The Impact of Dietary Changes on Agriculture, Trade, Environment and Health: A Literature Review

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Abstract

Animal-source foods are a major component of global diets and are increasingly criticised because of their adverse impacts on environment, climate and health. A shift in diets towards plant-based foods is a discussed option to overcome these problems. Much of the scientific emphasis so far has been on estimating the potential of such a dietary change to reduce greenhouse gas emissions and improve health outcomes while less attention has been attracted on studies analysing the impacts on agricultural markets. This paper aims to provide a comprehensive overview and, therefore, summarizes existing studies on the effects of a reduced consumption of animal-source foods on agricultural markets, greenhouse gas emissions, food security and health. In addition, available studies on the so-called rebound effect are presented. The identified studies suggest that a reduction in the consumption of meat in the EU or OECD would lead to a 1-10% decrease in meat world market prices, depending on the magnitude and particularities of the assumed dietary changes. This would translate to a 3-10% reduction in production. The lower domestic demand for meat could also negatively affect welfare outcomes and GDP. However, it has to be mentioned that these studies do not take into account the consequences of improved environmental and health conditions. In fact, our review indicates that reductions in greenhouse gas emissions could generally be proportional to the magnitude of plant-based diets. The maximum reduction potentials of 60-70% could be found for global vegetarian or vegan diets. However, some studies indicate that a shift in food expenditure towards other resource-intensive goods could lead to a rebound effect. Further, this overview suggests that environmental and public health objectives might be in alignment as all identified studies indicate that a reduction in meat consumption in high-income countries could be associated with lower rates of mortality and non-communicable diseases. This overview reveals the complex relationships between food demand, agricultural supply, international trade, environment, health and food security.

Keywords

dietary change; animal-based foods; meat; agriculture; health; emissions

1 Introduction

Animal-based foods, in particular meat, play a vital role in global diets by providing important amounts of proteins, minerals and vitamins. Currently, food balance sheet data show that on a global level, approximately 43 kg of meat and 88 kg of milk are consumed per capita and year (Figure 1). On average 18% of the daily calorie consumption and almost 40% of protein intake is provided by animal-based products. However, differences between regions are substantial, not only in terms of quantities consumed, but also with respect to the importance of animal-source foods in diets. In Africa, only 8% of calories are supplied from animal-source foods in general and only 3% from meat, whereas in the Americas, Europe and Oceania 25-30% of total calories are consumed through animal-based products (FAO, 2020). The latter corresponds to a daily intake of 800-1000 kcal and is well above the level of 300 kcal per day from animal-based foods which is consistent with a healthy and sustainable diet according to a recent report by the EAT-Lancet commission on Food, Planet and Health (WILLETT et al., 2019, Figure 2).

In the context of urbanisation, economic growth and social transformation, the consumption of fat, sugar, processed as well as animal-based foods is increasing, while the consumption of traditional staple foods and fibre is decreasing. This transformation process first began in high-income countries, but due to the globalisation of the food system and increasing amount of industrially processed foods, this dietary change also occurred at a much faster rate in low- and middle-income countries (POPKIN, 1993). These changes in diet are linked to obesity and certain diseases such as cancer and coronary heart diseases which pose a bigger risk than many other risk factors such as smoking (AFSHIN et al., 2019). Shifting towards more plant-based diets

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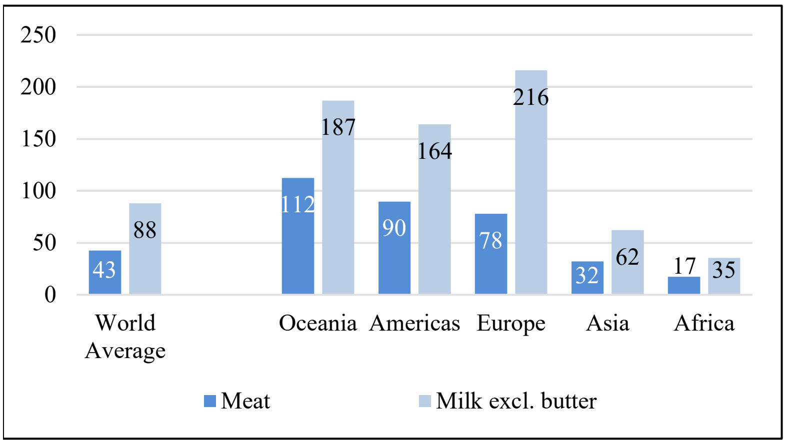
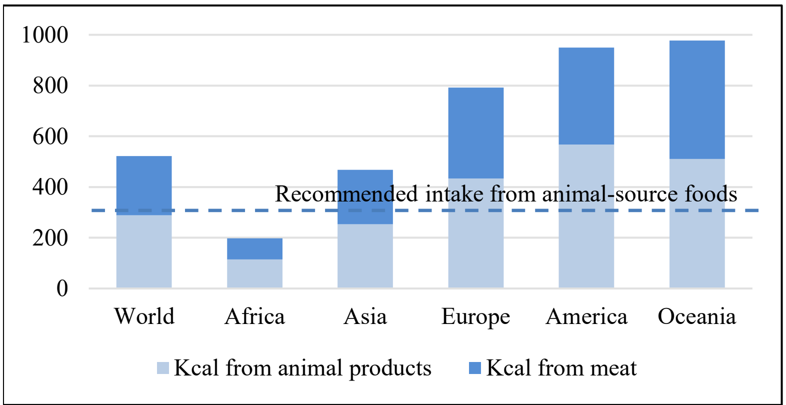
Figure 1. Meat and milk consumption by regions in 2017 (in kg per capita and year)



Source: own representation of FAOSTAT-Food Balance Sheets (FAO, 2020)

Figure 2. Kilocalorie intake from animal-source foods by regions in 2017 (in kcal per capita and day)



Source: own representation of FAOSTAT-Food Balance Sheets (FAO, 2020)

could therefore be a possible way to prevent deaths and improve public health.

The overconsumption of animal-based foods is not only of concern from a public health perspective, but also from an environmental point of view. Livestock production accounts for 14.5% of global anthropogenic greenhouse gas (GHG) emissions contributing significantly to climate change and global warming (GERBER et al., 2013). Especially against the background of the global target to prevent the global temperature from rising above 2°C of pre-industrial levels, emission reductions in agriculture, in particular in the livestock sector, but also along the entire food chain are gaining in importance. (UNFCCC, 2011). Apart from the production of GHG emissions, animal husbandry has a further, profound and far-reaching impact on the environment. Approximately 26% of global ice-free areas are used as grassland for livestock and an additional 33% of arable land for animal feed production. Moreover, overgrazing is a major source of land degradation while the expansion of livestock farming contributes significantly to deforestation (FAO, 2006). In particular, conversion of land for animal feed production or pasture degrades biodiversity (BENTON et al., 2021). To this is added the fact that agriculture is the largest user of water, accounting for 70% of water withdrawals (WWAP, 2018) of which 30% are due to animal husbandry (MEKONNEN and HOEKSTRA, 2012). Today's water withdrawal is already close to maximum sustainable levels, however, factors such as population growth, increases in industrial production as well as higher food demand, particularly for animal-based products, are expected to push up the demand for water further (WWAP, 2018). For these reasons, production- or consumption-side changes on animal production are increasingly being discussed in politics and science, but these would be associated with trade-offs between health, environment and economic objectives.

