Received: 4 July 2022 | Revised: 29 November 2022 | Accepted: 19 January 2023

DOI: 10.1111/1477-9552.12530

ORIGINAL ARTICLE

JAE Journal of Agricultural Economics

From fork to farm: Impacts of more sustainable diets in the EU-27 on the agricultural sector

Jörg Rieger[1] | Florian Freund[2] | Frank Offermann[1] | Inna Geibel[2] | Alexander Gocht[1]

[1]Institute of Farm Economics, Thünen Institute, Braunschweig, Germany

[2]Institute of Market Analysis, Thünen Institute, Braunschweig, Germany

Correspondence

Jörg Rieger, Institute of Farm Economics, Thünen Institute, Braunschweig, Germany.
Email: joerg.rieger@thuenen.de

Funding information

Horizon 2020 Framework Programme, Grant/Award Number: 773682

Abstract

The implications of dietary changes for the environment and for human health are well documented, but the impacts on the agricultural sector are less well researched. We fill this gap by specifying scenarios in which European consumers' diets approximate the EAT-Lancet dietary recommendations to varying degrees and estimate the effects on agricultural production, incomes and emissions using an agro-economic modelling framework. The combination of different models allows for a detailed assessment of consequences for the agricultural sector from the global through European NUTS2 level to the farm level at different time scales. Shifting European consumption towards the EAT-Lancet recommendations leads to decreasing production of animal-based products, while production of fruits and vegetables increases sharply. The results indicate that the agricultural sector could benefit from a dietary shift, though the results are mixed at country, regional and farm levels. In particular, countries and regions that are highly specialised in animal farming are likely to lose income—at least in the short run—while regions with higher shares of vegetable and fruit farms can expect income gains. In Germany, pig and poultry farms may experience losses of up to 34% of their income, whereas farms with a high share of vegetables could gain more than 30% in income. Our results have implications for the policies to assist these extensive structural adjustments in response to widespread dietary changes.

KEYWORDS

agricultural income, climate change, European Union, modelling framework, scenario analysis, sustainable diets

JEL CLASSIFICATION
Q11, Q15, C61, C68

1 | INTRODUCTION

The current food system is neither healthy nor sustainable. It causes one-third of worldwide anthropogenic GHG emissions (Crippa et al., 2021) and supports diets that are deficient in fruits, vegetables, nuts and legumes and excessive in red and processed meats, leading to substantial morbidity and mortality. Animal products, particularly meat from ruminants, account for the majority of GHG emissions in current food systems and are a major driver of deforestation and biodiversity loss (IPCC, 2019). Globally, approximately 43 kg of meat and 88 kg of milk are consumed per capita per year. In Europe, these figures are twice as high, with 78 kg of meat and 216 kg of milk per capita per year. As a result, Europeans consume an average of almost 800 kcal per day from animal-based foods (FAO, 2020), which is well above nutritional recommendations (DGE, 2017) and an estimated healthy and sustainable amount of 300 kcal per day (Willett et al., 2019).

Although supply-side measures such as technological and management advances to improve agricultural yields, fertiliser efficiency, manure management or feed conversion rates of animals are important, they will not be sufficient to stay within planetary boundaries and reduce agricultural GHG emissions to the level required to meet the 2°C target (Herrero et al., 2016; Springmann et al., 2018a). In addition, demand-side changes are needed to contribute to lower food-related GHG emissions and to reduce diet-related diseases, such as diabetes and coronary heart disease (Bajželj et al., 2013; Clark et al., 2020; Creutzig et al., 2016). In particular, the importance of dietary shifts towards reduced shares of animal-based foods is increasingly emphasised in social and political debates (Bonnet et al., 2020; Bryngelsson et al., 2016; Spiller et al., 2020; Willett et al., 2019).

Model-based studies indicate that food-related GHG emissions can be reduced by up to 29% when national dietary guidelines with lower calorie intakes and smaller shares of animal-based foods are implemented (Behrens et al., 2017; Springmann et al., 2016). Global vegetarian or vegan diets have the potential to reduce food-related GHG emissions by as much as 60%–70% (Springmann et al., 2016). Taking future income and population growth into account, dietary change has great potential to mitigate emissions from the food and agricultural sector (Godfray et al., 2018; Tilman & Clark, 2014). Against this background, the EAT-Lancet Commission on Food, Planet and Health proposed a healthy and sustainable diet to protect the health of both people and the planet. Adopting this diet would require significant changes to our current diet. In most regions, the consumption of animal-based foods, in particular red meat, would need to be reduced significantly, while the consumption of fruits, vegetables, legumes, whole grains and nuts would need to be substantially increased. Estimates of the EAT-Lancet Commission show that such dietary changes could reduce GHG emissions by up to 80%, while premature mortality could be decreased by 19% (Willett et al., 2019).

Overall, dietary changes towards a more plant-based diet are already evident in Europe, with meat consumption being particularly affected. For example, data from the FAOSTAT Food Balance Sheets show that per capita consumption of red meat decreased by 4.3 kg between 2010 and 2019. In countries such as Germany, France, the Netherlands and Belgium, the decline in red meat consumption is even greater, at 7–11 kg over the same period (FAO, 2020). These data are also in line with surveys from some European countries, showing that the proportion of vegetarians and vegans is increasing. A representative survey conducted by the Forsa Institute for Social Research and Statistical Analysis (2021) in Germany shows that 2% of respondents reported following a vegan diet, while another 10% said they were vegetarians (Forsa, 2021). At the same time, social acceptance and access to, as well as the selection of, vegetarian and vegan alternative products, is increasing. Plant-based alternatives can be found in almost all drugstores and supermarkets, and restaurants are increasingly offering plant-based alternative dishes. This makes it increasingly easy for consumers to implement a more plant-based diet and could have an impact on future diets (Kerschke-Risch, 2015).

Although the implications for the environment and health of large dietary changes have already been explored to a large extent, the consequences for the agricultural sector are less well researched. The importance of complementing dietary and environmental analyses with economic models has been emphasised by Marette and Réquillart (2020). Existing studies have mainly focused on one part of diets, namely reductions in meat consumption, but have not thoroughly addressed the need to significantly increase consumption of fruits, vegetables, nuts and legumes (Cordts et al., 2014; Geibel et al., 2021; Jensen & Perez Dominguez, 2019; Santini et al., 2017). Specifically, the economic impact on the agricultural sector of a diet that is more in line with the EAT-Lancet study has not yet been analysed. However, it is the agricultural sector that would be most affected by such a major nutritional transformation.

We add to the literature in several ways. It is the first attempt to analyse the implications of a large shift towards healthier and sustainable diets on agricultural markets and the income of farms. In so doing, we combine three different agricultural-economic models—another novel aspect of our approach. The CAPRI and FARMIS models operate on different regional scales (NUTS2 and Germany) and are ideally suited to short- to medium-term analysis, whereas the MAGNET model operates at a national level and on a medium- to long-term scale. The advantages of different models and time frames can be exploited, while uncertainties associated with specific model estimates are mitigated. We simulate a partial closing (10%–30%) of the observed gap between recommended and dietary patterns in the EU in 2030 and 2050, as well as a full adoption of the EAT-Lancet diet in 2050. The article is structured as follows. The dietary scenarios are described in Section 2, and the model framework and baseline assumptions are described in Section 3. The results of the various scenarios for the economic and environmental indicators are reported in Section 4. Concluding remarks and discussion are provided in Section 5.

2 | SCENARIO DESCRIPTION

The EAT-Lancet diet (Willett et al., 2019) is a global reference diet that provides the first evidence-based recommendation for a healthy and environmentally friendly diet. This reference diet allows for an intake of 2500 kcal per capita per day and is rich in fruits and vegetables while being low in animal-sourced foods (see Table A1 in the Appendix S1). The main sources of fats and proteins are plant-based foods and unsaturated oils, while carbohydrates are mainly provided by whole grains. Combined with improved agricultural production practices and a reduction in food waste and loss, the EAT-Lancet Commission estimate that this diet would permit feeding 10 billion people in 2050 within planetary boundaries.

Here, we model two scenarios in 2030 and 2050, respectively, which assume a partial shift of EU-27 consumption patterns towards the EAT-Lancet diet. To derive these partial shift scenarios, we first calculated the differences in product-specific consumption (in kcal per capita) between the reference scenario and the EAT-Lancet diet for all EU-27 countries in the year 2030. In a further step, different levels of achievement towards the Lancet diet were derived by closing the calculated difference by 10% (Lancet_low) and 30% (Lancet_high) in 2030. If the EAT-Lancet proposition figure in kcal per capita and day is lower than the consumption in the reference scenario, for example for pork, then consumer demand will be reduced by the previously calculated changes in calorie intake; and vice versa for food products for which the Lancet diet recommends an increased consumption, for instance vegetables. For the calculation of consumption patterns in 2050, we assumed that the adjustment of consumption patterns would follow a linear trend that could be extrapolated to 2050 based on the short-run scenarios

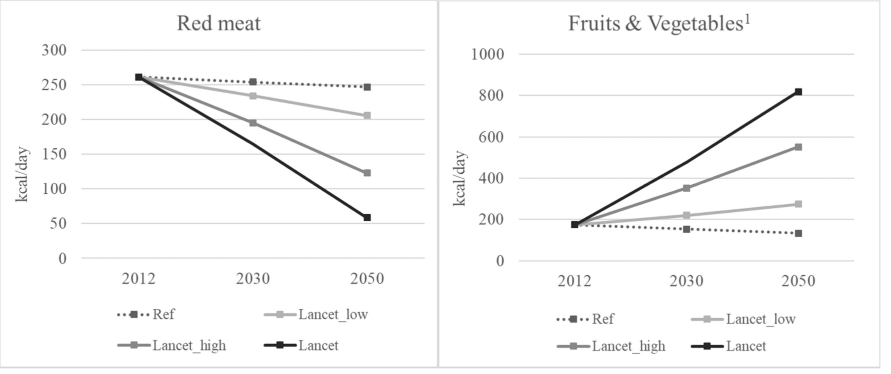

FIGURE 1 Different levels of approximation towards the recommendations of EAT-Lancet in the short- and long-run scenarios for selected products. *Source*: Own calculation with the CAPRI model.

in 2030. The approach is presented for selected products in Figure 1, which shows the different levels of approximation towards the recommendations of EAT-Lancet in the short and long run. In addition to the scenarios assuming a partial shift, we defined a long-run scenario assuming a complete shift in consumption patterns according to the EAT-Lancet diet in 2050 (Lancet_full). We refrained from considering a full Lancet dietary shift for the short-run scenario as this was deemed unrealistic over 10 years. The short-run scenarios for the year 2030 are implemented in the CAPRI model, while the long-run scenarios referring to the year 2050 are simulated with the MAGNET model. In the models, the differences between the reference diet and the simulated diets are implemented as preference shocks in the demand systems.

