trigger second or third round effects in the model and might in some cases result in an initially counter-intuitive outcome of some indicators.

While agricultural production at EU level is only marginally affected when food waste and losses are reduced together, the decomposition demonstrates that reducing food losses leads to a significant increase in output and reducing food waste leads to a smaller reduction.

Overview of scenario impacts on food system objectives and indicators for the EU

Sustainable *Food System objectives* – *EU*		**Related SDGs**	**FL** (-50%)	**FW** (-50%)	**FWL comb.**	**FWL & Costs**	**FWL & Energy price**	**FWL & Diets**
Social *End hunger and achieve healthy diets for all*	**Improved diets**	2						
	Cheaper food	1, 2						
	More ag jobs	8						
Environment *Sustainable use of biodiversity and natural resources*	**Reduced land use**	15, 12						
	Less emissions	13, 12						
	Reduced water use	6, 12						
Economy *Eliminate poverty and increase income and wealth*	**Economic growth**	8, 9						
	Agri sector growth	2, 8, 9						
	Higher producer prices	2, 8, 9						

Important remarks:

- Indicators in bold are those relevant for the **whole society** and not a specific sector.
- Coloured circles indicate the direction towards reaching an objective.
- The expected reduced productivity due to environmental oriented policies in the Farm to Fork strategy could be counterbalanced with the increased efficiency as shown in the FWL scenario. Consequently, **the impacts on the agricultural sector** would look differently.
- Not creating more agricultural jobs while producing more, means a higher labour productivity.
- The reduced use of natural resources improves **biodiversity** and thus creates additional (socioeconomic) values.
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Scenarios:
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FWL & Diets: as FWL with a healthier diet (EAT-Lancet)

Source: MAGNET model, transformation of results into more qualitative statements.

Acknowledging that many factors drive the direction and magnitude of results, the combination of the price-increasing and –decreasing measures would be important to reflect the holistic nature of wide-reaching initiatives like the European Green Deal and its Farm to Fork strategy.

Another aspect, not yet integrated in mainstream economic impact analysis, is the value of biodiversity or natural habitats in general. The research on ecosystem services is seeking to close this gap, although it is constrained by the challenge of calculating a price for non-marketable resources that can be then integrated within national economic accounting systems.

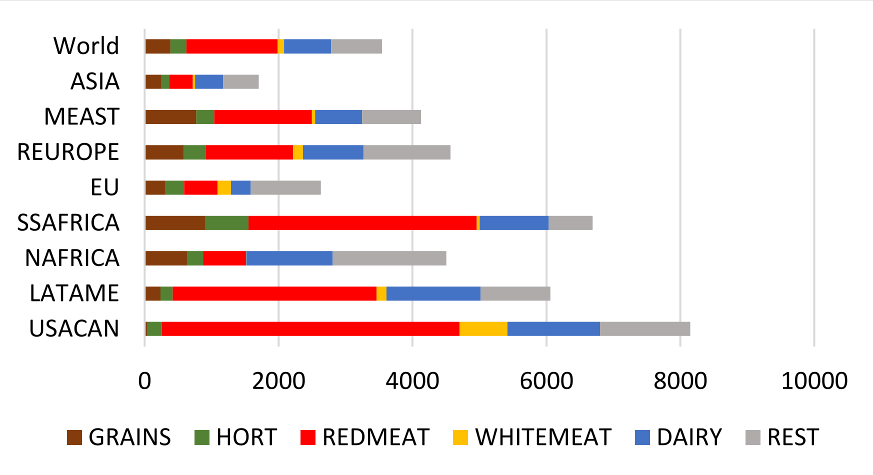
The study, employing the whole-economy MAGNET model, presents a methodology, an indicator framework and a multitude of visual analytics to better understand the state and potential future evolution of the food system in the wider bioeconomy in a global context. The scenarios selected represent important synergetic policy instruments for tackling the most pressing challenges of today and the future.

Main findings

How do our food purchasing patterns affect the world we live in?

In a first stage, the report describes in detail the current state and expected development of food consumption driven footprints in a business as usual baseline. The figures clearly indicate a highly diverse footprint per capita with the meat consumption dominating the land and emission footprint in particular in richer regions.

Final food consumption driven land footprints per capita and year, in m^2, year 2020

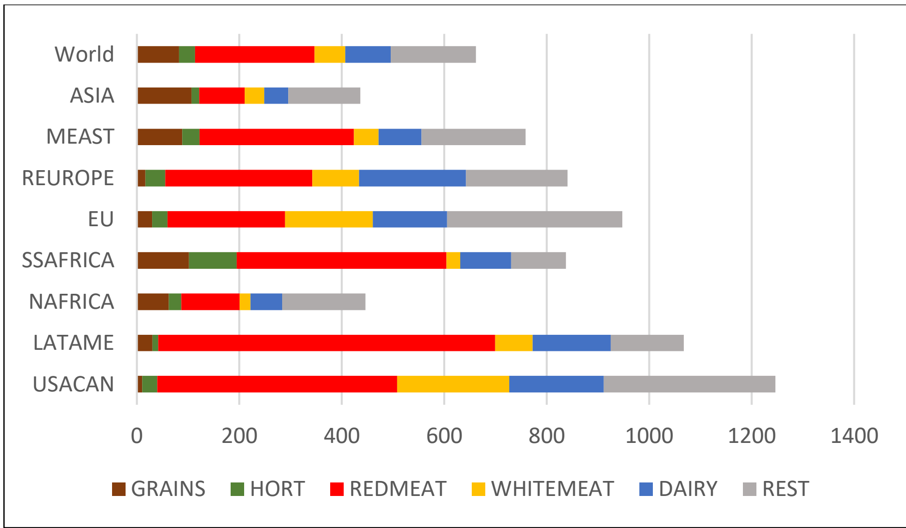


The graph shows the food demand driven footprint for agricultural land by regions, differentiated by grains, horticulture, red meat, white meat, dairy and the 'rest', which is composed of sugar, fish and other food. It shows the dominance of the livestock sector in the use of agricultural land (including arable and grazing land) is apparent in all regions, with the exception of ASIA and, to some extent, the EU.

Source: MAGNET simulation results.

The footprints include the whole production process, so are not directly related to the calories consumed per capita. In particular SSAFRICA has a rather low productivity per ha land.

Final food consumption driven emissions footprints per capita and year, in kg CO2e, year 2020

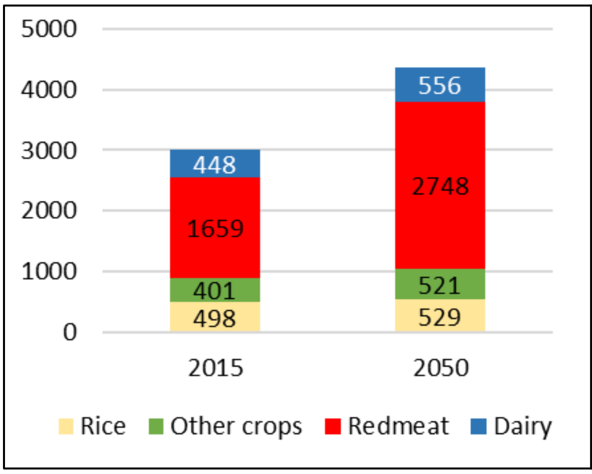


With regard to emission footprints, the share of meat in the emissions is slightly higher. This is the case in particular for regions with high consumption of red and white meat. Richer regions such as USACAN and EU have also a high contribution from the "rest", which includes in particular processed food.

Source: MAGNET simulation results.

The price of inactivity: impacts on our planetary boundaries

Baseline food demand driven global virtual emissions in 2015 and 2050, (MtCO2e) for different agricultural and food products



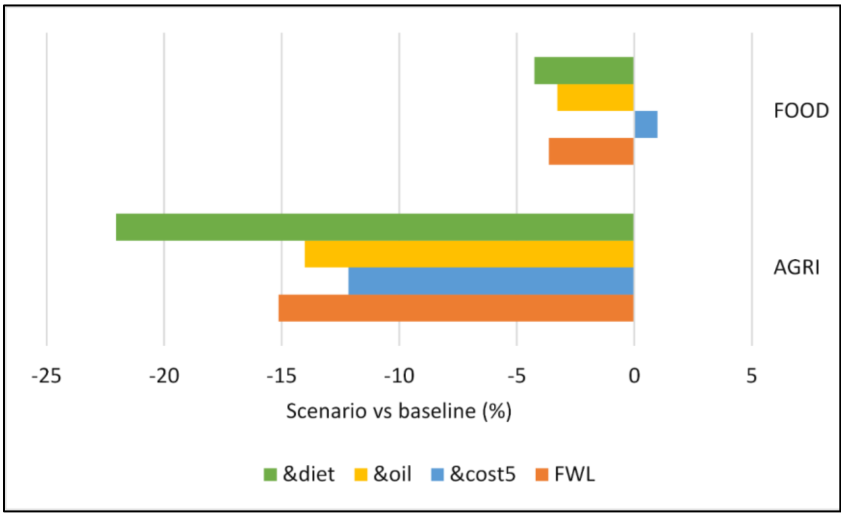
With a growing population and rising per capita incomes, particularly in those regions in the world most susceptible to changes in climate, food demand driven emissions for different agricultural and food products in the world are expected to increase, in particular in the case of red meat towards 2050. Main reason for the increase is population growth in the global South.

Source: MAGNET simulation results.

Taking action now reaps longer term benefits for ensuring safe planetary boundaries

The result in the orange bar presented in the following figure represents the main FWL scenario (combined food waste and loss reduction). To this specific scenario is added each of an additional compliance cost of 5% (&cost5), a higher oil price of 25% (&oil), and a healthier diet (&diet).

Impact on agri-food prices compared to the baseline in 2050.



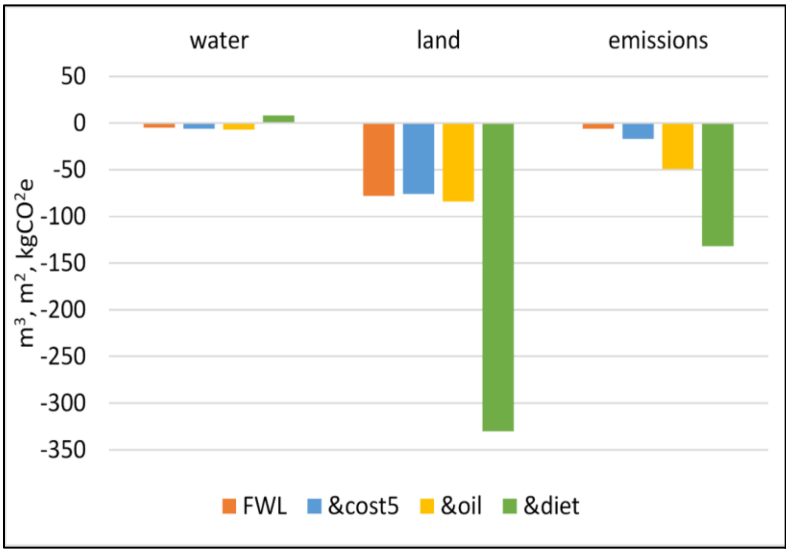
As a main result of the higher efficiency in the food chain through reduction of food waste and loss, global food prices decrease, and therefore lead to a higher food consumption, indicating a positive impact of all scenarios on food affordability. The region-wide reduction in food prices is a significant benefit for the most vulnerable members of the society, particularly poor households in developing countries and could thus contribute to reducing food insecurity.

Source: MAGNET simulation results.

The results highlight the positive impact of reducing food waste and loss 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 to some extent the budget share spent on food in high-income and emerging regions compared to the baseline.

While trade-offs, in particularly for the socio-economic situation of the farming sector, exist and have to be carefully analysed and addressed, the presented scenarios show a strong positive message regarding the reduction of the environmental impact in the depicted scenarios.

Global food demand driven footprint per capita compared to the baseline in 2050

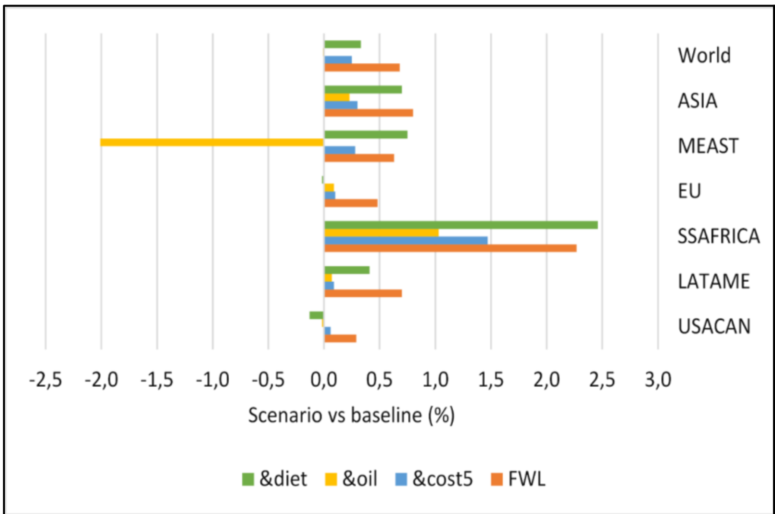


Global food demand driven land and emissions footprints fall in all scenarios, with the FWL scenario combined with a healthy diet (&diet) having the largest impact. Smaller footprint reductions In the FWL scenario are linked to the strong improvement of productivity and related consumption increase. Water abstraction shows a more mixed picture as it increases in many regions compared to the baseline, with the highest effects relating to the diet shift. While livestock production declines, the water-intensive and irrigation-based horticulture production significantly increases.

Source: MAGNET simulation results.

From a macroeconomic perspective, the scenario results indicate that GDP increases in all regions in the FWL scenario.

Impact on GDP compared to the baseline in 2050 (%)



The strongest benefits are felt in regions such as SSAFRICA, where efficiency gains from food loss reductions motivate improvements in their large agricultural sectors. Adding compliance costs clearly dampens GDP gains in all regions. The higher the assumed costs, the stronger the downturn on real GDP. A global tax on fossil energy drives energy prices up and also dampens FWL driven GDP gains or even leads to relative losses in fossil energy producing areas. Healthy diets together with FWL are creating additional growth in the global South, while richer regions see very small impacts.

Source: MAGNET simulation results.

Following the definition of sustainable food systems that deliver health and nutrition are defined in von Braun et al. (2021), the results can be grouped accordingly. The evaluations in the overview table are not representative for all related and important food system (and SDG) objectives, instead are a selection of indicators relevant for the whole society (in bold) and others focussed on the socioeconomic situation of the agri-food sector.

Related and future JRC work

With this report, the authors intend to contribute to the debate on the transformation of the global food system in the wider bioeconomy. Further improvements to the methodology are envisaged or are already in the pipeline. This includes the update and refinement of the footprints, more detailed characterisation of the food chain with more sector splits, a new (post-Covid) baseline, additional sectoral detail in the biochemicals market, an improved treatment of waste and circularity and continued expansion of the model indicators to more fully encompass the economic, social and environmental dimensions of sustainability.

Quick guide

Chapter 1 introduces the topic, provides a short overview on the main policies and literature and motivates the approach.

Chapter 2 presents the methodological approach, the assumptions for the baseline and the scenarios.

Chapter 3 provides a short overview of the main baseline trends as calculated in the related preceding publication on transition pathways. It then focusses on various aspects of the environmental food footprints as defined in this study.

Chapter 4 focuses on the results of food waste and loss reduction, investigating, in detail, the individual and combined impacts.

Chapter 5 depicts the results of the main scenarios from an economic, social and environmental perspective.

Chapter 6 discusses the results from different perspectives in a thematic context: the global food system, planetary boundaries, and the EU food system. Furthermore it provides comprehensive refelections on the modelling approach with its strengths and limitations.

Chapter 7 concludes.

1 Introduction

The path to a more sustainable planet is long, complex and diverse. The food system, as an actor in the transition towards a sustainable circular bioeconomy (von Braun et al., 2021), plays a central role in this transformation process. The world faces an 8% undernourished population with increasing obesity in developed societies, up to 30% of greenhouse gas emissions produced by food and agriculture, around one third of food lost or wasted and accelerating biodiversity loss (EC DG RTD SCAR, 2020c). A recent report even estimates that of all the food grown, 40% is lost or wasted (WWF, 2021). From a European perspective, in the context of the Sustainable Development Goals (SDGs), the greatest challenges are related to sustainable diets and agriculture, climate and biodiversity, as well as the achievement of a convergence in living standards (SDNS and IEEP, 2020).

To this end, applied research on the food system have to overcome reductionist approaches and fully account for the connection between agriculture, trade, the natural landscape, climate change and human behaviour (Nature Food, 2020).

While the depiction of trade-offs often sets the focus of the debates, the potential synergies of policies and instruments are sometimes omitted in the analysis. In the context of the wider bioeconomy and this food system, this means creating circularity, cascading use and, more generally, creating opportunities for greater sustainability in the use of renewable biological resources from land and sea – such as crops, forests, fish, animals and micro-organisms – to produce food, materials and energy.

The study contemplates the definition of food systems, embedded in the transformation towards a sustainable circular bioeconomy, prepared by von Braun et al. (2021) for the UN Food Systems Summit 2021:

'Food systems embrace the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and disposal (loss or waste) of food products that originate from agriculture (incl. livestock), forestry, fisheries, and food industries, and the broader economic, societal, and natural environments in which they are embedded' (von Braun et al., 2021 p. 30).

Globally, the Sustainable Development Goals set the agenda for advancing towards an economically, socially and environmentally sustainable planet in 2030 and beyond. The European Union has developed a comprehensive approach, embedding its policies and strategies into the SDGs as an overall framework (Figure 1).

Figure 1. EU's whole-of-government approach towards the Sustainable Development Goals

Source: EC SWD, 2020, Delivering on the UN's Sustainable Development Goals – A comprehensive approach.

The European Green Deal (EC Green Deal, 2019) roadmaps Europe's transition to a climate-neutral economy, as 'our current levels of consumption of raw materials, energy, water, food and land use are not sustainable' (SOTEU 2020). The quote also points to the central role of the food system being an integral part of the circular and sustainable bioeconomy (EC F2F Council Conclusions, 2020). Indeed, the Green Deal provides significant challenges for the EU agriculture and food sector, with its potential to reduce GHG emissions and chemical inputs, the reduction of food losses and waste through a circular bioeconomy and a shift to diets with fewer animal products (Guyomard et al., 2020; see also EC DG RTD 2020b). Various strategies within the Green Deal highlight the objectives for a sustainable economy.

The Farm to Fork Strategy aims to accelerate the transition to a sustainable food system. It underlines the environmental and health-related unsustainability of current food consumption (EC F2F, 2020) and proposes a way forward. The F2F strategy also commits to target SDG 12.3 by halving per capita food waste at retail and consumer levels by 2030. In the circular bio-based economy, also based on the usage of waste and residues, there is untapped potential for the farming sector. The implementation of food waste and loss reduction is detailed in the Circular Economy Action Plan.

With a view to halting biodiversity loss worldwide, the Biodiversity Strategy encourages the assessment of EU and global biomass supply and demand and related sustainability, taking into account the impact of trade, for example with products' environmental footprints.

These and other policies and initiatives under the umbrella of the Green Deal, aiming at a circular, sustainable and transformative EU economy, emphasise the key role of waste and diets, together with the importance of a carbon price (EC Climate Target Plan, 2020).

The central role of diets and waste and loss reduction for the transition to a sustainable bioeconomy and food system has received a great deal of attention as of late. The recent EC report *Pathways for Action* (EC DG RTD, 2020a) summarises that 'Food system transition is strongly supported by international bodies such as the FAO, the IPCC, the IPES-FOOD, the EAT-Lancet report, the EU Scientific Advisory Mechanism (SAM) food systems report and the SAM Food from the oceans report.' Indeed, the Group of Chief Scientific Advisors of the European Commission's Scientific Advice Mechanism (EC SAM, 2020) classifies a limited number of actions as scientifically consensual to achieving a sustainable food system, among them the reduction of food waste and loss and stimulation of dietary changes towards healthier and less resource-intensive diets. Similarly, the latest SCAR foresight identified three key pathways, which are healthy and sustainable diets, circular zero-waste food systems and greater diversity within the system (EC DG RTD SCAR, 2020c). In 2021, the EC Court of Auditors (ECA, 2021) wrote 'The CAP mostly finances measures with a low potential to mitigate climate change. The CAP does not seek to limit or reduce livestock (50 % of agriculture emissions) and supports farmers who cultivate drained peatlands (20 % of emissions).'

The World Resources Report *Creating a Sustainable Food Future* (Searchinger et al. 2018) illustrates that the shift in diets mainly reduces GHG emissions, whilst only partly supporting the objective of increasing food production. The report further shows the importance of reducing food loss and waste for both goals, SDG2 and SDG13. In a comparative model exercise, Leclere et al. (2020) demonstrate how more than two thirds of future biodiversity losses can be avoided by extending sustainable intensification and trade, reducing food waste and fostering more plant-based human diets. A further necessity to investigate the impacts of the diet scenarios arises from its links to the recent COVID crisis. The increasing demand for animal protein (followed by unsustainable agricultural intensification) is seen as the first of seven major anthropogenic drivers of zoonotic disease emergence (UNEP, 2020).

Recently, the critical role of cutting methane emissions to reduce the pace of climate change has been highlighted (United Nations Environment Programme and Climate and Clean Air Coalition, 2021; Ocko et al., 2021). Agriculture, in particular livestock and rice production, and waste contribute 40% and 20%, respectively, to anthropogenic methane emissions (United Nations Environment Programme and Climate and Clean Air Coalition, 2021). The report provides evidence that 'Three behavioural changes, reducing food waste and loss, improving livestock management, and the adoption of healthy diets (vegetarian or with a lower meat and dairy content) could reduce methane emissions by 65–80 Mt/yr over the next few decades.' (United Nations Environment Programme and Climate and Clean Air Coalition, 2021). The JRC report *Foresight Scenarios for the EU bioeconomy in 2050* emphasises the importance of both supply-side policies and demand-side societal action, as well as policy coherence between sectors and actors (Fritsche et al., 2021).

Policy has responded to the scientific evidence. However, the strategies and initiatives, while united under a common framework, by default incorporate trade-offs and potential synergies between the high-priority environmental (incl. climate change) goals and the two other sustainability dimensions of economy and society.

For instance, the environmental ambition in the F2F and BD strategies, also mirrored in the bioeconomy strategy objective of 'managing natural resources sustainably', would translate into a strong reduction in resource usage in agriculture. The EC JRC (Barreiro Hurle et al., 2021) study shows significant environmental benefits, mainly reductions in greenhouse gases, ammonia emissions, and gross nutrient surplus. While the results of this study (Barreiro Hurle et al., 2021) show a decline in EU production and variations in prices and income for selected agricultural products, the full extent in terms of positive environmental and economic benefits is not fully quantified.

A further, emerging criticism is the potential 'outsourcing' of the EU's environmental damage to other countries (Nature, 2020) through negative spillovers (SDNS and IEEP, 2020). This question of 'leakage' is nonetheless also contemplated in the above cited EC strategies.

Implementing a bundle of policies or measures related to waste reduction and diets could, however, create a triple win in the form of more efficiency, more healthy people and fewer environmental impacts, thus counteracting the potential leakage due to more sustainable food production (not analysed in this study). Therefore, this study investigates the impacts of food loss and waste and diets in a global, comprehensive and quantitative modelling context.

The methodological approach chosen to investigate the questions follows the overall principle of a comprehensive and policy-coherent approach as outlined in the European Green Deal (EC Green Deal 2019) and EC Staff Working Document 'Delivering on UN's SDGs' (EC SWD, 2020), taking into account the interdependency of global challenges (Aguilar, 2020). According to a recent Nature article, comprehensive economic analysis of the different proposed strategies and actions is lacking in food systems transformation literature (Fan, 2021).

In line with the EC Strategic Foresight Report (2020) and the EC Better Regulation Toolbox (2021), this study employs an economy-wide computable general equilibrium (CGE) simulation model called MAGNET. With its global coverage, the MAGNET model explicitly internalises resource limits within a closed system of economic activities and trade. As a result, it is well placed to examine and explain both the market synergies and trade-offs that arise from fragmented policies as well as understand the key drivers that motivate market trends. Further developments in providing a series of SDG and virtual trade indicators further enhance the model's credentials for analysing social and environmental dimensions. It is also worth noting that the MAGNET model has been recognised as a best practise approach in the analysis of the SDGs (M'barek and Philippidis, 2020) and transboundary impacts and spillover effects (OECD/EC-JRC, 2021).

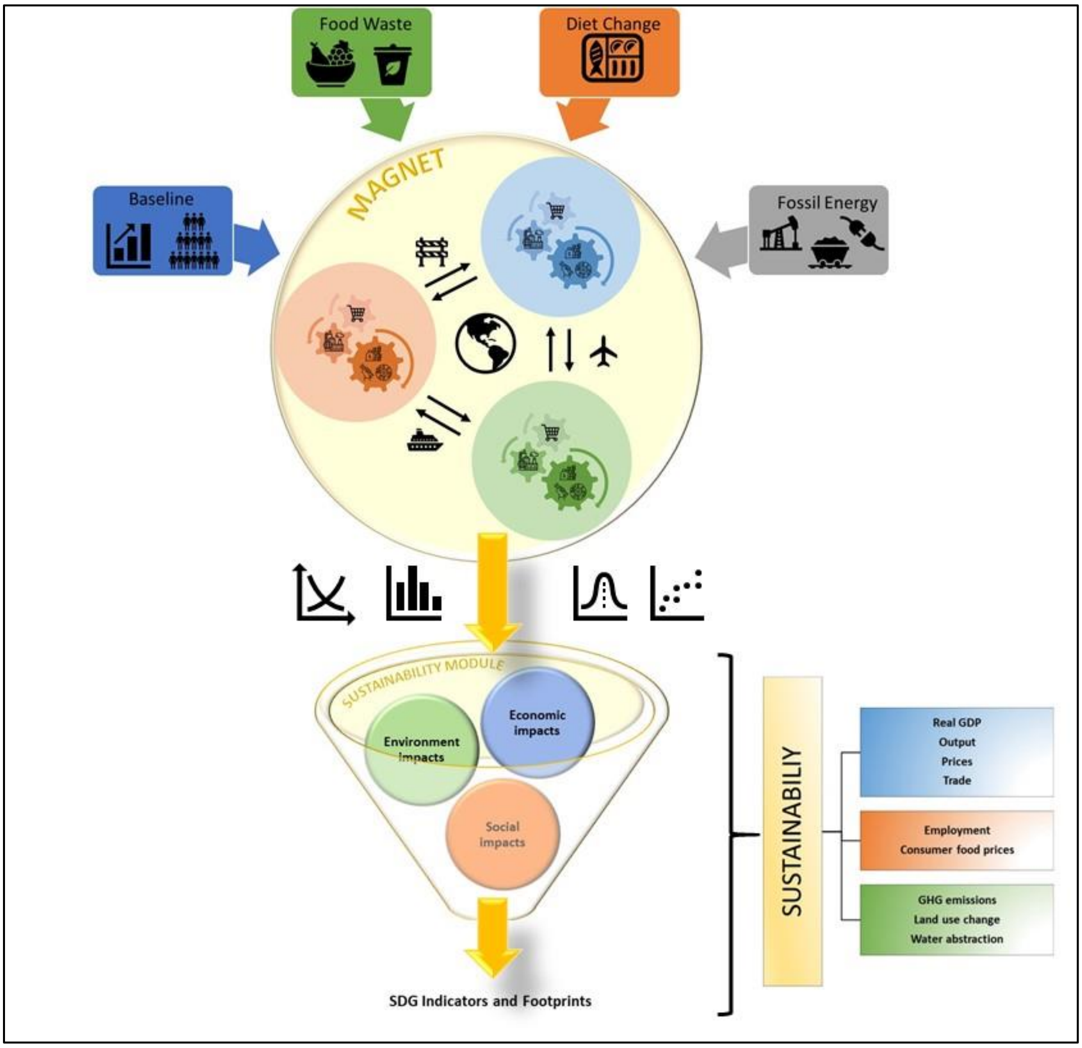
Figure 2 shows the concept of modelling approach with its tri-dimensional sustainability assessment.

The scenario design is inspired by, and builds upon, the report *Alternative Global Transition Pathways to 2050: Prospects for the Bioeconomy* (M'barek et al., 2019). This study provided a number of scenarios following the European Commission's Global Energy and Climate Outlook to 2050 to portray the central elements of the EU's vision for a prosperous, modern, competitive and climate neutral economy. For the current study, the reference scenario in M'barek et al. (2019) is used as a point of departure, further enriched with a comprehensive analysis of the EU's food system based on a recently published research paper on diet scenarios and footprints (Philippidis et al., 2021).

The main scenarios and related sensitivity analysis stem from the fact that any given policy measure and instrument has impacts on all sustainability dimensions, but it cannot tackle all three dimensions at the same time, as there are trade-offs (and synergies). Depicting the results through a wide range of indicators, the report addresses, in particular, the questions below related to the scenarios of food waste and loss reduction, healthier diets and sensitivity analysis regarding costs and oil price.

- How are food security and food prices impacted?
- What is the anticipated impact for the primary agricultural sector?
- To what extent can changes to both food supply chain efficiency and food demand behaviour impact upon virtual trade flows and associated leakage effects?
- To what extent can food demand and supply side efficiencies alleviate bottlenecks for biomass demand under the conditions of higher oil prices?
- Are food waste and loss reductions complementary measures?
- Can the scenarios provide stimulus to the bio-based industry while preserving the environment?
- From a holistic point of view, which synergies and trade-offs can be identified in the scenarios in the context of the three dimensions of sustainability (SDGs, footprints)?

Figure 2. Overview of modelling approach



Source: Authors' elaboration.

The report is structured as follows. After this introduction, Chapter 2 presents the methodological approach, the assumptions for the baseline and the scenarios. Chapter 3 provides a short overview of the main baseline trends as calculated in the related preceding publication on transition pathways. It then focusses on various aspects of the environmental food footprints as defined in this study. Chapter 4 focuses on the results of food waste and loss reduction, investigating, in detail, the individual and combined impacts. Chapter 5 depicts the results of the main scenarios from an economic, social and environmental perspective. Chapter 6 discusses the results from different perspectives in a thematic context: the global food system, planetary boundaries, and the EU food system. Furthermore it provides comprehensive refelections on the modelling approach with its strengths and limitations. Chapter 7 concludes.

2 Methodology

2.1 Database and model

The database employed for this study is version nine of the Global Trade Analysis Project (GTAP) database, with a benchmark year of 2011 and complete with 57 tradable sectors, five primary factors and 140 regions (Aguiar et al., 2016). The GTAP data not only includes information on the input-output structures of each of its 140 economies – including intermediate input purchases and final demands by private households, government and investors – but also records gross bilateral trade flows between trade partners. All transactions within the database are measured at basic, producer and purchaser prices with relevant tax/subsidy distortions and international transport margin data.

Through a large system of simultaneous equations, the accompanying computable general equilibrium (CGE) GTAP comparative static simulation model (Corong et al., 2017) enforces the underlying equilibrium accounting conditions imposed by the database. This is, namely, that supply and demand are cleared in all product and primary factor markets, that productive activities operate under zero economic long-run profits and that the value of macroeconomic output, expenditure and income are all equal.

As is typical to this class of neoclassical CGE trade model, the behaviour of agents (i.e. consumers, producers, investors) rests upon rational neoclassical optimisation assumptions (i.e. cost minimisation, utility maximisation), where linear homogeneous convenient functions combined with multi-stage budgeting permits parsimonious, yet flexible, treatment of production technologies through multiple level 'nesting' structures. The savings rates in each economy are assumed as a constant share of national income and global investment is allocated across regions following one of two investment rules (fixed shares or rates of return). To ensure a 'closed' macroeconomic system, the sum of the current and capital accounts (balance of payments) for each region nets zero.

In the standard single period 'comparative static' format, the user imposes changes or 'shocks' to a selection of typically exogenous variables (i.e. real GDP, population, primary endowments, taxes/subsidies, technology change) and the simulation model solves for a new matrix of prices and quantities that satisfy all market clearing and accounting conventions at the new equilibrium point.

The Modular Applied GeNeral Equilibrium Tool (MAGNET) (Woltjer and Kuiper, 2014) model employs the GTAP model and data structure at its core. MAGNET has an established pedigree in a number of high-profile foresight studies for international and intergovernmental organisations (M'barek et al., 2017; Kuiper et al., 2018; OECD, 2019a). The key strength of the MAGNET model is that it grants relatively straightforward access to non-standard state-of-the-art modelling extensions through a series of binary switches coupled to a Windows-based operating platform[1]. A number of relevant specialist MAGNET modules are employed for the current study on food loss, waste and diets.

Firstly, given the medium-to-long-term time horizon employed in this study, a recursive dynamic (vis-à-vis a comparative static) extension is required. The time pathway is broken into smaller discrete steps to characterise structural economic change and gradual capital accumulation, where end-of-period equilibrium solutions form the starting point for the follow period.

On the production side, agricultural factor market rigidities are explicitly characterised (i.e. imperfect agricultural land transfer between agricultural activities, imperfect capital and labour transfer to/from agriculture), whilst an endogenous land supply follows a calibrated asymptotic functional form to capture regional differences in the relative scarcity of this finite resource. The MAGNET model also benefits from a number of in-house activity splits from their parent sector classifications in the GTAP database. The explicit representation of various fertiliser and feed activities – as well as a new primary irrigation water factor, complete with separate irrigated and rainfed cropping activities[2] – greatly enhance the characterisation of crop and livestock technology nests. Additional sources (e.g. lignocellulosic biomass, woody biomass, waste) and uses (e.g. liquid and solid biofuels, bioindustry, feed by-products) of biologically renewable resources improve the treatment of competition for finite land resources and biomass for different purposes within the bioeconomy (food, feed, energy, industrial). As a result, there is a more comprehensive representation of the competitive pressures facing the agro-food system.

[1] For the interested reader, full documentation of the model and its extensions can be found at https://www.magnet-model.org/.

[2] Haqiqi et al. (2016).

On the demand side, iterative period-by-period recalibrations of the income elasticities within semi-flexible household food consumption functions help to moderate food purchases in regions with rapid increases in real per capita GDP growth. In this way, the relationship posited in Engel's Law is respected (i.e. income elasticities for food demand reduce at higher per capita income), whilst satisfying the theoretical adding up conditions in the demand function. A further key insight offered by MAGNET is the availability of a specialist nutrition module (Rutten et al., 2013). Satellite data on FAO nutritive factors are integrated into the model's demand system to calculate and trace annual and daily average nutrient intake within final food consumption.