In fact, livestock farming is an important agricultural sector in most countries. For example, in the EU more than half of agricultural holdings are keeping animals, generating 45% of the EU's agricultural production value (BREUER et al., 2019). Very similar patterns apply for the US and other high-income countries (USDA-NASS, 2017; FAO, 2020), but also on a global level livestock products account for 40% of the global agricultural production value (MAYEN, 2016). At the same time, livestock production in recent decades has increased rapidly. Global meat production increased by more than 350% over the last 50 years and has peaked at 342 billion tons in 2018 (Figure 3). In this period, production of other livestock products also increased strongly. Milk production doubled during this time, while egg production even quadrupled (FAO, 2020). A reduction in the consumption of animal-based products could lead to income losses for a large share of agricultural farms and might increase the pressure for structural change in the sector.

Considering population and income growth over the coming decades it is likely that these trends in animal-based food consumption and production will continue, thus, increasing the impact on climate change and environment. Especially low- and middle-income countries are expected to approach western diets and to increase demand for animal-source foods (GODFRAY et al., 2018). By contrast meat consumption in high-income countries has plateaued or even declined slightly in some regions (GODFRAY et al., 2018; BZL, 2019; SANS and COMBRIS, 2015). The effects of a shift towards meat-poor diets in high-income countries are intricate and affect economies, market actors, environmental indicators, public food availability as well as public health in very different ways. Scientific evidence on the impact of dietary change is diverse. Economic studies provide information on the impacts of dietary changes on markets, producer and consumer behaviour as well as welfare and trade. These estimates are very important from a societal perspective to identify which groups, sectors and countries, would benefit from more plant-based diets and which are more likely to face disadvantages. Economic and social considerations are important especially in political and public discussions, but also for developing possible policy instruments to achieve specific targets. Studies that use environmental and nutritional models can answer the question of what specific targets are desirable and how variations in diets might influence certain environmental indicators and public health.

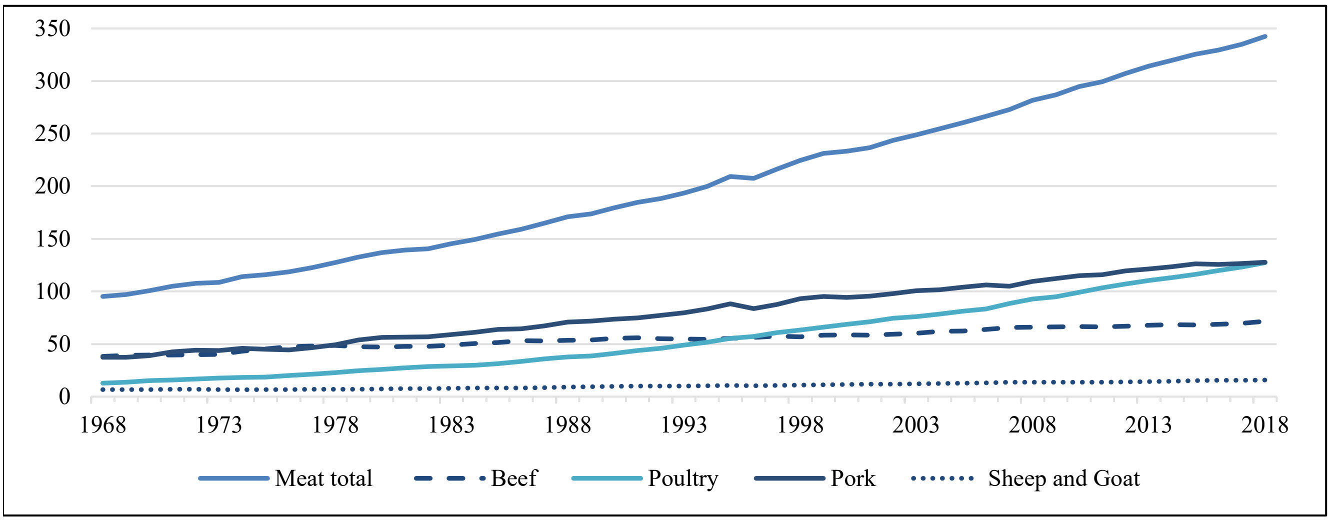
To our knowledge this is the first literature review that summarizes studies analysing the economic effects of changing diets. In addition, we also present scientific evidence on food security, environmental and health aspects. The objective of this literature review is to bring all of these dimensions together to contribute to a holistic picture of the potentials and consequences of widespread dietary change. This way the complex relationships and possible interactions between demand, supply, international trade, environment, health and food security shall be illustrated. As most studies rely on model-based scenarios, this review will also focus primarily on model-based studies. Finally, this review is intended to summarize the state-of-the art and to identify limitations in current studies to incentivize future research.

Based on this motivation the following sections give an overview of existing studies. The methodological approach of the literature review is presented in Section 2. Section 3 elaborates on the concrete effects of reduced demand for livestock products on the economy and agricultural sector. Section 4 deals with the effects on the environment, followed by the 5th section, which addresses possible rebound effects. Section 6 explores potential consequences for global food security. The health effects of more plant-based diets are discussed in section 7. The last section provides a summary and points out possible research gaps.

2 Materials and Method

We conducted a review of studies estimating the impact of shifting current diets to more plant-based diets on economic, environmental, food security and health indicators. We entered different word combinations mainly including "dietary change" and "impact on economy/environment/food security/health" on Google

Figure 3. World meat production 1968-2018 (in Mill. Tons)



Source: own representation of FAOSTAT-Production Data (FAO, 2020)

Scholar, PubMed and Science Direct. A detailed list of searched key words can be found in Appendix A: Supplementary Material-Method. The studies found were also screened for relevant references. Additionally, it was searched for publications of several non-governmental organizations such as OECD and FAO. Peer-reviewed studies were included, as well as appropriate grey literature such as dissertations, working papers and reports, which meet the inclusion criteria described below.

An important criterion for the inclusion of studies was the definition of a dietary scenario that included a quantified reduction in the consumption of animal-based foods. With regard to economic impacts, the search was for studies that estimate the effects of dietary change on prices, production, trade, welfare and GDP. Additionally, it was searched for studies quantifying the rebound effect of dietary changes. With regard to environmental effects of dietary changes, we focused on GHG emissions; with regard to food security, on malnutrition, undernourishment, nutrient deficiencies; with regard to health, on risk/rates of cancer, diabetes and mortality. Studies in English or German conducted from 1990 onwards were included if they estimated effects on any of the indicators described.

After an initial screening, we find that most of the studies, particularly economic studies, have adopted a model-based approach. However, we also found that the impacts of dietary changes on different dimensions were not always analysed using only classical model-based approaches. Therefore, and to complement the model-based studies, we included also studies using other methods e.g. econometric approaches when they meet the inclusion criteria. This is helpful in that the robustness of the effects can also be compared across different methodological approaches. However, studies with non-quantified changes in animal-based food consumption or studies comparing the impact of individual food items or meals rather than diets were not included.