Table 1 provides an overview of the consumption (in kcal/day) of different product groups for the different scenarios (product mapping of target foods in Table A2 in the Appendix S1). The food demand patterns reveal that the demand for red meat (pork, beef) and dairy products, as well as sugar, show the largest declines due to high levels of consumption for these products in the reference scenario compared to the EAT-Lancet recommendations.[1] For fruits and vegetables, and cereals and legumes, consumer demand in the scenarios shows the largest increases.

The average total calorie intake in the reference scenario for the EU-27 for 2030, taking into account food losses on the supply and demand side, is in line with findings in the literature about estimated average food requirements needed to maintain body weight (BW) and physical activity levels (PAL) (Hiç et al., 2016; van den Verma et al., 2020).

3 | IMPLEMENTATION AND BASELINE

The scenarios were analysed with different models from the Thünen Modelling network using the underlying baseline (Ref). To account for the short-term effects in 2030, we applied the partial equilibrium model CAPRI to determine price effects for European producers, considering a partial degree of implementations of EAT-Lancet recommendations. Equilibrium prices from CAPRI are used to illustrate the impact on farms specialising in certain production systems, using Germany as an example, using the farm group model FARMIS. As the ambitious EAT-Lancet diet has been developed as a target for a longer-term projection, we complemented the short-term analysis with the CGE model MAGNET, which allowed us to account for flexibility in factor markets and inter-sectoral adjustments required when factors, assumed to

[1]Consumption changes in Germany are very similar to the depicted changes in kcal intake for the EU-27 except for sugar where the reductions range between −2.8% and − 8.3% in 2030 and − 5.8% and − 17.3% in 2050 due to Germany having the lowest sugar intake of all EU member states in the reference scenario.

TABLE 1 Reference diets and the range of absolute and percentage changes for the scenarios in the EU-27.

		2030			2050			
		Ref	**Lancet_low**	**Lancet_ high**	**Ref.**	**Lancet_low**	**Lancet_ high**	**Lancet _full**
Beef	kcal/day	50.8	46.4	37.6	51.0	41.7	23.2	7.5
	%-change		−8.7	−26.0		−18.2	−54.5	−85.3
Pork[a]	kcal/day	203.0	187.8	157.4	195.9	163.8	99.6	51.0
	%-change		−7.5	−22.5		−16.4	−49.2	−74.0
Poultry	kcal/day	77.9	76.0	72.2	86.0	82.0	73.9	62.0
	%-change		−2.4	−7.3		−4.7	−14.1	−27.9
Dairy	kcal/day	352.4	332.0	291.2	361.5	318.4	232.3	153.0
	%-change		−5.8	−17.4		−11.9	−35.7	−57.7
Eggs	kcal/day	39.0	37.0	33.0	40.3	36.1	27.7	19.0
	%-change		−5.1	−15.4		−10.4	−31.3	−52.9
Sugar	kcal/day	297.8	280.0	244.4	274.6	237.1	162	120.0
	%-change		−6.0	−17.9		−13.7	−41.0	−56.3
Vegetable oil	kcal/day	395.2	391.0	382.8	439.9	431.2	413.8	354.0
	%-change		−1.1	−3.1		−2.0	−5.9	−19.5
Fruits and vegetables[b]	kcal/day	153.1	219.5	352.5	131.6	270.2	551	818
	%-change		43.6	130.3		105.3	318.6	521.6
Cereals	kcal/day	525.4	553.9	611.0	460.0	520.3	640.9	811.0
	%-change		5.4	16.3		13.1	39.3	76.3
Total[c]	kcal/day	2292.3	2321.5	2380.3	2285	2345.1	2467.9	2503
	%-change		1.3	3.8		2.6	8.0	9.5

Source: Own calculation with the CAPRI model.

[a]Lancet recommendations for lard/tallow is added to pork meat.

[b]Tubers/starchy vegetables, tree nuts and legumes (soya, pulses) are included. Only the aggregate fruits and vegetables, including legumes and tree nuts, are depicted as in MAGNET; just one category for all mentioned products is available. A more detailed depiction of diet shifts is provided in Table A3 in the Appendix S1.

[c]Other food (sunflower seeds, rapeseed, table wine, coffee, tea, cocoa, lamb meat and fish) included in total kcal consumption.

be more sluggish in the short term, become more variable in the long run. Here, we investigated the full diet shift but also the moderate shifts. An overview of our models is shown in Figure 2.

To compute the magnitude of changes in European consumption patterns in the short run for the diet scenarios, the partial equilibrium model CAPRI has a highly detailed and regionally differentiated representation of supply and demand of agricultural products in the EU and a link to international markets. The CAPRI model (Britz & Witzke, 2014) combines regional supply models and a global market model. The supply module is based on programming models for each of the approximately 280 NUTS2 regions of the EU (or similar administrative units in auxiliary countries). The farm production decisions are modelled based on mathematical programming models depicting the supply at the regional level with approximately 50 primary and processed agricultural products, including the current ceilings and financial support implemented by the Common Agricultural Policy (CAP) after 2014. This includes greening measures, premium schemes, entitlements and voluntary coupled support (VCS). Animal products are highly interlinked via the young animal market, and the herd flow model and fodder ratios depict animal production adjustments in the EU and its interlinkage to global markets. The interaction between animals and crop production is established via the feed module. This module defines the quantities of feed categories or single feed stuffs used per animal, depending on their prices. Total feed use might be produced regionally (grass, fodder root crops, silage maize, or other

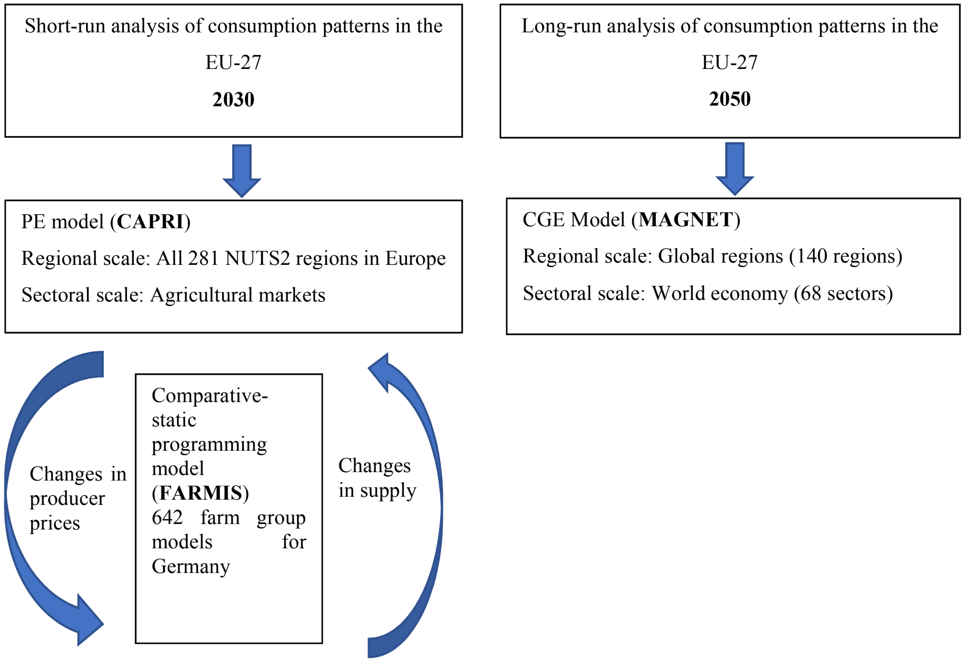

FIGURE 2 Modelling framework to analyse consumer demand shifts in 2030 and 2050. *Source*: Own depiction. [Colour figure can be viewed at wileyonlinelibrary.com]

fodder from arable land) or bought from the market. Market prices change with each iteration of the market module of CAPRI. The supply model uses positive mathematical programming for calibration. Supply that is not observed or small in the baseline stays zero or relatively small, even if higher price changes occur, which, while sensible in the short term, is less realistic in the long run. The market model is a *spatial, non-stochastic global multi-commodity* model defined by a system of behavioural equations differentiated by commodity and geographical units. Food consumption is specified at the country level based on FAO food balance sheets and Eurostat (Britz & Witzke, 2014). Consumer food demand is based on generalised Leontief expenditure functions (Ryan & Wales, 1999) and the resulting indirect utility functions depend on prices and changes in income. To ensure a diversified consumption bundle, minimum consumption levels, which are price- and income-independent elements of the generalised Leontief demand system, are specified in the calibration procedure. International trade in the CAPRI market model is implemented following the Armington assumption (Armington, 1969).