2.2 Virtual trade flows and footprints – methodology and data

One methodological advance for this study is the measurement of the global sustainability impacts arising from changes in food demand patterns through the calculation of virtual trade flows and associated tier three (i.e. farm-to-fork) food demand footprints. Given its model structure, CGE models fully internalise the structure of the interdependencies between competing sectors, not only in terms of their demand for scarce factors of production (capital, labour, land), but also by fully tracking the sales destinations of productive activities, as inputs to other production processes or as finished products to consumers, both in domestic and foreign markets. For this reason, the input-output relations which are embedded within the CGE framework serve as an ideal platform upon which to calculate and track the full impacts of food demands and their subsequent implications on the corresponding quantities of hidden or 'virtual' flows of non-tradable physical resources (e.g. land, emissions, water) that track each of these transactions.

To compute the intensities of virtual commodities, global satellite data is required at the required level of sectoral and regional concordance within the MAGNET database. Thus, for agricultural land areas, data for the benchmark year (2011) are taken from the FAO statistical division (2020). Agricultural land areas include cultivated cropland covering arable land areas and permanent crops, as well as permanent pasturelands (meadows and pastures) used by ruminants. The greenhouse gas emissions data is taken from the GTAP centre (Aguiar et al., 2016). The data includes estimates of CO_2 emissions from combustion activities (GTAP version 9), which are based on the energy volumes for each GTAP sector and region. In addition, non-CO_2 gases (methane, nitrous oxide and fourteen fluorinated gases (F-gases) are also recorded (Irfanoglou and van der Mensbrugghe, 2015), employing data for 2010 from EDGAR 4.2 (2011)[3] for non-agricultural activities and FAOSTAT (2014) for agricultural activities. Thus, combined, the data covers four categories of emissions gases mapped to individual sectors as combustion activities or process emissions and final demand-driven emissions. Global abstracted irrigated crop water usage is based on the work of Haqiqi et al. (2016). The authors combine the GTAP database for cropland usage in 2000 (Lee et al., 2005) with high spatial resolution data on irrigated and rain-fed cropland areas (Portmann et al., 2010). Combined with irrigated water requirements data for 29 crop activities (Siebert and Döll, 2010) and scaling to the total water withdrawal estimates in 2011 from AQUASTAT[4], they generate water abstraction totals by crop type consistent with the standard GTAP crop classifications.

2.3 Model aggregation, assumptions

For the study, the choice of activities and regions is shown in Table 1. With a focus on agri-food activities, the study takes full advantage of the available crop, livestock and fish commodity coverage in MAGNET. As noted above, fertiliser and feed commodities are chosen to improve the technology nests for cropping and livestock activities, whilst additional sources of biomass supply and usage are also included. With changes in energy usage and emissions forming a key part of any medium-to-long-run simulation narrative, additional (non-biological) renewable and fossil energy sources are also included to allow for detailed assumptions regarding projected changes in the energy markets. Any remaining manufacturing activities act as 'blenders' of semi-finished bio-based products with rival fossil-based equivalents in the production of material and energy outputs for final uses.

To avoid the high computational burden arising from large-scale sector and regional aggregation global studies, the choice of regions is carefully limited whilst also representative of the major continents and players on world food and energy markets.

[3] https://edgar.jrc.ec.europa.eu/.
[4] http://www.fao.org/aquastat/en/.

Table 1. Disaggregation of commodities and regions

<u>Commodity disaggregation (70 commodities)</u>

Arable and horticulture (15)

Rainfed paddy rice (pdr); rainfed wheat (wht); rainfed other grains (grain); rainfed oilseeds (oilsd); rainfed raw sugar (sug); rainfed vegetables, fruits and nuts (hort); rainfed other crops (crops); irrigated paddy rice (pdri); irrigated wheat (whti); irrigated other grains (graini); irrigated oilseeds (oilsdi); irrigated raw sugar (sugi); irrigated vegetables, fruits and nuts (horti); irrigated other crops (cropsi); crude vegetable oil (cvol).

Livestock, meat and fish (7)

Cattle and sheep (cattle); pigs and poultry (pigpoul); raw milk (milk); cattle meat (meat); other meat (omeat); dairy (dairy); processed fish products (fishp).

Fertiliser (1)

Fertiliser (fert).

Other food and beverages (4)

Sugar processing (sugar); vegetable oils and fats (vol); processed rice (pcr); other food and beverages (ofdbv).

Other 'traditional' bio-based activities (5)

Fishing (fish); forestry (frs); wood products (woodpro); paper products (paperpro); textiles & clothing (textcloth).

Biomass supply (11)

Energy crops (energy); residue processing (res); pellets (pel); by-product residues from rice (r_pdr); by-product residues from wheat (r_wht); by-product residues from other grains (r_grain); by-product residues from oilseeds (r_oilsd); by-product residues from horticulture (r_hort); by-product residues from other crops (r_crops); by-product residues from forestry (r_frs); municipal waste (waste).

Bio-based liquid energy (5)

1st generation biodiesel (biod); 1st generation bioethanol (biog); 2nd generation thermochemical technology biofuel (ft_fuel); 2nd generation biochemical technology biofuel (eth); bio-kerosene (bkero).

Bio-based and non-bio-based animal feeds (3)

1st generation bioethanol by-product distillers dried grains and solubles (ddgs); crude vegetable oil by-product oilcake (oilcake); animal feed (feed).

Renewable electricity generation (3)

Bioelectricity (bioe); hydroelectric (ely_h); solar and wind (ely_w).

Fossil fuels and other energy markets (10)

Crude oil (c_oil); petroleum (petro); gas (gas); gas distribution (gas_dist); coal (coa); coal-fired electricity (ely_c); gas-fired electricity (ely_g); nuclear electricity (ely_n); electricity distribution (ely); kerosene (kero).

Other sectors (6)

Chemicals, rubbers and plastics (crp); other manufacturing (manu); aviation (avi); other transport (trans); food services (foodsvcs); services (svcs).

<u>Regional disaggregation (13 regions)</u>

USA and Canada (North America); 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).

Source: Authors' elaboration.

2.4 Baseline

The baseline or 'business as usual' (BAU) of this simulation study takes a time path from 2011 to 2050, split into five discrete time intervals (see Tables below). To motivate the market projections, a series of drivers are shocked, largely following in-house projections taken from the European Commission's Global Energy and Climate Outlook (GECO) reference scenario (Keramidas et al., 2018; Weitzel et al., 2019)[5]. Thus, GECO provides a source for changes in real GDP, population and fossil fuel prices (see Table 2, Table 3, Table 4).

Table 2. Assumed real GDP projections to 2050

	GDP ($ billion)	Real GDP growth rates (%)				
	2011	2011-2015	2015-2020	2020-2030	2030-2040	2040-2050
USA & Canada	17 298	9.4	1.9	18.7	21.8	17.9
Brazil	2 475	4.2	5.0	26.5	28.1	25.0
Latin America	3 456	13.2	15.4	41.3	40.4	36.4
North Africa	605	18.6	21.1	69.9	54.8	41.0
Sub-Sah. Africa	1 450	21.8	24.5	73.1	74.2	68.6
EU	17 643	5.7	6.8	14.3	13.9	15.6
Rest of Europe	2 652	16.1	17.8	36.5	29.9	22.0
Russia	1 866	6.1	7.0	13.4	19.3	5.1
Middle East	2 585	15.6	17.9	41.9	35.4	25.8
India	1 873	34.7	35.4	100.9	65.2	50.8
China	7 306	36.1	34.7	60.0	38.9	24.9
Rest of Asia	10 483	11.3	12.8	27.3	25.9	22.5
Oceania	1 599	12.3	14.5	31.6	31.7	27.1

Source: Keramidas et al. (2018).

Table 3. Assumed population projections to 2050

	Population millions	Population change (%)				
		2011-2015	2015-2020	2020-2030	2030-2040	2040-2050
USA & Canada	346.1	2.9	11.2	6.9	5.7	4.7
Brazil	196.9	3.5	5.1	5.9	3.1	1.0
Latin America	404.9	4.8	15.4	8.8	6.0	3.6
North Africa	166.5	7.3	21.3	11.8	8.8	6.5
Sub-Sah. Africa	878.8	11.7	24.7	24.6	20.4	16.1
EU	507.8	1.0	6.9	1.6	0.8	-0.0
Rest of Europe	243.1	3.3	17.8	4.3	2.4	1.3
Russia	143.0	0.2	7.3	-2.0	-2.5	-1.2
Middle East	220.7	6.7	18.1	14.1	10.8	8.1
India	1 221.2	5.0	35.2	9.6	6.5	3.9
China	1 344.1	1.8	34.4	0.4	-3.1	-5.3
Rest of Asia	1 245.2	4.6	12.8	8.4	5.5	3.2
Oceania	36.8	5.8	14.5	11.3	9.1	7.5

Source: Keramidas et al. (2018).

Table 4. Fossil fuel prices between 2011 and 2050 ($ per barrel of oil equivalent, 2015 prices)

Fuel type	2011	2015	2020	2030	2040	2050
Coal	24.2	24.3	24.5	27.3	31.2	33.6
Crude oil	86.9	88.8	91.2	89.1	96.2	106.6
Gas	38.8	44.6	51.8	61.0	71.8	77.9

Source: Keramidas et al. (2018).

[5] Full details are available online from Keramidas et al., (2018). The supplementary information document also provides further discussion.

A summary overview of the key market drivers within the baseline is provided in Table 5.

Table 5. A summary of the exogenous drivers in the baseline

Exogenous driver	Details
(i) Region-wide productivity	Region-wide productivity calibrated to regional real GDP rates (Keramidas et al., 2018).
(ii) Capital stock	Changes at the same percentage rate as real GDP (fixed capital-output ratio).
(iii) Labour force	Changes at the same percentage rate as regional population (fixed long-run employment rate).
(iv) Population	Exogenous rates of population change (Keramidas et al., 2018)
(v) Carbon tax	Global increases in carbon tax ($/tonne) by time period on all activities (Weitzel et al., 2019).
(vi) Energy input shifters	Calibrated input-output technology shifters to mimic energy balance trends by energy type and usage (Keramidas et al., 2018).
(vii) Land productivity	Exogenous land productivity shocks from Shared Socioeconomic Pathway Two, 'Middle of the Road' (SSP2).
(viii) Energy final demands	Exogenous final energy demand taste shifters to mimic pathway trends (Keramidas et al., 2018).
(ix) Global fossil fuel price	Exogenous changes in fossil fuel prices (Keramidas et al., 2018).
(x) Biofuel mandates	Exogenous mandates on first-generation and advanced-generation biofuels by region.

Source: Authors' elaboration.

A further refinement to the baseline was the recreation of a plausible food demand pathway consistent with the BAU narrative. On running the BAU, it became apparent that daily per capita kilocalorie (kcal/pc/day) intake greatly exceeded reasonable expectations (even when considering food waste rates). For example, examining FAO (2020) time series data between 1961-2017, the peak kcal/pc/day intake in the EU and North America was 3 448 kcal/pc/day in 2017 and 3 793 kcal/pc/day in 2005, respectively. Thus, a series of BAU runs experimenting with downward shifters on the income elasticities was performed to ensure the model outcomes remained as close as possible to these peak values. In rapidly growing regions, income elasticity shifters were also implemented to ensure the same rates of catch-up in nutritive intake observed in the initial baseline experiment.

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.

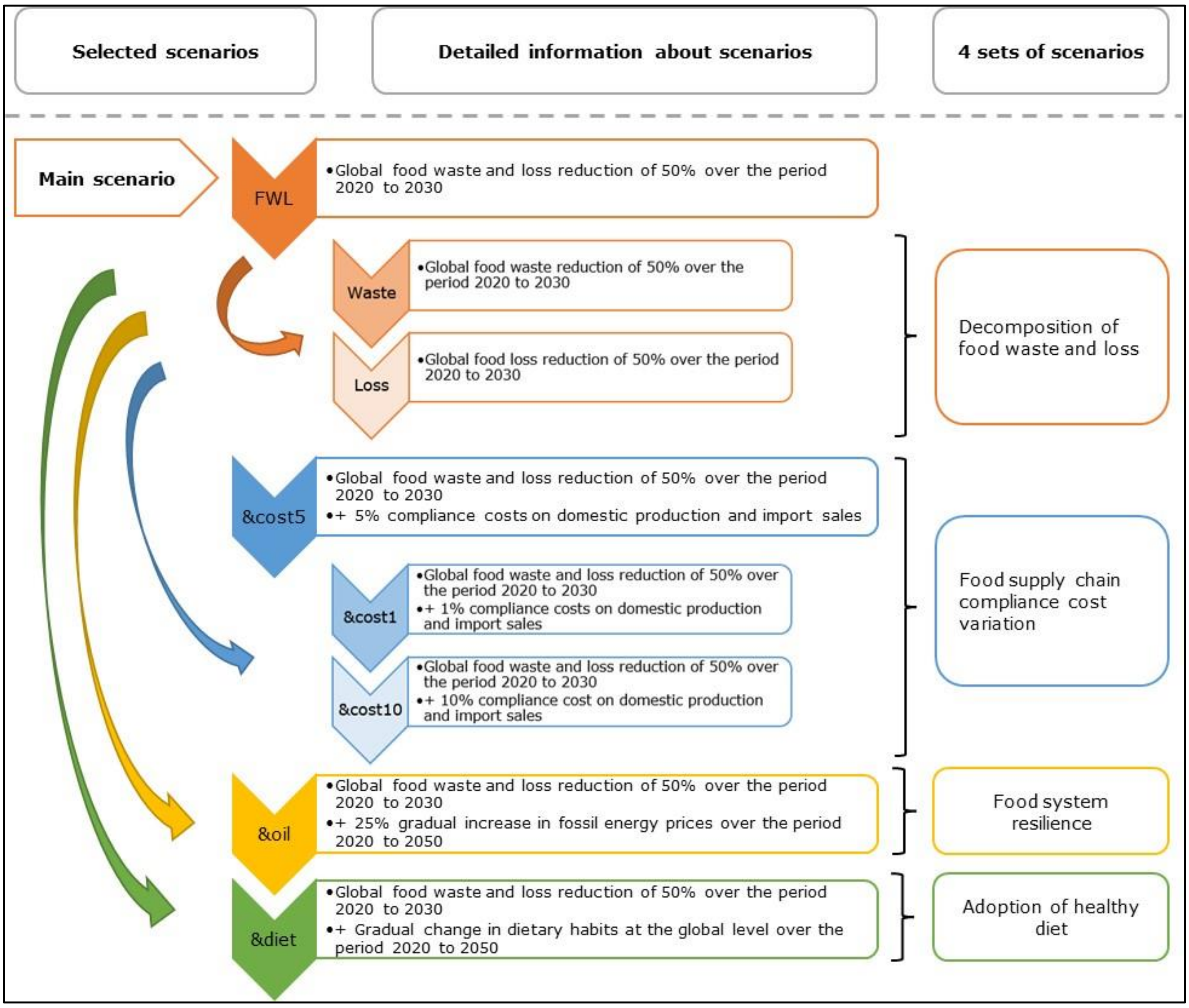
2.5 Scenario design

This study aims at assessing the impact of behavioural changes with regard to food consumption with a focus on food waste and loss (FWL). Therefore, the main scenario of this study is the scenario FWL that simulates a global reduction of food waste and loss by 50% over the period 2020 to 2030. Using this scenario as starting point, this study conducts four sets of scenarios as outlined in Figure 3. The first set 'Decomposition of food waste and loss' consists in addition to FWL of one scenario that reduces only food waste at consumer and retail level by 50% over the same period (Waste) and another scenario that reduces only food loss by 50% at the remaining stages of the supply chain (Loss). As of yet, no estimates are available at global level to account for the impact of the cost attributed to the reduction of food waste and loss. To account for this, the second set of scenarios 'Food supply chain compliance cost variation' including scenario FWL plus scenarios &cost5, &cost1, &cost10 investigates the impact of different assumptions with regard to the cost associated with reducing food waste and loss (details in Section 2.5.1).

The other two sets of scenarios provide further insights regarding changing market conditions.

One objective of this study is to analyse the impact of food waste and loss reductions on the sustainability of the food system. The third set 'Food system resilience' assumes that reducing food waste and loss generates increased agri-food availability at lower prices which would result in increased demand for agri-food products for non-food uses. To investigate the impact of this expectation on sustainability, the scenario &oil explores the impact of higher fossil energy prices.

Figure 3. Scenario overview



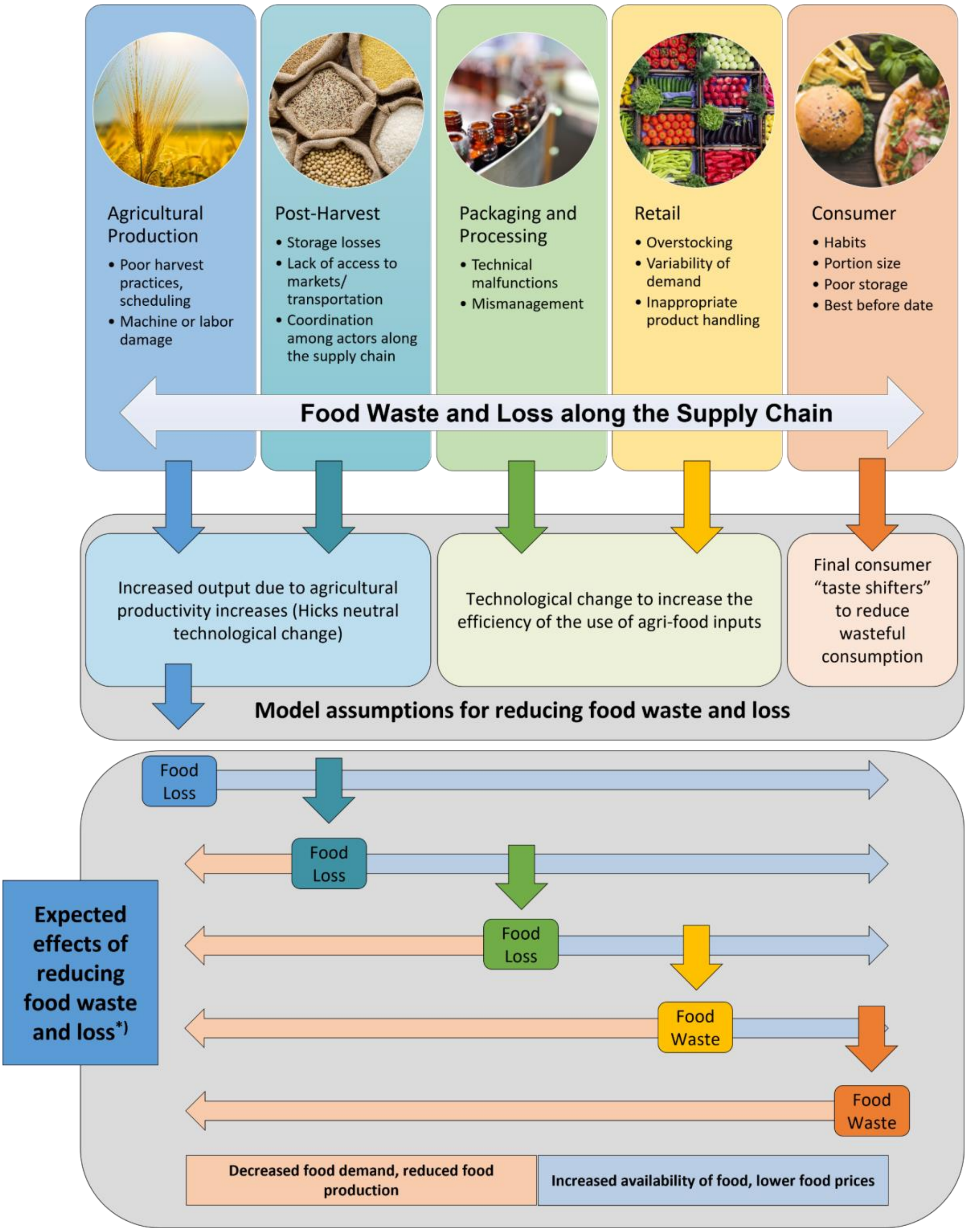
Source: Authors' elaboration.

In line with ongoing discussions on necessary consumer behaviour changes (food waste, meat and dairy consumption, etc.) to increase sustainability, the fourth set of scenarios 'Adoption of healthy diet' aims to shed some light on the potential contribution of these two elements of consumption and, in particular, assess where they amplify or enhance one another and where they alleviate their contributions. Therefore, in the scenario &diet we introduce a dietary transformation over the period 2030 to 2050 based on the EAT-Lancet report (Willet et al., 2019) (details in Section 4.7.2). To facilitate the comparison of the diet scenario and FWL scenarios, the share of red meat, white meat and dairy consumption is kept constant in the baseline and all FWL scenarios.

2.5.1 Food waste and loss scenarios

In this study we aim to assess the impact/contribution of food waste and loss reduction on/to the three dimensions of sustainability. FAO (2011) provides estimates along five steps of the supply chain – from food loss (i.e., agricultural production, post-harvest, processing and packaging) to food waste (retail and consumer) – for seven commodity groups and seven aggregated regions (Figure 4).

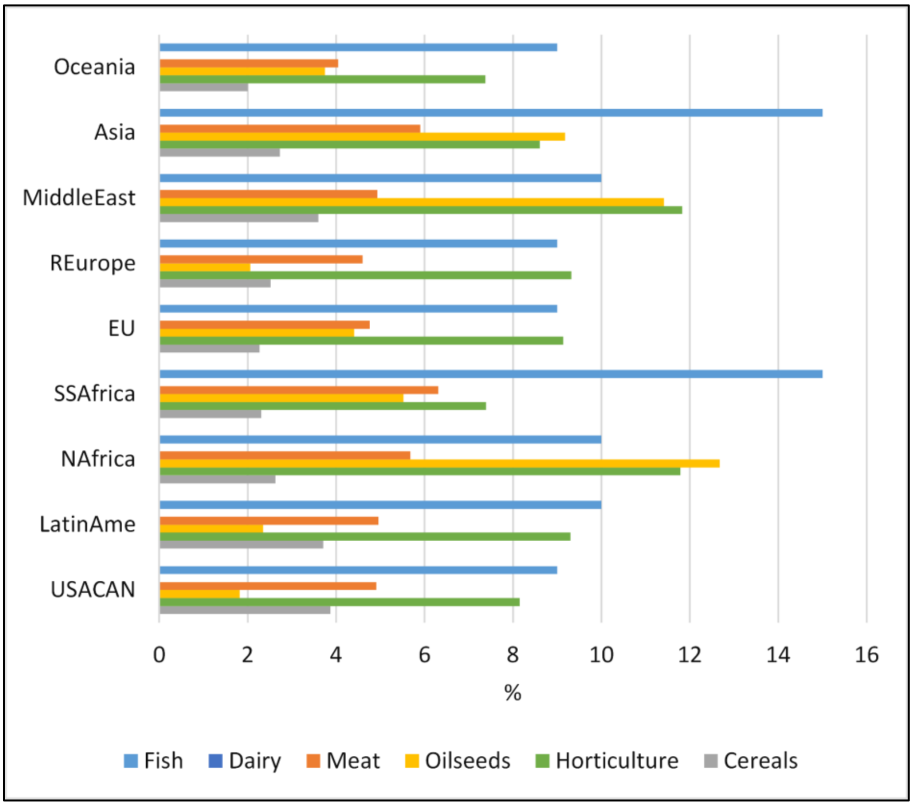
Figure 4. Overview modelling approach of reducing food waste and loss along the supply chain



Source: Authors' elaboration, FAO 2019.
Note: *) Expected effects of reducing food waste and loss along the supply chain are based on the FAO 2019 (FAO report 2019 http://www.fao.org/3/ca6030en/ca6030en.pdf#page=105)

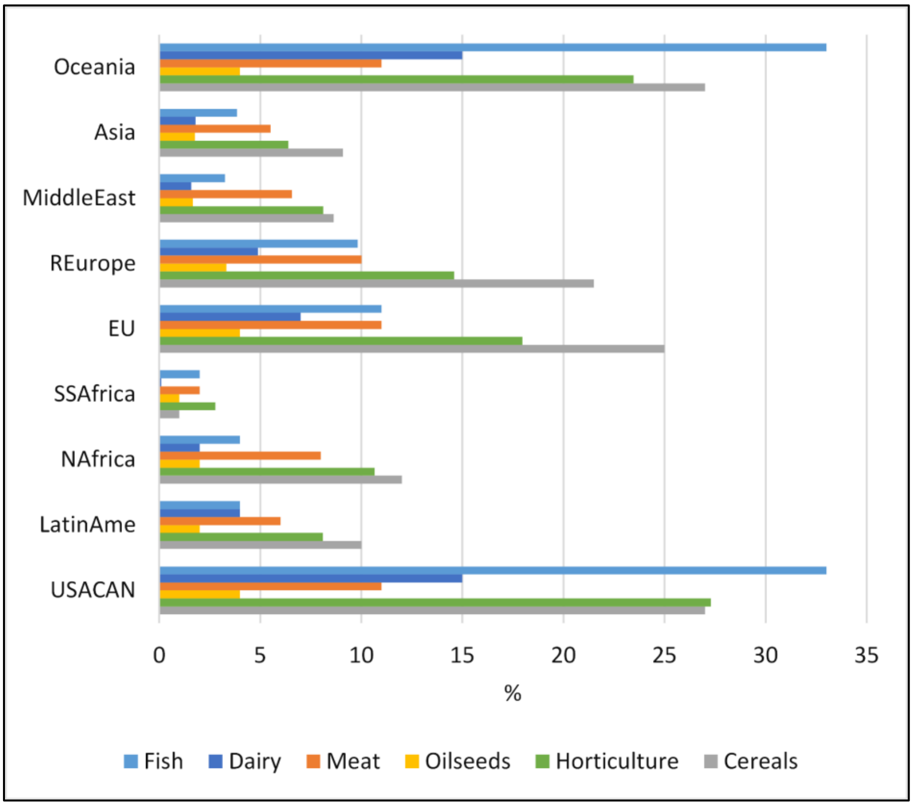
In addition, this figure shows how reducing food waste and loss at the five steps of the supply chain are implemented in the model and lastly also gives an overview of the expected impact of reducing food waste and loss on food production, food demand as well as prices.

Figure 5. Consumer food waste rates (%) according to MAGNET country aggregation and sectors



Source: Own computation based on data from FAO 2011, FAOSTAT 2020, GTAP database (Aguiar et al. 2016).

Figure 6. Food waste rates (%) at retail level according to MAGNET country aggregation and sectors



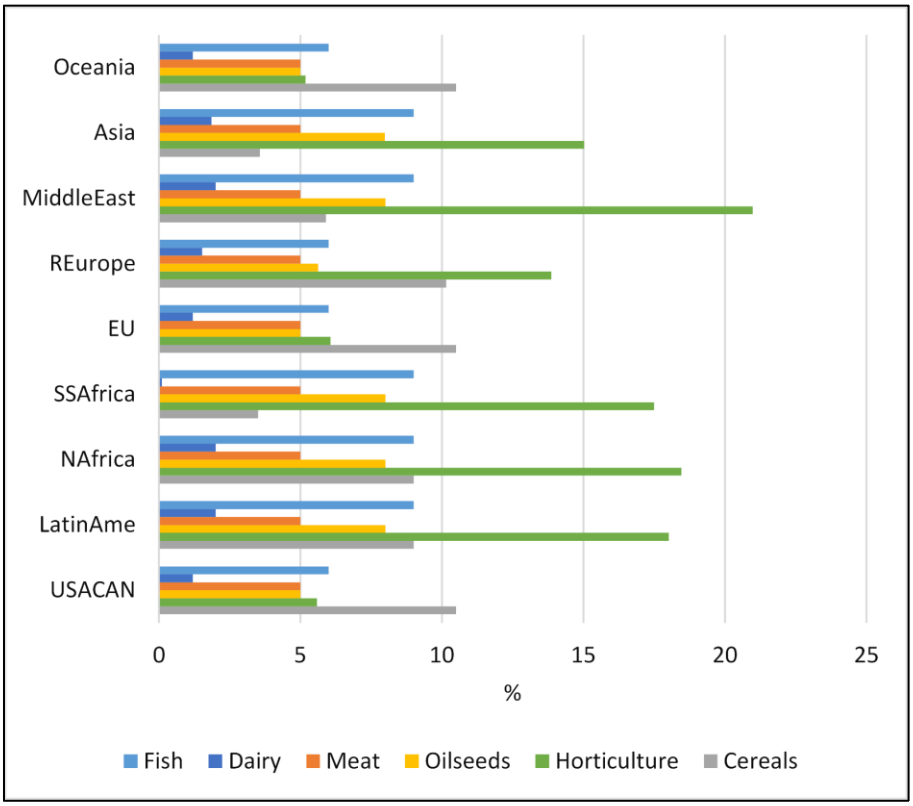
Source: Own computation based on data from FAO 2011, FAOSTAT 2020, GTAP database (Aguiar et al. 2016).

Utilising this information, we calculated the agricultural and food production weighted food loss and waste rates for the chosen aggregation in this approach. This is particularly important for the aggregated fruit and vegetable sector in the MAGNET model and underlying GTAP database that includes fruits, vegetables, roots and tubers as well as nuts. This aggregation differs considerably from the FAO food groups, providing information on oilseeds and nuts, roots and tubers as well as fruits and vegetables separately. Food waste shares according to MAGNET commodity and regional aggregation are presented in Figure 5 and Figure 6, whereas the food loss shares according to MAGNET commodity and regional aggregation are presented in Figure 7 to Figure 9.

The novelty of this study is looking at food loss and food waste reductions at the same time and, therefore, accounting for gains and losses on both sides and how the changes interact with one another considering food waste and loss reductions at the global level.

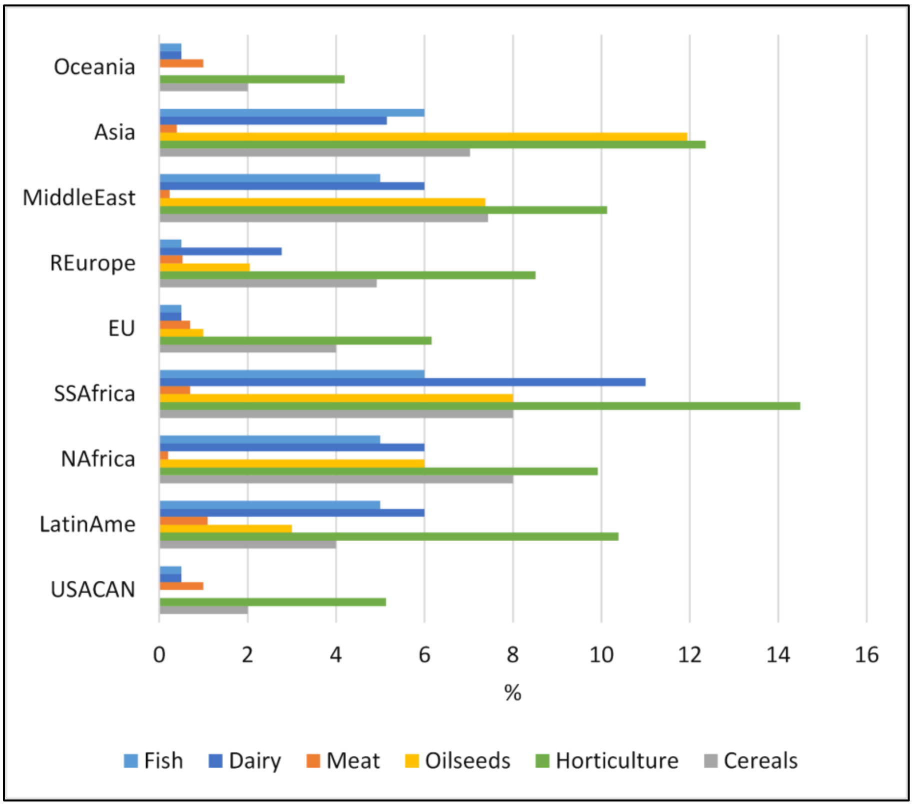
The modelling of food waste reductions by commodity category is performed using household budget share shifters that adjust endogenously to meet targeted household consumption reductions, as applied by Philippidis et al. (2019), to assess the impact of food waste in the European Union. This approach considers food waste as a reduction in the quantity of food resulting from decisions and actions of food services and consumers. Reducing food waste for consumers corresponds to less expenditure on food commodities and for food retailers as lower food input demand for the food service sector depicted by an increases in food input efficiency in the food service sector. This depiction of food waste reductions is therefore guided by an altruistic sense of moral suasion on the part of food consumers.

Figure 7. Food loss rates (%) at processing and packaging level according to MAGNET country aggregation and sectors



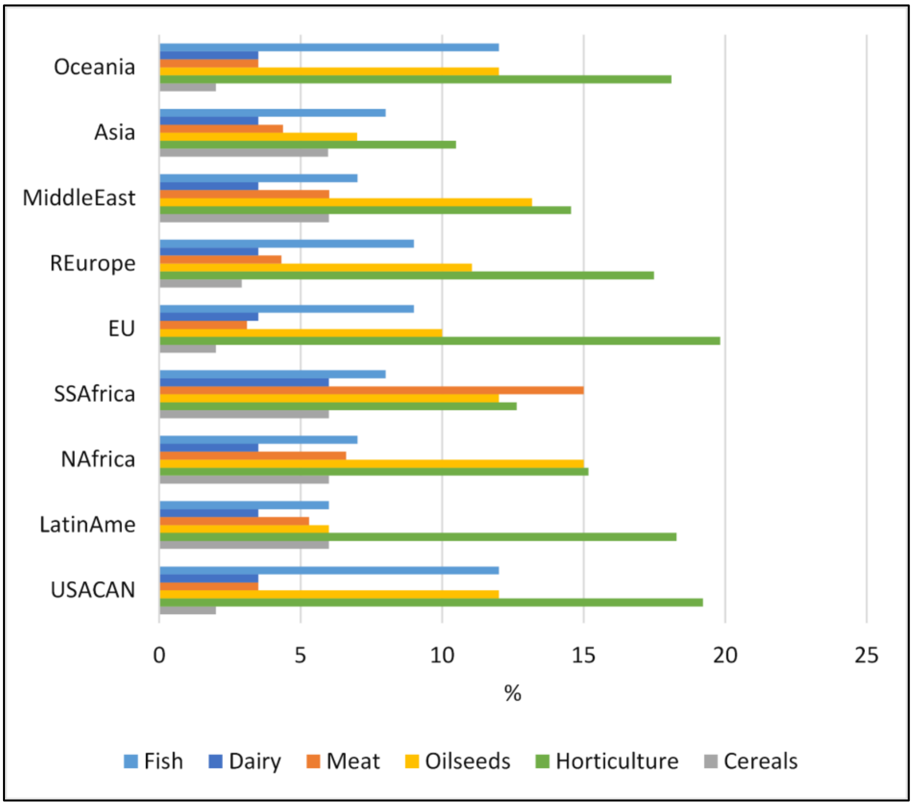
Source: Own computation based on data from FAO 2011, FAOSTAT 2020, GTAP database (Aguiar et al. 2016).

Figure 8. Post-harvest loss rates (%) according to MAGNET country aggregation and sectors



Source: Own computation based on data from FAO 2011, FAOSTAT 2020, GTAP database (Aguiar et al. 2016).