The focus of this review is to provide an overview of the possible impact dimensions and to illustrate and suggest possible interactions. In total, 27 studies published in English and 3 studies (HAß et al., 2020; SCHMITZ, 2019; CORDTS et al., 2014) published in German were included in our final analysis. Of these, 24 were published in scientific journals, 4 can be classified as grey literature and one is a dissertation. As far as we could tell, 29 of the studies were carried out by independent scientists. The study by SCHMITZ (2019) was funded by a foundation that is close to the poultry industry.

3 Impact on Agricultural Markets

3.1 Impact on Agricultural Markets

Changing dietary patterns have multiple impacts on the agricultural sector including local and international prices, production quantities and international trade flows. This section gives an overview of studies that aim to quantify those effects for national and global markets. A summary of the results is given in Table 1. A description of the applied models can be found in Appendix B: Supplementary Material – Model Description.

A study by SANTINI et al. (2017) is based on the partial equilibrium model Aglink-Cosimo. The analysis estimates a decline in meat demand by 11% in high-income countries, which is derived from a doubling of the vegetarian and flexitarian population and implemented for the period 2014-2024. Simultaneously, meat demand is reduced by 5% in some Latin American countries, where meat consumption levels are high. The reduction in meat consumption is assumed to be partially substituted by other foods to compensate for the reduction in protein intake. Therefore, the consumption of cereal, dairy products and eggs increases by 5% while the consumption of legumes and oilseeds rises by 2% over 10 years. The result analysis focusses on the impact on the EU only. Among others it is shown that the declining demand for poultry and pork leads to price reductions in the EU by 12-14% and production declines in the range of 4-5%. These changes in the European meat demand and supply decrease world market prices by 4-10% which leads to an increase in meat demand from the rest of the world. Declining demand for poultry and pork in the EU is to some extent offset by a strong increase in exports by 45-48%. In comparison to the EU pork and poultry sector, prices fall much stronger (-27%) in the EU beef sector. The demand for beef in the rest of the world increases, but the competitiveness of the beef sector suffers more from a relatively large price difference between EU and world market prices. Therefore, beef exports increase by only 38% compared to the other two meat types, so that the declining demand must be relatively more offset by reductions in the EU production (-8%). Similarly, the reduced demand for animal feed cannot be fully compensated by a growing use of cereals for human consumption and an increased demand from the rest of the world, therefore the average price for animal feed declines by approximately 4%. SANTINI et al. (2017) also simulate another simpler scenario in which the decline in meat is not offset by increased consumption of other foods. This scenario shows approximately the same price, production and trade effects for pork, poultry and beef. Only the demand for feed falls more sharply, as the increase in dairy and egg production, as well as human consumption of cereals, is eliminated, so that feed prices fall by 8%.

JENSEN and PÉREZ DOMÍNGUEZ (2019) use Aglink-Cosimo to simulate a protein shift in the European diet as part of the EU Agricultural Outlook (EC, 2019). This shift implies that 50% of protein intake is taken up from plant-based foods and 50% from animal-source foods. By 2030, such a scenario would lead to a reduction in the consumption of meat, dairy products, eggs and fish by 17%, respectively. The reduced calorie intake is assumed to be compensated by an increase in the consumption of cereals, legumes, vegetables and nuts. The simulation results show that in such a scenario EU prices for meat fall by 18% and for dairy products by 17%. This led to an increase in meat exports by 50% and to a reduction in meat production by 8%. Similar adjustment processes apply to the dairy sector, with production dropping by 5%. The reduction in demand for animal feed cannot be fully offset by an increased use of cereals for human consumption, thus, EU cereal prices decline by 6%. At the same time, the area under cultivation for cereals decreases by 0.9%. Strikingly, human consumption of soybeans increases, pushing EU soya prices up by 19%. As a result, the area under soybean cultivation grows by 5% in the EU. JENSEN and PÉREZ DOMÍNGUEZ (2019) conclude that a shift towards more plant-based diets is likely to have moderate impacts on European prices and production which is mainly due to large export opportunities. However, if other high-income countries experience a similar change in eating habits, the possibilities for the EU to export meat and dairy products might be limited.

Further insights into the effects of a reduced demand for meat is provided by the study of CORDTS et al. (2014). As part of the study, the effects of a 18% reduction in meat consumption in OECD countries are estimated by using the partial equilibrium model IMPACT. The percentage decrease in meat demand is derived from the German National Consumption Study II (NCS II) which refers to the year 2006 (MRI, 2008). In contrast to SANTINI et al. (2017) and JENSEN and PÉREZ DOMÍNGUEZ (2019), CORDTS et al. (2014) find by means of linear, multivariate regressions that a reduction in meat consumption is not fully compensated by an increased consumption of other foods. The consumption of fruit and vegetables increases by about 0.5% if meat consumption is reduced by 18%, but the consumption of other foods such as wheat, eggs and potatoes declines by 2-3%. According to the authors a possible reason could be that a diet low in meat is associated with an overall healthier diet. In the final model, the dietary changes derived from the NCS II are implemented for all OECD countries in 2020. The results show that the world market price falls by 10% due to the decline in demand for meat by 18% in all OECD countries. The effects on OECD production are relatively small, with a decrease of 3%. Similar to the results in SANTINI et al. (2017), meat demand in the rest of the world increases due the decline in the world market price. This rise in demand offsets 55% of the meat demand reduction in OECD countries in terms of volume. Consequently, possible positive effects on environment and food security from a reduction in meat consumption in OECD countries cannot be fully realised at global level. However, CORDTS et al. (2014) argue that consumer behaviour in high-income countries provide a global role model. Thus, other countries could also shift to a more plant-based diet in the long run. Another effect of the reduced meat demand could be the release of animal feed, hence, prices for arable crops such as cereals or maize that are mainly used as animal feed could decline. However, the model results indicate that the increased meat demand from the rest of the world moderates such effects. Therefore, prices for cereals fall by maximum 1.7%. Due to the generally healthier diet, demand for milk, eggs and potatoes also declines, so that the respective prices decrease by 1-2%. The reduction in production of those goods is relatively smaller and amounts to maximum 1%, but in total CORDTS et al. (2014) conclude that price and production effects on foods other than meat are relatively small.

A study by SCHMITZ (2019) analyses the effects of a reduction in meat consumption in the EU of 50% by using the PE model AGRISIM. The reduction in meat demand is not compensated by other foods and leads to price reduction on the world market ranging from 6-10%. As in SANTINI et al. (2017) these price reductions increase meat demand in the rest of the world, which offsets about half of the decline in EU demand in terms of volume. A striking result is the compensation of the declining EU demand by a tremendous increase in EU meat exports by more than 1,000%. For beef, the EU even develops from a net importer to a net exporter. The overall economic welfare losses in the EU resulting from halving the demand for meat amount to USD 11.6 billion p.a. If additionally, demand for milk and eggs falls by 50%, the economic welfare loss

Table 1. Overview of modelling studies estimating the market effects of dietary change