To assess the impact on farm income for different farm types in the short run, the producer price change from CAPRI is fed into the FARMIS model, a comparative-static process-analytical programming model for farm groups (Braun, 2020; Deppermann et al., 2014; Ehrmann, 2017). The specification of this model is based on information from the German Farm Accountancy Data Network (FADN), which covers about 10,000 farms per year, supplemented by data from farm management manuals. The use of aggregation factors allows for the representation of the sectors' production and income indicators. Prices are generally exogenous and provided by CAPRI. Aggregated production responses are returned to CAPRI, and this iterative process is repeated until convergence between model results is reached.[2] There is an exception to this for specific agricultural production factors, such as land and young livestock, where (simplified) markets are modelled endogenously, allowing for the derivation of respective equilibrium prices

[2]This process is similar to the iterative sequential solution of the CAPRI market module and its regional supply models (Britz & Witzke, 2014).

TABLE 2 Assumption of the 2030 and 2050 baseline.

Model	Policy	Base year	Projection year
CAPRI	Brexit; CAP after 2014; VCS; greening measures; Standard free trade agreements	2012 based on Eurostat and other databases	2030
MAGNET	Brexit; CAP direct payments, Free trade agreements	2014 GTAP 10 and other databases	2050
FARMIS	Cap after 2014, greening measures	FADN 2018	2030

Source: Own depiction.

under different policy scenarios. Homogeneous farm groups are generated by the aggregation of single-farm data. For this study, farms were stratified by region, farm type, farm size and management system (conventional or organic), resulting in 626 farm groups that represent the German agricultural sector.

The diet shifts of the long-term scenarios are implemented in the MAGNET model to analyse the economic and environmental consequences for the agricultural sector in 2050. MAGNET is a multi-regional applied computable general equilibrium (CGE) model with agricultural detail based on microeconomic theory (Woltjer & Kuiper, 2014). The GTAP model and database are at its core (Hertel, 1998) and complementing these are dedicated modules on agricultural factors and good markets as well as on environmental aspects. The model is solved by finding a price vector that simultaneously clears all factors, goods and service markets. The demand for private households is specified by an aggregated constant difference elasticity (CDE) implicit expenditure function, which was first proposed by Hanoch (1975). The CDE function is non-homothetic and allows the budget shares of different goods and services to adjust with income changes. Different regions in the model are linked via trade flows subject to border policies, as well as transportation costs. Similar to the CAPRI model, international trade is governed by the Armington (1969) assumption, which allows for modelling intra-industrial trade flows in line with observed trade data. The model comprises information on agricultural, industrial and service sectors and is able to capture the interactions between these sectors. Further information about the specifications of the models used is provided in Table A4 in the Appendix S1.

To improve consistency between the models, we established a common baseline scenario for the modelling system, based on trend-based assumptions on exogeneous variables and agricultural policies up to the year 2030 for the short-run analysis (Haß et al., 2020) and up to 2050 for the long-run analysis. Sustainability, health and animal welfare aspects of diets influence the demand of European consumers for food. For some foods, particularly meat, dietary changes are already evident and more pronounced than in other high-income countries (EC, 2019, 2020; Sanchez-Sabate & Sabaté, 2019). The dietary shifts from past trends are captured in the baseline. Hence, the baseline may be interpreted as a projection in time covering the most likely future development of the agricultural sector and demand behaviour under status-quo policies, and including all future changes already foreseen in the current legislation. It serves as an evaluation point for scenario analysis. The baseline accounts for trends in population growth by country, inflation, GDP growth, technological progress such as yield growth, and increasing feed and fertiliser efficiency. An overview of the baseline assumptions is given in Table 2. The diet scenarios are evaluated in comparison to the baseline and thus provide a comparative static analysis of dietary changes.

4 | RESULTS

The dietary changes described above are implemented as preference shocks of the demand systems in the CAPRI and MAGNET models. The resulting consequences for producer prices, production, international trade, agricultural income and GHG emissions are described in the following section.

4.1 | Prices

Impacts on producer prices are directly related to the magnitude of simulated consumer demand changes for the respective products. For all diet scenarios in the short and long run, producer prices for red meat products, milk and sugar show the greatest declines in the EU-27 as a result of the comparably high level of simulated demand reductions of European consumers (see Figure 3). The difference in the magnitude of price changes between CAPRI in 2030 and MAGNET in 2050 is mainly based on different supply-side flexibilities of the two models due to differences in modelling scope and assumptions. Factors markets are relatively flexible in MAGNET, allowing factors to move within and across sectors, which results in smaller prices and larger output effects compared to CAPRI. This is in line with a longer-term perspective.

The average producer price in the EU-27 for beef declines between −6.6% and −18.4% in 2030 for the Lancet_low and the Lancet_high scenarios, respectively. In the long run, the producer prices are reduced between −0.4% for Lancet_low and − 3.8% for the assumed full implementation of the EAT-Lancet dietary recommendations (Lancet_full). For pork (−5.1% to −15.4% in 2030, 0.05% to −1.2% in 2050) and milk (−7.1% to −21.7% in 2030, −0.1% to −1.6% in 2050), the diet scenarios also result in lower producer prices in the EU-27 with similar changes in Germany. Other animal products, such as eggs and poultry producer prices, are less affected in both models, as the consumption levels in the reference scenarios are closer to the EAT-Lancet recommendations. For vegetables and fruits, the producer prices in the EU-27 increase significantly in the short and the long run as the daily kcal intake in most EU countries is much lower

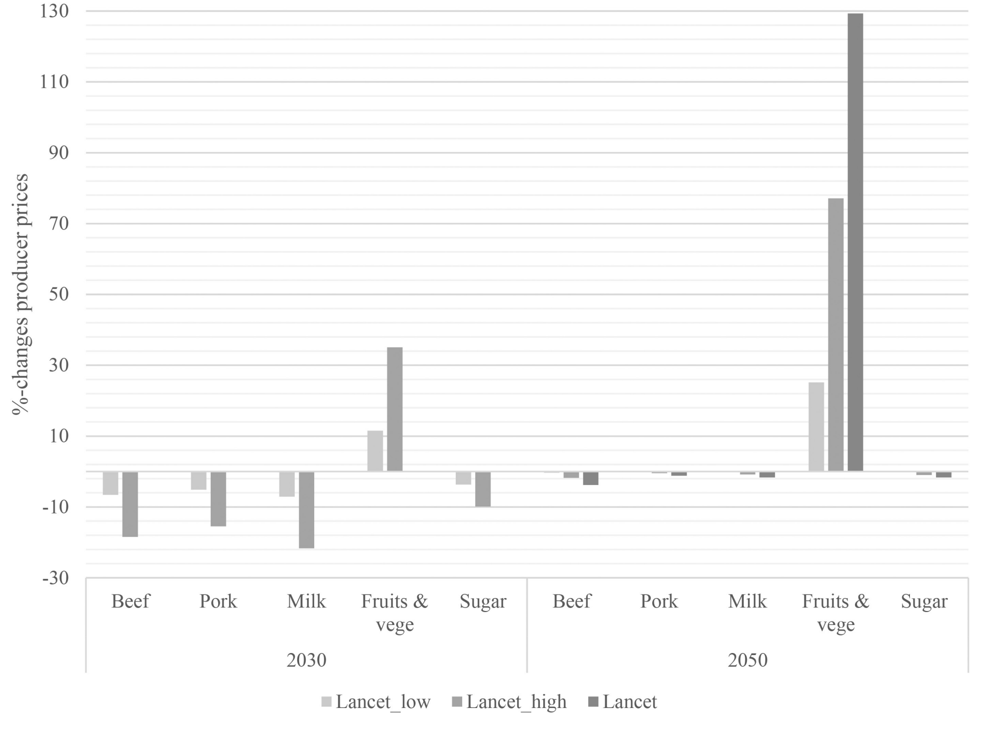

FIGURE 3 Range of percentage changes in producer prices for the diet scenarios compared to the reference in the short and long run for selected products in the EU-27. *Source*: Values for 2030 are based on the CAPRI model; values for 2050 are based on the MAGNET model.

compared to the EAT-Lancet diet. On average, the producer price in the EU-27 for fruits and vegetables[3] increases between 11.5% and 35.1% in 2030. In the long run, the comparably high demand shifts for fruits and vegetables, ranging from 105% to 522%, raise the producer prices between 25% and 129% in 2050 for the EU-27.

Similar to the producer prices changes, the EU consumer prices in the diet scenarios decline for meat, dairy products and sugar, and increase for vegetables and fruits (see Table A5 in the Appendix S1). In 2030, the average consumer price in the EU-27 for beef is reduced by −3.7% to −10.4% for the Lancet_low and the Lancet_high scenarios, respectively. In the long run, consumer prices decline between −0.3% and −3.7% for the full implementation of the EAT-Lancet recommendations. The high demand shift for vegetables and fruits in the EU-27 raises consumer prices substantially in the short and the long run. In 2030, average consumer prices for vegetables and fruits increase between 7.3% and 19% and in 2050 between 16.3 and 73.3%. The changes in consumer prices and demand also affect total consumer expenditures for food, resulting in increases between 2.8% and 9.4% in 2030 and in the long run between 2.6% and 12.5% in the Lancet_low and the Lancet_high scenarios. For the full implementation of the EAT Lancet dietary suggestions, expenditure for food rises by 29% in 2050, mainly driven by the high consumer prices for vegetables and fruits.

4.2 | Production and trade effects

The production changes in the EU-27 that result from the demand changes are shown in Figure 4. It can be observed that, in general, the changes in production are smaller than those in demand due to international trade effects.