Figure 9. Agricultural production losses according to MAGNET country aggregation and sectors



Source: Own computation based on data from FAO 2011, FAOSTAT 2020, GTAP database (Aguiar et al. 2016).

Following Kuiper and Cu (2020), we consider food loss as a reduction in the quantity of food resulting from decisions and actions by food producers in the supply chain. Hence, we assume that reducing food loss related to agricultural production losses and post-harvest losses leads to an increase in the output productivity of the agricultural sector, whereas reducing food loss related to processing and packaging leads to an increase in the efficiency of input use imposed as an input-saving productivity shock.

In the absence of estimated costs for food waste and loss reductions, Kuiper and Cui (2020) assume that efficiency gains to reduce food loss incur a zero cost, while Philippidis et al. (2019) apply an ad-hoc approach imposing rough assumptions equal to 1%, 5% or 10% of the value of production, respectively.

In our scenarios presented in Figure 3, we assume that all regions across the globe meet the SDG 12.3 target and reduce food waste and loss by 50% in 2030; in the scenario we assume that food waste and loss reductions are cost neutral. To quantify the impact of either food waste or food loss reductions we run the simulations separately. To the best of our knowledge, there are no empirical estimates on the magnitude of these costs; however, the evidence clearly suggests that food waste and loss reductions are not costless. To overcome this problem, we follow Philippidis et al. (2019) for the sake of comparability and validation of the results and run a sensitivity analysis assessing the impact of different cost assumptions on the results. In particular, we assume that the cost arises on the supply side due to, for example, modification of production as well as packaging processes, investments in improved storage facilities or the mode of transportation. This is based on the hypothesis that the compliance cost per unit of sales could trigger the necessary behavioural changes in food consumption and food production. Our sensitivity analysis of the compliance cost considers incremental rises equivalent to 1%, 5% and 10% of the value of the sales flows in each country or region and of each agricultural and food commodity. By implementing these determined costs into the cost function, the per unit cost of service inputs increase for each relevant agricultural and food commodity.

2.5.2 Diet scenario

This scenario aims to assess other changes of consumer behaviour such as dietary changes at the global level in addition to food waste and loss reductions Questions such as what a healthy diet is and how a transition to a healthy and sustainable diet across the globe can look like arise from this objective.

Related to the first question, Herforth et al. (2019) provide a descriptive global overview of food-based dietary guidelines and highlight similarities among countries but also countries' specificities. As a result, the study concludes that across countries recommendations include that the main part of the diet should consist of fruits and vegetables and starchy staples; in addition the diet should entail proteins, both animal-sourced and plat-based, and only limited amounts of salt, sugar and fat. However, the guidelines about dairy, red meat, fats and oils, and nuts consumption vary across countries.

Related to the second question, a long history of research aiming at understanding global dietary patterns and the nutrition transition in general (e.g. Popkin, 2004) and investigating consumption behaviour and diets and their impact on health and sustainability over time (e.g Tilman and Clark, 2014) provides further insights. The EAT Lancet reference diet (Willet et al. 2019) serves as a first attempt to define a diet that aligns both, health requirements and environmental requirements.

According to the EAT-Lancet report (Willet et al. 2019), a transformation to healthy and more sustainable diets by 2050 can be achieved by substantial dietary shifts. Overall, this would require more than doubling the consumption of plant-based and healthy food (i.e., vegetables, legumes, fruits and nuts), while at the same time reducing the consumption of animal-sourced and/or unhealthy foods (i.e. red meat, white meat dairy products and sugar) by more than 50% at the global level. To account for the different dietary patterns across the globe for example due to cultural, religious or affordability reasons, the EAT Lancet report (Willet et al. 2019) gives guidance on alternative and feasible diets.

Inspired by the EAT Lancet report (Willet et al. 2019), this study gradually introduces a feasible reference diet over the period 2020 to 2050, in addition to reducing food waste and loss by 2030, to direct consumption patterns towards a more sustainable and healthier diet ('&diet' scenario) as shown in Figure 10. The EAT Lancet report (Willet et al., 2019) proposes reducing the consumption of red and white meat and dairy products and increasing the consumption of fish, fruits and vegetables. For a feasible reference diet, the '&diet' scenario also includes regional exceptions owing to cultural, religious or affordability considerations thereby excluding some region-commodity pairs from the introduced dietary changes[6]:

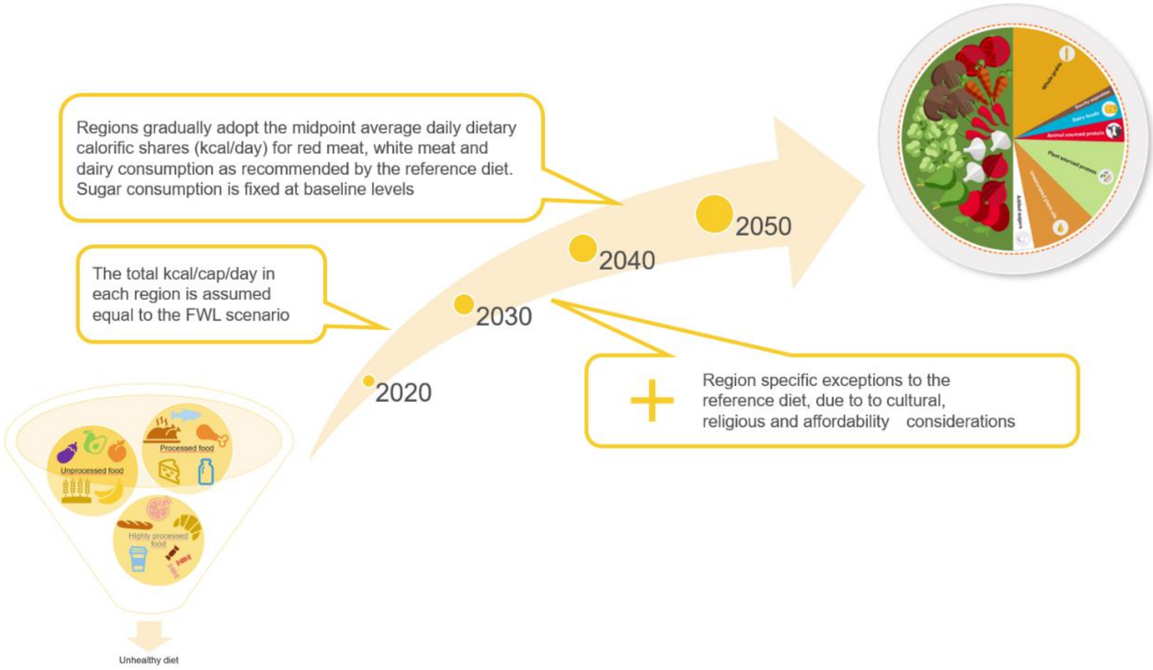
[6] Philippidis et al. (2021) provide further insights into the assessment of different dietary assumptions on biophysical indicators.

- Religiously prescribed diets with regard to meat consumptions: Examples are limited beef consumption in predominantly Buddhist regions, and limited pork consumption in predominantly Islamic regions;
- Cultural specificities: One wide-spread example is lactose intolerance in Asia;
- Affordability criteria: Many low-income countries, still suffer from inadequate diets with regard to daily energy intake as well as the composition of the diets as incomes are still not sufficient. Consequently, no dietary changes are introduced in SSAFRICA.

Furthermore, sugar consumption is fixed at baseline levels, and average daily per capita energy intake in each country is set equal to the one in the scenario FWL.

While this study accounts for different assumptions with regard to the extent of potential costs associated with food waste and loss reductions, no costs are linked with the dietary changes needed in order to achieve the suggested feasible reference diet. Although dietary changes will be associated with cost, this assumption has been chosen as there is no reliable information on how high these costs will be.

Figure 10. Overview modelling dietary changes



Source: Own elaboration, right figure from https://eatforum.org/learn-and-discover/the-planetary-health-diet/

3 Baseline

3.1 Baseline in key numbers

The baseline used as a reference in this study is described in the M'barek et al. (2019) and Philippidis et al. (2020) in detail, including the overall developments with SDG metrics.

It should be noted that the impacts of the COVID-19 pandemic are not included, although for the purposes of this long-term (i.e., 2050) assessment, these short-term disruptions to global markets are not expected to radically change the findings of this study.

The main assumptions regarding the macroeconomic evolution are presented in Chapter 2.4. Overall, an unfettered economic growth towards 2050 is foreseen, where, at the global level, annual income per capita doubles by 2050 to reach EUR 15 600. China and Sub-Saharan Africa see annual income rates growing rapidly; however, in the latter case, somewhat dampened per capita increases owing to high population growth in this region. The EU keeps its place among the high-income regions with a moderate pace of 1.2% growth per year. There is evidence of global income convergence, although this is slow.

Over time, the global economy is projected to become more energy-efficient and to reduce greenhouse gas emissions per EUR million GDP, mainly caused by a mix of energy saving, energy efficiency and decarbonisation (i.e. greater uptake of renewables, especially electrification). While, overall, the share of renewables increases strongly over the time period to 2050, the share of biorenewables shrinks over time. Nevertheless, the global output of conventional biofuels rises from 80 million tonnes of oil equivalent (Mtoe) in 2015 to 291 Mtoe by 2050.

Overall, more biomass is needed to feed the planet. Global food production increases by about 60% from 2015 to 2050, which amounts to an increase of 6 billion metric tonnes over the period. The biggest growth in absolute terms takes place in Asia (2.5 billion metric tonnes). The highest growth in percentage takes place in Africa (165%) to feed a rapidly growing population. The EU-27 increases its annual food production by about 10%, reaching 1 billion metric tonnes by 2050. Overall, the temporal trend line shows that agri-food prices are expected to remain stable over the whole period, in line with recent projections from other institutions.

Regional income and population pressures fuel global increases in agricultural land use of 8%, which is equivalent to 80% of current agricultural land in the USA and Canada combined. Demand factors drive considerable land use increases in Africa (26%) and Latin America (10%), which are met by biophysical estimates of potentially available land. With rising land use, a similar rise in irrigated abstracted water is observed. There is ample evidence that agricultural land use affects biodiversity (see, for example, IPBES, 2019). Hence, assuming moderate improvements in production practices, the pressure on the planet's resources would still increase.

Global emissions could rise by 15 giga tonnes of CO2e by 2050 without action; that is about one third higher than in 2015. Rapid growth in developing regions (e.g. Africa with 175% higher emissions) and emerging regions (e.g. India at 80% higher) are the main drivers. The EU (-18%) as well as USA/Canada (-11%) reduce emissions towards 2050. In the reference scenario, CO2 emissions remain the largest contributor to total global emissions (around 62% in 2050), although methane (CH4) and nitrous oxide (N20) are growing much quicker, owing partly to continued growth in livestock numbers and agriculture and also because CO2 emissions growth is much slower due to a degree of decarbonisation within the energy market.

3.2 Baseline from a footprint perspective

In this section, the current situation and the trend of food demand resource use related to land, water, emissions and energy is presented through footprints and virtual flows. With regard to the scenarios related to changing patterns of food production and demand, the description of the current state of the food system is the essential starting point of the analysis. The reader is informed that, in this new complementary baseline description, we focus on numbers for the year 2020.

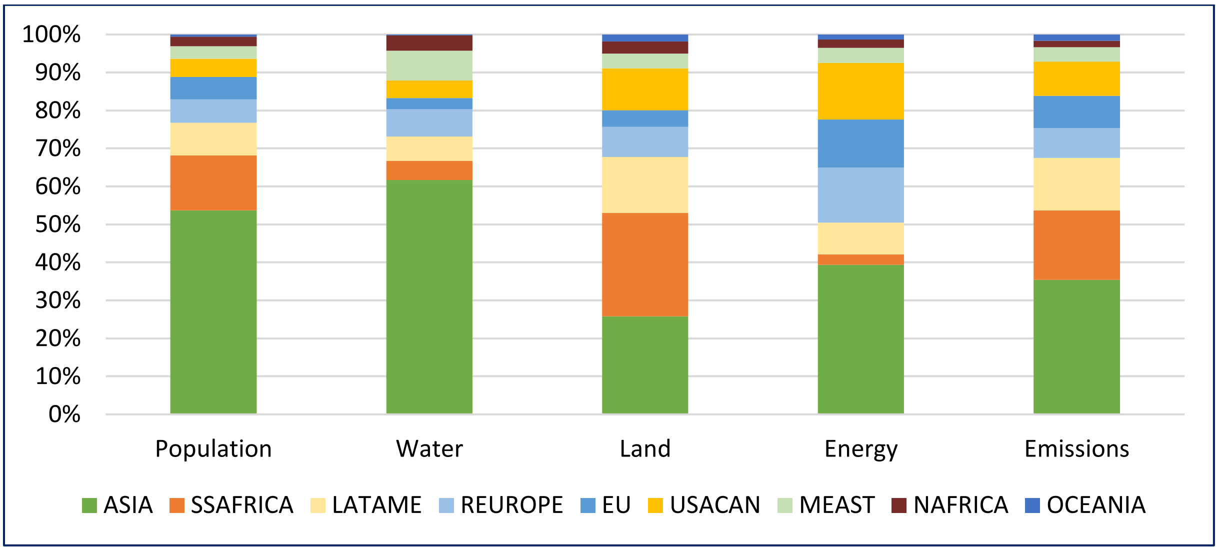
The use and variety of environmental footprints is growing according to Vanham et al. (2019), though predominantly not integrated within a coherent framework (Vanham, 2019). The methodology applied, the global coverage and the coherence between environmental footprints are indeed critical to comparative or future-oriented studies. For example, if the footprint covers the entire food chain, including transport and retail, or if the EU aggregate includes the UK or not – with the UK being an important net food importer.

In the following, we describe the final food consumption footprints from a regional and sectoral perspective, distinguishing also between footprints per person and aggregate regional footprints. As an efficiency and productivity measure, we calculate the input of environmentally relevant production factors (land, irrigation water, energy) and emissions per tonne of product. We shed light on the international dimension of the food system with its transboundary impacts through virtual trade, focussing on the role of the EU. Lastly, we show the evolution of the footprints towards 2050.

3.2.1 Footprints within major world regions

Cross referencing the regional shares of each resource (food consumption footprints for irrigation water, land, energy, emissions) and population of the key regions (Figure 11), the weight for ASIA is under-proportional for land. On the contrary, the rather low productivity in agriculture in SSAFRICA manifests itself through a very high share of land, but little use of energy. USACAN, and to a lesser extent the EU, display high shares in energy use.

Figure 11. Share of resource use compared to population, year 2020



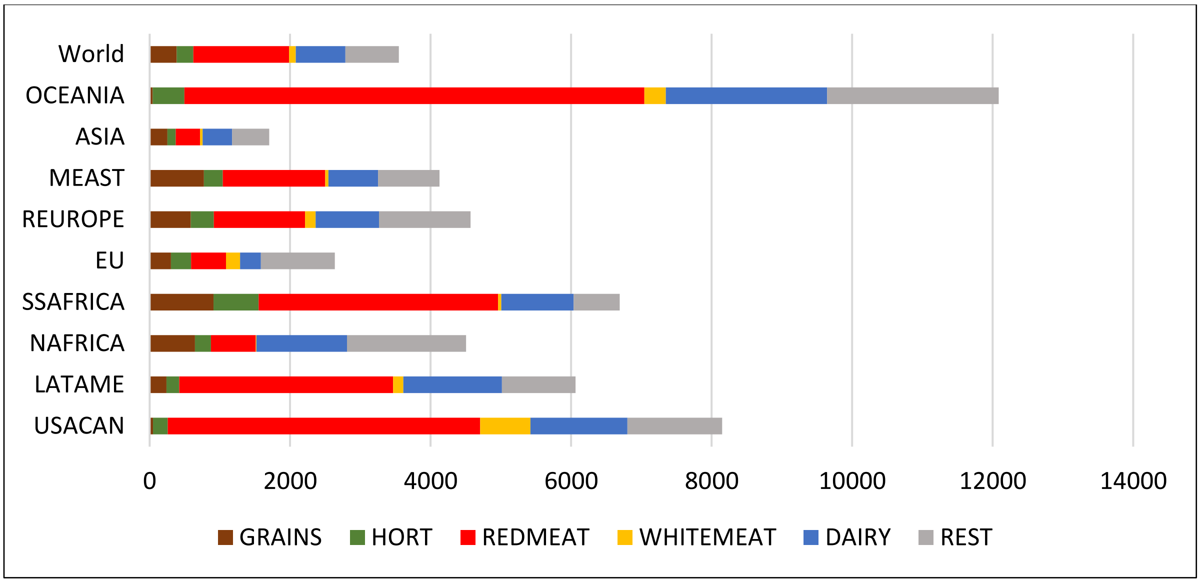
Source: MAGNET model results.

3.2.2 Footprints by region and sector

The following figures show a series of food consumption footprints per capita and region in the year 2020. In the context of diet and waste analysis, the per capita approach seems appropriate. The figures show the footprint in the respective metrics differentiated by grains, horticulture, red meat, white meat, dairy and the 'rest', which is composed of sugar, fish and other food.

The dominance of the livestock sector in the use of agricultural land (including arable and grazing land) is apparent in all regions, with the exception of ASIA and, to some extent, the EU (Figure 12).

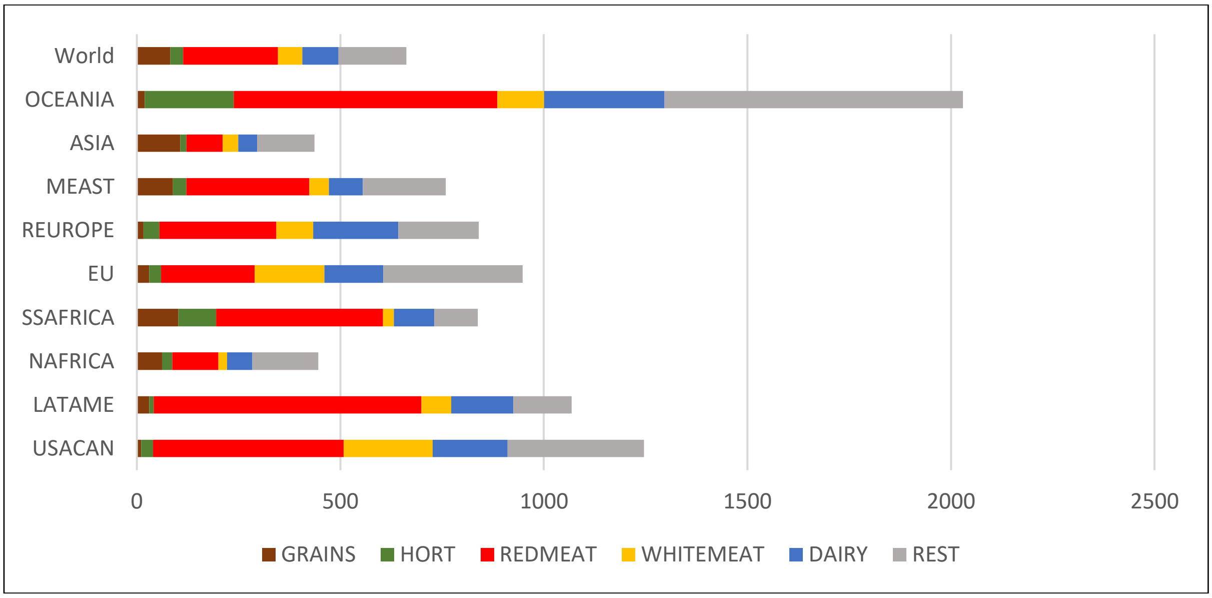
Figure 12. Final food consumption driven land footprints per capita and year, in m^2, year 2020



Source: MAGNET model results.

Turning to emissions footprints, the Figure 13 shows that red meat is the main origin of emissions in most regions. ASIA is the exception, primarily due to the high methane emissions in rice production. These calculations exclude fertiliser, which would add, on average, approximately 30% in emissions.

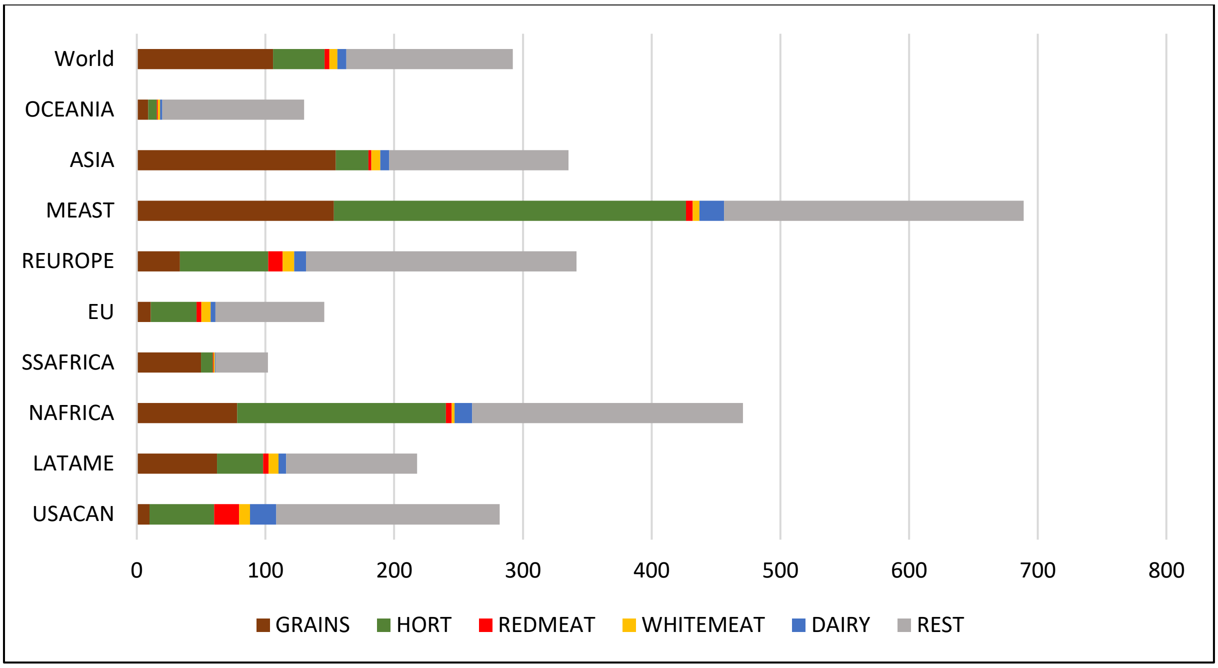
Figure 13. Final food consumption driven emissions footprints per capita and year, in kg CO2e, year 2020



Source: MAGNET model results.

The water footprints are calculated only for crops. This is motivated by the fact that more than 80% of water use (EEA 2020, for the EU) is directly related to the irrigation of crops. The arid regions in the world have high water footprints, in particular MEAST and NAFRICA, with horticulture dominating the usage. Worldwide, rice consumption has the highest water footprint, mainly due to the importance of rice production in ASIA (Figure 14).

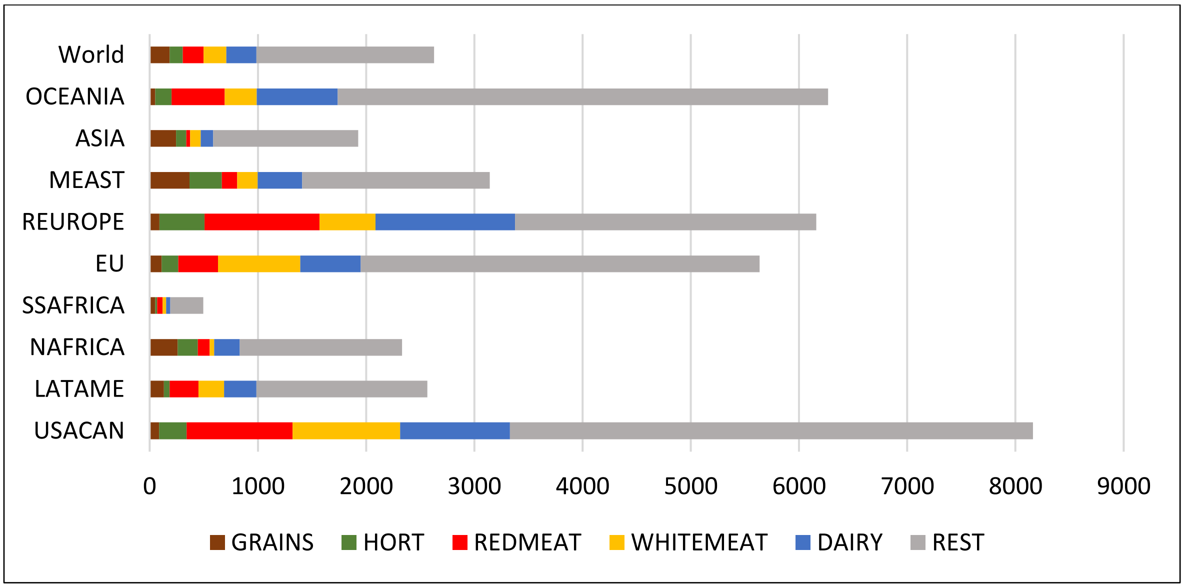
Figure 14. Final food consumption driven water footprints per capita and year, in m³, year 2020



Source: MAGNET model results.

The energy footprint mirrors the state of mechanisation and processing of agri-food systems in the world, with SSA showing the lowest energy use. Similar to the emissions, energy usage significantly increases if fertiliser is included, in particular in OECD countries (Figure 15).

Figure 15. Food consumption driven energy footprints per capita and year, in MJ, year 2020

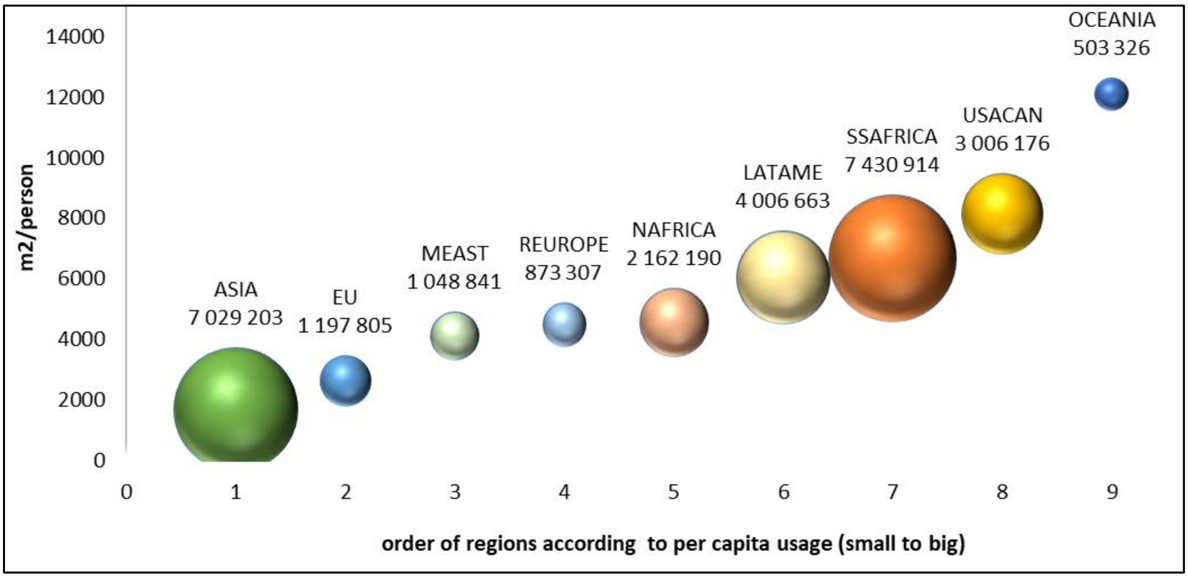


Source: MAGNET model results.

3.2.3 Virtual commodity usage and footprints by region

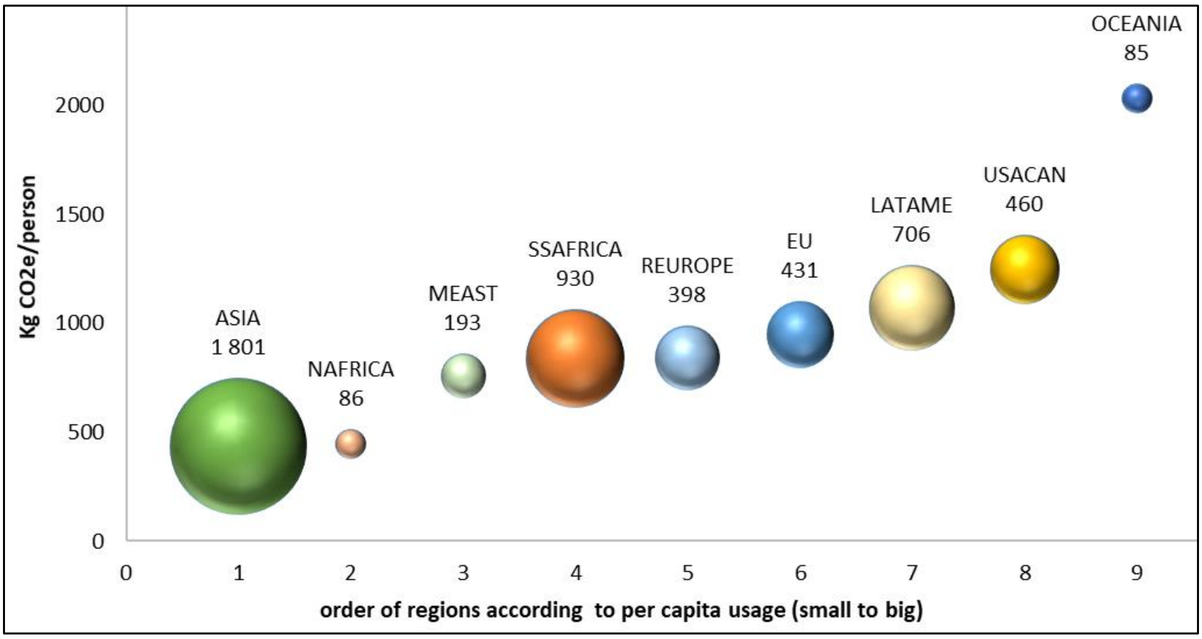
Developing a systemic approach to a globally more efficient food system requires looking at both the individual food consumption footprints as well as the total size of regional footprints. This is needed to design instruments/policies which target, on the one hand, the entire food system (including optimised food chains and trade) and, on the other hand, the individual consumer (e.g. through a change of diets). Figure 16 to Figure 19 order the regions according to their per capita usage (small to big), while the size of the bubbles represents the total aggregate regional footprints. Evidently, there is a correlation between the population of a region and the total footprint.

Figure 16. Land footprint, total (km²) and per capita (m²), year 2020



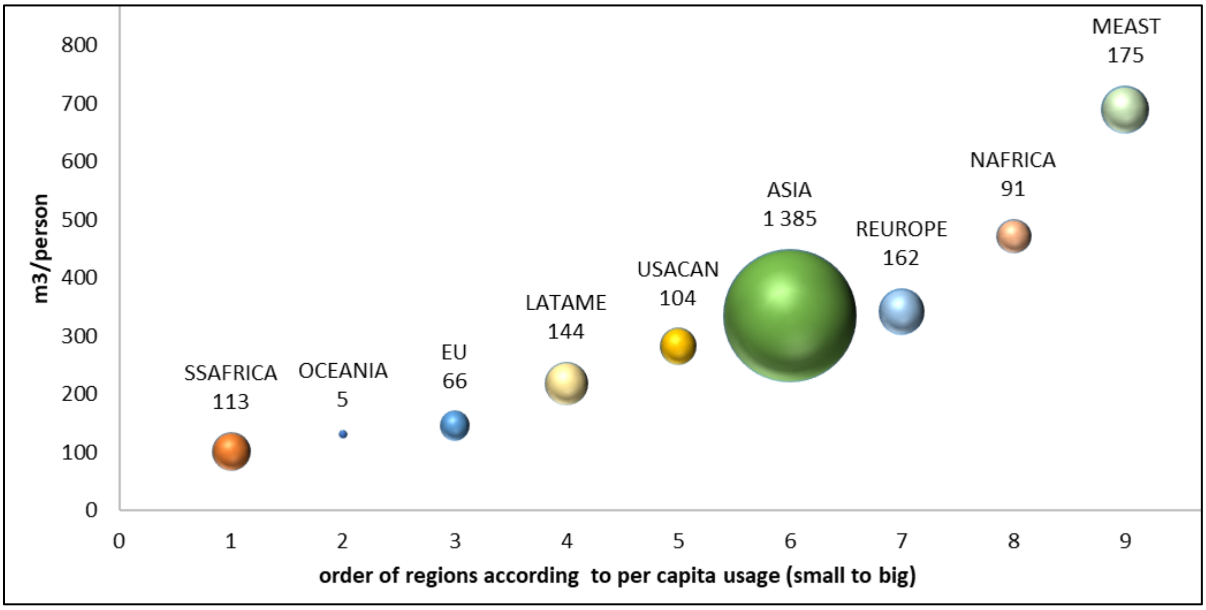
Source: MAGNET model results.

Figure 17. Emissions footprint, total (million T CO2e) and per capita (kg CO2e), year 2020



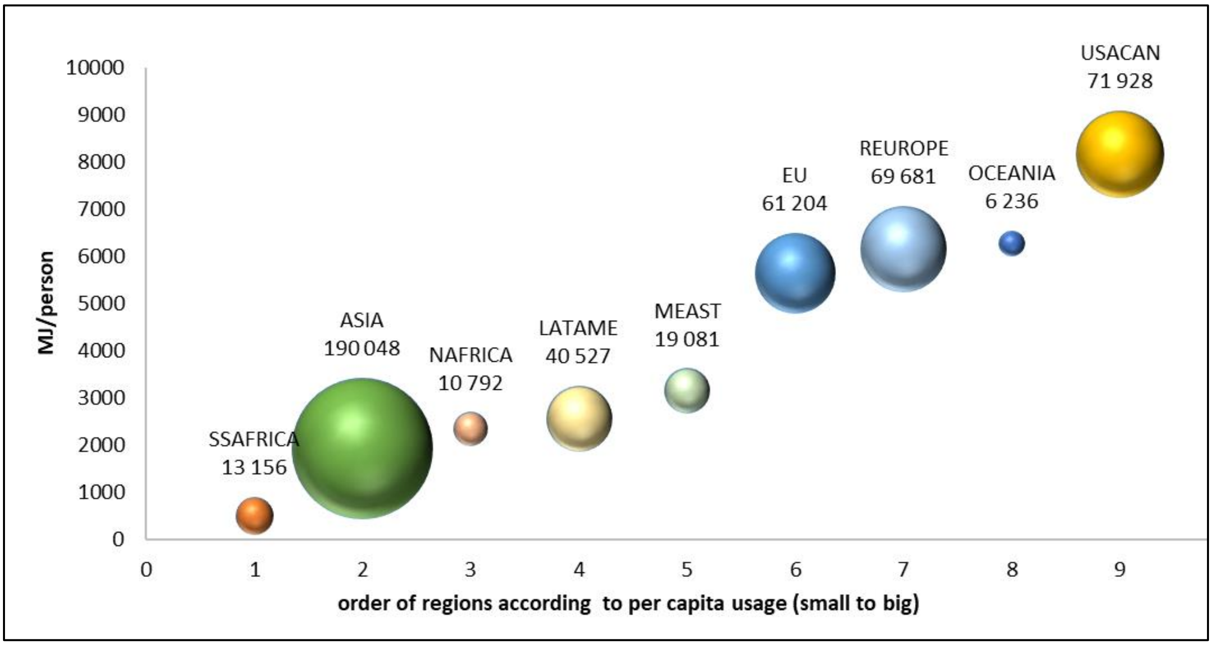
Source: MAGNET model results.