Author	Model (PE/GE)	Scenario	Reference-year	Product	World Market Price [%]	EU-Price [%]	EU-Production [%]	EU-Imports [%]	EU-Exports [%]	EU-Welfare Effect [Billion USD]
SANTINI et al. (2017)	Aglink-Cosimo (PE)	-11% demand for meat EU	2024	Beef	-4	-27	-8	-19	+38	
				Pork	-10	-14	-4	-14	+48	
				Poultry	-5	-12	-5	-1	+45	
JENSEN et al. (2019)	Aglink-Cosimo (PE)	-17% demand for meat EU	2030	Meat		-18	-8		+50	
				Milk		-17	-5		+53	
SCHMITZ (2019)	AGRISIM (PE)	-50% demand for meat EU	n.a.	Beef	-7			Change Importer to Exporter		-11,6
				Pork	-10				+1034	
				Poultry	-6				+1738	
	AGRISIM (PE)	-50% demand for meat, milk and eggs EU	n.a.	Beef	-7					-17,3
				Pork	-10					
				Poultry	-6					
				Milk	-14					
				Eggs	-6					
	GTAP (GE)	-50% demand for meat EU	n.a.	Meat	-0,1					-100,7
CORDTS et al. (2013)	IMPACT (PE)	-18% demand for meat OECD-Countries	2020	Meat	-10		-3 (OECD)			
				Milk	-1		-0.8 (OECD)			
HAß et al. (2020)	CAPRI (PE) + MAGNET (GE)	Approx. - 12% demand for meat EU	2030	Beef	-3	-9	-10			
				Pork	-3	-9	-10			
				Poultry	-2	-6	-8			
				Mutton & Goat	-2	-9	-8			

Note: PE = partial equilibrium model; GE = general equilibrium model
Source: own representation of study results

in the EU increases to USD 17.3 billion p.a. and prices for milk and eggs decline by 14% and 6%, respectively. In a second part of the study, SCHMITZ (2019) conducts simulations with the CGE model GTAP. In contrast to partial equilibrium models, this model not only depicts agricultural markets but also the other sectors of an economy. The simulation results show that if EU meat demand is halved, world market prices fall by 0.1%. Even if global meat demand is reduced by 50%, prices only decrease by 1.1% in the GTAP model. According to SCHMITZ (2019), the total welfare loss in the EU caused by halving meat consumption amounts to USD 100.7 billion p.a.

A recent report by HAß et al. (2020) includes an EU-wide scenario for the reduction of meat consumption due to changes in consumer preferences. The scenario is implemented for the year 2030 and was calculated by using the CAPRI, MAGNET and FARMIS models. The modelling-linkage works in such a way that the shift in preferences is implemented in CAPRI and the resulting percentage changes in meat and plant-based food demands are then implemented in MAGNET. The MAGNET model provides changes in world market prices, EU prices and EU production. Trade effects are also estimated, but only for Germany. In a second model-linkage producer prices from CAPRI are transferred to FARMIS to analyse the economic consequences of the implemented dietary change for farm types. In contrast to previous studies, the scenario is based on dietary recommendations of the EAT-Lancet Commission and only reduces meat consumption above the recommended consumption level of 140 kcal/day. This ‘overconsumption’ of meat is reduced by 20% in 2030, but simultaneously 20% of the foregone calories are assumed to be substituted by fruits, vegetables and legumes. This calorie-based approach considers the heterogeneity of meat consumption in EU member states, so that countries with higher overconsumption of meat products will experience a stronger decline in demand. In total, these assumptions lead to a decline in the production of beef, pork, poultry, mutton and goat meat by 12.5%, 12.9%, 13.2% and 11.4%, respectively.

Simultaneously, consumer demand for soya, legumes, fruits and vegetables increases by 6-8%. The reduction in demand for meat causes EU producer prices to fall in the range of 6-9%, while meat production declines by approximately 10%. The impacts on the world market are less pronounced. On a global level, meat prices and production fall by 1-3%. As in previous studies, exports to third countries increase, so that declines in EU production are smaller than in consumption. Similar to JENSEN and PÉREZ DOMÍNGUEZ (2019), the authors argue that the possibility of exports would disappear if the rest of the world were to change its diet according to the assumed patterns. However, in the absence of a global dietary change such trade effects could be a source for carbon leakage. Thus, developments in trade are of particular importance when evaluating possible impacts on environment and greenhouse gas emissions. Further results show that the reduction in meat demand leads to declines in animal feed prices by 1-3%, while prices and production of fruits and vegetables increase by 1-3%.

The consequences of changes in producer prices are relatively complex and could affect agricultural farms differently depending on the type of production. By using the FARMIS model, a comparative-static programming model for farm groups, HAß et al. (2020) estimate the impacts on German farms and find that particularly pig farmers might suffer from income losses of 37%. Beef and milk producers are slightly less affected, but are also likely to face income losses of 12% and 6%, respectively. In contrast to that, arable farms are not expected to experience any losses, while permanent crop farms might benefit from the increase in fruit demand due to income gains by almost 4%. An overview of the reviewed studies is given in Table 1.

3.2 Impact on GDP

In addition to modelling studies analysing price and production effects of changing diets, there are also a few studies addressing the relationship between Gross Domestic Product (GDP) and meat consumption, only. A modelling approach with the IFPRI standard CGE model by LOCK et al. (2010) leads to the conclusion that a reduction in the demand for livestock products in the UK has only little impact on GDP. A reduction in domestic demand for meat sources by 85% reduces GDP by 0.02% which corresponds to approximately GBP 300 billion. The effects of a reduction in demand for dairy products by 62% are stronger as GDP is reduced by almost 0.04% or GBP 512 billion. Similar scenarios for a reduction in domestic demand for animal-source foods in Brazil show even smaller decreases in GDP. However, the impacts on GDP are stronger when export demand for Brazilian animal-source foods is affected. Especially, a reduction in export demand for Brazilian meat can lead to a reduction in GDP by 0.07% (BRL 1400 billion). Whereas the effect of these scenarios on overall GDP is relatively small, the impact on the agricultural sectors in the UK and Brazil is more pronounced. The contribution of the meat and dairy sector to GDP falls for both countries by up to 30%. Moreover, the results indicate that an equal decrease in the demand for all animal-based foods is likely to have less of an impact on agriculture and the economy in the UK and Brazil compared to scenarios where only meat or dairy consumption is shocked.

Further results from econometric studies are ambiguous. PAIS et al. (2020) analyse a panel data set for 14 European high-income countries (HIC) from 1970 to 2013 and conclude that a 50% decrease in meat consumption would lead to a decrease in GDP by 4% on average. MARQUES et al. (2018) derive elasticities from an Autoregressive Distributed Lag model based on a panel data set of 77 countries from 1995 to 2013. In contrast to PAIS et al. (2020), their results indicate that a 1% increase in meat consumption decreases GDP in high - and upper-middle income (UMIC) countries by 0.12% and 0.37%, respectively. For middle- and low-income countries such a 1% increase in meat consumption has a positive impact in the short-run and can increase GDP by up to 0.07 percentage points. However, results for the long-run were not significant, thus, not confirming an impact of changes in meat consumption on GDP for middle- and low-income countries in the long-run (Table 2).