In 2030, the largest production decreases in the EU-27 are projected for beef (−2% to −5.2%), pork (−2.7% to −7.3%) and sugar (−10.2% and − 26.7%). Also, production of other animal products such as dairy products decreases in the EU-27 (−3% to −8.5%) whereas poultry production is reduced only marginally (−0.3% to −0.9%) with similar changes for Germany for all products. In the short run, the diet scenarios also result in substitution effects in European bioethanol production from agriculture. The supply of bioethanol from sugar increases between 10.4% and 31.5% in the EU-27 and the use of cereals decreases between −4% and − 12.9%, resulting in an increased production of bioethanol of 2% for the Lancet_high scenario. The reduced input of cereals in bioethanol production in addition to the lower production of feed cereals is used to close the gap of increased consumer demand of cereals in the diet scenarios for the EU-27, leading to only marginal changes in production of cereals. For fruits and vegetables, the production in the EU-27 is expanded between 3.6% and 10.5%, driven by higher producer prices in the diet scenarios.[4]

In the long-run scenarios, the pattern in production changes is similar to 2030 for all products; however, the magnitude of changes is much greater. In 2050, the diet scenarios including the full implementation of the EAT-Lancet diet would reduce production of beef between −15.9% and −74.1%, as well as reducing production of pork (−13.4% to −57.2%), dairy (−9.1% to −42.6%) and sugar (−8.1% to −33.7%). The production of fruits and vegetables in the EU-27 increases by 27.5% in Lancet_low and 69.6% in the Lancet_high scenario and is almost doubled when assuming the full implementation of the EAT-Lancet recommendations.

The magnitude of production changes in the EU member states is dampened by international trade, as the respective producers of these products in non-EU countries are also affected

[3]Including producer price changes for legumes in CAPRI as legumes are part of the aggregate fruits and vegetables in MAGNET.
[4]We conducted a sensitivity analysis for low (−50%) and high (+50%) supply elasticities for the diet scenarios in the EU-27 for 2030 with CAPRI. The results are presented in Table A6 in the Online Appendix. We see that, as expected, using higher elasticities results in lower prices and higher production and vice versa for lower elasticities in the EU compared to the scenario above. The sensitivity of producer prices to the assumptions on supply elasticities is comparatively low, with the greatest changes being for milk, vegetables and legumes.

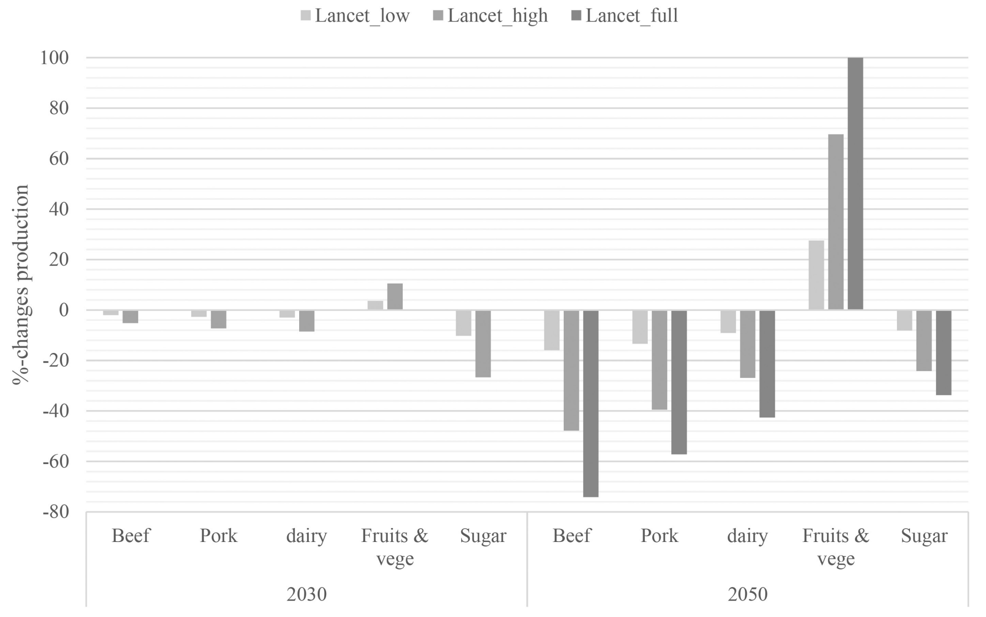

FIGURE 4 Range of percentage changes in production for the diet scenarios compared to the reference in the short and long run for selected products in the EU-27. *Source*: Values for 2030 are based on the CAPRI model; values for 2050 are based on the MAGNET model.

by the dietary changes in the EU. In non-EU countries, the demand changes in the EU based on the EAT-Lancet recommendations and the corresponding price changes for the European agricultural sector result in lower producer and consumer prices for animal products and higher prices for vegetables and fruits. These price effects induce supply and demand adjustments in non-EU countries, resulting in lower supply and higher demand for animal products and vice versa for vegetables and fruits (see Table A7 in the Appendix S1). The increased demand for fruits and vegetables in the EU is satisfied to some extent by increased imports from non-EU countries where producer prices increase, while products for which domestic demand is decreasing in the analysed scenarios, like meat, are increasingly exported to non-EU countries facing lower producer prices and higher demand (see Table 3).

The changes in trade flows are particularly large for fruits and vegetables, where imports increase between 46% and 167% in 2030 and 127% to 529.9% in 2050 for the Lancet_low and Lancet_high scenarios, respectively, with the increases mainly being driven by increased imports from Central and South America. In the long-run scenarios, the full implementation of the EAT-Lancet recommendations will result in imports of fruits and vegetables more than ten times greater than in the reference scenario so that the sharp increases in consumer demand, which cannot be covered by increased production in the EU-27, are satisfied. As a result of reduced consumer demand for animal products in the EU member states, imports decrease considerably for beef, pork and dairy products in the short- and long-run scenarios. Export flows of all animal-based products increase in all EAT-Lancet scenarios, with differences in the magnitude of effects in the short- and the long-run scenarios. In 2030, the production decline for animal products in the EU-27 is much lower, resulting in higher exports compared to the long-term scenarios where factors are assumed to be more variable than in the short run, allowing for higher production changes within the EU-27. The largest export increases can be observed for beef, with increases between 13% and 56% in 2030 and 0.5% to 8.6% in 2050, followed by pork and dairy products.

TABLE 3 Percentage and absolute changes in trade (€ millions) for the EU-27 with non-EU countries compared to the reference 2030 and 2050 for the diet scenarios.

Simulation year		2030				2050					
Model		CAPRI				MAGNET					
Scenario		Lancet_low		Lancet_high		Lancet_low		Lancet_high		Lancet_full	
Imports/ Exports		Imp.	Exp.	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.
Products											
Beef	%-Δ	−23	13	−54	55	−16	1	−50	4	−71	9
	Abs.Δ	−790	649	−1827	2646	−819	21	−2491	145	−3700	329
Pork	%-Δ	−12	6	−33	17	−16	0	−50	3	−70	6
	Abs.-Δ	−344	621	−958	1837	−546	−1	−1688	468	−2404	1155
Dairy	%-Δ	−18	2	−39	7	−11	1	−35	4	−54	8
	Abs.-Δ	−418	556	−918	1751	−472	181	−1459	1108	−2288	2350
Fruit & veg.	%-Δ	46	−8	167	−18	127	−15	530	−30	1078	−37
	Abs.-Δ	12,366	−1580	44,991	−3375	41,366	−2210	171,361	−4607	348,707	−5601
Sugar	%-Δ	−14	7	−33	21	−11	1	−33	5	−46	8
	Abs.-Δ	−120	91	−286	269	−553	44	−1656	179	−2323	328

Source: Values for 2030 are based on the CAPRI model; values for 2050 are based on the MAGNET model.

4.3 | Environmental effects

The impact of both scenarios on non-CO_2 greenhouse gas emissions of the agricultural sector for the short- and long-run perspectives on a European and global scale are shown in Figure 5. For the simulation year 2030, the diet scenarios result in a reduction in global GHG emissions from the agricultural sector and range between −13.1 and −48.6 million tonnes CO_2-equivalents (−0.2% to −0.9%) and in the long run between −22.2 to −88.1 million tonnes of CO_2-equivalents (−0.2% to −0.7%) for the Lancet_low and Lancet_high scenarios, respectively. In 2050 the full implementation of the EAT-Lancet recommendations would result in a decline of global non-CO_2 greenhouse gas emissions of 88.1 million tonnes CO_2-equivalents (−1.1%) compared to the reference. Emission savings arise predominantly in the livestock sector, particularly for beef. The general pattern of GHG reductions for the product categories in the EU are similar in the short and the long run as products for which EU demand drops (e.g., meat and dairy) are produced and imported less and exports increase. For products with increasing demand in the EU (e.g., vegetables and fruits), the production and imports increase and exports decrease, resulting in higher GHG emissions in the EU and non-EU countries for these products (see Figure A1 in the Appendix S1).