Figure 18. Water footprint, total (km³) and per capita (m³), year 2020



Source: MAGNET model results.

Figure 19. Energy footprint, total and per capita (MJ), year 2020

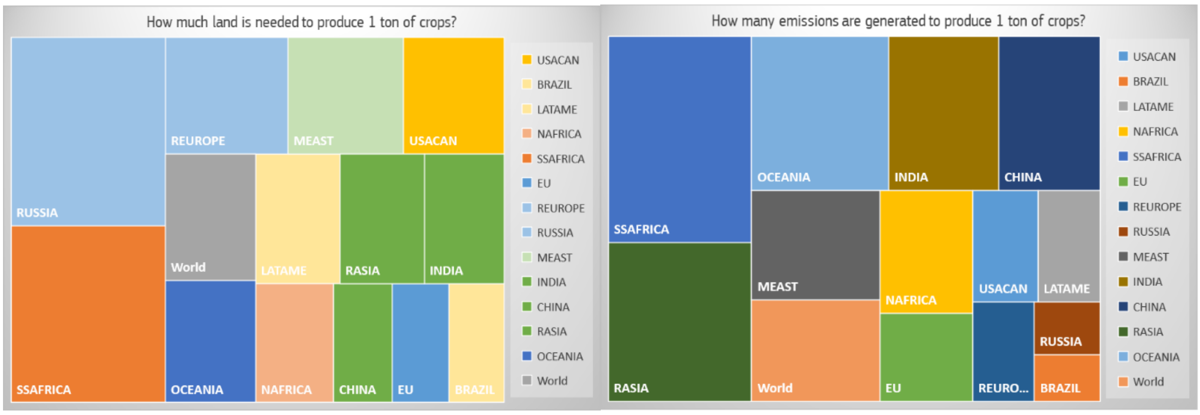


Source: MAGNET model results.

3.2.4 Resource productivity within major world regions

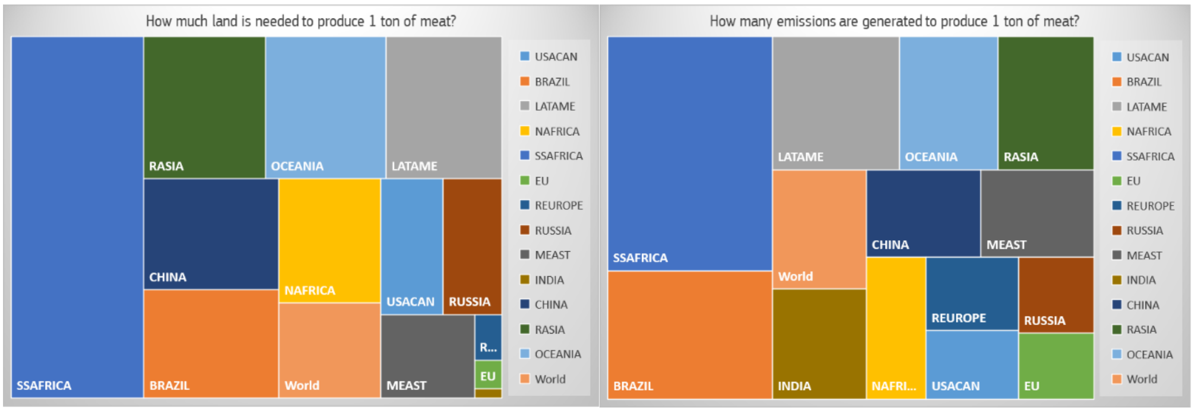
An important criterion for describing the performance of the agri-food system is the calculation of supply-side footprints per tonne of product. Figure 20 and Figure 21 present a comparative overview of the relative contribution of land and emissions by region/country needed to produce one tonne of crops and meat, respectively. The high land footprint for SSAFRICA can be explained by extensive livestock production.

Figure 20. Resource productivity per tonne of crops (land and emissions)



Source: MAGNET model results.

Figure 21. Resource productivity per tonne of meat (land and emissions)



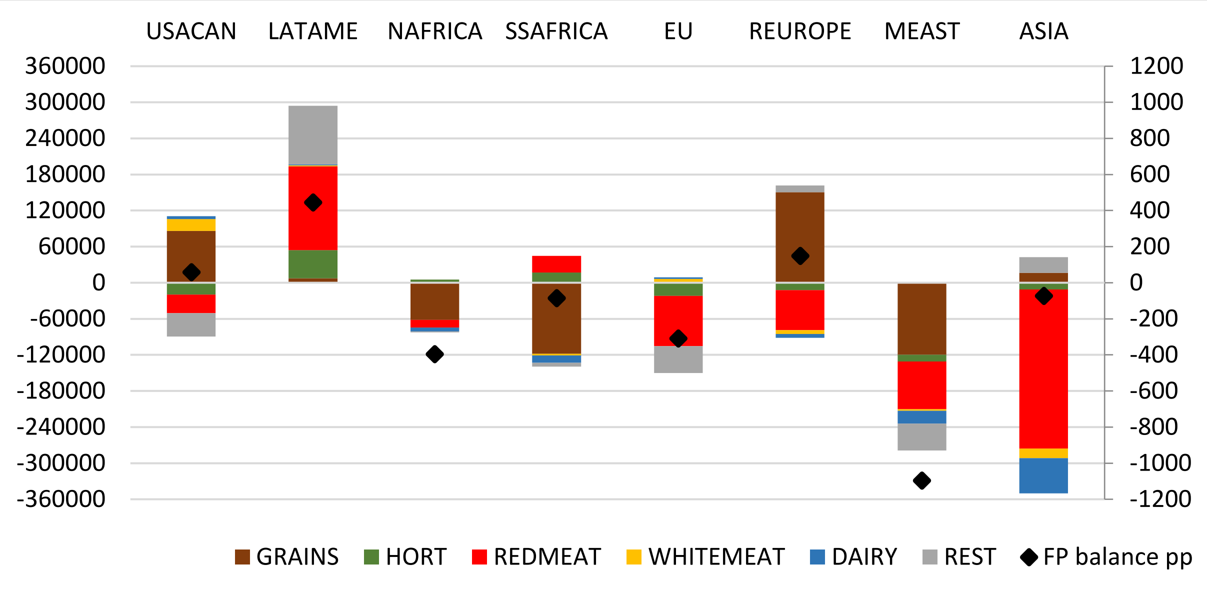
Source: MAGNET model results.

3.2.5 Virtual trade and the role of the EU

Virtual trade maps the level of sustainable resource usage to the food demand needs of each of the regions in our study. In this way, it internalises the full resource implications of consumer purchase patterns, not only in terms of the type of products they consume but also the regional origin of the products we eat.

Comparing the virtual (land and emissions) trade of the regions (Figure 22 and Figure 23), we can observe that LATME (red meat and oilseeds in 'REST') and REUROPE (grains) and, to a lesser extent USACAN (grains), are the breadbasket of the planet. The main importers are Asia (red meat), the MEAST (grains, red meat), EU (red meat) and SSA and NAFRICA (grains). When adding the footprint balance per person, ASIA and SSA exhibit a much smaller virtual trade footprint.

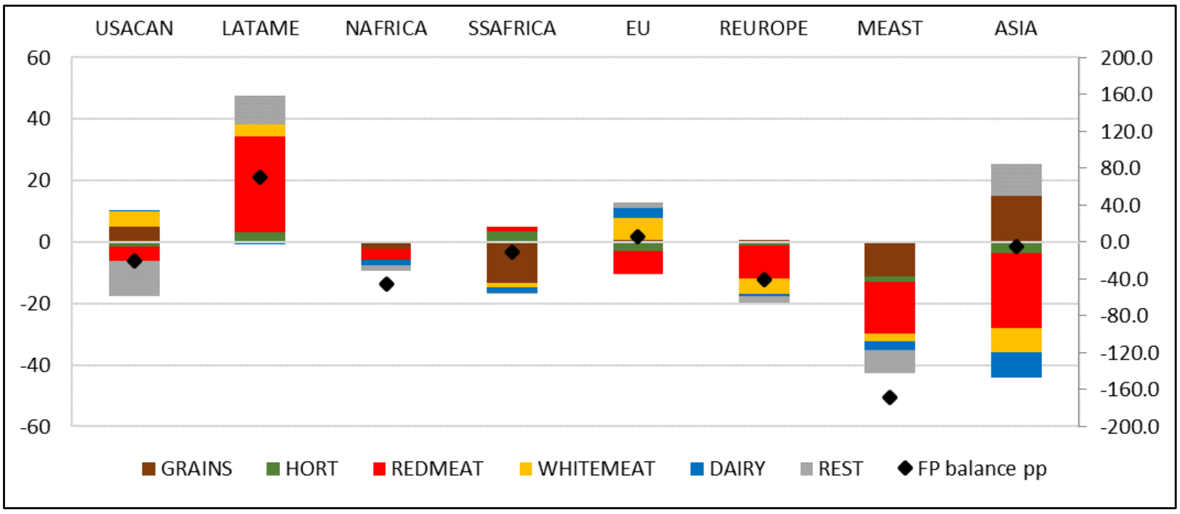
Figure 22. Aggregate virtual land trade in km^2 and per person in m^2, year 2020



Source: MAGNET model results.

The picture changes slightly when looking at the emissions trade (Figure 23). In particular, the EU turns from a deficit per capita land footprint to a surplus emissions footprint. This is mainly due to the more efficient, i.e. less GHG-emitting red meat production in the EU. In addition, the less land-intensive and export-oriented sectors of pork and horticulture are improving the balance. USACAN displays a contrasting development.

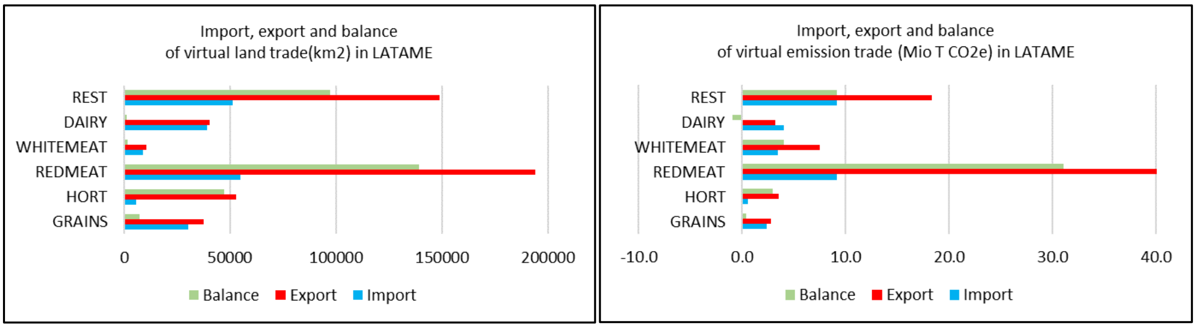
Figure 23. Aggregate virtual emissions trade in ktoe and per person in MJ, year 2020



Source: MAGNET model results.

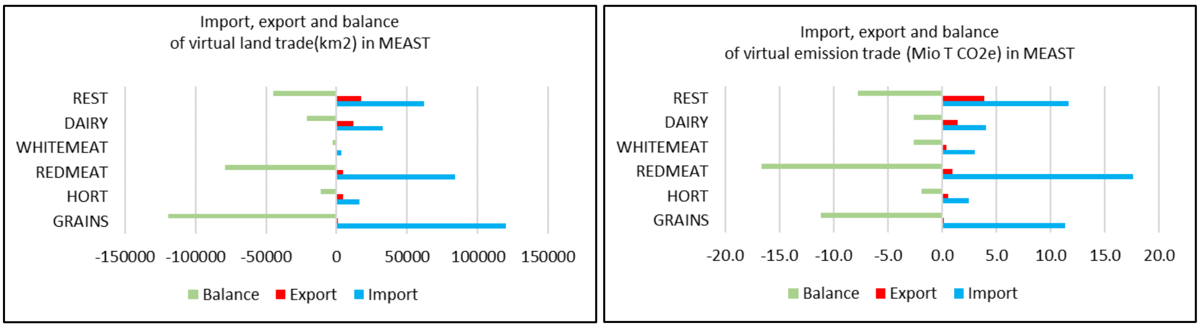
Figure 24 to Figure 26 provide more detail on the virtual land and emissions trade of a typical export-oriented region (LATAME), net food importer (MEAST) and a more differentiated profile (EU).

Figure 24. Import, export and balance of virtual land (left) and emissions (right) trade, LATAME, year 2020



Source: MAGNET model results.

Figure 25. Import, export and balance of virtual land (left) and emissions (right) trade, MEAST, year 2020



Source: MAGNET model results.

Figure 26. Import, export and balance of virtual land (left) and emissions (right) trade, EU, year 2020

Source: MAGNET model results.

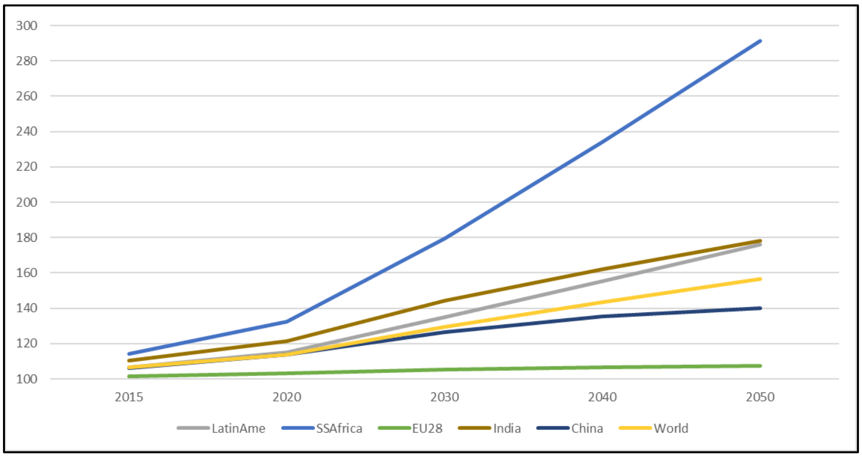
In Figure 26 (left hand panel), the EU presents a negative balance for red meat, horticulture products and the rest, in particular oilseeds and processed goods. In the case of emissions (right side panel), the balance becomes positive, i.e. the EU exports more emissions than it imports. It should be noted that the EU's food consumption footprint has changed due to the UK leaving the EU[7]. The net import position of the EU-27 – with 141.000 km^2 per year – is about 70.000 km^2 smaller than in the EU-28 (this is comparable to the size of the Czech Republic).

3.2.6 Footprints towards 2050

Driven by regional variations in rising per capita incomes, demographic growth, the increase in domestic food production reaches almost 60% in 2050 compared to 2015, in line with the FAO long-term projections (Figure 27).

[7] The UK had a high share in crops, meat and dairy imports to the EU.

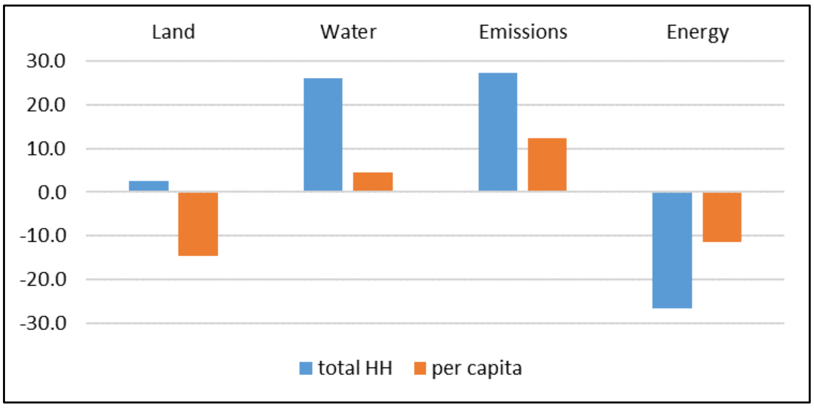
Figure 27. Domestic food production over time in different regions, index (2011=100)



Source: MAGNET model results.

Translating increased food demand into per capita footprints, the baseline shows an increase in total use from aggregated households for land, water and emissions, but not for energy (Figure 28). While land increases slightly (less than 3%), water usage and emissions increase by 26% and 27%, respectively. The land use per person reduces considerably due to land productivity improvements and rising population; however, changing diets lead, in particular, to a 12% increase in emissions (more details below). Energy reduces significantly for the total household use and per person.

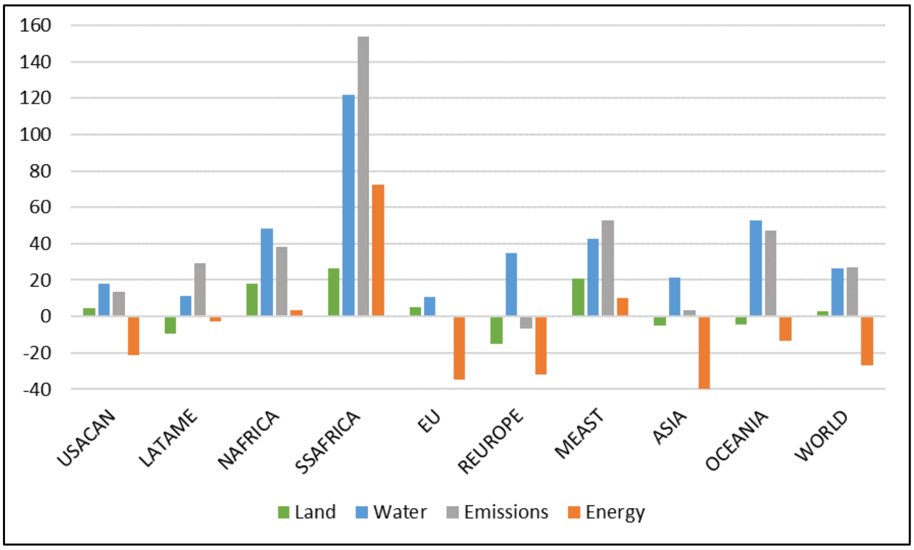
Figure 28. Global food demand driven per capita footprints in % change, 2050 vs 2015



Source: MAGNET model results.

From a regional perspective (Figure 29), the percentage changes in footprints in SSA stand out considerably, as all of them are increasing. Additionally, MEAST and NAFRICA show remarkable increases in all FPs. The other regions roughly follow the global trend. LATAME depicts a small reduction in land use.

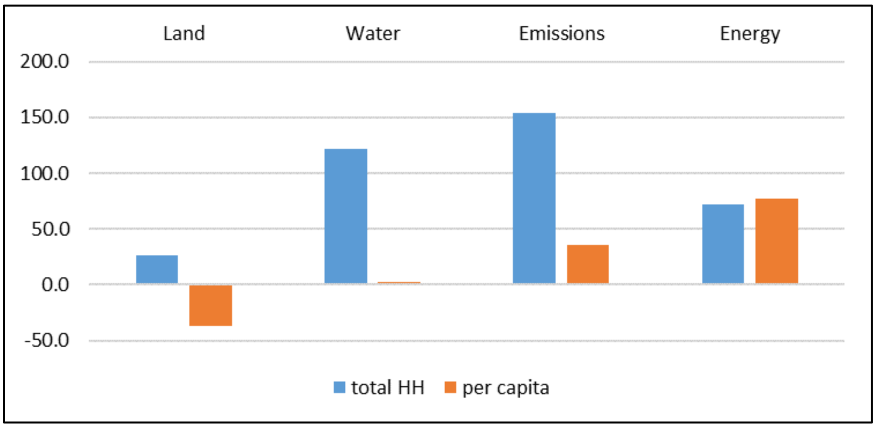
Figure 29. Food footprints in % change, 2050 vs 2015, in different regions



Source: MAGNET model results.

As shown above, the magnitude of changes in Sub-Saharan Africa is much stronger due to the high population and economic growth. In particular, water and emissions rise 122% and 154%, respectively. The assumed productivity growth allows, to a considerable extent, the reduction of the per person land footprint (Figure 30). With changing diets and more intensive production, the use of energy sees a strong increase in total and per capita.

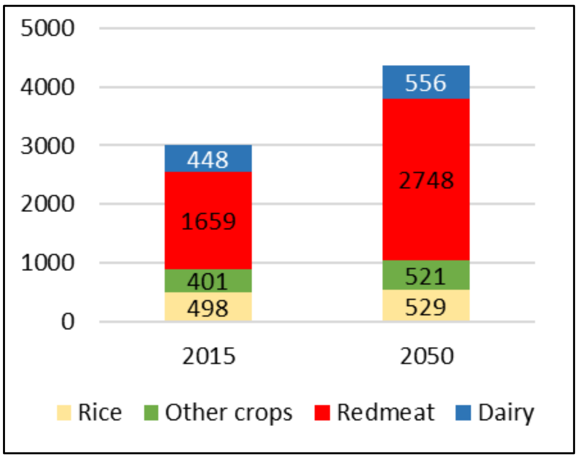
Figure 30. Food footprints in % change, 2050 vs 2015, Sub-Saharan Africa, for total households and per capita



Source: MAGNET model results.

Turning to final food demand driven global emissions (Figure 31), the growth is mainly due to the extension of red meat production and consumption.

Figure 31. Final food demand driven global emissions, 2015 and 2050, in MtCO2e, by agricultural and food products



Source: MAGNET model results.

4 Results of food waste and loss reductions

This section divides the discussion of results into two parts. The first part focusses on the impact of food waste reductions, food loss reductions as well as the combined impact of both food waste and food loss reductions on production and consumption at global as well as EU level. This analysis of results is followed by a second part that provides insights into the impact on assumptions with regard to the costs related to food waste and loss reductions.

4.1 Drivers of food waste and food loss reductions

Food waste and loss reductions impact on different stages of the supply chain. While food loss reductions are linked to supply changes, food waste reductions enter the market via changes in demand. This section therefore aims to shed light on how food waste and food loss reduction affects the agricultural and food market.

What do we expect from food waste and loss reductions along the supply chain?

Production side / food loss

This study accounts for food waste and loss reductions along five steps of the supply chain. The model accounts for the reduction of food loss due to agricultural production and post-harvest losses as an increase in the efficiency of agricultural production, so that an increased output volume can be produced with the same number of factors and inputs as before. This results in the supply curve shifting to the right, implying that at each market price a higher quantity of agricultural and food commodities is supplied. Reducing food loss would, ceteris paribus, result in an increased quantity supplied and a fall in market prices.

By contrast, it considers food loss reductions at the processing and packaging level as input efficiency increases – fewer inputs used to produce the same quantity of output as before, which results in the input demand curve of upstream markets shifting to the left, implying reduced input demand at each market price. Consequently, reducing food loss at this stage of the supply chain would, ceteris paribus, result in a reduced input quantity demanded and a fall in market prices.

Consequently, considering loss reductions at these three steps of the supply chain, economic theory suggests a clear fall in agricultural and food market prices; however, the impact on the agricultural and food quantity supplied and demanded is ambiguous and depends on the reduction potential at each step of the supply chain as well as the elasticity of demand and supply that determines how much consumers and producers react to price changes.

Consumption side / food waste

If looking at food waste reductions only, there are two approaches driving the results. Firstly, food waste reductions are translated into the model as a reduction in the household budget spent directly on food commodities, and also on food services (i.e., restaurants or takeaway). This results in the demand curve shifting to the left and thus a reduced quantity demanded at each market price. Secondly, the food waste savings at retail level are introduced as food input efficiency increases in the food service sector such that fewer inputs are required to produce the same quantity of food service output. As a result, the input demand curve for agricultural and food commodities shifts to the left, leading to reduced demand at each market price. In the absence of compliance cost increases, this results in a shift of the supply curve to the right for food service products, leading to an increased quantity supplied at each market price and thus, ceteris paribus, to a fall in market prices and an increased quantity supplied and demanded.

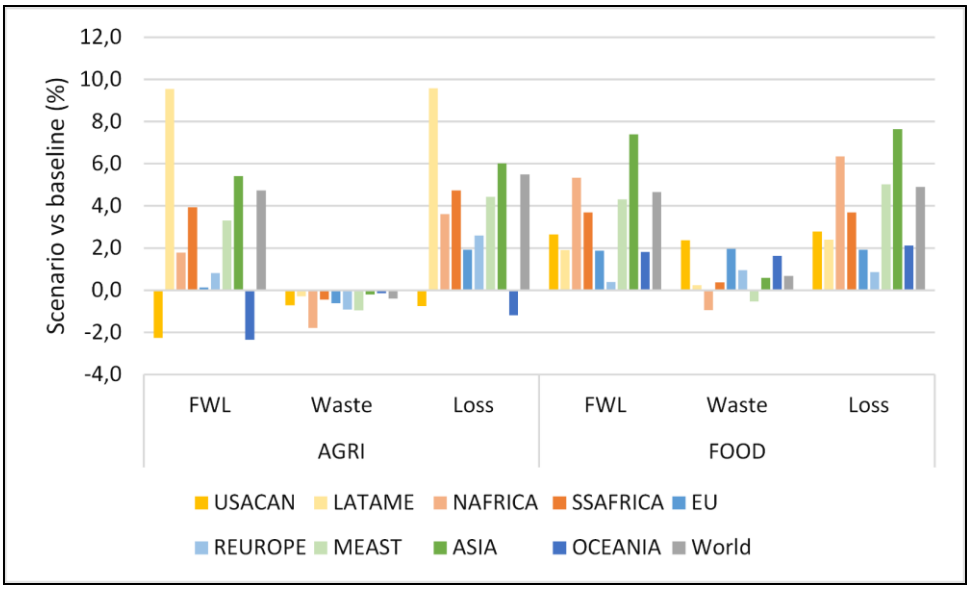
While the reduction of food waste at consumer level leads to a reduction in the quantity demanded, the demand for agricultural and food commodities reduces at the retail level due to the increased efficiency of input use. Consequently, economic theory suggests that, ceteris paribus, the reduction of food waste at retail and consumer level mutually reinforces their effects and leads to a decrease in market prices. However, the effect on the quantity demanded and supplied is less clear, particularly for food services products. Increased input use efficiency and the associated decline in input prices could lead to increased sales of food services at cheaper prices, but this depends on the extent to which market prices decline. It is also indeterminate to what extent reduced market prices stimulate a 'rebound effect' of rising household food consumption, thereby counteracting the waste-related lower demand quantity. As a result, the impact on quantity demanded and supplied is not clear from a theoretical perspective and is determined by the extent of the waste and loss reduction imposed.

4.2 Global impact of food waste and loss reductions

This subsection presents the impact of food waste and loss reductions at the global level for aggregated agricultural and food commodities. As Figure 5 to Figure 9 have shown, the shares of food waste and loss vary significantly by commodity and region, so a general equilibrium model is needed to account for all the linkages and rebound effects of global food waste and loss reduction. Figure 32 to Figure 37 show the impact of the implemented food waste, food loss and food waste and loss reduction scenarios carried out with the MAGNET model on economic indicators.

Comparing with the baseline in 2050 for a selection of regions, Figure 32 shows the overall impact on output quantity from food waste and food loss reductions in isolation, as well as the combination of both (FWL). Taking the same points of comparison, Figure 33 examines the impacts on market prices.

Figure 32. Output quantity deviations (%) for agriculture and food by region compared to the baseline in 2050



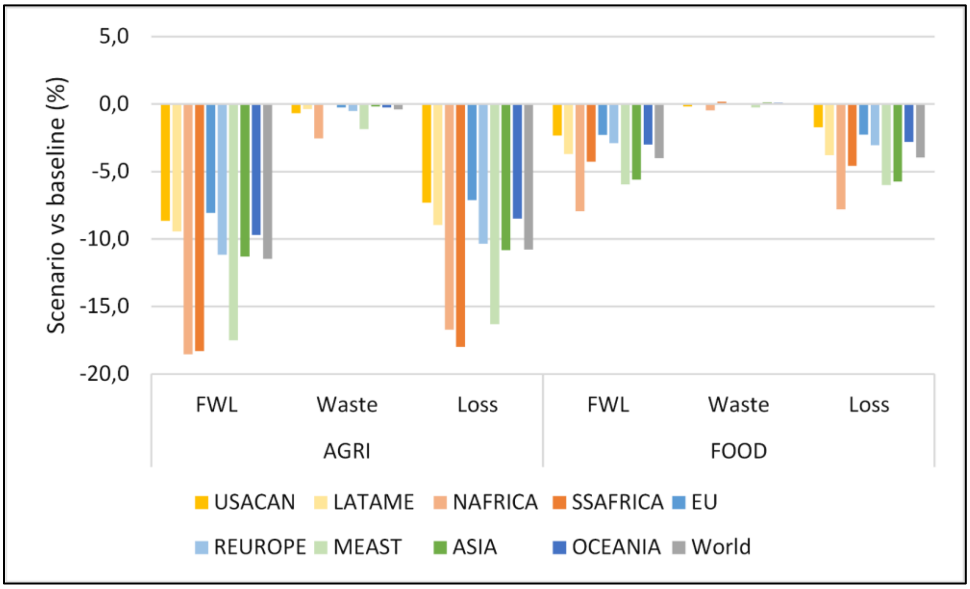
Source: MAGNET simulation results.

The results for food loss (assuming no compliance costs) show that, in all regions and at the world level, both agricultural and food production increase. Only USACAN and OCEANIA indicate a reduction in agricultural quantity compared to the baseline in 2050. The highest output rises are in LATAME, SSAFRICA and MEAST for agricultural products, while food production increases the most in NAFRICA, MEAST and ASIA. In the EU, reducing food loss leads to an increase in agricultural and food products smaller than 2% compared to the baseline.

Food waste, by contrast, reduces agricultural and food production due to the falling input demand in the service sectors, reduced consumer demand and increased food service production as processed food and food services become cheaper. Hence, reducing food waste at retail and consumer levels leads to a reduction in agricultural production in all regions, with the greatest effect in NAFRICA and MEAST and the smallest changes in ASIA, OCEANIA and LATAME. By contrast, although food production increases in most of the regions, with the highest rises in high-income regions such as USACAN, EU and OCEANIA, it falls further in NAFRICA and MEAST.

The FWL scenario shows the combined effects. The effect on agricultural and food production here is clearly driven by the reduction in food loss. In line with these developments, Figure 33 presents considerable price declines – mainly for agricultural but also for food commodities in all regions – due to the reduction in food losses, which is consistent with economic theory. The greatest effects are shown for NAFRICA, SSAFRICA and MEAST, while USACAN and the EU tend to exhibit the smallest price declines. Similar to the change in production volume, the reduction in food waste leads to rather small price declines for agricultural commodities; for food production, the market price changes are even smaller and, in contrast, even lead to a slight increase in food prices observed in SSAFRICA, EU, ASIA and the world.

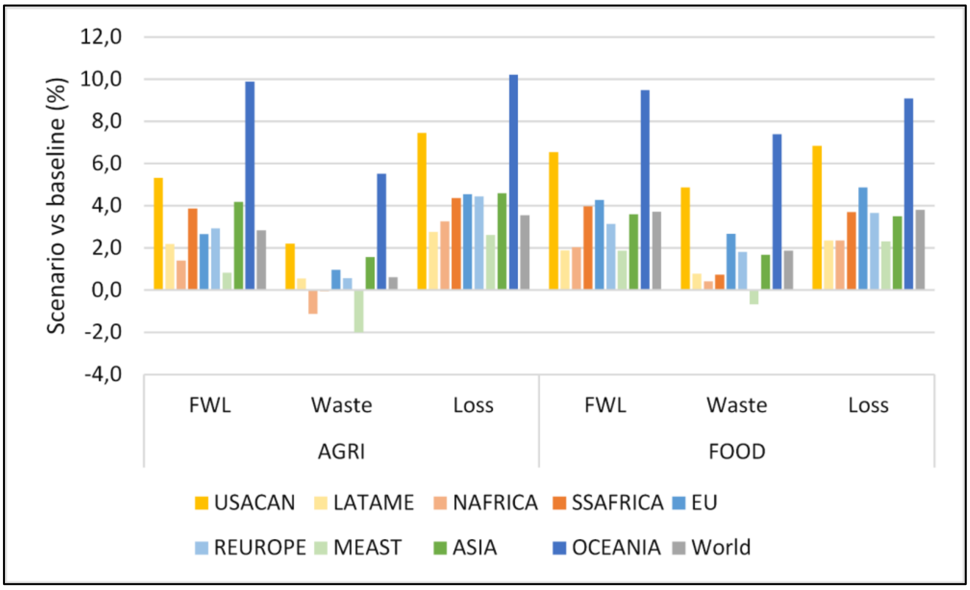
Figure 33. Market price deviations (%) for agriculture and food by region compared to the baseline in 2050



Source: MAGNET simulation results.

Reducing food waste and food losses increases agriculture and food consumption due to lower market prices in all regions. However, decomposing the results highlight that reducing food losses shows a clear and uniform effect across all regions, while the pattern of agricultural and food consumption as a result of reducing food waste is much more heterogeneous. The reduction of food losses leads to a higher availability of agricultural products and food at lower prices (Figure 32 and Figure 33), which consequently also leads to an increased demand for agricultural and food commodities in all regions, as shown in Figure 34.

Figure 34. Global consumer demand changes (%) to agricultural and food commodities compared to the baseline in 2050



Source: MAGNET simulation results.

By reducing food waste, consumers spend less of their budget on food by reaching the same level of utility, which is expected to lead to a reduction in the quantity demanded. However, in Figure 34 we observe that the demand for agricultural products and food is increasing in most regions. This is a 'rebound effect' from falling market prices, as consumers respond to these price changes by increasing their consumption. The selected modelling approach enables us to account for these rebound effects by not only showing the first-order impacts of demand changes but also the resulting second-order impacts of real purchasing power changes. The larger impact on food demand can be explained by a shift in consumption from staple foods to more luxury products, which is accompanied by an increase in budgets. The only exceptions are North and Sub-Saharan Africa for agricultural and the Middle East for agricultural and food consumption.

The extent of the impact of food waste and loss reductions is clearly driven by the size of the shock. In USACAN and EU, production growth due to reducing food loss tends to be relatively smaller compared to regions such as LATAME or SSAFRICA that have much higher post-harvest losses and losses at the packaging and processing stages. Therefore, the efficiency gains from reducing food loss in these regions are larger, and thus increase the competitiveness of these producers compared to the EU and USACAN. In addition, agricultural and food production in high-income regions is already rather efficient. Consequently, emerging and low-income countries start from a much lower base and hence benefit from much bigger changes in technological progress. Market prices fall significantly (further than production rises), which drives the consumption of agricultural and food products, and the consumption of these products for non-food purposes. So, in line with the expectations, food loss reductions contribute to increasing the availability of food commodities, increasing the affordability of food commodities, but nothing can be said about the accessibility.