4 Impact on Greenhouse Gas Emissions

Agriculture is facing major challenges due to climate change and a shift of societal expectations towards a more sustainable agri-food system with higher animal welfare standards and healthier products. At the same time, intensive agricultural land use and a steady increase in productivity have consequences for the environment and climate change. Livestock farming in particular is very resource intensive, using approximately 26% of global ice-free areas as grassland and an additional 33% of arable land for animal feed production (FAO, 2006). More frequently, climate gas emissions from animal husbandry are criticized which mainly consist of methane and nitrous oxides from digestive processes of ruminants, storage and application of manure as well as from animal feed production. Overall, it has been estimated that 14.5% of global anthropogenic emissions, which corresponds to 7.1 gigatons of CO_2-equivalent, can be attributed to the livestock sector with cattle being the largest contributor (FAO, 2017; GERBER et al., 2013, Figure 4).

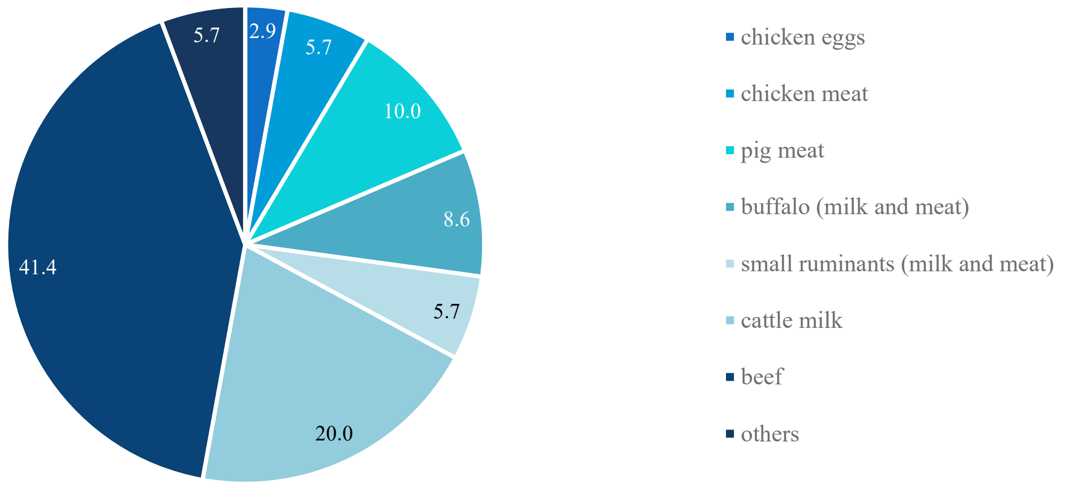
Evidence on the impacts of agriculture and animal husbandry on the environment is diverse and addresses effects on climate, land and resource use. In the following, we will provide a brief overview of scientific studies

Table 2. Overview of studies analysing the impact of animal-source food consumption on GDP

Author	Model	Scenario	Reference year	Effect on GDP [%]
LOCK et al. (2010)	IFPRI standard CGE	3 scenarios: - 33% demand for all animal-source foods | - 85% meat demand | -62% dairy demand in the UK	2004	> - 0.04
		3 scenarios: - 11% demand for all animal-source foods | - 18% meat demand | -28% dairy demand in Brazil	2004	> - 0.025
		- 18% domestic meat demand and - 85% export meat demand Brazil	2004	-0.073
		- 28% domestic dairy demand and - 62% export dairy demand Brazil	2004	-0.027
PAIS et al. (2020)	PCSE+ FGLS	- 50% meat consumption in HIC EU	1970 - 2013	-4.00
MARQUES et al. (2018)	ARDL	+ 1% meat consumption (elasticity)	1995 - 2013	- 0.125 HIC 0.371 UMIC

Note: PCSE = panel corrected standard error model; FGLS = feasible generalized least squares model; ARDL = autoregressive distributed lag model
Source: own representation of study results

Figure 4. Share of products in global livestock GHG emissions (in %)



Source: own representation based on GERBER et al. (2013): 18

that focus on the impact of dietary change on several of these different indicators. In the main part of this chapter, however, we will focus on studies that focus on the potential of dietary change to reduce GHG emissions. This is mainly due to the higher number of available studies and the fact that the impact on GHG emissions is often discussed in the context of the Paris Agreement.

Agriculture is the largest global user of water, accounting for 70% of water withdrawals of which 30% result from livestock production (WWAP, 2018). A study by MEKONNEN and HOEKSTRA (2012) finds that from a water use perspective, it is more efficient to produce calories, protein and fat from plant-based foods than from livestock products. Accordingly, a vegetarian diet in the US could reduce the food related water footprint by about 30%. SPRINGMANN et al. (2020) analyse the impact of a healthy and sustainable diet according to a recent report by the EAT-Lancet commission on Food, Planet and Health which includes a maximum calorie intake from animal-based foods of 300 kcal per day and concludes that this diet on a global level could reduce the freshwater use by 10% in 2050. In relation to land use, STEHFEST et al. (2009) estimates that globally eliminating beef consumption would reduce land use for pasture by 80% and for crop production by 6% in 2050 compared to 2009 levels. A total renunciation of meat could result in a 10% reduction in cropland area. Evidence on the impacts of dietary change on eutrophication, acidification and biodiversity is rare, however, life cycle assessments (LCA) indicate that more plant-based diets may have a positive impact on these indicators as well (RÖÖS et al., 2013).

Scientific studies frequently use life cycle assessments (LCA) to evaluate the impact of food and other products on the environment along its entire life cycle. CLUNE et al. (2017) find in a meta-analysis of 369 studies that beef has by far the greatest impact on climate with the production of 26.61 kg CO_2-equivalent per kilogram meat. In comparison, pork and poultry produce only 5.77 kg and 3.65 kg CO_2-equivalent per kilogram of meat, respectively. Among plant-based foods rice causes the greatest emissions with 2.55 kg CO_2-equivalent per kilogram. POORE and NEMECEK (2018) carry out a meta-analysis of over 1,500 studies and reach the same ranking of foods, but with generally higher values. In their analysis meat from beef cattle herds emits 60.4 kg CO_2-equivalent/kg, while beef from dairy herds causes 34.1 kg CO_2-equivalent/kg. The difference between those two production types can primarily be explained by the fact that emissions from dairy herds are allocated to both dairy and meat products according to the produced unit of measurement (e.g. calories or proteins), whereas beef herds only cause emissions from meat production (GERBER et al., 2013; POORE and NEMECEK, 2018). Pork and poultry meat cause significantly less GHG emissions with 10.6 and 7.5 kg CO_2-equivalent/kg, respectively. In addition, pig and poultry meat require approximately 90% less land and have a 50-70% lower freshwater use. Different values of individual life cycle assessments can be attributed to different methods, particularly in different system boundaries, production systems and production sites. Nevertheless, both meta-analyses show a clear ranking of food categories with regard to their greenhouse gas potential, regardless of the specific values. Animal-source foods, in particular ruminant meat, have significantly higher resource requirements with correspondingly higher environmental and climate impacts than plant-based foods. Therefore, dietary change in theory holds a large mitigation potential.

However, the study by SCHMITZ (2019) based on the GTAP model indicates that halving meat and milk consumption in the EU reduces global CO_2 emissions only by 0.001%. SCHMITZ (2019) argues that there is a shift in consumption and production towards non-food goods, which offsets emission reduction from dietary change. This scenario refers to CO_2 emissions only, but it must be taken into account that the majority of GHG emissions from agriculture are caused by methane and nitrous oxide emissions (HAENEL et al., 2020; UMWELTBUNDESAMT, 2019). When including these methane and nitrous oxide emissions in the PE model AGRISIM, halving the consumption of meat and milk in the EU leads to a 4.2% reduction in CO_2-equivalent emissions.