The results of the diet scenarios in the short and long run differ with respect to the countries where the main share of GHG reductions occurs. In 2030, the emission reductions in the EU-27 are comparatively small, ranging between −2.8 and 12.1 million tonnes CO_2-equivalents (−0.7% to −3.2%) due to lower production changes within the EU and higher exports to the rest of the world. The main reductions in GHG emissions occur mostly in non-EU regions, where the production of animal products decreases and the production of fruits and vegetables show strong increases, resulting in a replacement of non-EU production with higher emission intensities (more GHG emissions per kg produced) by European exports. The European emission reductions resulting from the EAT-Lancet scenarios are in a sense exported, resulting in further decrease of GHG emissions in non-EU countries and negative emission leakage. The nutrient balances in 2030 are hardly affected by the EAT-Lancet diet scenarios due to comparably low

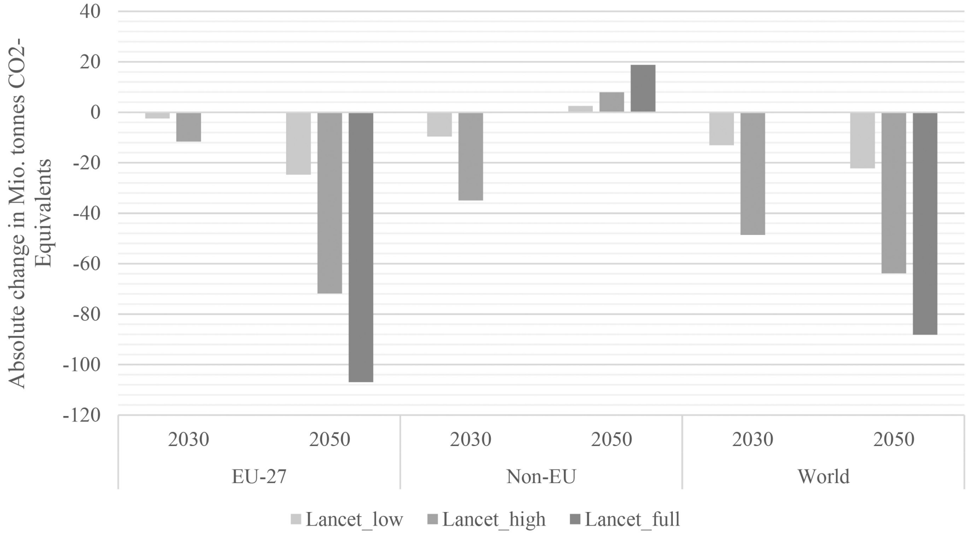

FIGURE 5 Absolute changes in total non-CO_2 greenhouse gas emissions from the agricultural sector for the EAT-Lancet scenarios in the EU-27, non-EU and on a global level compared to the reference scenarios. *Source*: Own computations with CAPRI (2030) and MAGNET (2050).

changes in agricultural production in the EU-27, which result in a marginal reduction of nitrogen surplus between −3.2% (−2 kg/ha) and −5.3% (−3.4 kg/ha) for the EU-27.[5]

In 2050, due to high production reductions for beef and dairy, the main share of GHG emissions is reduced within the EU-27 between −24.7 and −106.9 million tonnes CO_2-equivalents (−5.1% to −22.1%). Similar to the short-run scenarios but to a lesser extent, the production of meat and dairy products in non-EU countries is reduced and substituted by European imports with lower emission intensities. For all EAT-Lancet scenarios in 2050, the increase in emissions for fruits and vegetables, particularly in non-EU countries, due to higher import demand from the EU-27, slightly offsets European GHG reductions resulting in minor emission leakage.

4.4 | Income effects

To shed light on how dietary changes might affect agricultural incomes across the EU-27 and Germany we compare sectoral incomes for primary agriculture in the short run (2030) and the long run (2050). We also illustrate the heterogeneity of farm-level effects by providing a more detailed analysis of incomes. To further our understanding of income changes at the farm level, we use the FARMIS model, which is applied to German FADN data.

4.4.1 | Long-run sector income effects are positive

The analysis of EU-wide economic effects for the agricultural sector in CAPRI resulting from the EAT-Lancet diet scenarios is based on the gross value added (GVA) plus premiums as the main indicator of producer (farmer) welfare. The GVA is the difference between revenues (output quantities valued at farm gate prices) and intermediate input costs (input quantities with the exemption of the primary factors land, capital and labour multiplied by their farm gate prices). The GVA plus premiums is hence the sum the farming sector can spend to remunerate labour, capital and land, independent of the property rights of these factors (Britz & Witzke, 2014).

[5]Information about nutrient surpluses is not available in the MAGNET simulation of the EAT-Lancet long-run scenarios.

TABLE 4 Percentage changes in total agricultural income compared to reference scenarios.

Simulation year	2030		2050		
Model	**CAPRI**		**MAGNET**		
Scenario	**Lancet_low**	**Lancet_high**	**Lancet_low**	**Lancet_high**	**Lancet_full**
Country					
Germany	−4.9%	−12.1%	2.8%	10.6%	22.7%
EU-27	0.3%	5.4%	9.7%	36.2%	71%
World	0.2%	1%	1.8%	7.1%	14.3%

Source: Own computations with CAPRI and MAGNET.

Similar to CAPRI, in MAGNET sectoral income is measured as added value evaluated at producer prices. The sectoral income changes are shown in Table 4.

In the case of EU-27, shifts to healthier diets predominantly cause sectoral farm income to rise. In essence, this is driven by the fact that income losses resulting from the decline in producer prices and production of animal products, feed and sugar are dominated by higher prices and production for vegetables and fruits. On the contrary, because Germany is highly specialised in animal-based products, it will lose agricultural income unambiguously. However, those losses materialise predominantly in the short run (2030), whereas in the long run (2050), when production factors adjust accordingly, the losses are dissipated. On the global level, total agricultural income increases mainly as a result of increased production of fruits and vegetables in non-EU countries to meet increased import demand from the EU-27. The large gains in the long-run sector income can partly be explained by a general increase in consumption quantities (in kcal/day) in line with the EAT-Lancet diet and because value added in fruits, vegetables and nuts is relatively high.

4.4.2 | Income effects are very heterogeneous in the short term

Focusing on the income effects across regions of the European Union from the short-run EAT-Lancet diet scenarios[6] we find a very uneven geographical spread, as can be seen in Figure 6. This is true not only on a country level, but also for NUTS2 regions within the countries.

Particularly for regions with a high share of animal production activities, agricultural income decreases due to the reduced consumer demand in the EU for these products and the resulting decline in producer prices in the EAT-Lancet diet scenarios. Vice versa, for most regions with a strong focus on the production of vegetables and fruits, agricultural income increases due to the higher demand and producer prices for these products. In Figure 6, a clear trend is visible that the magnitude of the changes in agricultural income increases with higher demand shifts when comparing the Lancet_low and Lancet_high scenarios for the NUTS2 regions in the EU-27.

In Ireland, which mainly focuses on beef and dairy production, the declining prices for these products reduce agricultural income between −24.8% and −66.8% for the Lancet_low and Lancet_high scenarios, respectively. Income losses in Denmark range between −17.2% and −43% and are mainly driven by reduced producer prices for pork meat (−5.1% to −15.5%). For Germany, which has the highest production of pork meat and dairy products in the EU-27, the increase in prices and production for vegetables, fruits and legumes does not compensate for the decline in prices for the production of animal products in livestock-intensive regions (e.g., Weser-Ems), resulting in income losses between −4.9% and −12.4%. Italy and Spain, which are the biggest producers of vegetables and fruits in the EU-27, representing around 35% of EU

[6]Here we rely on results of CAPRI because there is no information on the NUTS2 level available in MAGNET.

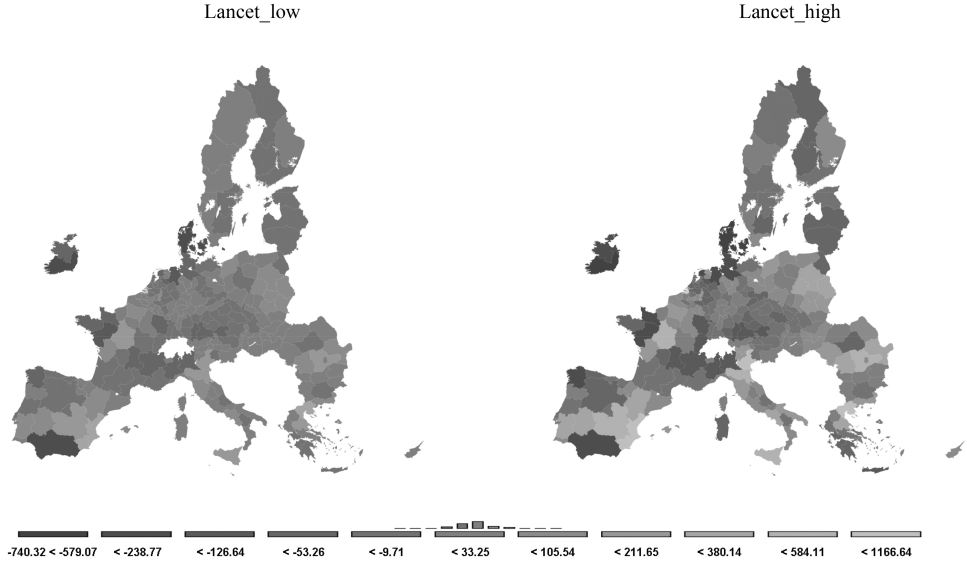

FIGURE 6 Absolute differences in agricultural income (gross added value + premiums) in € millions for scenarios Lancet_low and Lancet_high at NUTS2 level compared to the reference scenario 2030. *Source*: Own computations with CAPRI.

production in the reference scenario, benefit from the increased demand for these products in both EAT-Lancet scenarios. Agricultural income in Italy increases between 3.2% and 12.3% for Lancet_low and Lancet_high, respectively, as a result of higher prices for vegetables and fruits compensating for the substantial income reduction in livestock intensive regions such as Piemonte (−24.6% to −63.6%) and Lombardia (−13.8% to −28.5%) in the Po valley. In Spain, the income for the agricultural sector increases by 3.4% for the Lancet_low scenario and 15.7% for Lancet_high scenario with heterogeneous outcomes for the NUTS2 regions. In Galicia, which is the main producer of dairy products in Spain, agricultural income is reduced between −12.8% and −34.3% due to lower producer prices resulting from decreased demand for dairy products. For Castilla-Leon, which has the highest share of beef production in Spain, the decline in producer prices for beef result in comparably low income losses of −2.8% for Lancet_low and −5.4% for Lancet_high as the additional income from vegetables and fruits partly compensates for the losses in the beef sector. Interestingly, results for both EAT-Lancet scenarios show that the greatest reduction in agricultural income in Spain is in Andalusia, which is the most important producer of vegetables and fruits in Spain. The main reason for this is the large income loss from olive oil production due to the reduced demand for olive oil (see Table 1) in our diet scenarios. Andalucía in our reference scenario in 2030 represents 50% of olive production for olive oil in the EU and around 84% in Spain. The comparably large decline in producer prices for olives ranging from −51% to −150% in combination with price reductions for animal products outweighs the additional agricultural income from increased prices and production for fruits and vegetables.