At the same time, high-income regions tend to have higher waste rates, which results in a larger impact on agricultural and food production compared to lower-income regions. Food waste reduction leads to a decline in the production of agricultural products, and hence a fall in market prices in addition to the one observed due to food loss reductions. Furthermore, it leads to an increase in the production of food commodities (except in NAFRICA, MEAST) because fewer and cheaper inputs are used for the production of processed food commodities. The production of processed food and food services has become cheaper, due to food loss reductions at processing and packaging stages, so that fewer inputs are needed per unit of food output and due to food waste reductions at retail level, which has increased the efficiency of the food services sector. The observed price falls for primary agricultural products further enhances these effects. As a result, food products can be offered at lower prices, which in return drives demand for food commodities in all regions.

Due to the reduced budget spent on agricultural as well as processed food and food services associated with waste reductions, together with a significant fall in market prices, consumption patterns move towards food services as well as processed food such as meat and dairy products, which have become less expensive. Thus, the impact of food waste and loss reductions clearly affects agricultural and food commodities differently.

In this subsection, results have only been presented for aggregated agricultural and food commodities. However, the differences between these aggregates – especially with regard to waste and changing consumption patterns – have shown that a closer look at more detailed commodity information is necessary. The following subsection therefore discusses the impact of food waste and loss reduction on selected economic indicators for disaggregated agricultural and food commodities in the EU.

4.3 Impact of food waste and loss reductions in the EU

This section assesses the impact of reducing food waste and losses at disaggregated sector level for the EU. Figures 35 to 37 present the impact on agri-food output, market prices and consumption. In each figure the upper graph shows the development in the baseline in 2050 (dark blue bars) compared to the base year 2011 equal to 100 (light blue line), the lower graph shows the deviations of the scenarios from the baseline in 2050.

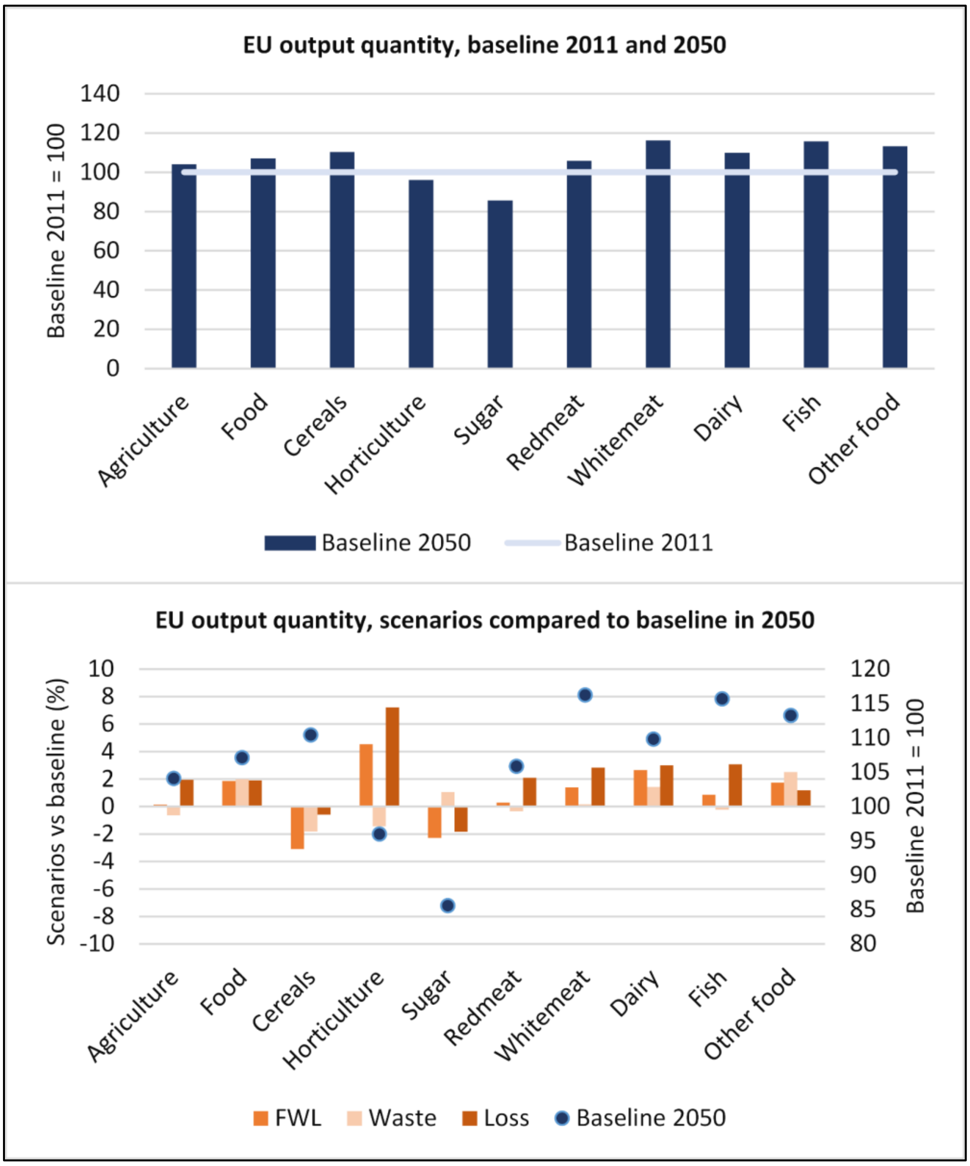
While agricultural production at EU level is only marginally affected when food waste and losses are reduced together, the decomposition demonstrates that reducing food losses leads to a significant increase in output and reducing food waste leads to a smaller reduction Figure 35.

In contrast, production volumes of processed foods such as meat and dairy products and other foods generally increase and reinforce the production increases observed in the baseline. While the reduction of food losses drives the results for dairy and meat products, the production of other foods is predominantly influenced by the reduction of food waste. In addition, food waste reduction leads to slight declines in red meat and fish production.

In general, the baseline has revealed that market prices for agricultural products and food tend to decrease until 2050 (Figure 36). The results of the food waste and loss scenarios indicate a significant reduction in market prices in all sectors, mainly due to the reduction in food losses. The highest price reductions are in the horticulture, cereals, sugar and fish sectors. While the reduction in food waste leads to a smaller yet still significant decline in prices for cereals and horticulture compared to food loss, it leads to a slight increase in prices for meat, dairy and fish (Figure 36).

Figure 35 shows that cereals, in particular, and horticulture drive these results, as these sectors have, on average, the highest food waste and loss rates along the supply chain of all primary agricultural sectors in the EU, but also in the other regions.

Figure 35. Production quantity changes (%) for selected agri-food sectors in the EU compared to the baseline in 2050



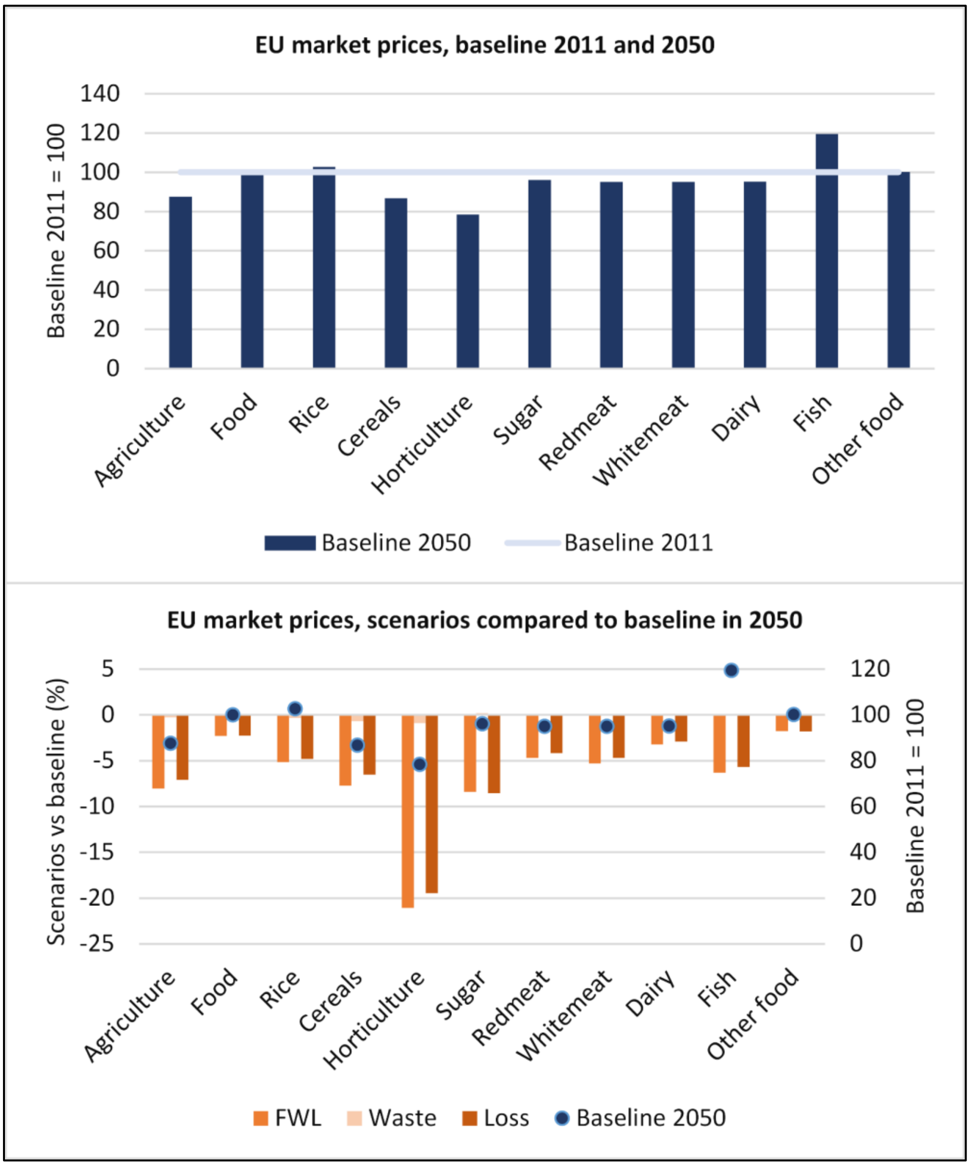
Source: MAGNET simulation results.

EU cereal production reduces compared to the baseline until 2050. In contrast, production volumes of processed foods such as meat and dairy products and other foods generally increase and reinforce the production increases observed in the baseline. While the reduction of food losses drives the results for dairy and meat products, the production of other foods is predominantly influenced by the reduction of food waste. In addition, food waste reduction leads to slight declines in red meat and fish production.

Figure 35 shows a reduction in agricultural production for all three food waste and loss scenarios, with the impact of the food loss scenario being the smallest. In contrast, horticultural production already reduces in the baseline. While the reduction in food waste exacerbates the decline in production in the baseline, the reduction in food losses and the combined FWL scenario counteract this effect.

In contrast, production volumes of processed foods such as meat and dairy products and other foods generally increase and reinforce the production increases observed in the baseline. While the reduction of food losses drives the results for dairy and meat products, the production of other foods is predominantly influenced by the reduction of food waste. In addition, food waste reduction leads to slight declines in red meat and fish production.

Figure 36. Market price changes (%) for selected agri-food sectors in the EU compared to the baseline in 2050

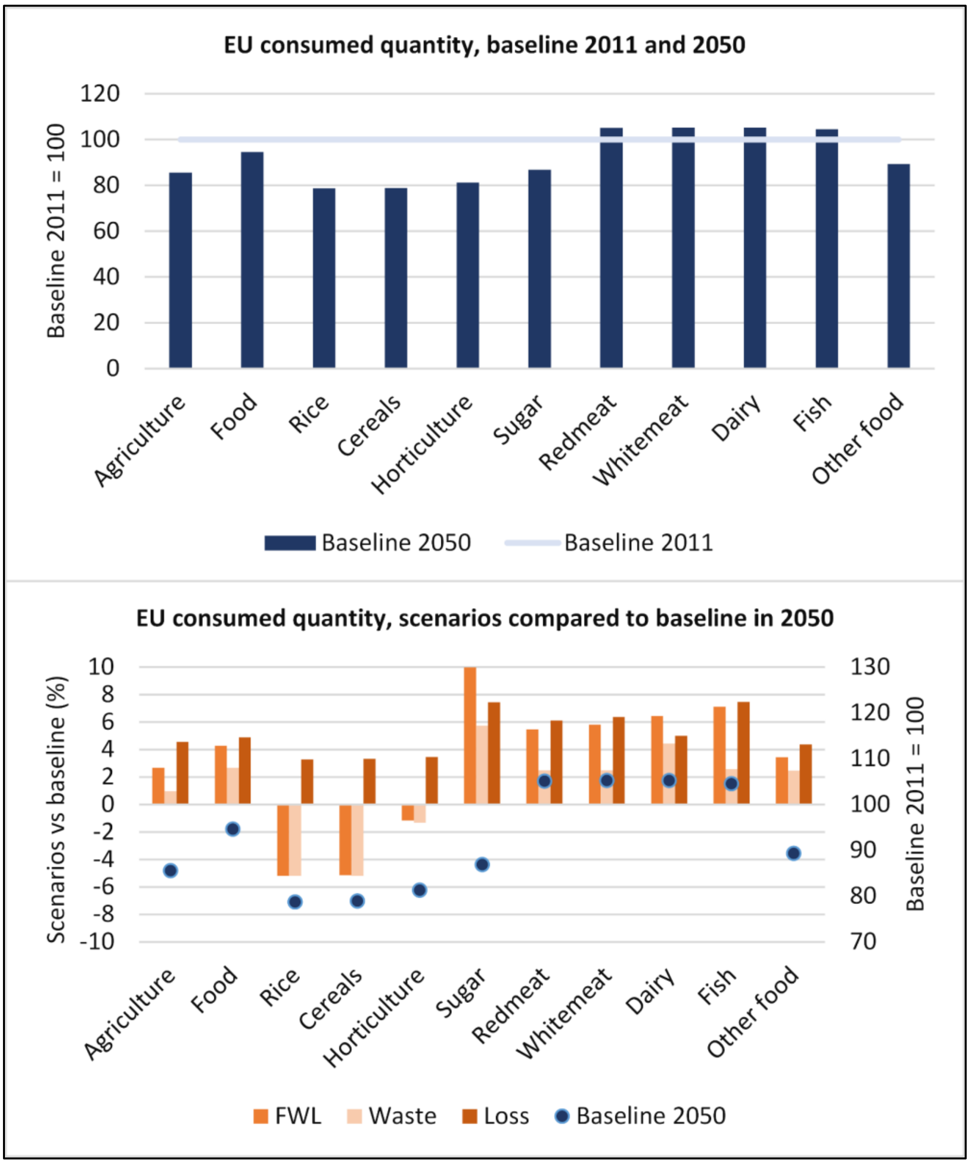


Source: MAGNET simulation results.

The baseline results have shown that the volume of agricultural products, as well as sugar and other food consumed, decreases until 2050 (Figure 37), while the demand for red and white meat, dairy products as well as fish products tends to increase over the baseline period. The reduction in food losses shows notable increases in the consumption of agricultural and other foods, with the highest increases in the consumption of meat, dairy, fish and other processed foods. Reducing food waste gives a much more heterogeneous picture of the impact on consumption. Consumption of cereals and horticultural products decreases, while the demand for food increases, albeit less than in the food waste reduction scenario. As a result, food loss reduction unambiguously increases food consumption through cheaper prices, whereas the effect of food waste depends on the magnitude of the rebound effect.

For the EU, the model results reveal that, for reduced food waste, consumers reduce their demand for cereals significantly and only slightly for horticulture, as the waste rates for these products are comparatively high, which in return leads to a significant reduction in market prices and cereal production. Horticulture production increases despite the significant decline in market prices. The decline in market prices is exacerbated by reductions in agricultural production and post-harvest losses, improved efficiency in food processing and packaging as well as food service production, leading to a further decline in demand for agricultural commodities.

Figure 37. Changes in EU quantity demanded (%) for selected sectors for the baseline and vs the baseline.



Source: MAGNET simulation results.

However, countervailing trends can be observed that reverse the effects on food production described above. Lower market prices stimulate demand for food, leading to increased demand for meat, dairy products, fish and other processed foods that – due to rebound effects – results in only minimal production reductions (red meat) or small production increases (white meat, dairy products). Waste rates for meat and dairy products are among the lowest in the EU. The rather limited increase in food production suggests that other regions are increasing their competitiveness in these sectors more than the EU by reducing food waste and losses, thus gaining at the expense of EU producers.

A similar effect can be observed for sugar. While sugar consumption in the EU increases significantly in all three scenarios, sugar production develops in line with falling market prices: it decreases in the Food Loss and FWL scenarios and increases only slightly in the Food Waste scenario. Regions like LATAME – which are already more efficient in sugar production than the EU in the baseline – can increase their efficiency even further compared to EU sugar production, so that the increased consumer demand is satisfied by increased sugar imports.

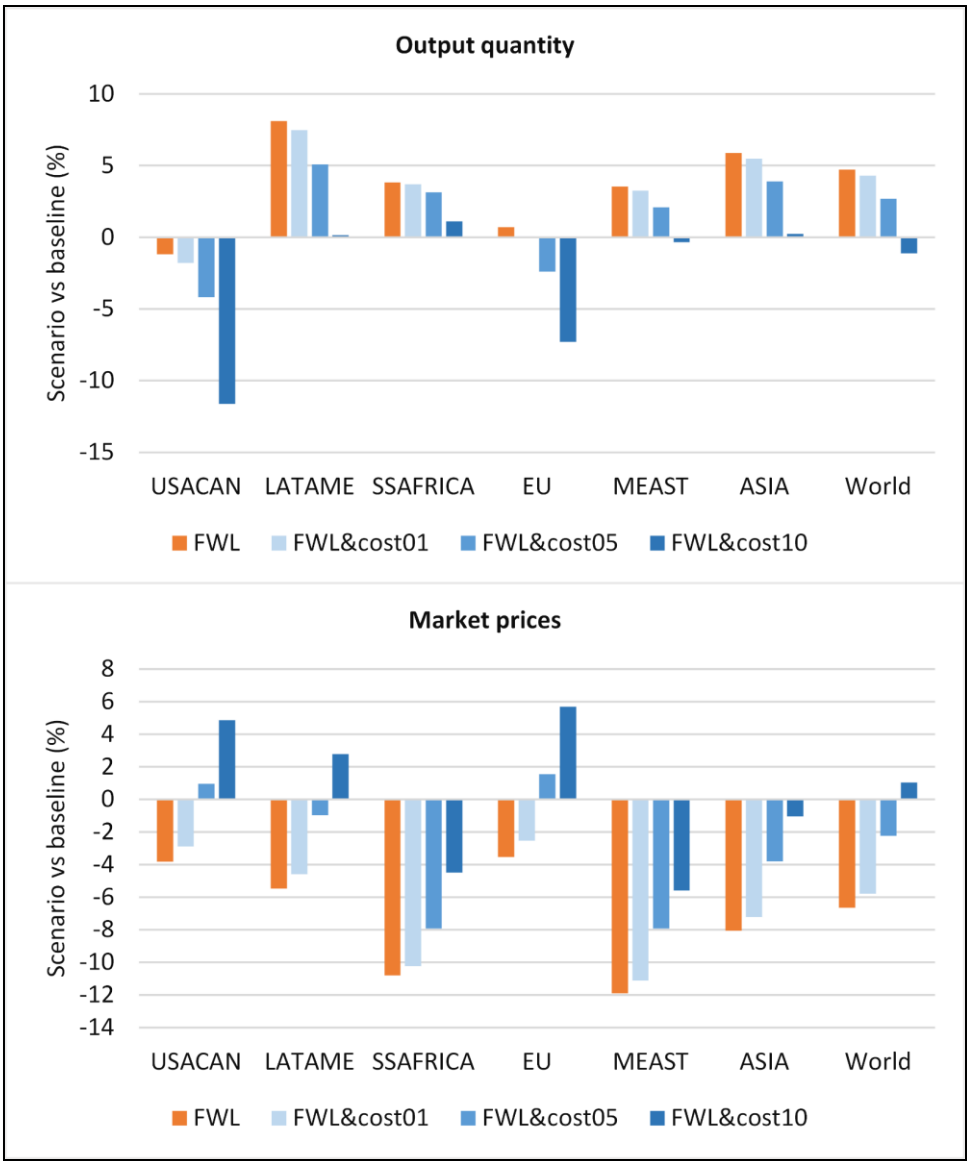
Moreover, such low sugar prices also increase demand for sugar for non-food use, which is discussed in Subsection 4.2.

4.4 Sensitivity analysis of compliance costs

The results discussed in Sections 4 to 4.3 assume that food waste and losses fall without additional compliance costs. As discussed in Section 2.5.1, reducing food waste and loss is not cost-neutral, but no reliable estimates are available at global level that would have been suitable for our analysis. To overcome this problem and shed at least some light on the impact of such costs, this section discusses the result of a sensitivity analysis in relation to different assumptions about the magnitude of these costs.

Figure 38 shows the impact of adding costs of 1%, 5% and 10%, respectively, of the sales value of each agricultural and food product to the FWL scenario on global aggregated agri-food production and market prices for selected regions, while Figure 39 shows the impact on EU agri-food sectors' production and market prices.

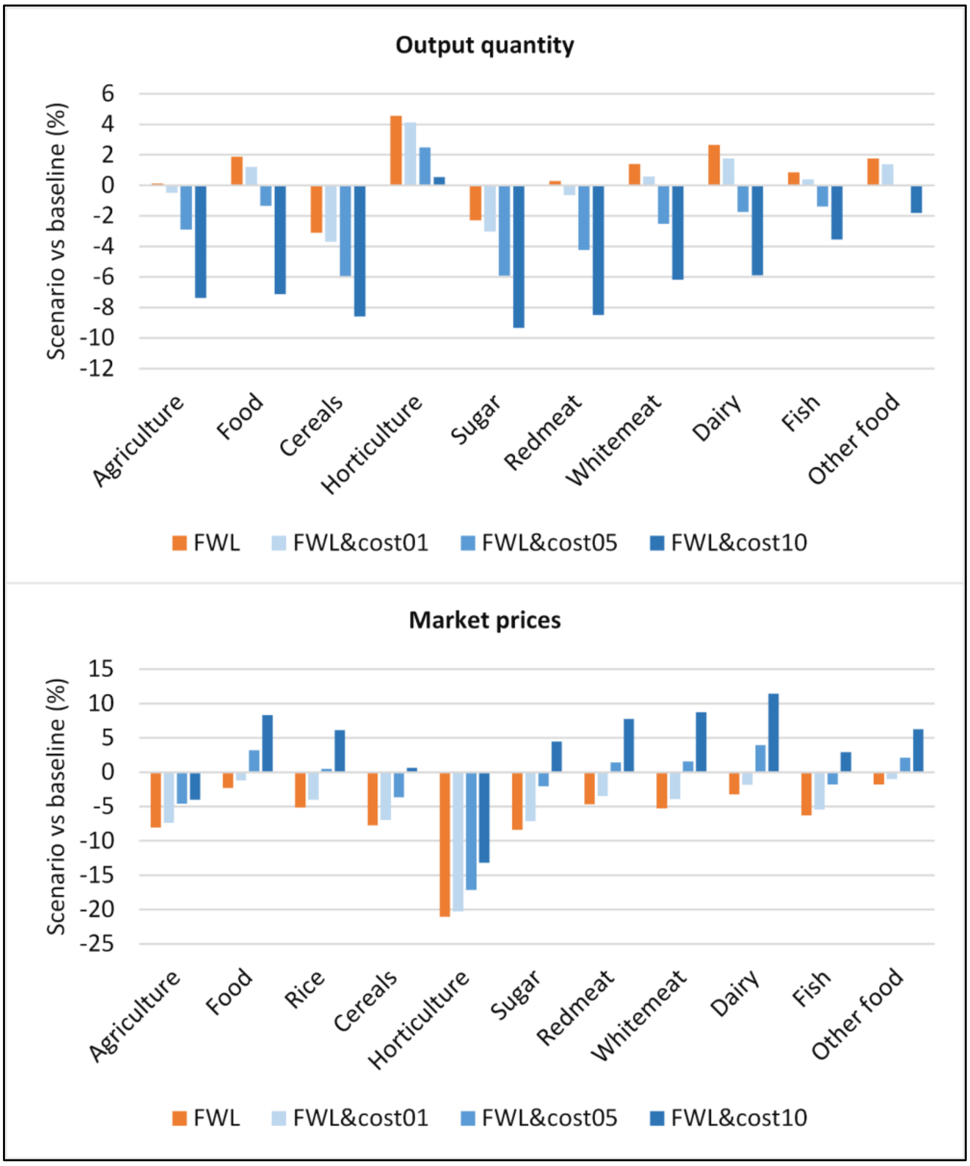
Figure 38. Market impact in selected regions – FWL with associated costs



Source: MAGNET simulation results.

The results clearly demonstrate that the introduction of costs leads to a decrease in agri-food production. For example, in a region such as USACAN, where the FWL scenario leads to a slight reduction in agri-food production, the addition of costs amplifies this effect, and the higher the costs the starker the decline in production. In other regions, such as LATAME and ASIA, it leads to a reduction in observed production increases, which in some regions (EU, MEAST and World) even reverse the effect of the FWL scenario and lead to reduced production with increasing associated costs. Market prices are affected in a similar way, i.e. the higher the assumed costs, the lower the decline in market prices in each region compared to the FWL scenario. While the market prices tend to fall less in scenario FWL&cost01 compared to the baseline as in scenario FWL, market prices fall considerably less or even increase compared to the baseline in some regions – such as the EU in scenarios FWL&cost05 and &cost10 compared to the baseline.

Figure 39 EU market impact – FWL with associated cost



Source: MAGNET simulation results

In line with development at global level, Figure 39 shows that, compared to the FWL scenario, the higher the assumed costs, the greater the decline in production in all agri-food sectors in the EU, and vice versa for market prices.

While adding costs increases the observed effect in sectors such as cereals and sugar, it reduces the positive effects in sectors such as horticulture, white meat, dairy and other food products. In terms of market prices, the results clearly show that adding such compliance costs leads to rising food prices, especially rising prices for meat and dairy products.

In general, the results confirm that the higher the costs of reducing food waste and losses, the more likely it is that production gains will turn into production losses compared to the baseline and the decline in market prices will tend to decrease. The sensitivity analysis shows a clear effect of costs on production, i.e. the higher the unit costs in a sector, the higher the decline in production. In the absence of available estimates of the costs associated with reducing food waste and losses, the sensitivity analysis highlights the importance of such estimates.

While adding 1% or 5% of the associated costs often leads to still quite moderate effects, considering 10% leads to more than a doubling of the effects on prices and quantities of the FWL_cost05 scenario. These figures clearly demonstrate that an analysis of food waste and losses that ignores the associated costs of compliance or adaptation, risks presenting a biased picture of agricultural and food market developments.

Consequently, we consider both the FWL scenario and the FWL_cost05 (midpoint cost) scenario in the following analysis of food waste and loss reduction, dietary change and fossil energy taxation on the three dimensions of sustainability.

5 Results of combined scenarios

This section assesses the impacts of four selected scenarios simulating first a 50% reduction in food waste and loss in 2030 (FWL) and then the combination of FWL with the assumption of 5% compliance cost (&cost5), with a time linear change in consumption pattern towards the feasible reference (plant-based) diet as proposed by the EAT Lancet report (Willet et al. 2019), considering exemptions as described in Section 2.5.2 (&diet) and with the gradual introduction of a 25% global tax on fossil energies until 2050 (&oil) – on the three pillars of sustainability using indicators and footprints. The first subsection focuses on market indicators to firstly discuss the economic impacts at global level and then examine the impacts on the EU, followed by a subsection discussing the social impacts, with a particular focus on the labour market as well as food availability and affordability. This section concludes with the assessment of environmental impacts, looking at indicators and footprints that measure impacts on emissions, land use and water abstraction.

When looking at the ambitious sustainability targets the world strives for, recent policy reforms and directions have shown that no single policy can achieve these targets alone. However, different measures that contribute to achieving certain targets affect one another by creating trade-offs or synergies. Therefore, this study aims at assessing the impact of the four selected scenarios (FWL, &cost05, &oil, &diet) to show their impact on different indicators and to shed light on potential interlinkages and rebound effects to contribute to a better understanding of trade-offs and synergies.

5.1 Economic impact

The previous section has already discussed the impact of reducing food loss at agricultural production, post-harvest and processing levels as well as reducing food waste at retail and consumer levels. Model results have revealed that food loss related to the production site leads to an increase in the quantity of agricultural and food commodities, which reduces market prices and, as a result, reduces input costs for food processing and thus boosts demand for now cheaper agricultural and food commodities. Furthermore, we have seen that reducing consumer food waste, as well as waste related to food services and retail, subsequently counteracts these effects. Household food expenditure for certain products is now reduced; however, the rule on market prices that equalise supply and demand apply so that food waste and loss reductions taking place at the same time could result in increased food consumption as food, in general, becomes cheaper compared to the baseline. However, Section 4.2 has clearly shown that the magnitude of these effects depends on the assumption with regard to the compliance cost associated with food waste and loss reductions. The tax imposed in the &oil scenario increases the market price for fossil energies and thus leads to reduced demand for fossil energies from consumers, but also producers that use fossil energies as input. The &diet scenario introduces – on top of food waste and loss reduction – a significant reduction in red and white meat, as well as dairy consumption, and is thus expected to counteract the increasing demand for these products due to cheaper market prices driven by food waste and loss reductions.

5.1.1 Global perspective on the economic impact

Figure 40 shows changes in output quantities, market prices as well as the consumption of agri-food in the four selected scenarios compared to the baseline in the year 2050.

Overall, agri-food output increases in all scenarios, despite falls in USACAN and EU, while market prices generally decrease, and agri-food consumption expands. However, the extent to which these effects occur reveals distinct differences in price development and output and consumption changes between regions and scenarios.

The greatest effects on agricultural and food output are in low-income and emerging regions such as SSAFRICA, Latin America and ASIA. Reducing food loss in these regions leads to an increase in agricultural productivity, which results in a significant fall in market prices. Food waste reductions lead to reduced household demand for agricultural and food commodities as well as input demand for food services, which enhances the fall in markets prices. By contrast, in high-income countries such as USACAN and EU, the food waste effect is greater as waste rates tend to be higher in these regions. In return, a fall in market prices drives the consumption of agricultural and food products (Figure 40), as well as consumption for non-food uses. The fall in production and market prices combined with an increase in domestic demand, leads to a relative increase in the reliance on food imports for the EU and USACAN.

Figure 40. Global changes in agri-food markets compared to the baseline in 2050 (%)

Source: MAGNET simulation results.

As discussed extensively in Section 4.2, costs associated with food waste and loss reductions and production are inversely related. As a result, the &cost scenario tends to reduce the production increases in low-income and emerging regions due to food waste and loss reductions. It further decreases production reductions in USACAN and turns a production increase in the EU into a decrease; however, the magnitude of these effects depends on the underlying assumption with regard to the extent of the compliance cost. Market prices thus fall less in all regions when considering costs, or even increase compared to the baseline for USACAN and the EU and lead to a significant reduction in agri-food consumption compared to the FWL scenario.

Taxing fossil energies increases input costs for producing commodities in general. However, this affects the sectors that use fossil energies extensively. There are benefits of increased fossil prices to the agricultural sector if an agricultural production sector is less fossil fuel-intensive compared to the economy average. In the &oil scenario, market prices for fossil energies increase, thus bio-based energies such as biofuels and biodiesel become more competitive and demand for these products increases, which results in a higher input demand for agri-food commodities from these production sectors (switch from fossil to bio-based energies). Consequently, agri-food production increases in all regions compared to FWL, particularly in countries that produce sugar crops for bioethanol, such as LATAME. While production at world level increases almost twice as much as in the FWL scenario compared to the baseline, the model results reveal a fall in market prices in the &oil scenario (-5.5%) that is more in line with the FWL scenario (-6%), which is driven by this increased demand for bio-based production sectors. In general, the rise in fossil prices leads to an economic slowdown, which results in a reduction in real incomes and, thus, demand.

The &diet scenario reduces the calorific shares of red and white meat as well as dairy consumption, while it increases the calorific share of fish consumption. The combined simulation of food waste and loss reductions and these dietary changes shows that, overall, agri-food consumption increases in all regions except in SSAFRICA and ASIA compared to the FWL scenario. The above-mentioned dietary changes lead to a significant reduction in red and white meat as well as dairy consumption, and boost fish consumption. In addition, results highlight significant increases in horticulture and cereal consumption as well as other food commodities, so that overall agri-food consumption tends to increase to reach the same kcal consumption per capita as in the FWL scenario. Agri-food production in all regions falls by adding diet shifts compared to the FWL scenario. These economic costs relate to a decline in meat and dairy production sectors. Furthermore, diet shifts lead to asymmetric effects on the different regions. Figure 40 shows the largest reduction of agri-food production in developed regions, as these regions have higher shares of meat in their diet, so greater adjustments are needed to achieve the levels of the EAT Lancet feasible reference diet (most dramatic shifts in industrialised countries). The reduction in the consumption of livestock products leads to a further decline in cereal and other crop production as they are heavily used as feed input to livestock. In return, cereals and horticulture in human consumption increase due to the introduced diet shift. One would expect that the loss of the livestock business hits LATAME, in particular, which is the largest producer of beef meat. However, due to its extensive and very competitive production – and a rather small impact on the feed sector – the impact on its beef production is relatively smaller than in other regions, and it still seems to maintain a rather high export share. There are falling real incomes in livestock-producing regions, other regions such as ASIA and NAFRICA that only partially accept, or SSAFRICA that does not accept the feasible reference diet benefit at all.