An analysis by BEHRENS et al. (2017) finds larger reductions in GHG emissions due to a reduced consumption of animal-based foods. BEHRENS et al. (2017) use national dietary recommendations, data on average national diets from FAO Food Balance Sheets from 28 high-income countries and 9 middle-income countries and couple this data with a multiregional, environmentally extended, input–output (MRIO) database. In general, national dietary recommendations, especially in high-income countries, support a reduction in sugar, oil, meat and dairy consumption, while in lower middle-income countries an increase in meat consumption compared to average national diet is recommended. BEHRENS et al. (2017) find that diets in high-income countries produce on average 2.4 kg CO_2-eq. per capita and day, with 70% caused by animal-source foods. In contrast, diets in lower middle-income countries cause 1.1 kg CO_2-eq. per capita and day with 22% caused by livestock products. Thus, diets according to national dietary guidelines could reduce diet related GHG emissions by 13-25% in high-income countries, but increase emissions in lower middle income-countries by 12-17%.

A more advanced study by SPRINGMANN et al. (2016) combines a global health and the economic IMPACT model to analyse the health and environmental effects of global dietary guidelines with less livestock products and a higher proportion of fruits and vegetables. According to their results, such a dietary change can reduce global GHG emissions from food production by 29%. More extreme scenarios with global vegetarian or vegan diets indicate that total GHG emissions can be reduced by 60 - 70% if compared to the reference scenario in 2050. WESTHOEK et al. (2014) address a very similar research question and evaluate the impact of a reduction in animal-source food consumption in the EU by using the MITERRA-EUROPE model, which identifies changes in biophysical parameters such as N and CO_2 emissions due to the assumed shock. The results indicate that an EU-wide reduction in the consumption of animal-based products by 50% can lead to significant emission reductions. Compared to the reference year 2004, N and GHG emissions could be reduced by 40% and 19-42%, respectively. HAß et al. (2020) simulate the effects of a 12% reduction in meat demand in the EU and find that GHG emissions would decline by 50 billion tons CO_2-equivalent which corresponds to a decline of 2% in the EU and 0.4% globally. Based on these figures, HAß et al. (2020) emphasize that a reduction in meat consumption in the EU would not lead to increases in GHG elsewhere, thus, excluding potential leakage-effects.

RANGANATHAN et al. (2016) focus in their analysis with the GlobAgri-WRR model on US diets and underline that the environmental impact of American diets in terms of land use change and GHG emissions are twice the impact of the average world diet, which mainly is a result of the high intake of animal-based foods. If, however, half of the US population would change to a vegetarian diet, the per capita GHG emissions from agricultural production and land use change could be reduced by 57% and 48%, respectively. A reduction of calorie intake from beef by 73% could reduce 33-36% of diet related per capita GHG emissions. The authors further mention that a restriction on beef consumption would bring about significant environmental improvements and at the same time it would be relatively easy to implement, as it would only affect one product.

A more complex scenario by REVELL (2015) is based on a partial equilibrium model and estimates the effects of a 25% decline in meat demand in industrialised countries, a global CO_2 tax and a reduction in greenhouse gas production in the livestock sector due to technical progress simultaneously. The mitigations potential turns out to be lower than in SPRINGMANN et al. (2016), WESTHOEK et al. (2014) and RANGANATHAN et al. (2016). According to REVELL (2015) GHG emissions from livestock will decline by 14% between 2010 and 2050, indicating that a reduction in meat consumption in industrialised countries alone and even in combination with other measures will not be sufficient to significantly reduce GHG emissions from the livestock sector by 2050. To achieve large reductions, global dietary patterns would have to change substantially.

In a similar vein, the study of HEDENUS et al. (2014) analyses food-related greenhouse gas emissions in the context of the Cancun Agreements which aim to prevent global temperature to rise above 2°C of pre-industrial levels (UNFCCC, 2011). In the year 2000, global methane and nitrous oxide emissions from agriculture amounted to 7.1 gigatons CO_2-equivalent. According to HEDENUS et al. (2014), global greenhouse gas emissions must fall to at least 10 gigatons CO_2-equivalent p.a. by 2050 in order to achieve the 2°C target with a 50% chance. Estimates with the MiMiC model indicate that emissions from food-related agriculture will amount to 12 gigatons CO_2-equivalent p.a. in 2050 which mainly result from the production of animal-based foods (80%), in particular of ruminant meat (45%). Further results show that technical mitigation options can reduce greenhouse gas emissions from food-related agriculture to about 8 gigatons CO_2-equivalent p.a. in 2050. However, the results clearly show that the technical reduction potential in the beef sector is relatively low compared to other meat sectors and dairy farming. Therefore, changes in dietary patterns could contribute to a further reduction of greenhouse gas emissions. If additionally, 75% of beef were to be replaced by other meat, agricultural emissions could be further reduced to 4.9 gigatons CO_2-equivalent p.a. A combination of technical mitigations options and a 75% reduction in the consumption of meat and milk products could even reduce food-related agricultural emissions to 3.1 gigatons CO_2-equivalent p.a. TILMAN and CLARK (2014) calculate the effects of a reversed scenario and find that GHG emissions from food production would increase by 80% if the current diets (in 2009) will not change by 2050, taking into account population and income growth. In contrast, global vegetarian (includes dairy products and eggs, but no meat or fish) and pescatarian diets (vegetarian diet including fish) would lead to reductions in GHG emissions by 0.5 and 0.1 gigatons CO_2-equivalent p.a. in 2050 compared to 2009 levels. However, a scenario where the global diet is the average of a Mediterranean (includes moderate amounts of meat), vegetarian and pescatarian diets, does not lead to reductions, but also does not increase GHG emissions by 2050, while allowing for small amounts of meat consumption. An overview of the results is given in Table 3.

5 Rebound Effect

The model-based analyses presented in the previous section implicitly include mechanisms that re-direct the spending of money that is caused by changes of dietary patterns. However, it was not explicitly addressed how these changes in diets influence the expenditure behaviour of households. Moreover, it is not clear whether a reduction in the consumption of animal-based foods will lead to higher spending on food and other commodities or even savings due to a more plant-based diet. In the latter case, it is of importance to analyse how the potentially released money is spent, especially when it comes to greenhouse gas emission. In this section we provide an overview of the literature that addresses these pending questions (Table 4).

GRABS (2015) addresses this question of re-spending money saved due to a dietary shift explicitly by using a budget survey of 4,000 Swedish households covering 117 product categories in 2006. On this basis GRABS (2015) estimates average expenditures and environmental footprints in terms of energy use and greenhouse gas emissions of Swedish consumers. The study shows that a switch to vegetarian diets leads to savings in energy use by 1.8% and CO_2-equivalent emission by 4.1% per capita and year. The shift to a vegetarian diet is based on a complete-diet substitution, so that the number of consumed calories is held constant at initial levels by increasing expenditures, and thus the consumption, on cereals, fruits, vegetables, nuts and legumes. Moreover, GRABS (2015) finds that consumers are saving money by switching to a vegetarian diet. On average, consumers spend 10% less on food and drinks, which is equivalent to 1.8% of their total annual budget. In a second step, GRABS (2015) estimates the total re-spending of these savings according to the consumers initial preferences. The results indicate that the re-spending of the saved money decreases the initial reductions in the two environmental indicators. In fact, 96% of the initial reductions in energy use as well as 49% of the initial reductions in greenhouse gas emission are eliminated. This rebound-effect is particularly high for low-income consumers, because they tend to re-spend their money on relatively environmentally intensive necessities such as cars or household appliances. With increasing income, the rebound effects are becoming smaller, since consumers purchase more luxury goods or services, which are often more environmentally friendly.