The regional analysis highlights that Income effects are diverse and depend on the structure of agricultural production; in particular, regions mainly focusing on the production of animal products could face severe income losses. This heterogeneity is expected to be even larger at the farm level due to the high specialisation of many farming systems in Europe. Aggregated results may therefore 'hide' the dispersion of income effects, especially at the tails of the distribution of income changes. Therefore, we complement the aggregated results with a case study for Germany with a detailed farm-level analysis to identify the extent of adaptation needs in specific farming systems for scenarios of widespread dietary changes. The producer price change estimations

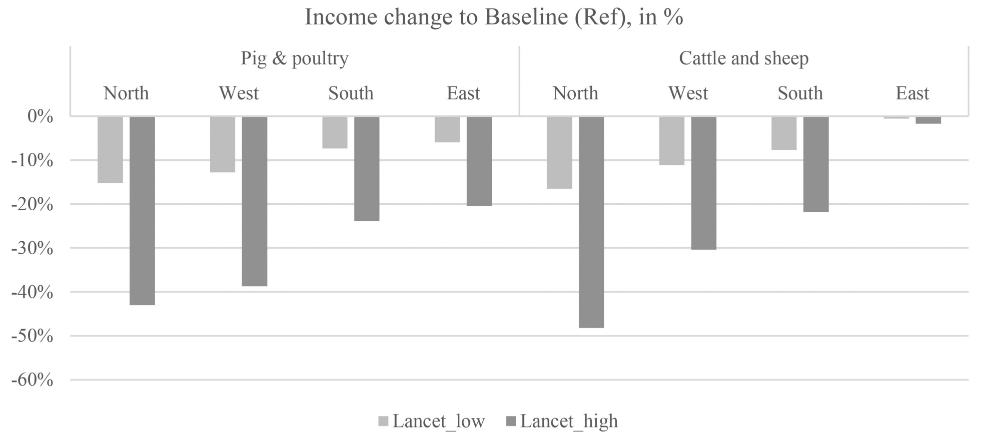

FIGURE 7 Impacts on farm income (FWU, farm net value added per work unit) in pig and poultry farms and cattle and sheep farms in different regions of Germany. *Source*: Own computations with FARMIS.

from the CAPRI model for Germany (see Table A8 in the Appendix S1) were transferred to the FARMIS model to assess the impact on farm income for different farm types in Germany.

We calculate income per labour unit as farm net value added per annual work unit,[7] which is also used in the EU FADN as a key income indicator to account for the productivity of the agricultural workforce and the diversity of farms (EC, 2018). To account for income effects of changes in land rental prices and provide an assessment of potential impacts on the long-term viability of farms, we additionally calculate farm net income (family farm income), which represents the remuneration to fixed factors of production of the farm (work, land and capital) as well as the remuneration to the entrepreneur's risks (loss/profit) in the accounting year. Many different approaches to viability assessment exist, the most common of which is comparing family farm income to a reference income (O'Donoghue et al., 2016).

On average, farm incomes decrease between −8% in the Lancet_low scenario and −22% in the Lancet_high scenario, but with large differences between farm types (Figure A2 in the Appendix S1). Whereas permanent crop farms benefit from the increased demand for fruit, with incomes rising by up to 11% in the Lancet_high scenario, large negative income changes are projected for pig and poultry farms (−34%) and for dairy farms (−48%) in the Lancet_high scenario.

However, these averages hide the heterogeneity that exists even within farm types. For example, the income development in arable farms strongly correlates with the importance of vegetable production, and arable farms with a high share of vegetables see income increases of 30% and above (compare Figure A3 in the Appendix S1). The large differences in the effects for some livestock farm types are shown in the regional differentiation of the results (Figure 7). While other grazing livestock farms in the northern regions suffer income losses of 35% due to their specialisation in cattle fattening with comparatively high stocking densities, the relative losses in other grazing livestock farms in the eastern regions of Germany, which have considerably lower stocking densities, are much lower, since in these regions in particular direct payments linked to acreage stabilise income. Among the pig and poultry farms, the highly specialised farms in the northern and western regions are affected to a much greater extent than the farms in the south or east, which are often more diversified.

The reduced profitability leads to a fall in rental prices, especially for grasslands. The resulting reduction in rents paid (e.g., in dairy farms, where expenses for rents are reduced by 20%) implies

[7]Farm net value added (FNVA) is used to remunerate the fixed factors of production (labour, land and capital) whether they be external or family factors.

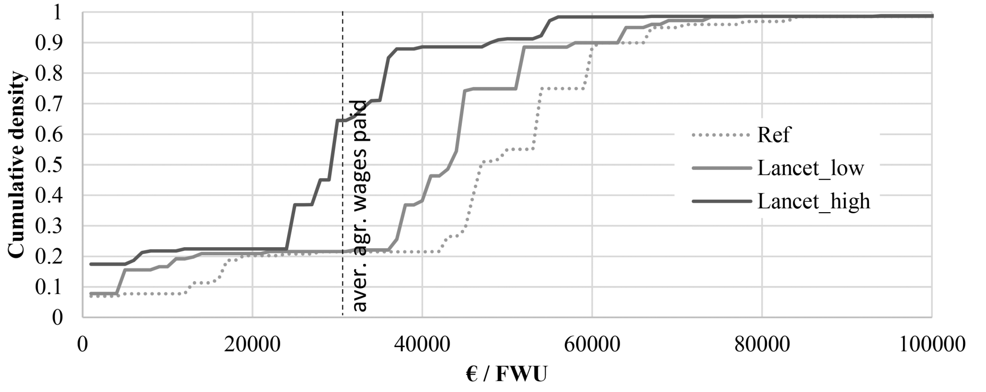

FIGURE 8 Shift in net income distribution (farm net income per family worker) in pig and poultry farms in Germany. *Source*: Own computations with FARMIS.

that a part of the income losses is transferred to land owners. However, even considering these adjustments in the land market, income losses remain high for some farms, indicating significant pressure for more fundamental structural change to adjust to this scenario. To assess the extent to which long-term farm viability is endangered in the analysed scenarios, Figure 8 provides an overview of the income distribution of pig and poultry farms, which are most affected by the lower demand for animal products. Comparing the average family farm income per family worker to the average wages paid in the baseline scenario (approx. 30,000 €/FWU) shows that the share of farms below the threshold remains stable in the Lancet_low scenario, while the share increases dramatically to more than 60% in Lancet_high.

5 | CONCLUSIONS AND POLICY IMPLICATIONS

An increase in plant-based diets is an important driver towards a healthier and ecologically sustainable planet. However, what this transition means for the agricultural sector in general and for individual farms in particular has not been well explored. We fill this gap using an agro-economic modelling framework. Within this framework, we specify several scenarios in which European consumers' diets approximate the EAT-Lancet recommendations to varying degrees in 2030 and 2050 and analyse the consequences on sector production, prices and incomes for the EU-27 and farm income for Germany. In line with dietary changes, production and prices of animal-based products decrease, while production and prices for fruits and vegetables increase sharply. International trade buffers the impact on agricultural markets, however, by increasing imports for fruits and vegetables, as well as exports for meat and dairy. Dietary changes are also accompanied by reductions in agricultural GHG emissions, which are in line with previous studies.

The results indicate that overall, the agricultural sector in the EU-27 could benefit from a dietary shift, while on country, regional, or farm level the results are mixed. In particular, countries that are highly specialised in animal farming, such as Germany, Ireland and Denmark, are likely to lose income. In contrast, regions with higher shares of vegetable and fruit farms like Spain, Portugal and the Netherlands can expect income gains. Interestingly, however, the specific circumstances matter, as is illustrated by the example of Andalusia, where a reduced income from olive oil production exceeds the income increases associated with fruits and vegetables. The aggregated results, however, can hide the heterogeneity of effects on different farms. We therefore analyse the farm effects using Germany as a case study, where the agricultural sector is expected to be particularly affected by a transition to healthier diets due to its dominant livestock sector, especially in the short run when production factors can only be adjusted to a limited extent.

The results indicate that dairy (pig and poultry) farms on average may experience losses up to one-half (one-third) of their income, while farms with a high share of vegetables could gain more than 30% in income. The strong influence of individual farm structure and the prevailing specific production system on the results of economic impacts even within one farm type implies that the use of European-wide farm level models, such as IFM-CAP (Elouhichi et al., 2018), could be helpful for further investigating the heterogeneous income effects for different farm groups throughout Europe.

We contribute the literature on the potential impacts of healthier and environmentally friendly consumer diets for the agricultural sector in several ways. Our study focuses on the detailed analysis of the economic impacts for the agricultural sector in the EU-27, which has not been sufficiently addressed in the literature before. The combination of different agro-economic models provides a detailed analysis of consequences for the agricultural sector from the global level through the European regional level to the farm type level in Germany over different time scales. In addition to different geographical and sectoral foci, the use of several models has the advantage that the results can be interpreted against the background of different supply-side responses and other particularities of the models. The differences in the short and long run as well as the drastic income changes in some farm types, highlighted by the farm-level model, point to the need for extensive structural adjustments of the agricultural sector to cope with widespread dietary changes.