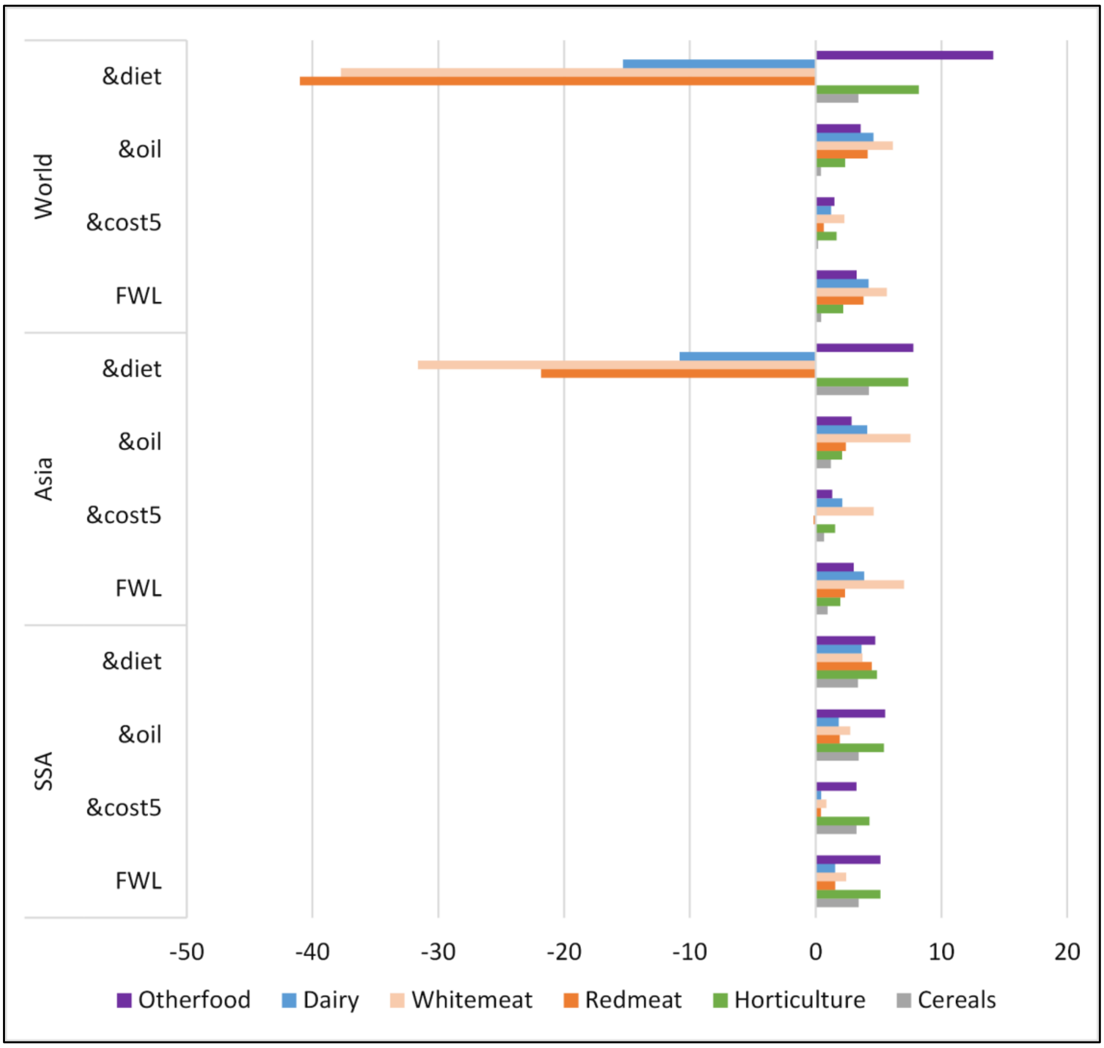
In all regions, agri-food market prices further decline, driven in particular by a huge drop in meat and dairy prices.

At world level, agricultural and food prices decline by more than 5% in the FWL scenario and by 7% in the &diet scenario. Hence, the &diet scenario further contributes 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 global level. However, production in high-income countries reduces while consumption increases – even more than in low-income or emerging countries – compared to the baseline.

Nevertheless, the diet scenario is the scenario that leads to the greatest impact on the results. The diet shift boosts agri-food consumption in high-income countries and the world average, however, leads to a slight reduction in agri-food consumption in SSAFRICA and ASIA. These developments lead to a further reduction in the production of agri-food commodities in most regions, except for Latin America when compared to the FWL scenario only.

The changes in SSAFRICA relate to the exemption from the dietary changes as discussed in Section 2.5.2. The diet shift in other regions combined with FWL reductions and the associated price declines due to 'oversupplies' drives food demand in SSAFRICA. Here, results show rather stable / slightly decreasing cereal and horticulture consumption, while red and white meat as well as dairy consumption significantly increases due to the large fall in world market prices of meat and dairy (Figure 41). Consequently, dietary patterns in these regions shift towards a diet that includes an increased number of proteins from animals and could thus contribute to improving malnutrition and related diseases due to a lack of proteins in diets. However, this will not be further assessed in this report.

Figure 41. Detailed consumption changes in selected regions compared to the baseline in 2050



Source: MAGNET simulation results.

In addition, ASIA presents a reduced increase in food consumption compared to the FWL scenario. This relates to an overall smaller reduction in products from animal origin as some countries in Asia are exempt and in many countries the calorific share from meat is also still comparably low. As a result, the shift in consumption towards cereals, horticulture and other food is lower.

Changes in agricultural and food production as well as price changes affect the total output from economies. On the one hand, prices decrease and, in some regions, (USACAN and EU) agri-food production also reduces 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, meaning that the output from these sectors increases, while the overall impact of the &diet scenario is less clear. Figure 42 shows the impact of the four scenarios on the regions' GDP compared to the baseline. While the results indicate 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 the total GDP and, accordingly, benefit the most from the efficiency gains. Adding costs reduces these GDP gains in all regions. The higher the assumed costs, the stronger the downturn on real GDP, but the extent to which GDP gains reduce varies across regions.

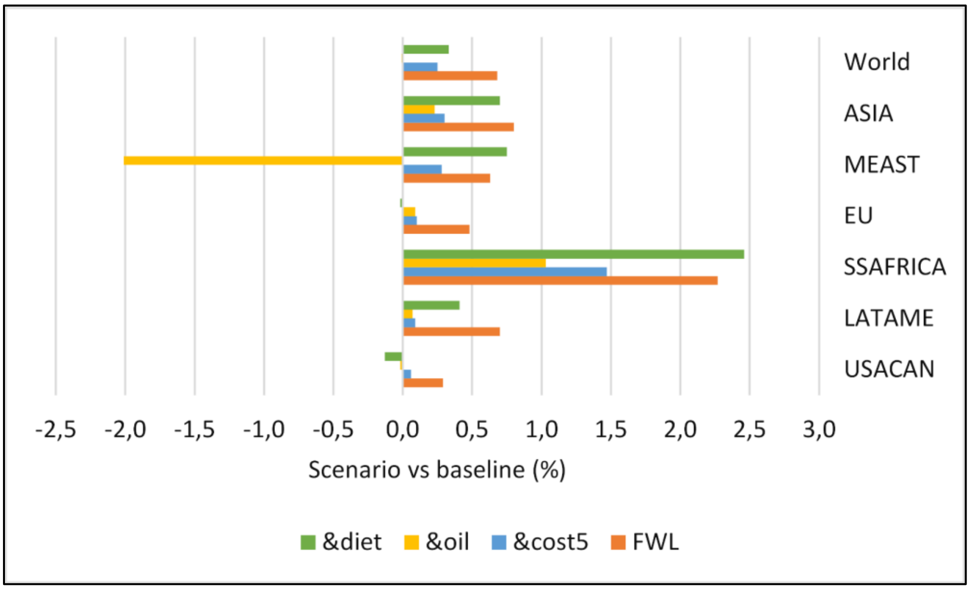
In contrast, a global tax on fossil energy drives energy prices up and consequently leads to lower GDP gains or even losses, as the increase in energy costs can only be partially compensated by the growth of the non-food bio-based sectors. Thus, as oil prices rise, the results confirm an even deeper global slowdown effect. GDP in the MEAST is most affected by these developments, as the region is heavily dependent on fossil energy production.

Overall food loss and waste reduction reveal a positive impact on GDP, as expected from increased consumption and production efficiency. The initial rates of food waste and loss clearly drive the impact on GDP. Usually, food waste rates are higher in high-income regions such as OCEANIA, the EU and USACAN and therefore drive the GDP results, whereas food loss rates dominate the effect in low-income countries. For example, SSAFRICA benefits the most from food losses with regard to real GDP as the agricultural sector accounts for a high share of the total GDP. If the agricultural sector becomes more efficient by reducing food losses (highest rates in SSAFRICA, and other low-income countries), this increases the output from the agricultural sectors, but due to a more efficient use of resources it also releases resources that can be used in other sectors and therefore increases output in these sectors.

FWL reduction leads to the highest effects in SSAFRICA. In developing countries, the agricultural sector accounts for a much larger share of the total GDP. Therefore, efficiency gains in agri-food production affect GDP more. In addition, producer side effects (food loss) mainly drive the results. Developing countries have much higher food loss reduction potential compared to developed countries. Positive impacts in other countries are reduced compared to FWL, as energy becomes more expensive.

The change in diets is introduced as a pure demand-side shock that leads to a reduction of agri-food production in developed countries, in particular the EU and USACAN. Hence, 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 a reduction 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.

Figure 42. Impact on GDP compared to the baseline in 2050 (%)



Source: MAGNET simulation results.

The positive economic outcomes from the transition to healthier diets in the health sector arising from, for example reduced healthcare costs or rising labour productivity, are not included in this modelling exercise. Hendriks et al. (2021) estimate a (negative) externality of approximately 20 trillion USD associated with current global food consumption patterns, which includes a cost of 11 trillion USD associated with increased mortality related to diseases. This is compared to the value of total global food consumption of around 9 trillion USD.

Springmann et al. (2016) found that in scenarios of improving diets, the monetary value of health improvements would be comparable to, or even exceed, the value of the environmental benefits. Estimates of economic benefits in the year 2050 range from 1–31 trillion US dollars, equivalent to 0.4–13% of global gross domestic product (GDP). The cost of obesity alone is estimated at 3.3% of GDP in OECD countries (OECD, 2019b). A recent study by the Tallard et al. (2022) reveals that healthier diets reduce the risk of malnutrition and less obesity, resulting in about 86 million less obese persons in the EU.

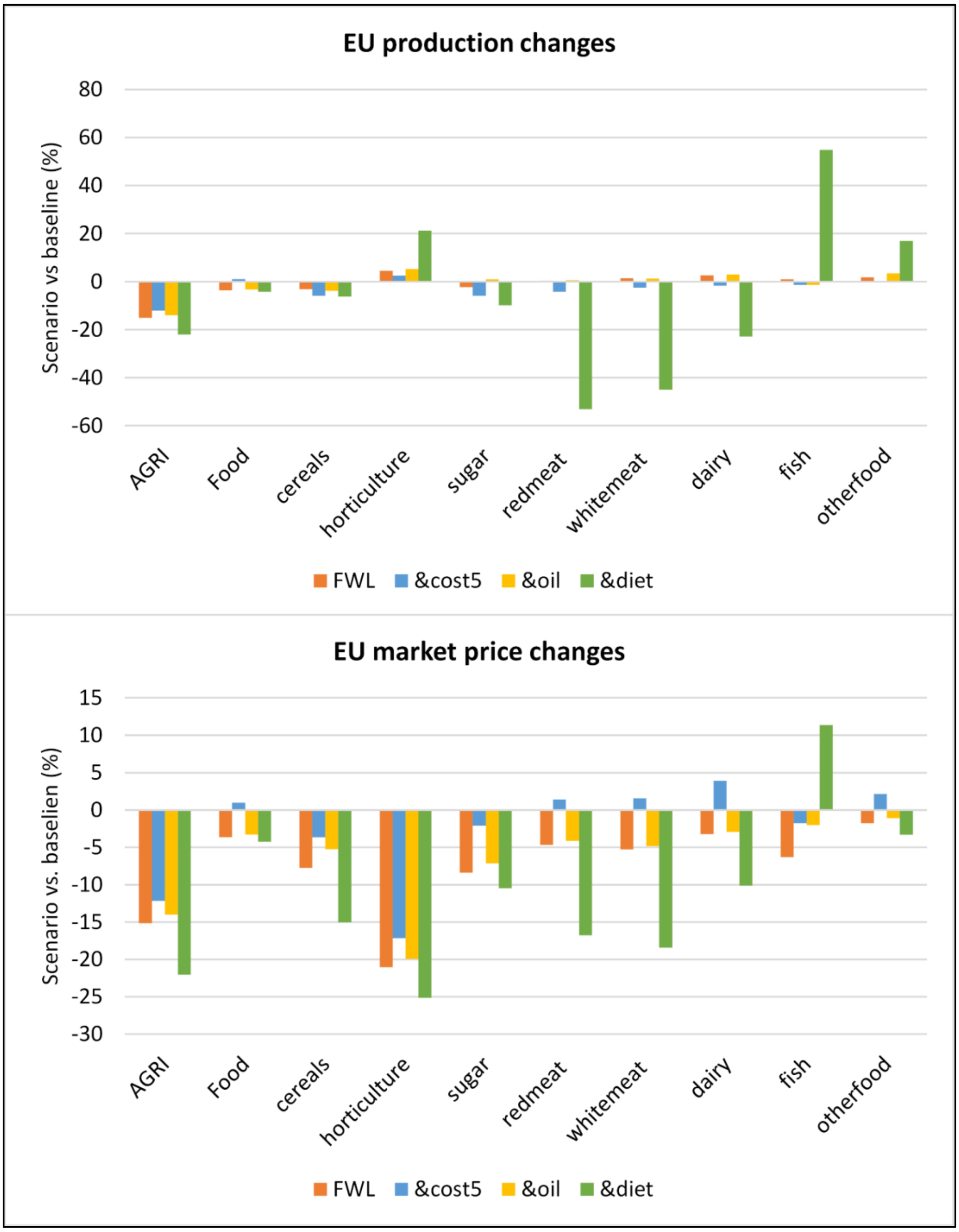
The scope of this study also excludes the impact on and of climate change; thus, it does not investigate the costs of inaction to limit climate change and biodiversity needs. Latest research shows possible options of aligning the climate action narrative with one of increasing welfare and sustainable development (Koeberle et al., 2021).

Finally, a quantitative assessment by Sanderson and O'Neill (2020) find that the peak costs for a 1.5 degree Celsius stabilisation target, resulting from a later start to mitigation, are frontloaded and higher. For example, the peak costs for a 1990 start to mitigation are estimated at 17% of global GDP in 2070, whilst the corresponding result for a 2020 start to mitigation is 35% of global GDP in 2035.

5.1.2 Economic impacts in the EU

The previous section discussed the global impact of the four selected scenarios on agri-food markets. This section aims at providing deeper insights related to the effects on selected products in the EU. On an aggregated level, FWL reduction leads to a distinct reduction in agricultural production and a slight decline in processed food production. On a disaggregated level, the picture is heterogeneous. Figure 43 highlights the reduction in cereals, while horticulture production increases and, furthermore, points to a rise in meat and dairy production in the EU related to FWL. Whether the production of processed food increases due to FWL reductions depends on the assumption of the cost associated with it as shown by scenario &cost5. The impact of fossil price increases is rather small on agri-food production in the EU, with the greatest impact on other food, fish and sugar production. Taking sugar as an example, scenario &oil leads to increased sugar production, but a reduced fall in sugar prices and lower household sugar demand compared to scenario FWL. This result is driven by substituting fossil fuels with biofuels and thus increased biofuel demand leading higher demand for sugar inputs.

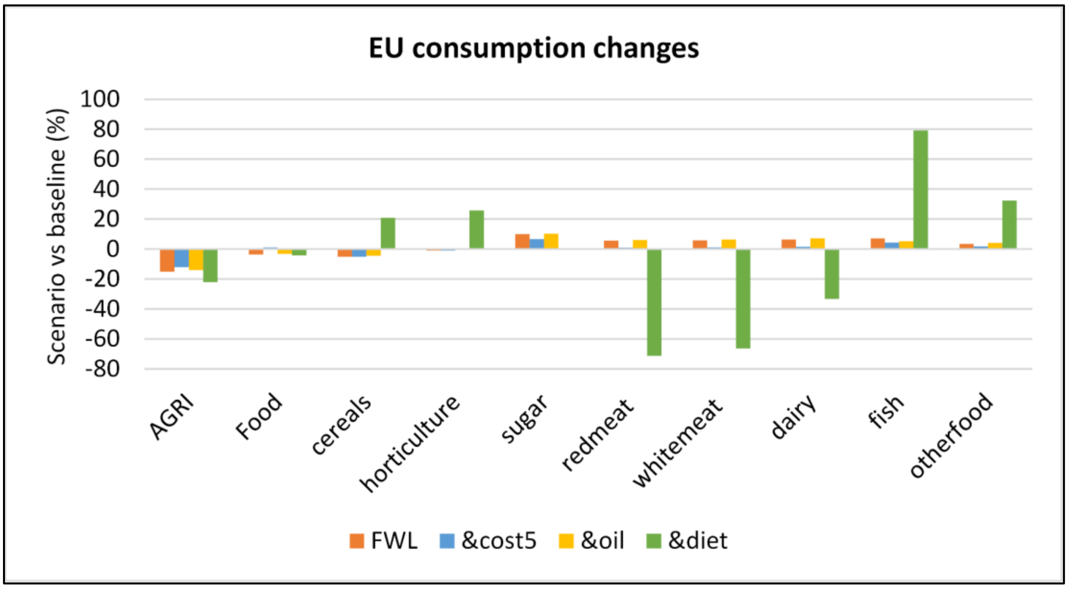
Figure 43. Impact on EU agri-food markets compared to baseline in 2050 (%)



Source: MAGNET simulation results.

In line with the market price falls of agriculture and food commodities, the results indicate a shift in EU diets (Figure 44) towards processed food, particularly meat, dairy and fish in the EU due to a FWL reduction that is less observable when accounting for costs, whereas the consumption of cereals and horticulture declines (Figure 44). Meat and dairy imports tend to increase relatively more than EU production to satisfy the demand in the EU. As a result, FWL and also scenario &oil amplifies trends already observed in the baseline. The introduction of the &diet scenario turns these effects around and leads to a clearly increase share of vegetables and fruits and reduced shares of meat and dairy products in EU diets, as the impact of FWL reduction related to increased production efficiciency is nearly outweighted by price induced consumption increases.

Figure 44. Impact on EU agri-food consumption compared to baseline in 2050 (%)



Source: MAGNET simulation results.

For the EU, Himics et al. (2022) analysed the co-benefits of plant-based (flexitarian) diets on agricultural ammonia emissions, air quality and human health, and showed that economic benefits of improved health would mitigate losses in agriculture.

5.2 Social impact

5.2.1 Global perspectives on social impact

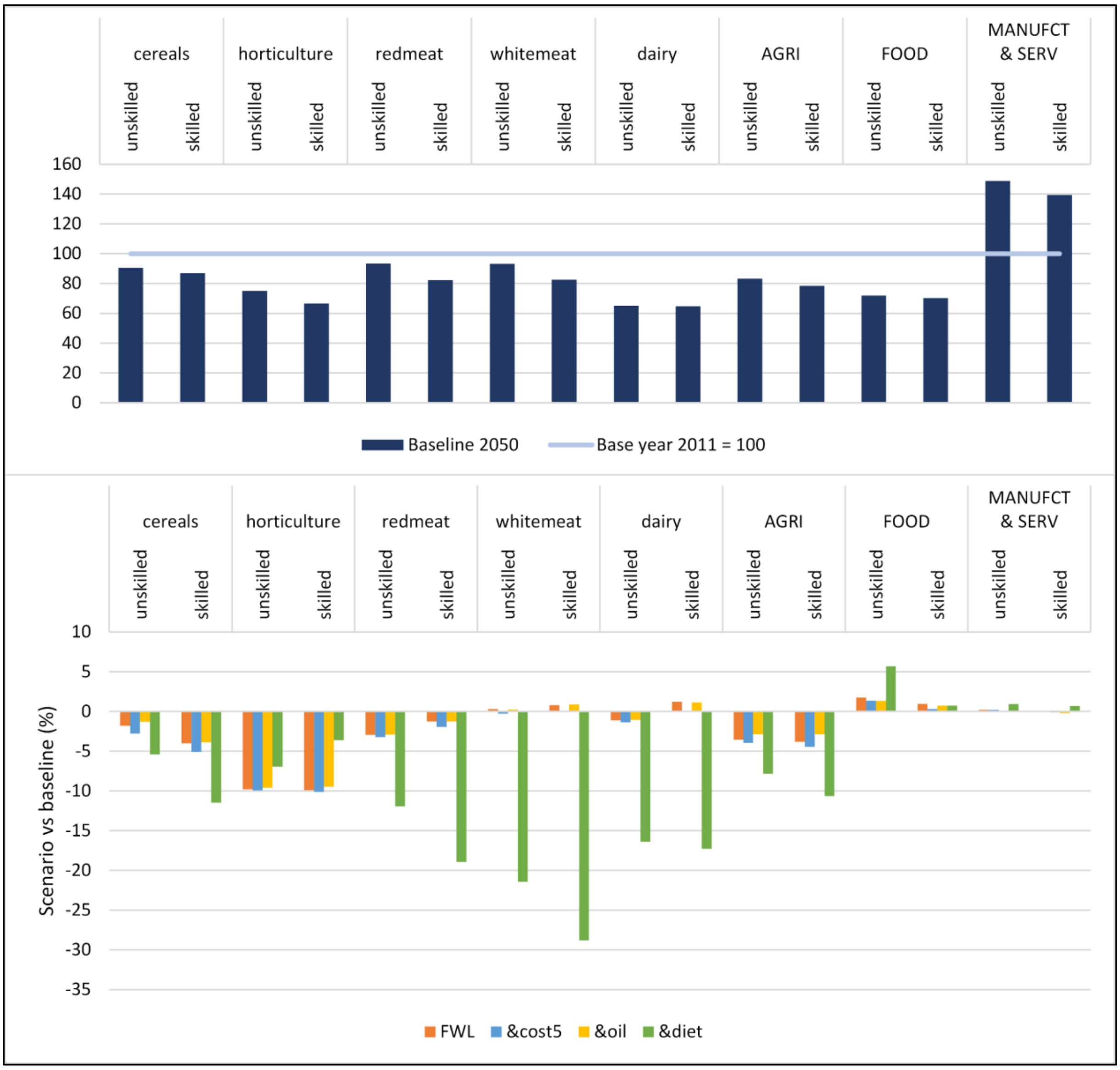
This subsection first focuses on employment in the agri-food sector (Figure 45), followed by food affordability (Figure 46), to provide some insights into the social sustainability implications of the four scenarios.

The first graph in Figure 45 presents the change in employment for unskilled and skilled workers in the baseline. The change from 2011 to 2050 is depicted in dark blue, while employment in 2011 equals 100 (light blue). The second graph then shows the changes in employment for each of the four scenarios compared to the baseline in 2050. 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 -3.8 % of skilled and -3.6% of unskilled workers compared to the baseline in 2050. 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 45). Due to the considerable fall in agri-food market prices, people spent less of their income on food, which increases consumption of non-food commodities and thus increases employment in other sectors such as manufacturing.

Adding costs associated with FWL reductions leads to a smaller increase in agrifood output compared to the baseline and, thus, an increased loss of jobs compared to FWL in the agricultural sector on a global scale. By contrast, the &oil scenario tends to keep jobs in the agri-food sector at global level, as it boosts the demand for agricultural products for non-food use and reduces the competitiveness of sectors that are highly dependent on fossil energies and, thus, partially prevents an outflow of workers from the agricultural sector as the input intensity of fossil fuels is lower in agri-food than manufacturing.

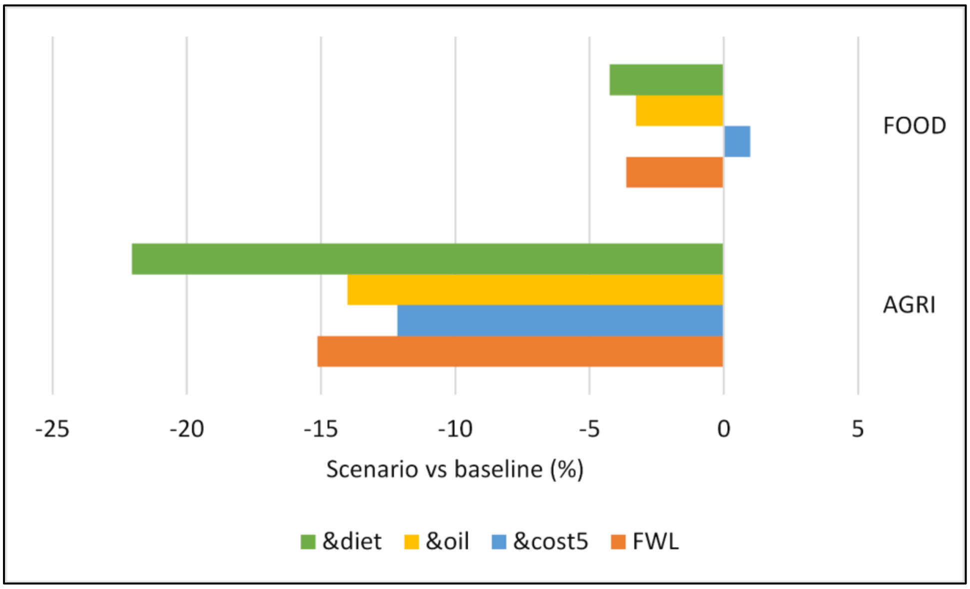
Despite these effects, the addition of costs or a global tax on fossil energy does not have a large impact on agricultural employment, whereas the change in global dietary habits results in a much stronger decline of labour demanded by the agricultural sector. However, in this case, the sharp decline in meat and dairy consumption drives the fall in labour, while the increase in fruits and vegetables consumption increases employment in this production sector compared to the FWL scenario. Adding the diet shift redistributes employment loss more towards livestock and less towards horticulture, as expected. Employment in the cereal sector benefits less compared to horticulture. As cereals are an important input for livestock production, the diet shift results in a further decline of labour demand. These effects are less desirable at a global as well as regional level as all scenarios are associated with reduced employment in the agricultural sector. Job losses in the agricultural sector are particularly important for low-income regions in which many, often small-scale, farmers could be affected. In contrast, the impact of all scenarios on employment in the food sector is small but positive (+1.8% (5.7%) unskilled labour and +1% (0.8%) skilled labour in the FWL (&diet) scenario). In addition, the manufacturing and services sectors benefit from the lower labour demand of the agricultural sector. As the share of workers employed in agriculture is rather small compared to the manufacturing and service sectors, the significant impact on employment in the agricultural sector only leads to small percentage changes in the manufacturing and service sectors (+0.9 % unskilled workers and +0.7 % skilled workers in scenario &Diet). These changes show that workers originally employed in agriculture are moving into food processing, manufacturing and services. This process could be supported by policy, e.g. through training opportunities to facilitate the development of new jobs in these sectors that are useful to support dietary changes and improved waste management.

Figure 45. Impact on employment compared to the baseline in 2050



Source: MAGNET simulation results.

Figure 46. Impact on agri-food prices compared to the baseline in 2050.



Source: MAGNET simulation results.

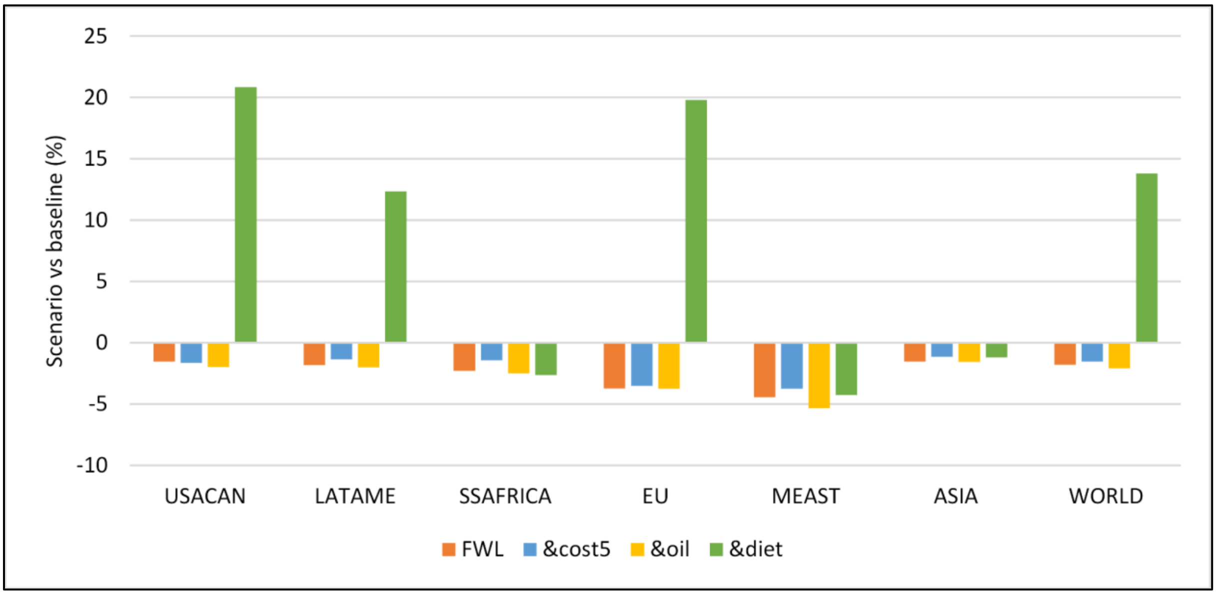
As previously shown, agricultural and food consumption increases in all regions, while global agricultural and food prices decrease, indicating a positive impact of all scenarios on food affordability (Figure 46). The region-wide reduction in food prices is a significant benefit for the most vulnerable members of the society, particularly poor households in developing countries and could thus contribute to reducing food insecurity. To further assess this, Figure 47 displays 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 the 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 reduction in the expenditure share in SSAFRICA. Moreover, Figure 41 shows the positive impact of the &diet scenario, in particular, on the average diet composition in SSAFRICA, indicating overall increased food consumption with higher relative increases for horticulture, meat and dairy compared to staple foods.

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 to poor people as it increases food affordability; however, on the other hand, it results in reduced farm income and thus contributes to a possible increase in poverty.

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.

One caveat is the price impact on farm households in developing countries. Here, it clearly depends on the extent to which international price transmission reaches the local market, and thus how much prices on local markets decline and thus reduces farm household incomes, which cannot be assessed by a global CGE model such as MAGNET.

Figure 47. Change (%) in the budget share of food by region compared to the baseline in 2050



Source: MAGNET simulation results.

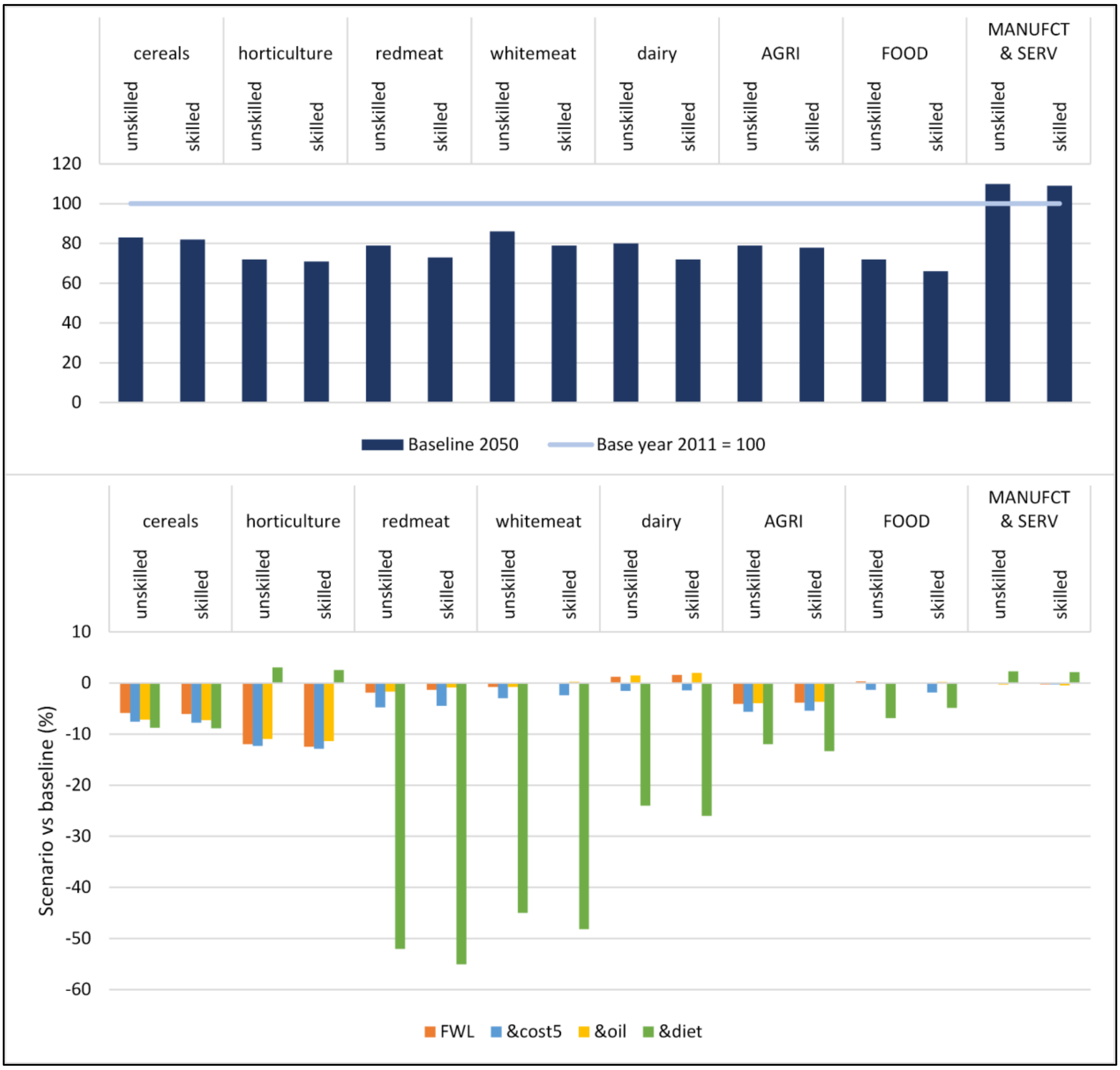
5.2.2 Social impacts on the EU

Looking at the impacts of the four selected scenarios on EU society, Figure 48 shows that the EU agricultural sector suffers a loss of -4% of unskilled workers and -3.8% of skilled workers in the FWL scenario compared to the baseline that increases by adding costs and more than triples when including the diet shift. Compared to the global level, the impact on employment in the food sector is mixed. While unskilled and skilled employment in the &diet scenario falls (-6.9% and -4.9%), scenario FWL leads to an increase in unskilled labour (+0.3%) and a decrease in skilled labour (-0.1%). The disaggregation of job losses by sectors confirms the development at global level. FWL leads to job losses in the cereal and horticulture sector and slight increases in the meat and dairy sector, while &diet increases labour demand for horticulture production and dramatically reduces labour demand for meat and dairy production. This figure also shows the fall in labour demand of the cereal sector as a result of reduced cereal inputs to livestock. As previously discussed, the oilseeds sector (not shown in Figure 48) benefits from increased fossil energy prices that boost the demand for agricultural commodities for non-food use such as oilseeds for biofuel production and consequently results in an increase in jobs in the &oil scenario in the oilseeds sector.

FWL, &oil and &diet leads to remarkable falls in agri-food prices, thus reducing the cost of the food basket in the EU.