Table 3. Overview of studies analysing the GHG mitigation potential of dietary change

Author	Model	Scenario	Reference year	Reductions in global GHG Emissions from Agriculture [CO_2-equivalent]
BEHRENS et al. (2017)	EXI-OBASE3.3	Implementation of national dietary guidelines in high-income countries	2011	13-25%
SCHMITZ et al (2019)	GTAP	- 50% milk dairy and meat consumption EU	n.a.	0.001%
	AGRISIM	- 50% milk dairy and meat consumption EU	n.a.	4.2%
SPRINGMANN et al. (2016)	Global Health + IMPACT Model	Implementation of global dietary guidelines	2050	29%
		Global vegetarian or vegan diets	2050	60 - 70%
HEDENUS et al. (2014)	MiMiC	75% of ruminant meat and dairy consumption replaced by other meat + technical mitigation	2050	59%
		75% of ruminant meat and dairy consumption replaced by cereals and pulses + technical mitigation	2050	74%
WESTHOECK et al. (2014)	MITERRA-EUROPE	- 50% animal-based food consumption EU	2004	19 - 42%
REVELL (2015)	Partial Equilibrium Model	-25% meat demand in industrialized countries + global CO_2 tax + GHG emissions reductions in livestock production	2050	14%
RANGANATHAN et al. (2016)	GlobAgri-WRR	50% of US population follows a vegetarian diet	2009	48 - 57%
		Beef consumption reduced to world average (-73% kcal from beef) US	2009	33 - 36%
		Elimination of overconsumption of animal-based protein (leads to halving kcal intake from all animal-source foods) US	2009	42 - 44%
		Beef consumption reduced by 1/3 and substituted by pork and poultry US	2009	13-14%
HAß et al. (2020)	CAPRI	Approx. - 12% demand for meat EU	2030	0 .4% (2% EU)

Note: the GTAP-simulation of SCHMITZ (2019) only considers CO_2-emissions, methane and nitrous oxide are not included.
Source: own representation of study results

Table 4. Overview of studies analysing the rebound effect of dietary change in households (HH)

Author	Country	Base year	Metric	Rebound Effect [%]			Scenario
				Average	Low-Income HH	High-Income HH	
GRABS (2015)	Sweden	2006	Energy	96	130	76	**Vegetarian diet** (-100% meat and fish)
			CO_2-eq.	49	88	25	
ALFREDSSON (2004)	Sweden	1996	Energy	300	-	-	**Green diet** (-75% meat and meat products, -55% for some dairy products, other foods also reduced)
			CO_2 emissions	200	-	-	
LENZEN und DEY (2002)	Australia	1994	Energy	-	123	112	**Recommended diet** (-50% meat, - 40% dairy, other foods also reduced)
			CO_2-eq.	-	55	45	
CARLSSON-KANYAMA et al. (2005)	Sweden	2001	Energy	No Rebound Effect (Savings 13-32%)			**Diet with low energy intensity** (substituting beef and veal by game meat, chicken and pork by legumes)

Note: ALFREDSSON (2004) calculate the rebound effect by dividing the new emission or energy level by the initial level. When applying the formula for rebound effects from GRABS (2015):[(Baseline Effect - First Round Effects) - (Baseline Effects - Second Round Effects)] / (Baseline Effects - First Round Effects), the rebound effect in ALFREDSSON (2004) is 417% for energy and 338% for CO_2 emissions
Source: own representation of study results

Another study based on a microsimulation model with household data from Sweden by ALFREDSSON (2004), finds even stronger rebound effects. A “green” diet with less dairy products (up to 55%) and 75% less meat products initially leads to a fall in CO_2 emissions and energy requirements by 13% and 5%, respectively. However, the rebound effect eliminates all of these reductions. In fact, the green diet is 15% cheaper, so that approximately USD 1,047 p.a. and household are saved. If the saved money is spent the same way as an increase in income, Swedish households will re-spend their money mainly on travel, recreation, food and clothes, so that CO_2 emissions and energy requirements even increase by 2% each, when compared to the CO_2 and energy levels of the initial diet. Since the consumption of all goods is associated with CO_2 emissions and energy use, ALFREDSSON (2004) concludes that changes in consumption patterns will only lead to reductions in emissions and energy requirements in the short-term, in the long-run, however, overall consumption needs to be reduced to make a significant difference.

LENZEN and DEY (2002) estimate the effects of a dietary change according to dietary recommendations in Australia. These include a general reduction of food intake across all food categories with reductions in meat and dairy product consumption by approximately 50% and 42%, respectively. In total, the dietary change leads to decreases in food consumption by 39% compared to the average Australian diet in 1995. Consequently, energy use and greenhouse gas emissions from food consumption fall by 30% and 37%, respectively. However, simultaneous savings in expenditure of AUD 788 per capita and year induce rebound effects. The re-spending of these savings according to average expenditure structures fully eliminates the reductions in energy consumption and even leads to an increase in energy use by 4-7% per capita depending on the income of the consumer. In the case of greenhouse gases, the rebound effect eliminates approximately 50% of the initial reductions. Similar to the findings of GRABS (2015), the rebound effects are lower for high-income households.

In contrast to these studies CARLSSON-KANYAMA et al. (2005) find that changing diets can indeed reduce the energy use of Swedish households by 13-32%. CARLSSON-KANYAMA et al. (2005) collected data on inhabitants in a central neighbourhood of Stockholm in 2001, their income, consumption patterns, values and neighbourhood. Based on available shopping and consumption opportunities, the authors construct a diet that is more energy efficient than current diets by substituting energy-intensive foods like beef and veal by locally available substitutes like game meat. Pork and chicken are replaced by legumes, whereas fruits and vegetables from greenhouses are substituted by locally and organically field-grown varieties. Such a change in diet is immediately available, but leads to an increase of food expenditures by 10%. In order to cover this additional expenditure, expenses needed to be shifted from travel to food and from new bought household goods to second-hand substitutes.

The reviewed studies underline that evidence on the rebound effect is not clear cut. This is mainly due to the uncertainty of consumer behaviour when shifting to new diets. It is uncertain how households and consumers will change their preferences, consumption patterns and expenditures when abstaining from the consumption of animal-source foods. However, when estimating the potential of dietary change to contribute to climate change mitigation and other environmental improvements, a closer look at possible rebound effects might be useful.