Given that the EAT-Lancet diet is associated with better outcomes in terms of emissions, health and agricultural incomes, its (partial) adoption should be supported by policies. This could be achieved by a mixture of monetary instruments, such as taxes and subsidies (Latka et al., 2021; Springmann et al., 2018b; Veerman et al., 2016) and complementary non-fiscal measures, such as information campaigns and product labelling (Hyseni et al., 2017; Mazzocchi, 2017). It has also been demonstrated that agricultural and trade policies are often not well designed for delivering public goods. Hence, redesigning agricultural subsidies and trade policies is another option for supporting healthy and sustainable diets (Freund & Springmann, 2021; Springmann & Freund, 2022). In addition, other supply-side measures such as technological and management advances to improve agricultural yields, fertiliser efficiency, or feed conversion rates of animals are required to further shift production towards environmental and nutritional objectives. Hence, a coherent policy package has to be designed to incentivise the consumption, production and trade of certain food types beneficial for the environment and health.

The policy implications also depend on the speed of dietary shifts. If these evolve slowly over time, as they mostly have in the past, the sector should be able to adjust and avoid disruptive losses. As our research shows, even in a country dominated by animal farms like Germany, there are potential profit opportunities for farms specialising in the production of fruits and vegetables. This should ease the transition of the sector, given that markets provide the correct price signals. To help farmers to spot trends in dietary patterns and act accordingly, governments should provide data on consumer behaviour on a regular basis. If dietary shifts are accelerating, for example due to nudging policies, policy intervention may become important. Policies can support adaptation by lowering adjustment costs (e.g., by reducing regulatory obstacles to the transformation of production systems and value chains, and providing infrastructure and extension services for the introduction of new systems and production lines) and dampening social impacts in the most affected regions (e.g., supporting retraining or, possibly, providing temporal income support in cases of hardship).

The focus of this study is primarily on the economic consequences of dietary changes and their impacts on GHG emissions. However, adopting the EAT Lancet diet could have multiple environmental effects, such as effects on water use, biodiversity, eutrophication or acidification, (Springmann et al., 2020; Stehfest et al., 2009; Tuninetti et al., 2022), as well as nutritional consequences, such as nutrient bioavailability (Verger et al., 2018), which should be accounted for in future studies to provide a more complete evaluation of societal benefits and costs of dietary changes. Also, for our analysis, we focused on the situation in the EU-27 and implemented dietary shifts only for EU countries. When other countries also changed their dietary patterns according to more sustainable diets, this would also affect the EU agricultural sector through international trade flows. However, the effect on agricultural incomes in the EU is unclear, as diets would have to adjust differently in low-, middle-, and high-income countries. Although export opportunities for animal products from the EU to other high-income countries would probably decrease, opportunities for exports of animal products from the EU to low- and middle-income countries could increase (Drogue et al., 2020). In addition, increasing domestic demand could reduce import opportunities for fruits and vegetables. Another limitation of this study is that we focus exclusively on resulting non-CO_2 emissions, where the agricultural sector is an important emitter, and do not consider CO_2 emissions (or sinks) from the land use, land-use changes and forestry (LULUCF) sector in the short and the long term. Nor have we considered greenhouse gases from the upstream sector, such as the production of mineral fertilisers, nor emissions from the downstream sectors, such as the processing and marketing of food.

The modelling framework should be developed further to account for adjustment costs and to be able to more explicitly differentiate the time path of adjustments. At the farm level, some approaches exist (e.g., Britz et al., 2016) which dynamically model the time path of adjustments, including farm exits, by considering the economic life of quasi-fixed factors and farmers' characteristics such as age and successors, though most of these are limited in scope due to the high data requirements. Agent-based models (Kremmydas et al., 2018) that account for the interconnectedness of economic entities may be particularly suited for modelling the adjustments in the most affected regions if they manage to incorporate the value chain (e.g., slaughterhouses, processing facilities) in their analyses.

ACKNOWLEDGEMENTS

The research was undertaken as a part of the Nutri2Cycle project that receives funding from the European Union's Horizon 2020 Framework Programme for Research and Innovation under Grant Agreement no 773682. We thank members from the Thünen Modelling Network who shared their perspectives with us in the development of this work. Our thanks are also due to anonymous reviewers for their constructive comments on an earlier draft.

Open Access funding enabled and organized by Projekt DEAL.

ORCID

Jörg Rieger https://orcid.org/0000-0002-5130-7841
Florian Freund https://orcid.org/0000-0003-0803-6238

REFERENCES

Armington, P.S. (1969) A theory of demand for products distinguished by place of origin. *IMF Staff Papers*, 16, 159–178.

Bajželj, B., Allwood, J.M. & Cullen, J.M. (2013) Designing climate change mitigation plans that add up. *Environmental Science & Technology*, 47(14), 8062–8069. Available from: https://doi.org/10.1021/es400399h

Behrens, P., Kiefte-de Jong, J.C., Bosker, T., Rodrigues, J., Koning, A. & Tukker, A. (2017) Evaluating the environmental impacts of dietary recommendations. *Proceedings of the National Academy of Sciences*, 114(51), 13412–13417. Available from: https://doi.org/10.1073/pnas.1711889114

Bonnet, C., Bouamra-Mechemache, Z., Réquillart, V. & Treich, N. (2020) Viewpoint: regulating meat consumption to improve health, the environment and animal welfare. *Food Policy*, 97, 101847. Available from: https://doi.org/10.1016/j.foodpol.2020.101847

Braun, J. (2020) *Weiterentwicklung eines sektorkonsistenten Betriebsgruppenmodells um Treibhausgasemissionen und Bewertung von ausgewählten Minderungsstrategien*. Düren: Shaker (Berliner Schriften zur Agrar- und Umweltökonomik), p. 23.

Britz, W., Lengers, B., Kuhn, T. & Schäfer, D. (2016) A highly detailed template model for dynamic optimization of farms-FARMDYN. Edited by University of Bonn. Inst. Food Resour. Econ. Version Sept, 147 (2016). Bonn.

Britz, W. & Witzke, P. (2014) CAPRI model documentation 2014. Available from: http://www.capri-model.org/docs/capri_documentation.pdf [Accessed 6 May 2018]

Bryngelsson, D., Wirsenius, S., Hedenus, F. & Sonesson, U. (2016) How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture. *Food Policy*, 59, 152–164. Available from: https://doi.org/10.1016/j.foodpol.2015.12.012

Clark, M.A., Domingo, N.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J. et al. (2020) Global food system emissions could preclude achieving the 1.5°C climate change targets. *Science*, 370(6517), 705–708. Available from: https://doi.org/10.1126/science.aba7357

Cordts, A., Duman, N., Grethe, H., Nitzko, S. & Spiller, A. (2014) Potenziale für eine Verminderung des Fleischkonsums am Beispiel Deutschland und Auswirkungen einer Konsumreduktion in OECD-Ländern auf globale Marktbilanzen und Preise für Nahrungsmittel. *Proceedings Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaues e.V.; German Association of Agricultural Economists*, 49, 209–222. Available from: https://doi.org/10.22004/ag.econ.261538

Creutzig, F., Fernandez, B., Haberl, H., Radhika, K., Mulugetta, Y. & Seto, K.C. (2016) Beyond technology: demand-side solutions for climate change mitigation. *Annual Review of Environment and Resources*, 41(1), 173–198. Available from: https://doi.org/10.1146/annurev-environ-110615-085428

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N. & Leip, A. (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2(3), 198–209. Available from: https://doi.org/10.1038/s43016-021-00225-9

Deppermann, A., Grethe, H. & Offermann, F. (2014) Distributional effects of CAP liberalisation on western German farm incomes. An ex-ante analysis. *European Review of Agricultural Economics*, 41(4), 605–626. Available from: https://doi.org/10.1093/erae/jbt034

DGE. (2017) *Vollwertig essen und trinken nach den 10 Regeln der DGE*. Bonn, Germany: Deutsche Gesellschaft für Ernährung. Available from: https://www.dge.de/index.php?id=52 [Accessed 11 May 2021]

Drogue, S., Perignon, M., Darmon, N. & Amiot, M. (2020) Does a better diet reduce dependence on imports? The case of Tunisia. *Agricultural Economics*, 51(4), 567–575. Available from: https://doi.org/10.1111/agec.12572

EC. (2018) EU Farm Economics Overview based on 2015 (and 2016) FADN data. European Commission (EC). Available from: https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/performance-agricultural-policy/studies-and-reports/economic-analyses-and-briefs/agricultural-and-farm-economics_en [Accessed 15 January 2021]

EC. (2019) *EU agricultural outlook for markets and income, 2019–2030*. Brussels: European Commission (EC), DG Agriculture and Rural Development.

EC. (2020) *EU agricultural outlook for markets, income and environment, 2020–2030*. Brussels: European Commission (EC), DG Agriculture and Rural Development.