The effect of costs associated with FWL on the food basket clearly depends on the assumptions with regard to the size of these costs. However, adding costs clearly reduces the positive impact of pure FWL reductions. The higher these costs, the more likely it is that FWL reductions contribute to an increase in the cost of the food basket compared to the baseline in the EU. In addition, Figure 48 indicates changes in dietary composition in the EU due to FWL reductions. The reduction in market prices leads to an increase in the consumption of processed food in line with existing consumption patterns, so that meat and dairy consumption rises, while cereal and horticulture consumption falls. This development contradicts the SDG objective targeting less meat consumption and increased vegetable and fruit consumption to improve health and shows the need to change consumer behaviour towards a more sustainable and healthy diet as introduced in the &diet scenario.

Figure 48. Development of EU employment from 2011 to 2050 for selected sectors by skill type



Source: MAGNET simulation results.
Note: MANUFACT&SERV also includes energy and extraction sectors but does not include bioeconomy sectors.

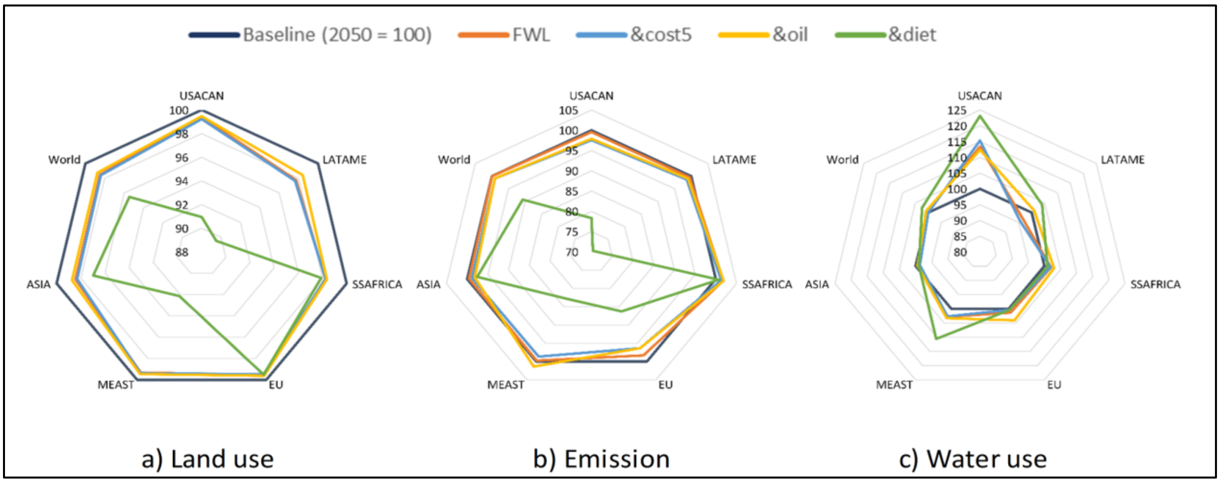
5.3 Environmental impacts

Subsection 5.1 discussed the economic impacts with a focus on production and consumption changes. This subsection now evaluates the impact of these changes on environmental indicators.

5.3.1 Global perspective on environmental impacts

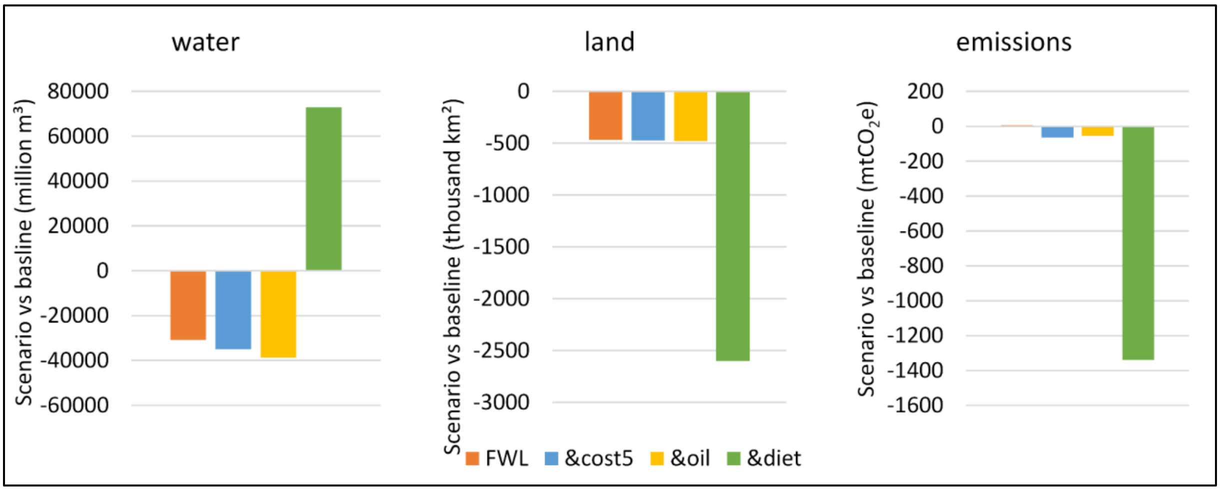
Global food loss reductions, fossil energy price changes and shifts in food consumption patterns due to dietary changes or waste reduction affect agri-food consumption, production and the use of production factors as well as trade differently in all regions. As production in the different regions differs with regard to technology, efficiency and the use of production factors – including natural resources – the impact on the environment also differs. As a result, the impact of the selected scenarios is expected to vary between the regions. Figure 49 provides a general overview of how much the selected scenarios impact on (a) land use, (b) emissions and (c) water use. Land use, emissions and water use in the baseline is set equal to 100 in the year 2050. FWL reductions lead to output increases in all regions. However, due to more efficient agricultural and food production, less land is required compared to the baseline, with the greatest improvements in LATAME and SSAFRICA. The addition of fossil fuel price increases only leads to a significant effect in LATAME; this result is due to the substitution of fossil fuels by biofuels, which in turn increases the demand for sugar inputs for biofuels and thus leads to an expansion of land used for sugar production compared to the FWL scenario. While the impact of the &diet scenario is rather negligible in the EU and SSAFRICA, land use in the other regions declines remarkably with the greatest effect observed in LATAME, mainly driven by the decline in livestock production and thus reduced use of pastureland, which is not offset by increased land use for horticulture and therefore increased arable land. Global land use related to food consumption in the FWL, &cost5 and &oil scenarios declines minimally by around 0.5 km², whereas the &diet scenario leads to a reduction that is five times higher (Figure 50).

Figure 49. Global impact on overall agri-food land use, water abstraction, emissions



Source: MAGNET simulation results.

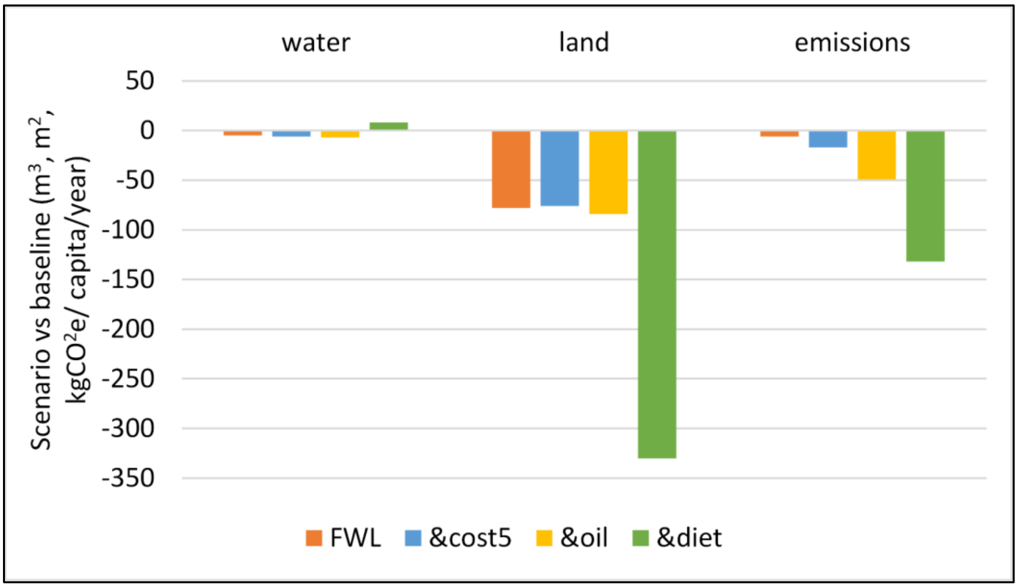
Figure 50. Global impact on land use, water abstraction, and emission changes related to household food consumption compared to the baseline in 2050



Source: MAGNET simulation results.

In line with the reduction in land use, emission reductions are also the highest in the &diet scenario, while the other scenarios lead only to rather small improvements in overall agri-food emissions (Figure 49). The effects are particularly pronounced in industrialised regions and regions that are among the main livestock producers, while regions that are, at least, partially exempt from the diet shift – such as SSAFRICA or parts of ASIA – exhibit only very small improvements. In ASIA, increased rice production also contributes to increasing emissions. While FWL reduction only minimally reduces emissions from agri-food production, the impact of associated costs positively impacts on further reductions. Dietary shifts from meat consumption towards increased vegetable and fruit consumption has a significant mitigating impact on emissions. This firstly relates to less cattle and related methane production, but, secondly, also to reduced grazing by cattle on pastureland, which improves the ability of the soil to absorb GHGs (Philippidis et al., 2021). Overall emission savings related to household food consumption compared to the baseline are rather small in scenarios FWL, &cost5 and &oil, whilst dramatically higher in the &diet scenario (Figure 50). This is also shown by the emissions footprint savings measured in $kgCO_2e$ per capita per year compared to the baseline, which reveals a clear trend with the lowest saving in the FWL scenario, then &cost5 and &diet and the largest impact on the footprint from the &diet scenario (Figure 51).

Figure 51. Global food footprint savings compared to the baseline in 2050

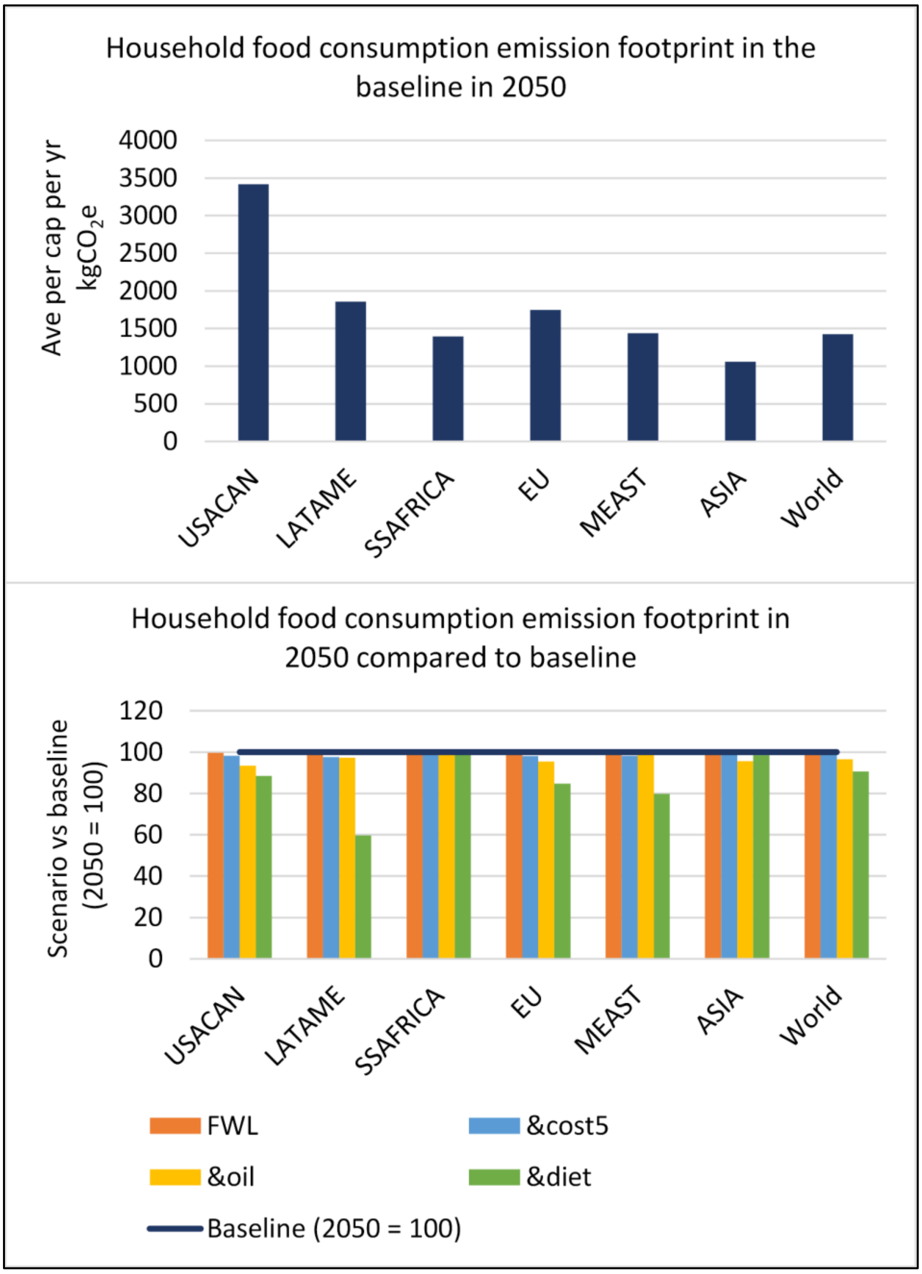


Source: MAGNET simulation results.

The impact of the selected scenarios on water abstraction (Figure 49) provides an image that deviates considerably from land use and emissions. In many regions, water abstraction increases compared to the baseline. Again, the highest effects relate to the diet shift. While livestock production declines, horticulture production significantly increases. Horticulture production is water-intensive, and largely depends on irrigation, and the increase in water abstraction for crops outweighs the savings from reduced livestock. However, the model does not account for all livestock water uses; it only depicts the indirect water consumption via feed input. Results show a strong increase in irrigated agricultural land used for horticulture in many regions such as USACAN and the MEAST. The impact of FWL is quite mixed: while water abstraction declines in LATAME and ASIA, it rises for USACAN. The &oil scenario affects regions quite differently; while this scenario leads to a distinct increase in sugar production in LATAME, agri-food production effects in the USACAN have been only moderate. However, water abstraction due to the &oil scenario increases in the USACAN and remains rather unaffected in LATAME. On a global scale, water consumption due to household food consumption (water footprint) decreases by around 30 829 million m^3 (5.1 m^3/c/y) compared to the baseline in 2050 in the FWL scenario and further declines in the &cost5 and &oil scenarios, whereas it significantly increases in the &diet scenario (around 72 948 million m^3 (8.2 m^3/c/y)) (Figure 50, Figure 51).

Figure 52 and Figure 53 provide further insights into the regional impacts of the scenarios on the emission and land footprints.

Figure 52. Emissions footprint changes by region

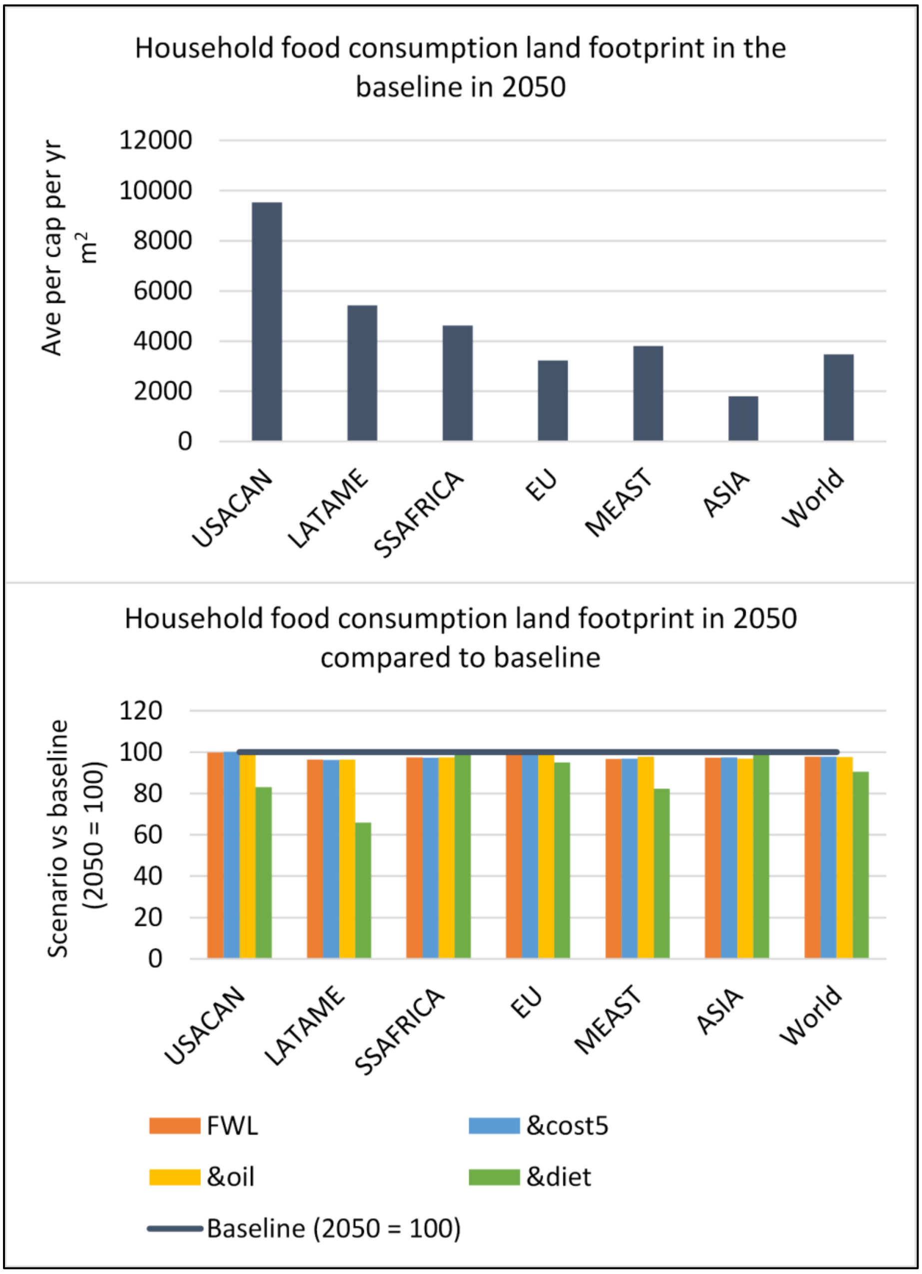


Source: MAGNET simulation results.

The figure on the left-hand side shows the emissions per capita per year in $kgCO_2$ equivalents related to household food consumption in the baseline, while the figure on the right-hand side shows the deviations from the baseline in the year 2050, which is set equal to 100.

The baseline portrays large differences between regions, with the highest emissions footprints in USACAN and OCEANIA. The FWL scenario has a rather small impact on the emissions footprint, of which the highest reduction can be observed in LATAME; &cost5 also only contributes to a very limited further improvement. A heterogeneous impact on agri-food consumption-related emissions can be observed in the &oil scenario, with the greatest improvement in USACAN and more or less no impact in the MEAST. Only the &diet scenario leads to a considerable reduction in emissions footprints equal to around 10% at global level and up to 40% in LATAME. The impact on SSAFRICA shows a different pattern. Here, the emissions footprint increases in all scenarios compared to the baseline, as all scenarios lead to increases in food consumption caused by lower agri-food market prices.

Figure 53. Land footprint changes by region



Source: MAGNET simulation results.

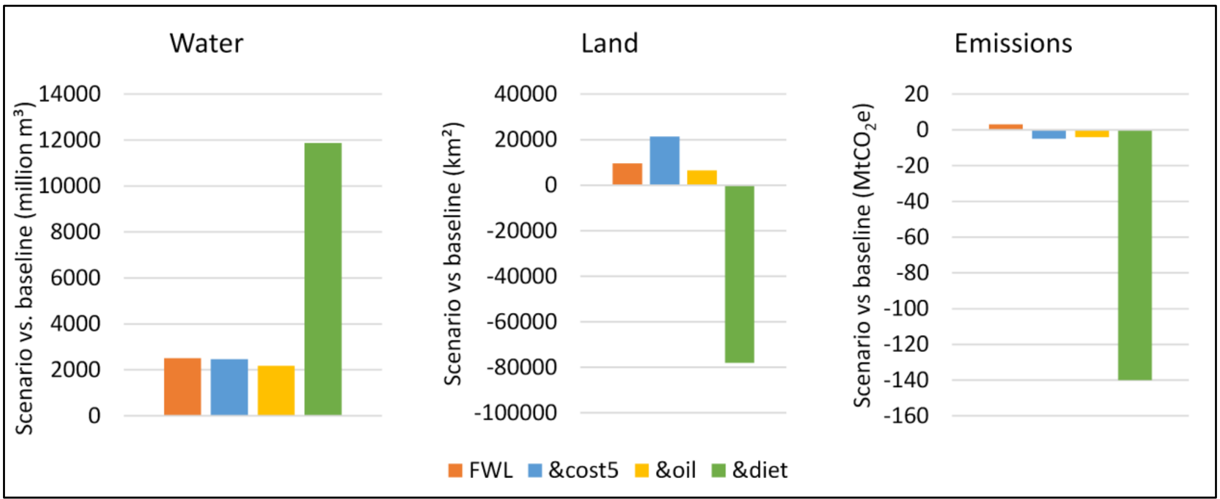
Figure 53 shows the impact of the four scenarios on land use related to household food consumption expressed as quantity of land used in m² per capita per year. Again, the figure on the left-hand side shows this footprint in the final year of the baseline (2050) and highlights the differences between regions. Looking at the EU, it becomes clear that the EU land footprint is already relatively low in the baseline in 2050 compared to other regions. The lower figure shows a deviation of the footprint in the four scenarios compared to this baseline in 2050, which is set equal to 100. This figure shows that the impact of the FWL scenario on the land footprint is higher compared to emissions at the global scale but is still a slight impact compared to the other scenarios. There is only a negligible impact on the EU land footprint, while the &cost5 scenario leads to a small improvement in the land footprints. The &oil scenario does not matter much with regard to total land use, as the results reveal a significant increase of land used for sugar and oilseed production. Again, only the &diet scenario has a significant impact on land use footprint reductions equal to around a 10% decline at global level compared to the baseline, and up to -35% in LATAME. The land footprint in SSAFRICA based on household food consumption slightly reduces per capita in all four scenarios despite increased food consumption. It remains more or less unchanged in the diet scenario, which can be partially explained by the exemption from the diet shift. While the impact of the selected scenarios has shown a positive impact on water abstraction (except for the &diet scenario), land use and emissions on a global scale, the EU deviates from these observations (Figure 54). In all four scenarios, water abstraction in the EU increases driven by an increase in the consumption of horticultural products that account for a higher share of irrigated land compared to rainfed land, compared to cereals and other crops. Water abstraction in the FWL, &cost5 and &oil scenarios reveals a rather similar increase of slightly more than 2 000 million m^3 compared to the baseline; however, this effect is almost six times higher in the &diet scenario.

The next subsection will thus shed some further light on the environmental impacts of the selected scenarios in the EU.

5.3.2 Environmental impacts on the EU

As shown in Figure 35 reducing food waste leads to a fall in agricultural production while reducing food losses results in increased agri-food production which is mainly driven by increased horticultural production. The resulting fall in market prices leads to an overall increase in the consumption of agri-food commodities due to reducing food losses, while reducing food waste shows a more heterogeneous picture.

Figure 54. Final food demand driven virtual commodity usage in the EU compared to the baseline in 2050



Source: MAGNET simulation results.

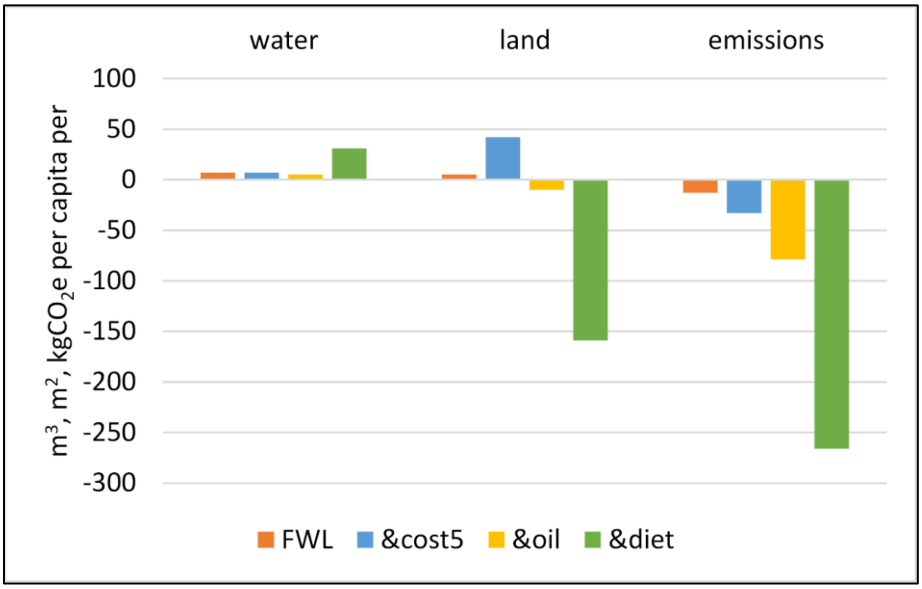
While Figure 54 presents the effects of the four scenarios on final food demand driven virtual commodity usage in the EU compared to the baseline, Figure 55 measures the impact presenting the deviations of the footprints measured per capita per year from the baseline.

In comparison to the global scale, FWL reductions lead to an increase in land use related to food consumption in the EU in Figure 54 and Figure 55. This effect becomes even more obvious when adding costs and reduces when considering an increase in fossil energy prices that diverts a higher share of the crop harvest to non-food uses and thus reduces the share of land indirectly consumed via food. In the EU, only the diet scenario results in a distinct reduction in land use compared to the baseline caused by the large cuts of meat and dairy consumption.

The effects on emissions are much more positive in the EU. While the FWL scenario still leads to a slight increase in total emissions related to food consumption in Figure 54, the emissions footprint per capita per year deviations compared to the baseline in 2050 clearly show a decline. This effect improves further when considering cost and increased fossil energy prices. Similar to the global scale, the dietary shift generates the highest emission reduction, equal to more than 250 kg CO_2 equivalents per capita per year.

Furthermore, Figure 55 shows an increase in the food consumption water use footprint per capita per year that slightly increases in all scenarios shown.

Figure 55. Final food demand driven footprints in the EU – deviations from the baseline in 2050



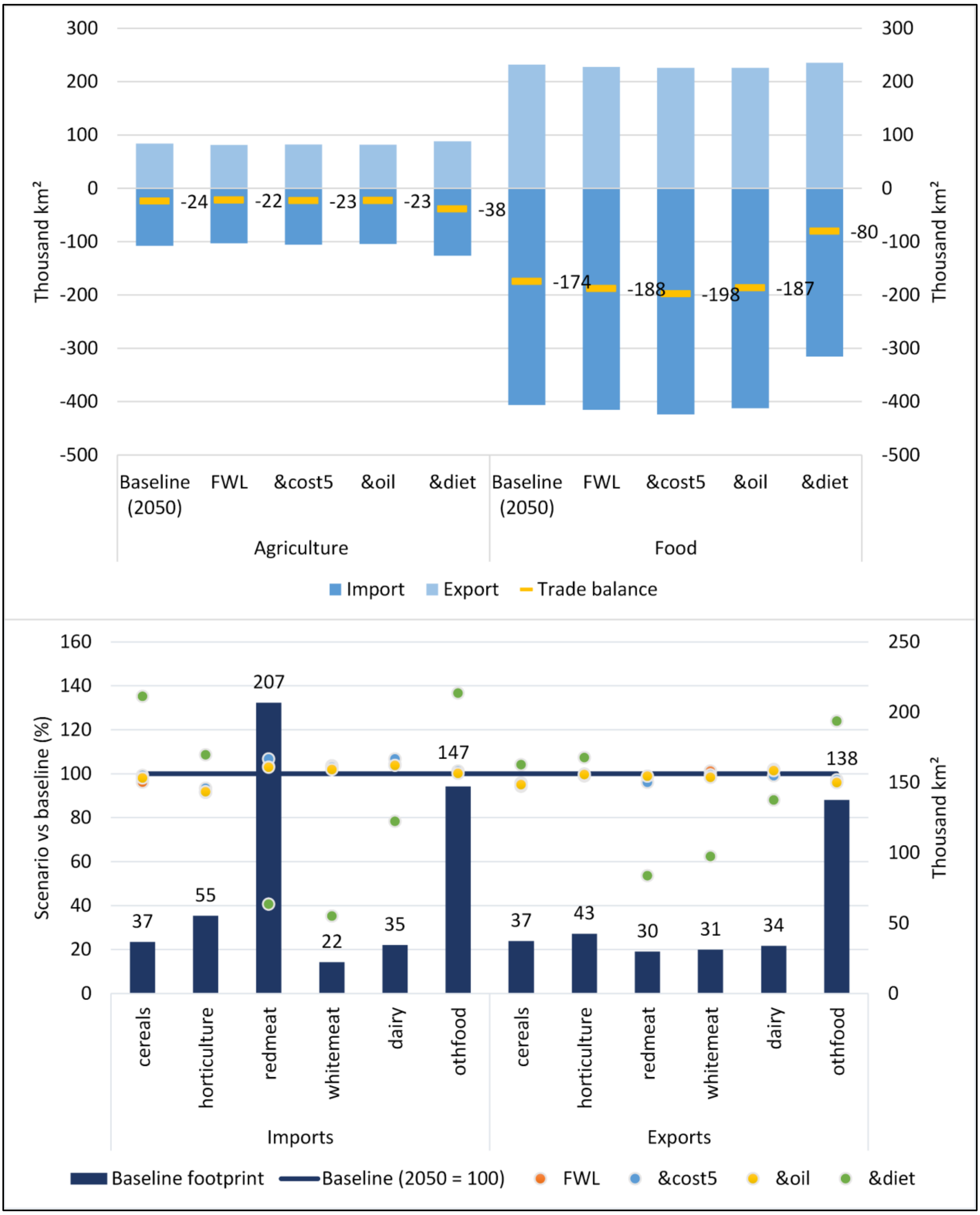
Source: MAGNET simulation results.

The increases of the EU land use footprints in the FWL and &cost5 scenarios raise the question of how much the scenarios affect virtual land trade.

In this regard, Figure 56 provides a further insight into the impact of virtual land imports, exports and the trade balance in the baseline and the four scenarios, on an aggregated level, looking at primary agricultural commodities and food commodities in the upper part of the figure. Land that is virtually imported or exported via trade of primary agricultural commodities changes only minimally – except for the &diet scenario – which leads to a much higher increase in virtually imported land to exported land and thus clearly worsens the trade balance. Looking at food consumption, the graph reports only negligible changes related to virtually exported land via food exports. However, the FWL, &cost5 and &oil scenarios impact on virtually imported land via food imports and hence significantly worsen the trade balance. In contrast to primary agricultural commodities, the &diet scenario significantly reduces virtual land imports and thus improves the trade balance.

The lower panel of Figure 56 shows the impact of the scenarios on virtual land trade for selected agri-food commodities. These graphs show virtual land imports and exports in the baseline, respectively (blue bars). In addition, the graphs show the deviations of the four scenarios from the baseline (dots) that is set equal to 100 in the year 2050 (orange line). FWL reductions lead to a reduction in virtually imported land, with the exception of meat and dairy products. A shift toward plant-based diets shows, as expected, that virtual land imports related to cereals and horticulture increase significantly, while virtual land imports related to red meat and dairy consumption dramatically decline. This is particularly important as red meat accounts for the highest amount of virtual land imports in the baseline in the year 2050. In 2050, the virtually exported amounts of land are smaller than the imported amounts of land. However, with regard to FWL reductions, virtual exports of land tend to reduce for all commodities except for dairy. Dietary changes lead to a similar pattern of changes compared to the baseline as for virtual imports, again with the highest impact related to red meat and dairy. Nevertheless, virtual land imports remain higher than exports so that the EU remains a net importer of land in all four scenarios.

Figure 56. Virtual land trade – EU



Source: MAGNET simulation results.

6 Discussion

This chapter summarises and discusses key results from different perspectives.

6.1 Results from a global food system and SDG perspective

Sustainable food systems that deliver health and nutrition are defined in von Braun et al. (2021) with the following three objectives: Objective 1 - End hunger and achieve healthy diets for all; Objective 2 - Sustainable use of biodiversity and natural resources, the protection of ecosystems and the safeguarding of land, oceans, forests, freshwater and climate; Objective 3 - Eliminate poverty and increase income and wealth.

Grouping the results of the study according to these objectives results in the following table. The evaluations in the overview table are not representative of all food system (and SDG) objectives, but rather are a selection of indicators relevant for the whole of society (in bold) as well as the socioeconomic situation of the agri-food sector.

Table 6. Overview of scenario impacts on food system objectives and indicators globally

Sustainable *Food System* *objectives* - *global*		**Related SDGs**	**FL** (-50%)	**FW** (-50%)	**FWL comb.**	**FWL & Costs**	**FWL & Energy price**	**FWL & Diets**
Social *End hunger and achieve healthy diets for all*	**Improved diets**	2						
	Cheaper food	1, 2						
	More ag jobs	8						
Environment *Sustainable use of biodiversity and natural resources*	**Reduced land use**	15, 12						
	Less emissions	13, 12						
	Reduced water use	6, 12						
Economy *Eliminate poverty and increase income and wealth*	**Economic growth**	8, 9						
	Agri sector growth	2, 8, 9						
	Higher producer prices	2, 8, 9						

Important remarks:

- Indicators in bold are those relevant for the **whole society** and not a specific sector.
- Coloured circles indicate the direction towards reaching an objective.
- The expected reduced productivity due to environmental oriented policies such as in EU's Farm to Fork strategy could be counterbalanced with the increased efficiency as shown in the FWL scenario. Consequently, **the impacts on the agricultural sector** would look differently.
- Not creating more agricultural jobs while producing more, means a higher labour productivity.
- The reduced use of natural resources improves **biodiversity** and thus creates additional (socioeconomic) values.
- General **health benefits** through a better diet and better environment create enormous socioeconomic benefits, not included in this study.

Scenarios:
FL (-50%): Food loss reduction by 50%
FW (-50&): Food waste reduction by 50%
FWL comb.: Food loss and waste reduction combined
FWL & Costs: as FWL with 5% costs for reduction
FWL & Energy price: as FWL with a 25% higher oil price
FWL & Diets: as FWL with a healthier diet (EAT-Lancet)

Source: MAGNET model, transformation of results into more qualitative statements.