Ehrmann, M. (2017) Modellgestützte Analyse von Einkommens- und Umweltwirkungen auf Basis von Testbetriebsdaten. Johann Heinrich von Thünen-Institut, Bundesforschungsinstitut für Ländliche Räume, Wald und Fischerei. Braunschweig (Thünen Report, 48). Available from: https://literatur.thuenen.de/digbib_extern/dn058604.pdf [Accessed 7 March 2018]

Elouhichi, K., Espinosa Goded, M., Ciaian, P., Perni Llorente, A., Vosough Ahmadi, B., Colen, L. et al. (2018) The EU-wide individual farm model for common agricultural policy analysis (IFM-CAP v.1): economic impacts of CAP greening: Publications Office. Available from https://publications.jrc.ec.europa.eu/repository/handle/JRC108693

FAO. (2020) *FAOSTAT statistical database. New food balances*. Rome: Food and Agriculture Organization of the United Nations. Available from http://www.fao.org/faostat/en/#data/FBS

Forsa. (2021) *Ernährungsreport 2021*. Berlin: Ergebnisse einer repräsentativen Bevölkerungsbefragung. Available from: https://www.bmel.de/SharedDocs/Downloads/DE/_Ernaehrung/forsa-ernaehrungsreport-2021-tabellen.pdf?__blob=publicationFile&v=2 [Accessed 27 June 2022]

Freund, F. & Springmann, M. (2021) Policy analysis indicates health-sensitive trade and subsidy reforms are needed in the UK to avoid adverse dietary health impacts post-Brexit. *Nature Food*, 2(7), 502–508. Available from: https://doi.org/10.1038/s43016-021-00306-9

Geibel, I., Freund, F. & Banse, M. (2021) The impact of dietary changes on agriculture, trade, environment, and health: a literature review. *German Journal of Agricultural Economics*, 70(3), 139–164. Available from: https://doi.org/10.30430/70.2021.3.139-164

Godfray, H.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J. et al. (2018) Meat consumption, health, and the environment. *Science*, 361(6399), 1–8. Available from: https://doi.org/10.1126/science.aam5324

Hanoch, G. (1975) Production and demand models with direct or indirect implicit additivity. *Econometrica*, 43(3), 395. Available from: https://doi.org/10.2307/1914273

Haß, M., Banse, M., Deblitz, C., Freund, F., Geibel, I., Gocht, A. et al. (2020) Thünen-Baseline. Braunschweig: Johann Heinrich von Thünen-Institut (Thünen Report, 82). Available from: https://www.thuenen.de/media/publikationen/thuenen-report/Thuenen_Report_82.pdf

Herrero, M., Henderson, B., Havlik, P., Thornton, P.K., Conant, R.T., Smith, P. et al. (2016) Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, 6(5), 452–461. Available from: https://doi.org/10.1038/nclimate2925

Hertel, T.W. (1998) Global trade analysis. modeling and applications: Cambridge [u.a.] Cambridge Univ. Press, 1998; 1. paperback ed.

Hiç, C., Pradhan, P., Rybski, D. & Kropp, J.P. (2016) Food surplus and its climate burdens. *Environmental Science & Technology*, 50(8), 4269–4277. Available from: https://doi.org/10.1021/acs.est.5b05088

Hyseni, L., Atkinson, M., Bromley, H., Orton, L., Lloyd-Williams, F., McGill, R. et al. (2017) The effects of policy actions to improve population dietary patterns and prevent diet-related non-communicable diseases: scoping review. *European Journal of Clinical Nutrition*, 71(6), 694–711. Available from: https://doi.org/10.1038/ejcn.2016.234

IPCC. (2019) Climate change and land – summary for policymakers. Available from: https://www.cifor.org/knowledge/publication/7508/

Jensen, H. & Perez Dominguez, I. (2019) *Scenario: a protein shift in the EU. EU agricultural outlook for markets and income, 2019–2030*. Brussels: European Commission, DG Agriculture and Rural Development.

Kerschke-Risch, P. (2015) Vegan diet: motives, approach and duration. Initial results of a quantitative sociological study. *Ernahrungs Umschau*, 62, 98–103 Available from: https://www.ernaehrungs-umschau.de/fileadmin/ernaehrungs-umschau/pdfs/pdf_2015/06_15/eu06_2015_wuf_kerschke-risch_eng.pdf

Kremmydas, D., Athanasiadis, I.N. & Rozakis, S. (2018) A review of agent based modeling for agricultural policy evaluation. *Agricultural Systems*, 164, 95–106. Available from: https://doi.org/10.1016/j.agsy.2018.03.010

Latka, C., Kuiper, M., Frank, S., Heckelei, T., Havlík, P., Witzke, P. et al. (2021) Paying the price for environmentally sustainable and healthy EU diets. *Global Food Security*, 28, 100437. Available from: https://doi.org/10.1016/j.gfs.2020.100437

Marette, S. & Réquillart, V. (2020) Dietary models and challenges for economics. *Review of Agricultural, Food and Environmental Studies*, 101(1), 5–22. Available from: https://doi.org/10.1007/s41130-020-00113-z

Mazzocchi, M. (2017) Ex-post evidence on the effectiveness of policies targeted at promoting healthier diets: Food and Agriculture Organization of the United Nations (Trade Policy Technical Notes, 19).

O'Donoghue, C., Devisme, S., Ryan, M., Conneely, R., Gillespie, P. & Vrolijk, H. (2016) Farm economic sustainability in the European Union: a pilot study. *Studies in Agricultural Economics*, 118(3), 163–171. Available from: https://doi.org/10.7896/j.1631

Ryan, D.L. & Wales, T.J. (1999) Flexible and Semiflexible consumer demands with quadratic Engel curves. *The Review of Economics and Statistics*, 81(2), 277–287. Available from: https://doi.org/10.1162/003465399558076

Sanchez-Sabate, R. & Sabaté, J. (2019) Consumer attitudes towards environmental concerns of meat consumption: a systematic review. *International Journal of Environmental Research and Public Health*, 16(7), 1220. Available from: https://doi.org/10.3390/ijerph16071220

Santini, F., Ronzon, T., Perez Dominguez, I., Araujo Enciso, S. & Proietti, I. (2017) What if meat consumption would decrease more than expected in the high-income countries? *Bio-Based and Applied Economics*, 6(1), 37–56. Available from: https://doi.org/10.13128/BAE-16372

Spiller, A., Renner, B., Voget-Kleschin, L., Arens-Azevedo, U., Balmann, A., Biesalski, H.K. et al. (2020) Politik für eine nachhaltigere Ernährung: Eine integrierte Ernährungspolitik entwickeln und faire Ernährungsbedingungen gestalten. *Berichte über Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft*, 1–833. Available from: https://doi.org/10.12767/buel.vi230.308

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L. et al. (2018a) Options for keeping the food system within environmental limits. *Nature*, 562(7728), 519–525. Available from: https://doi.org/10.1038/s41586-018-0594-0

Springmann, M. & Freund, F. (2022) Options for reforming agricultural subsidies from health, climate, and economic perspectives. *Nature Communications*, 13(1), 82. Available from: https://doi.org/10.1038/s41467-021-27645-2

Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H.J., Gollin, D. et al. (2016) Global and regional health effects of future food production under climate change: a modelling study. *The Lancet*, 387(10031), 1937–1946. Available from: https://doi.org/10.1016/S0140-6736(15)01156-3

Springmann, M., Mason-D'Croz, D., Robinson, S., Wiebe, K., Godfray, C., Rayner, M. et al. (2018b) Health-motivated taxes on red and processed meat: a modelling study on optimal tax levels and associated health impacts. *PLoS One*, 13(11), e0204139. Available from: https://doi.org/10.1371/journal.pone.0204139

Springmann, M., Spajic, L., Clark, M.A., Poore, J., Herforth, A., Webb, P. et al. (2020) The healthiness and sustainability of national and global food based dietary guidelines: modelling study. *BMJ*, 370, m2322. Available from: https://doi.org/10.1136/bmj.m2322

Stehfest, E., Bouwman, L., van Vuuren, D.P., Elzen, M., Eickhout, B. & Kabat, P. (2009) Climate benefits of changing diet. *Climatic Change*, 95(1–2), 83–102. Available from: https://doi.org/10.1007/s10584-008-9534-6

Tilman, D. & Clark, M. (2014) Global diets link environmental sustainability and human health. *Nature*, 515(7528), 518–522. Available from: https://doi.org/10.1038/nature13959

Tuninetti, M., Ridolfi, L. & Laio, F. (2022) Compliance with EAT–lancet dietary guidelines would reduce global water footprint but increase it for 40% of the world population. *Nature Food*, 3(2), 143–151. Available from: https://doi.org/10.1038/s43016-021-00452-0 van den Verma, M.B., Vreede, L., Achterbosch, T. & Rutten, M.M. (2020) Consumers discard a lot more food than widely believed: estimates of global food waste using an energy gap approach and affluence elasticity of food waste. *PLoS One*, 15(2), e0228369. Available from: https://doi.org/10.1371/journal.pone.0228369

Veerman, J.L., Sacks, G., Antonopoulos, N. & Martin, J. (2016) The impact of a tax on sugar-sweetened beverages on health and health care costs: a modelling study. *PLoS One*, 11(4), e0151460. Available from: https://doi.org/10.1371/journal.pone.0151460

Verger, E.O., Perignon, M., El Ati, J., Darmon, N., Dop, M.-C., Drogué, S. et al. (2018) A "fork-to-farm" multi-scale approach to promote sustainable food Systems for Nutrition and Health: a perspective for the Mediterranean region. *Frontiers in Nutrition*, 5, 30. Available from: https://doi.org/10.3389/fnut.2018.00030

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S. et al. (2019) Food in the Anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170), 447–492. Available from: https://doi.org/10.1016/S0140-6736(18)31788-4

Woltjer, G. & Kuiper, M. (2014) The MAGNET Model. Module description. University & Research centre (LEI Wageningen UR). Wageningen (LEI Report, 14–057). Available from: http://edepot.wur.nl/310764 [Accessed 7 March 2018]

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Rieger, J., Freund, F., Offermann, F., Geibel, I. & Gocht, A. (2023) From fork to farm: Impacts of more sustainable diets in the EU-27 on the agricultural sector. *Journal of Agricultural Economics*, 74, 764–784. Available from: https://doi.org/10.1111/1477-9552.12530