The social objective to end hunger and achieve healthy diets for all can be approached with the combination of food waste and loss reduction and, evidently, healthy diets. Available and affordable calories, in SSA in particular, would be made available through the more efficient food chain, reducing hunger, and, in other parts of the world, healthy diets limiting the sprawling problem of obesity. The combination of FWL&diet also avoids the problem of the higher costs of healthier diets (FAO, IFAD, UNICEF, WFP, WHO, 2020; Hirvonen et al., 2019),

The environmental impacts of the food system are also reduced. With the food system currently being responsible for up to 30% of greenhouse gas emissions (EC DG RTD SCAR, 2020c), the contribution of the combined FWL&diet scenario to the global temperature rise limit is paramount. The question of water use remains critical in parts of the world.

A more efficient food system with an improved input/output productivity can create economic growth and reduce the costs of food – which gets lost or wasted each year, estimated at almost EUR 1 trillion (EC DG RTD

SCAR, 2020c; FAO, IFAD, UNICEF, WFP, WHO, 2020). These gains would be needed to finance the transition towards a more efficient food system, including support for part of the farming community suffering under the changes. This support could be further strengthened through a level playing field on the energy market by making fossil energy sources more expensive, which is crucial for the overall GHG emission reductions. Again, also in the latter case of higher energy costs, specific attention has to be paid to the most vulnerable, which have to spend a significant share of their income on food and energy.

These broad lines should not pre-empt an in-depth analysis of the regional and sectorial specificities and, most importantly, the need to factor-in the costs of a FWL reduction.

A recent meta-analysis of the key transformations implemented in global analyses and their typical impact for relevant indicators, by Valin et al. (2021), insinuates similar impacts to our study.

The analysis clearly shows that one policy measure alone cannot address the system as a whole. A combination of different measures/instruments, going far beyond the scenarios presented in this study, is needed to address the three main objectives according to von Braun (2021).

6.2 Planetary boundaries and resource use

In this section, we show food consumption and production-based footprints (land, water, emissions, energy) for a selection of regions, taking into account the dynamics of time (2020 to 2050). In addition to the baseline (BL), the analysis also examines the combined food waste and loss reduction and diets scenario (FWL&diet).

It is important to note that the world average should not be interpreted as a planetary boundary, as analysed in EEA (2020). Thus, countries below the average are not necessarily in the 'safe operating space'. To further emphasise this point, the EEA (2020) estimates that the EU is overshooting its limit for land use (per capita) but does not exceed the global limit for the water footprint.

The Figures 57 to 60 provide a visual impression of the differences between regions and the trends over time as well as the potential impact of a more sustainable pathway for food production and consumption. The orders of magnitude (distances between regions, trends and scenarios) also indicate the importance of global trade exchange for a more resource-efficient food system. The colour coding in the graphs refers to the resource use per tonne of product.

The reader should note that due to the different regional aggregation for ASIA, the land/water/emission/energy footprints do not include China and India, whilst LATAME does not include Brazil.

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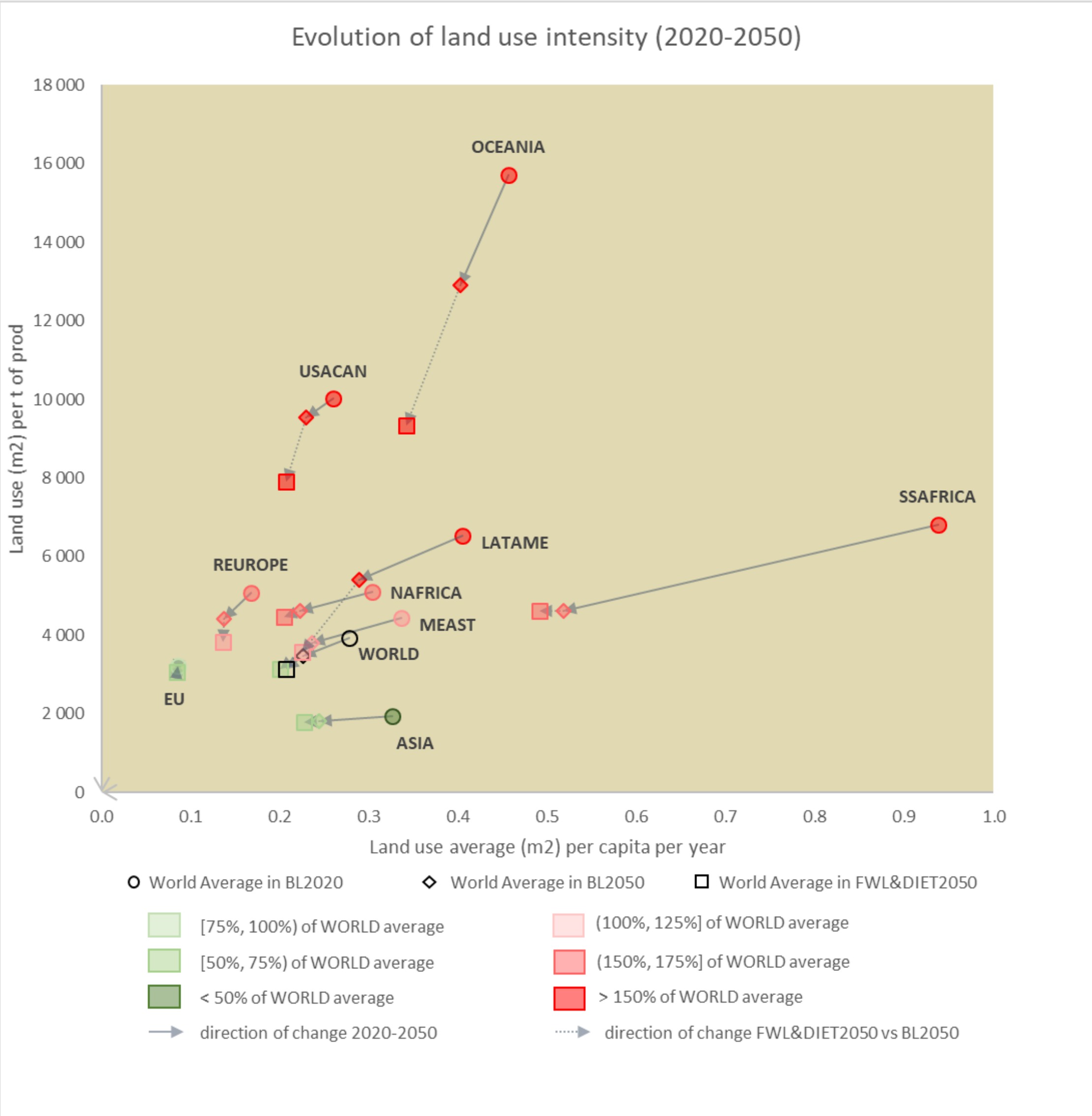
Exploring the current state of **agricultural land use intensity** per capita and per tonne of production, the vast spread between countries is eye-catching. The reader is reminded that high land use is not necessarily bad for the environment but could imply a low-intensity production model. The dynamics of the trends by region are motivated by projected heterogeneous increases in population and anticipated per capita income rises that induce further agricultural land pressures, coupled with agricultural land saving arising from anticipated improvements in regional agricultural land productivities.

Taking the world average as a basis for comparison, only ASIA and the EU exhibit higher intensity (i.e., relatively lower agricultural land requirement per tonne of production and per person) and therefore higher land efficiency. Most of the other regions are displaying a strong convergence in both indicators over time. In particular, SSAFRICA, LATAME and OCEANIA improve their production and consumption footprints. In the case of SSAFRICA, for example, the baseline trend is motivated by rapid population increase and strong land productivity gains. Significant population increase also plays a key role in reducing land use per capita in OCEANIA, the MEAST and NAFRICA. Comparing the FWL&Diet scenario with the 2050 baseline, the big improvement that is observed for both these footprints for OCEANIA and LATAME, and to a lesser extent, the USACAN, relates to reduced (red) meat consumption. This effect is generating major swings toward agricultural land saving, although all three regions remain above the world average. In the SSAFRICA region, the changes are negligible since this regions does not participate in the healthier diet, and rates of food waste are very much lower than in other regions.

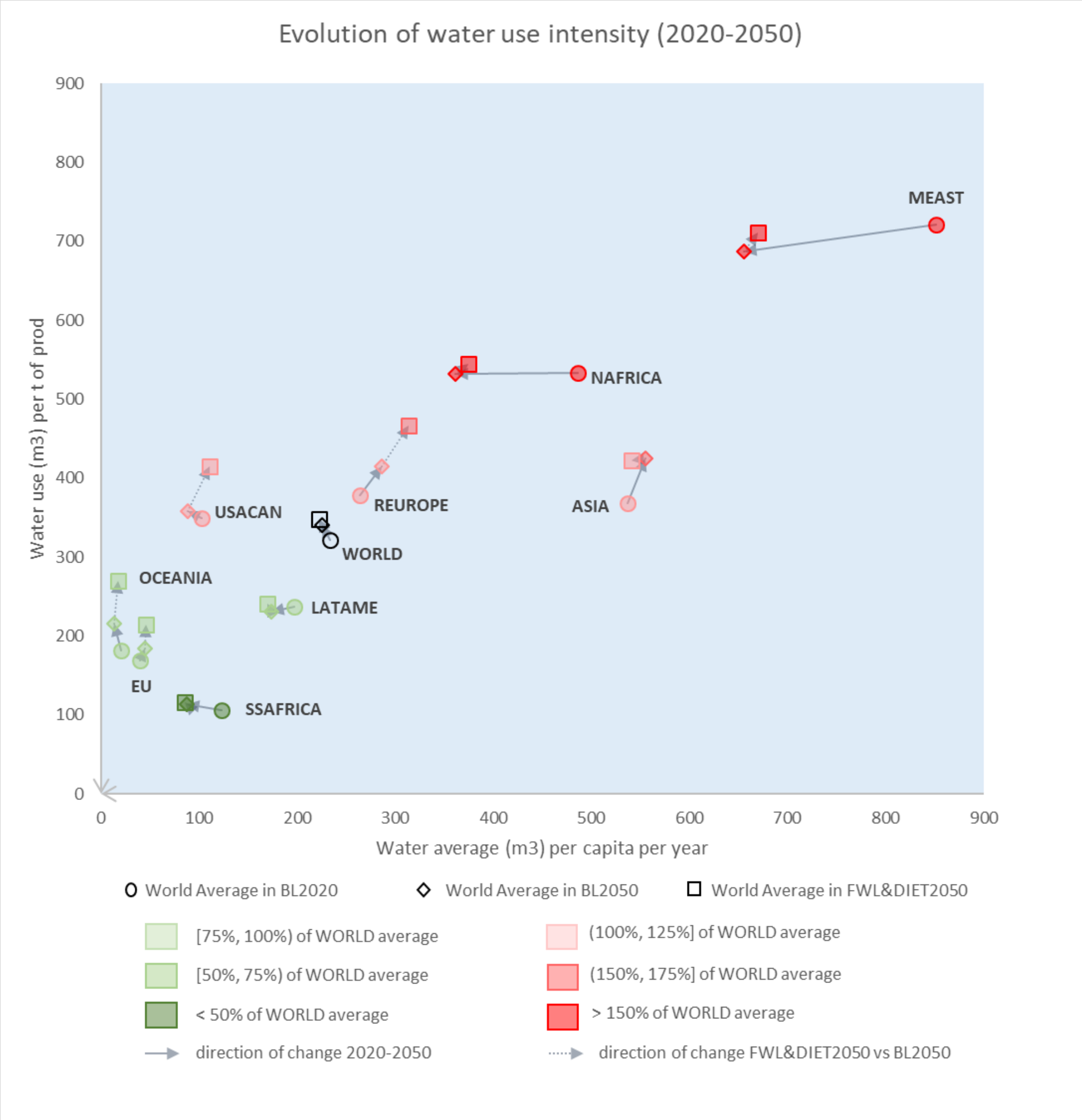
Figure 57. Evolution of food demand driven agricultural land use intensity for the baseline and vs the 2050 baseline



Source: MAGNET model results.

Regarding **water use** (for irrigation), we observe a wide span between regions. The EU remains far below the average of both the food consumption water footprint per capita and the production footprint for water use per tonne of product. The arid regions of the MEAST and NAFRICA present a strong reduction in their water footprint over time. ASIA, also having high per capita water use due to rice production, increases its use slightly.

Figure 58. Evolution of food demand driven water use intensity for the baseline and vs the 2050 baseline



Source: MAGNET model results.

Figure 59 shows that final food demand driven world **emissions** exhibit a slight increase over time reflecting a more intensive agricultural system responding to the burden of rapidly rising food demands by a more populous and wealthier global economy. Encouragingly, the FWL&Diet scenario is clearly shown to reverse the trend, i.e. reduction of per capita use and emissions per tonne of product. Behind the average global values, in the baseline one observes very heterogeneous developments across the regions. In general, OECD countries have higher emissions per tonne of product (in particular USACAN and OCEANIA, and to a lesser extent, the EU) than other parts of the world. Reflecting changes in food trade preferences and sluggish rises in food demands, over the thirty year horizon in the baseline, the emissions intensity in the USACAN and EU improves slightly, although it worsens in OCEANIA. Of these three regions, only the EU remains below the world average intensity. The EU increases the emissions footprint per product over time but remains below the world average. In SSAfrica, rapid per capita income rises and an intensification in agricultural production processes result in rising emissions intensities (per tonne and per capita), although this regions remains below the world average.

As noted above, when compared with the baseline in 2050, the FWL&diet scenario unambiguously reverses the trend. In LATAME, for example, production becomes more emissions-intensive over time, yet falls remarkably due to the impact of the diet scenario and reduced animal production. In SSAFRICA, the change is considerably less marked since this region does not adopt the healthy diet (due to affordability constraints) and has considerably lower rates of food waste and losses.

Figure 59. Evolution of food demand driven emissions intensity for the baseline and vs the 2050 baseline

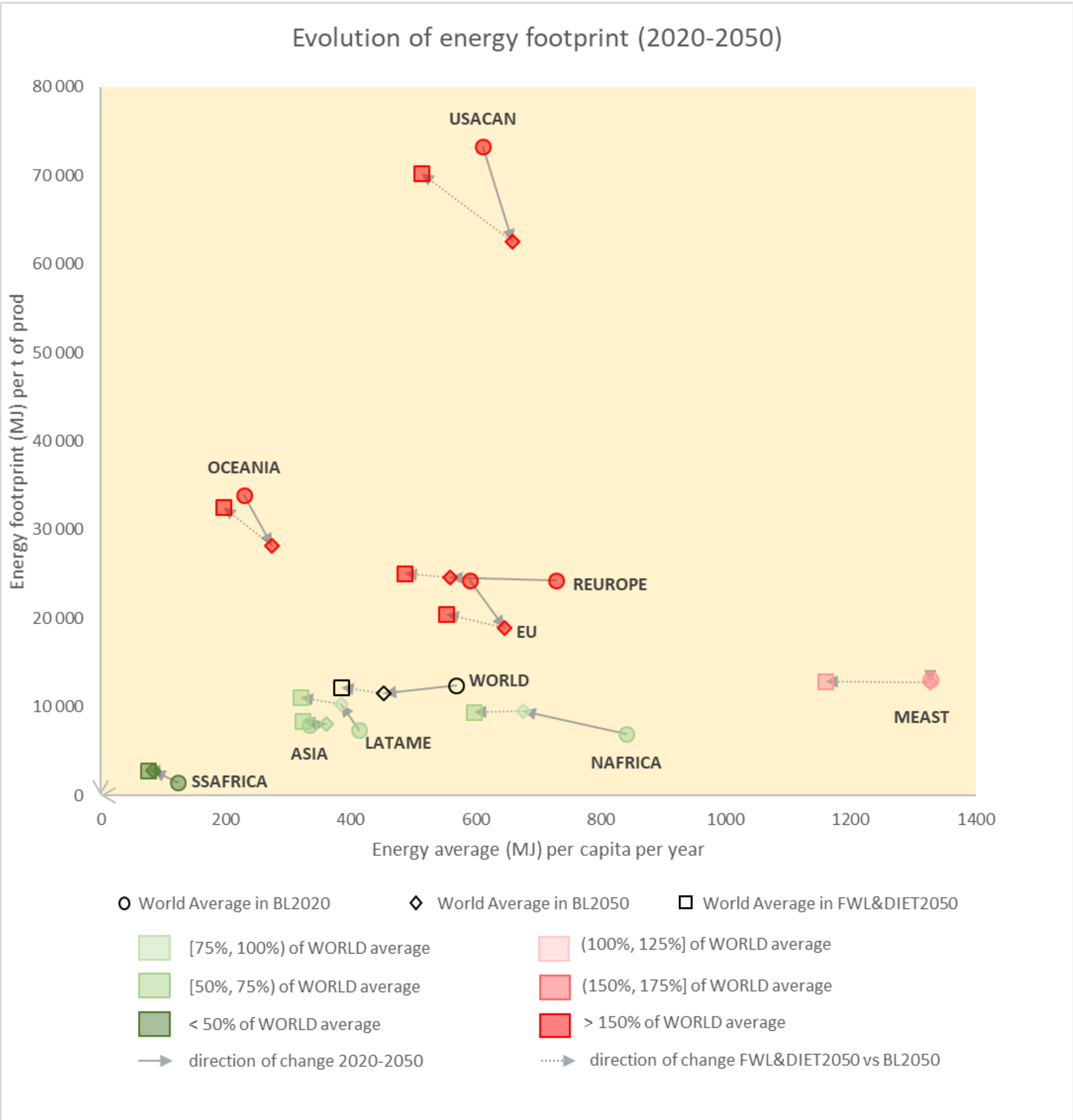
Source: MAGNET model results.

Reflecting the emissions trends shown above, the OECD countries exhibit **energy** footprints above the world average. This observation is particularly strong for the USACAN region. Not surprisingly, in the fossil fuel exporting regions of the MEAST, energy usage per capita is particularly high.

In the baseline period from 2020 to 2050, the world average energy intensity per tonne of product reduces slightly, while the per capita use reduces more markedly. This trend is driven by the energy market assumptions which, even in the baseline, assume some degree of energy efficiency gains. Note that in the wealthier regions where population growth is relatively slow, rising energy usage per capita remains more susceptible to real income per capita increases. In the developing world, population rises hold sway over the reductions in per capita energy usage, although rises in per tonne energy usage arises due to the intensification of agricultural practises to meet the strong rise in food intake in these rapidly developing economies.

When comparing the FWL&Diet scenario with the baseline in 2050, there is a trend toward reduced per capita demand, whilst energy footprints per tonne of production rise. As noted in section 5.1.1, globally and in the developing world, agri-food production rises, although economic growth in these regions brings increased energy intensification across all activities. In the EU and USACAN, on the other hand, domestic agrifood production falls (see Figure 40), resulting in rising energy usage per tonne.

Figure 60. Evolution of food demand driven energy footprints over time (2020-2050) and scenario



Source: MAGNET model results.

6.3 Results from an EU food system perspective

In this section, we again follow the sustainable food systems definition from von Braun et al. (2021), focussing on the EU. Broad lines are similar to the global analysis (7.1), with some differences primarily related to the different starting point for a high, not necessarily healthy, provision of calories and proteins in the EU.

Table 7. Overview of scenario impacts on food system objectives and indicators for the EU

Sustainable *Food System objectives* - *EU*		**Related SDGs**	**FL** (-50%)	**FW** (-50%)	**FWL comb.**	**FWL & Costs**	**FWL & Energy price**	**FWL & Diets**
Social *End hunger and achieve healthy diets for all*	**Improved diets**	2						
	Cheaper food	1, 2						
	More ag jobs	8						
Environment *Sustainable use of biodiversity and natural resources*	**Reduced land use**	15, 12						
	Less emissions	13, 12						
	Reduced water use	6, 12						
Economy *Eliminate poverty and increase income and wealth*	**Economic growth**	8, 9						
	Agri sector growth	2, 8, 9						
	Higher producer prices	2, 8, 9						

Important remarks:
- Indicators in bold are those relevant for the **whole society** and not a specific sector.
- Coloured circles indicate the direction towards reaching an objective.
- The expected reduced productivity due to environmental oriented policies in the Farm to Fork strategy could be counterbalanced with the increased efficiency as shown in the FWL scenario. Consequently, **the impacts on the agricultural sector** would look differently.
- Not creating more agricultural jobs while producing more, means a higher labour productivity.
- The reduced use of natural resources improves **biodiversity** and thus creates additional (socioeconomic) values.
- General **health benefits** through a better diet and better environment create enormous socioeconomic benefits, not included in this study.

Scenarios:
FL (-50%): Food loss reduction by 50%
FW (-50&): Food waste reduction by 50%
FWL comb.: Food loss and waste reduction combined
FWL & Costs: as FWL with 5% costs for reduction
FWL & Energy price: as FWL with a 25% higher oil price
FWL & Diets: as FWL with a healthier diet (EAT-Lancet)

Source: MAGNET model, transformation of results into more qualitative statements.

In the following, the analysis of this study is placed in the context of the conclusions of the EP analysis (Guyomard et al. (2020), pp. 62- 65).

Regarding the ***reduction of food losses and waste*** *(50%)*, the EP analysis summarises 'There will [be] a reduction in agricultural land use, GHG emissions and water use. The magnitude of these positive effects will depend on the size of loss and waste reduction, which itself depends on solution costs and market adjustments.' A similar conclusion can also be drawn by this study. The importance of the costs is demonstrated in the sensitivity analysis.

While agricultural production at EU level is only marginally affected when food waste and losses are reduced together, the decomposition demonstrates that reducing food losses leads to a significant increase in output and reducing food waste leads to a smaller reduction.

Looking at more details for the agricultural and food sector, results are highly heterogeneous across the EU sectors from the removal of FWL by 2030. Each have considerable differences in waste and loss rates, significant reductions in cereals and falls in fish and 'other food' (big sector), whilst elsewhere else (meat chain, dairy chain), production actually increases on the removal of FWL by 2030. Overall, the cereal contraction drives the contraction in EU primary agriculture, whilst fish and 'other food' (big sector) drive the food sector.

It is clear that – under the assumption of costless food loss reductions only (FWL) – the resulting efficiency gains (i.e. falling costs per unit of production - average costs) within the supply chain have a significant positive impact on the output of the agricultural and food sectors. It is interesting to note that the food waste reductions and the efficiency gains (food loss reduction) lead to notable reductions in feed and (from an environmental viewpoint) fertiliser usage.

The results demonstrate the importance of having compliance cost estimates for food waste and loss reductions.

Regarding the ***change in diets***, the EP analysis states 'A reduced consumption of animal products and a higher consumption of plant-based products would see a reduction of GHG emissions of the food system of around 10-15%.' This study did not analyse the change in diets in isolation. Calculating the difference between the FWL and FWL&diet scenario reveals a reduction of approximately 24% in GHG emissions in the EU food system, including only emissions located in the EU, and a reduction of approximately 36% in GHG emissions if the entire food footprint is included.

The large downward turn on meat and dairy demand seems to be such that even the (non-food) bio-based sectors witness contractions in their activities too. Diet change around the world undoubtedly has benefits for human health, labour productivity, etc., but other parallel measures are needed to soften the transition and create a level-playing field for the non-food biomass usage of crops in the wider the bioeconomy (see also next paragraph).

A rising oil price reduces EU real growth versus the baseline, affecting the different activities within the economy in different ways. Those that are more fossil energy-intensive may contract, whilst second-round resource reallocations may actually benefit other less energy-intensive energy activities. Compared with the baseline, agriculture and food in the EU does progressively worsen with the higher oil price. This suggests that, as the economy contracts and per capita real incomes (utility) fall with stronger income-demand elasticities on non-food products, there is a slight resource reshuffle towards agriculture and food (within a smaller EU economy).

6.4 Reflections on the modelling approach

This report presents a methodology, an indicator framework and a multitude of visual analytics to better understand the state and potential future evolution of the food system in a global context. The explicit linking of all main world regions through trade and comprehensive "farm to fork" food footprints enables the identification of the various spill overs and transboundary effects as well as synergies and trade-offs. The consumption-oriented, forward-looking scenarios highlight significant synergetic market driven instruments for tackling the pressing challenges of today and the future, thus presenting options for counteracting potential productivity reductions arising from more environmentally sustainable agricultural production systems.

Economic simulation models are a conceptual framework representing the economy in a structured but schematic and simplified manner. Model results can only be as good as the underlying databases and are influenced by assumptions made. In the absence of a consensus on the measurement of food waste and loss at global scale, this study follows the approach of FAO (2011) as introduced in section 2.5.1. Definitions vary for example regarding whether only edible food waste is considered or also inedible parts. In addition, according to FAO (2011) food waste includes food waste that occurs at retail and consumer level, while food losses related to agricultural production and post-harvest losses as well as to processing and packaging are considered as food loss. By contrast, other definitions consider everything except what is left on the field as food waste. Consequently, applying other measures would clearly affect the results.

At the time when this study was conducted, there was only one dataset (FAO, 2011) available at global level that provided consistent information on food waste and loss along five steps of the supply chain for at least seven global regions and seven aggregated food groups. Considering more detailed information including variation among countries and more disaggregated foods would allow more in-depth analysis of food waste and loss with a focus on specific countries in a global framework.

This study does not account for changes in consumer attitudes to food waste in the baseline. Following for example, Verma et al. (2020), future studies could account for the evolution of food waste as a function of (*inter alia*) wealth, applying time series information on food waste development. In addition, the baseline does not consider potential technological changes that might have contributed to reducing food losses in agricultural production and post-harvest losses in the baseline.

There are costs associated with the reduction of food waste and losses, however, there is still a high degree of uncertainty regarding the size of these costs. In the absences of available estimates at national and global level, this study applies an ad-hoc approach and assumes potential costs to be equal to 1%, 5% and 10% to the sales value of food products. This sensitivity analysis clearly shows that the extent to which these costs are incurred has noticeable implications for the results and thus highlights the need for future research in this area. In the applied modelling approach, these costs arise on the supply side and increase production cost. Consumers are implicitly affected via prices. Other costs related to changing consumer behaviour, e.g., through education, are not considered as it is less clear who has to bear these costs.

In line with the objective of this study, the MAGNET model simulates the impact of achieving the SDG 12.3 target. It is important to note that this study does not assess how this target could be achieved through the implementation of various policy instruments such as taxes and subsidies to change the behaviour of different actors in relation to the generation food waste and loss.

The baseline and scenarios FWL, &cost5 and &oil keep the caloric shares from red meat, white meat, dairy and fish constant to enable the evaluation of substitution effects in the &diet scenario. However, income development in the baseline as well as price changes also relevant to the other scenarios would have induced changes in the dietary composition that are not accounted for in this study. This assumption limits the ability to assess the nutritional impact of reducing food waste and loss.

Furthermore, the MAGNET model simulates a sustainable and healthy diet by changing the willingness to consume different products. This study does not assess how this could be achieved, for example, with appropriate policy instruments such as taxing meat consumption and subsidizing vegetable consumption. This is beyond the scope of this study, but is of course an interesting starting point for future research. In contrast to reducing food waste and loss, the costs associated with changing dietary behaviour are not assessed, although there are costs associated with changing dietary habits. However, little is known about the level of costs and who bears these costs, so adding costs would have added an additional set of scenarios to this study without providing further reliable evidence.

Furthermore, the MAGNET model includes households as one representative household per region. As a result, this study does not depict the impact of the different scenarios on poverty, food accessibility and food affordability of specific households.

Despite that the MAGNET model depicts the interlinkages and rebound effects of the whole economy, the presented outcome on economic, social and environmental sustainability solely tracks the impact of household food consumption on these measures. In addition, the model accounts only indirectly for water withdrawals related to livestock productions through feeding as it explicitly models only the water withdrawals from arable crops. Thus, the positive impact of dietary changes on water withdrawals due to less meat consumption is underestimated in this study. Nevertheless, according to Mekonnen et al. (2012) it is expected that the impact of additional water services is rather small.

In the applied modelling approach, the benefits of ecosystem services cannot be measured. At the time the study was conducted, to the best of our knowledge, there was no global economic model available that explicitly considered ecosystem services. However, ecosystem service models provide information on how production changes that affect the ecosystem structure lead to changed values of ecosystem services. Linking CGE models such as MAGNET to ecosystem services models would provide an interesting springboard for future research but is far beyond the scope of this study. Such an approach would also require an ecosystem services database covering multiple ecosystem services in EU member states. To overcome this gap, this study provides a qualitative discussion of the potential implications of model results for ecosystem services provision and associated benefits.

Both the reduction of food waste and losses and the change in dietary habits lead to a significant decrease in labour demand in the agricultural sectors. In this version of the MAGNET model, unemployment is not taken into account as the long-run equilibrium corresponds to the natural rate of unemployment, which is a common assumption in deterministic global CGE models.

7 Conclusions

The food system, embedded in the transformation towards a sustainable circular bioeconomy (Braun et al., 2021), plays a central role in tackling the grand challenges as outlined in the Sustainable Development Goals (SDGs), in particular related to sustainable diets and agriculture, climate and biodiversity, as well as the convergence of living standards.

This study builds on earlier work related to alternative global transition pathways towards 2050, with a specific focus on the biological part of the economy. It employs an economy-wide computable general equilibrium model with global coverage – MAGNET – to examine forward-looking scenarios, while explicitly linking all regions through trade and its related footprints.

This report presents a methodology, an indicator framework and a multitude of visual analytics to better understand the state and potential future evolution of the food system in a global context. The scenarios selected represent significant synergetic policy instruments for tackling most of the pressing challenges of today and the future.

The study presents three policy instruments primarily addressing each one of the following three sustainability dimensions, yet impacting the entire system: i) for the environmental dimension, the food waste and loss reduction; ii) for the social dimension, changing dietary patterns; iii) for the economic dimension (including the level playing field), a higher oil price (carbon tax). The scenarios therefore capture supply side considerations, with the food loss reduction and the oil price scenario, and demand side drivers in terms of the food waste reduction and dietary change.

From a global food system perspective, the social objective to end hunger and achieve healthier diets for all can be approached by the combination of food waste and loss reduction and, evidently, healthy diets. This would make calories available and affordable, particularly in the developing world, whilst concomitantly alleviating the environmental impact of the food system (i.e., lower greenhouse gas emissions). Investigating food system driven footprints for land, water, emissions and energy in more detail, we observe a spatial, sectoral and time-wise heterogeneous picture, which receives further modifications through the scenarios. Through explicit modelling of trade, the footprint metrics also highlight how consumption patterns in one region, may play a significant role in driving resource usage in another region (the so-called "leakage" effect").

Food waste and loss reduction are almost perfectly complementary measures. While food loss reduction can be seen as an efficiency gain – optimising the input-output relation on the supply side – the food waste reduction fosters a more sustainable demand side. Taken together, the market effects are softened for the farming sector. In reality, however, both measures involve costs along the food chain. Reducing food losses and waste on the supply side requires sustained investments to drive continued productivity improvements, whilst food waste reductions in demand may necessitate accompanying public policy measures (i.e., education, advertising) or even fiscal measures (fat-taxes or sugar taxes, 'healthy' food subsidies), to channel desirable behavioural outcomes. The results tentatively suggest that by accounting for costs, model outcomes can be noticeably affected. For example, the sensitivity analysis with systematically higher assumed producer 'compliance' costs for food waste reduction dampens, and in the extreme, even eliminates agri-food production gains in the other scenarios. From an overall economic perspective, the results indicate that GDP increases in all regions as a result of the FWL scenario, with the strongest impacts in regions such as Sub-Saharan Africa, which have a large agricultural sector share of the total GDP and, accordingly, benefit the most from the efficiency gains.

Turning to the question of whether the scenarios can provide a stimulus to bio-based industrial sectors while preserving the environment, we analyse a FWL& high oil price scenario. Indeed, the oil price increase induces a considerable movement in the liquid biofuel market, as expected. However, as advanced generation biofuels benefit from subsidy support and the falling oil price, this takes away non-food feedstock from the solid bioenergy sectors and the biomaterials sectors. So, again, a bundle of measures is needed to steer the transformation in the desired direction to ensure 'win-win' or even 'win-neutral' outcomes. Market forces alone cannot tackle the multiple objectives.

While the analysed diet scenario is clearly a simplified approach and would have to be accompanied by long-term transitional measures for the agri-food sector, the objective of improving the sustainability of production and consumption – primarily the emissions reduction and reduced land use – is fulfilled.

The analysis clearly shows that one policy measure alone cannot address the system as a whole. A combination of different measures/instruments, going far beyond the scenarios presented in this study, is needed to address all objectives and approximate the FAO's 'Four Betters' (better production, better nutrition, better environment, better life). Naturally, this requires a reformed financial system that takes a longer terms view of responsible R&D investment to channel innovations that benefit all, a series of supporting public policy measures (both fiscal and legal) and a significant degree of civic engagement in order to bring about societal change.

Although beyond the scope of this analysis, one should also consider the solutions proposed by a holistic concept such as the European Green Deal (including the bioeconomy and other related strategies) to overcome trade-offs, such as adverse impacts on the agricultural sector in the case of a strong change in the system arising from FWL&diets. While employment in some agricultural sectors could be reduced due to changes in the supply and demand of food, opportunities in the wider bioeconomy arise. An important number of new jobs are expected for uses of (non-food) biomass as non-fossil-based alternative materials in for instance bio-chemicals, bio-plastics, and construction.

While national economic accounting systems, which are the basis of economic models such as MAGNET, do not (yet) include the value of ecosystem services[8], released (unused) land creates new value for the ecosystem. In the case of the food system, an improved biodiversity increases pollination and therefore yields, apart from many other services such as clean air and clean water.

Related to the improved food system and ecosystems, health benefits (e.g. reduced diabetes, coronary diseases and cancer) arising from healthier diets in terms of reduced public expenditure on healthcare as well as the associated labour productivity benefits and their positive impact on wages and economic growth can be expected.

As with every modelling exercise, there are limitations the reader and user of the output should keep in mind. Economic simulation models are a conceptual framework representing the economy in a structured but schematic and simplified manner. Whilst the family of simulation models are not forecasting models, they still provide useful insights for understanding how a market shock (i.e., public policy, technology change, demand shift) can impact on market (and non-market) outcomes relative to the 'no change' or status quo situation (the baseline). As outlined in the methodology chapter and in more detail in Philippidis et al. (2021), the food footprints provide a better understanding of the environmental implications of food consumption, yet are subject to significant assumptions prone to change over time. Furthermore, Verkerk et al. (2021) contribute an exhaustive analysis to the debate on the holistic modelling of sustainability, stressing as most promising opportunities for future modelling activities the exploitation of model cooperation between established and emerging modelling approaches.

[8] According to the latest report "Accounting for ecosystems and their services in the European Union (INCA) — 2021 edition", the economic value provided by a wider set of ecosystem services in the EU amounted to € 234 billion in 2019. (https://ec.europa.eu/eurostat/en/web/products-statistical-reports/-/ks-ft-20-002). INTERNAL: see also https://ec.europa.eu/environment/news/measuring-what-ecosystems-do-us-new-report-ecosystem-services-eu-2021-06-25_en

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List of boxes

List of figures

List of tables

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