6 Impact on Food Security

In the next decades, population and income growth are expected to increase food demand substantially. According to UN projections, the world population will grow to almost 10 billion people by 2050, while GDP will quadruple, thus, raising average income levels (UN, 2019; OECD, 2012). In this context, it is worth mentioning that projections, especially those made over long periods of time, are subject to uncertainty, as the exact magnitude of many factors and their effects on the target value cannot be clearly determined. Due to the current COVID-19 pandemic, these projections are susceptible to even greater uncertainty. Nevertheless, such forecasts indicate that not only food in general will be in greater demand, but also more livestock products as their consumption is positively correlated with income level (BENNETT, 1941). However, as the conversion ratio of edible feeds into meat is significantly greater than one, reaching even four for some ruminant meats, voices are increasingly being raised calling for purely plant-based diets (WILKINSON, 2011). In the context of global population growth, it is considered that a lower animal-based food consumption can ensure global food security by releasing cereals for human consumption (ROSEGRANT et al., 1999). In this section we give an overview of the existing literature that investigates the role of animal- and plant-based diets in food security.

In a recent study, BERNERS-LEE et al. (2018) argue that an increase in meat and dairy consumption of 23% by 2050 as projected by the FAO (ALEXANDRATOS and BRUINSMA, 2012) could endanger global food security. In fact, the authors estimate that such a scenario would require a production increase of 119% as current crop production levels (2013) would lead to a daily calorie deficit of 1,337 kcal per capita. In contrast to that, a scenario where edible feeds are directly used for human consumption indicates that global food security can be ensured even without increases in agricultural production. However, BERNERS-LEE et al. (2018) emphasize that certain prerequisites regarding consumer decisions, distributional and socio-economic equity are necessary to exploit the potential of predominantly vegetarian diets in the context of global food security. RÖÖS et al. (2017) come to a very similar conclusion, underlining the resource-intensity of animal husbandry. According to their analysis animal-based diets can only be preserved if food waste is substantially reduced while agricultural productivity is massively increased, thus, it is likely that only a purely plant-based diet can provide adequate amounts of food for the global population in 2050.

KLÜMPER (2014) analyses the impact of a reduction in meat consumption on global hunger. By using a partial equilibrium model and the FAO method (FAO, 2003) to receive national distributions of food energy under the consideration of income and non-income factors, KLÜMPER (2014) estimates the number of starving people. The results indicate that the number of starving people worldwide can be reduced by 5% (60 million) if demand for meat in OECD countries is reduced by 50%. ROSEGRANT et al. (1999) draw less optimistic conclusions from their simulation with the IMPACT model, stating that reducing meat consumption in high-income countries (HIC) is not an effective strategy to improve food security in low-income countries (LIC). Scenarios with a 50% reduction in meat consumption in high-income countries show that calorie availability in low-income countries increases only by 40 kcal per capita and day in 2020 compared to the baseline scenario. The effect is even smaller (18 kcal/capita/day) when the reduced calorie intake from meat is fully compensated by an increase in cereal consumption in high-income countries. This is also reflected in the number of malnourished children, which only decreases by 1-2.5%. ROSEGRANT et al. (1999) illustrate several opposite effects that lead to this result. On the one hand, reduced meat consumption in high-income countries leads to an increase in exports, thus, raising meat supply and decreasing meat prices in low-income countries. This way meat is becoming more available and accessible. Indeed, the consumption of meat increases in low-income countries, but at the same time calorie intake from other animal-source products such as milk and eggs declines as a result of a substitution effect. Moreover, reduced demand for meat impacts the price of maize and other coarse grains which are mainly used as feed, but prices for wheat and rice which are the main staple in low-income countries remain unaffected. Hence, the effect on food security is limited as the consumption of staple foods does not increase. Furthermore, decreasing meat prices lead to production declines in low-income countries, thus, lowering agricultural incomes and food demand from agricultural households. Therefore, the overall impact on total calorie intake and thus, food security is small, indicating that the effects of dietary changes might not be as straightforward as suggested by several studies that calculate the theoretical potential of meat-less diets to contribute to food security.

An overview of existing evidence is given in Table 5. It is obvious that feeding 10 billion people in

Table 5. Overview of studies analysing the impact of dietary change on food security

Author	Method	Scenario	Reference year	Food Security Indicator (FSI)	Change in FSI
KLÜMPER (2014)	PE-Model	-50% reduction in meat consumption OECD	2011	Number of starving people	-5%
ROSEGRANT et al. (1999)	IMPACT	-50% reduction in meat consumption in HIC	2020	Calorie availability in LIC	+ 40 kcal/capita/day
				Malnourished children under 5 years in LIC	-2.5%
		-50% reduction in meat consumption & substitution by cereal consumption in HIC	2020	Calorie availability in LIC	+ 18 kcal/capita/day
				Malnourished children under 5 years in LIC	-1%

Source: own representation of study results

2050 is not an easy task and that it requires changes in consumer behaviour, advances in production technologies as well as progresses in the abatement of food wastes and losses along the entire supply chain. The renunciation of livestock products in high-income countries can only be one part of various instruments to meet this challenge (GODFRAY et al., 2018).

7 Health Effects

Livestock products, in particular meat, provide many biologically valuable proteins and other nutrients such as B vitamins, iron and zinc (BOHRER, 2017; BOUVARD et al., 2015; CASHMAN and HAYES, 2017). However, especially high levels of meat consumption can lead to negative health effects. There is evidence that eating meat can increase the risk of diabetes, cancer and coronary disease (ROHRMANN et al., 2013; BARNARD et al., 2014; GODFRAY et al., 2018). This section takes a closer look at the link between animal-based food consumption and public health. A summary of results is given in Table 6.

SCARBOROUGH et al. (2012) develop the DIETRON model in order to estimate the effects of a 50% decline in the consumption of livestock products in the UK. The calorie supply is kept constant by increasing fruit, vegetable and cereal intake. Compared to 2008 levels such a scenario could lead to a reduction in the incidence of cancer, stroke and coronary heart diseases, thus preventing or delaying 36,910 deaths. However, 75% of these avoided deaths can be attributed to the strong increase in fruit and vegetable consumption by more than 160%. Reductions in meat and dairy consumption which are measured by salt and fat intake account for 9% of prevented deaths. However, the authors indicate that the positive health effects of a reduction in meat consumption might be underestimated as the association of red and processed meat with colorectal cancer was not explicitly included in the model.

BIESBROEK et al. (2014) conducts an *ex-post* regression analysis based on a dataset of 35,057 participants whose dietary patterns were recorded at one point in time between 1993 and 1997 in the Netherlands. Afterwards the participants were followed for 16 years to check for the occurrence of diseases. By using the Cox Proportional Hazard (CPH) model, the effects of a reduction in total meat consumption by one third, corresponding to 35 g/day, are estimated. Similar to SCARBOROUGH et al. (2012) the effects are larger if the reduction in meat intake is substituted by cereals, fruits and vegetables or fish. In fact, the risk of all-cause mortality can be reduced by 19% if fish is consumed instead of meat. In scenarios where meat is substituted by pasta, rice or couscous or by fruits, vegetables and nuts, risks decline by 11% and 6-9%, respectively. A substitution by potatoes and dairy products leads to no changes, while a scenario with no replacement of meat shows that the risk of all-cause mortality declines by 4%. These results indicate that the health impact of a reduction in meat consumption strongly depends on general dietary patterns and substitution possibilities. SORET et al. (2014) applies the Cox Proportional Hazard model in combination with dietary and disease records of 96,000 Adventist in the US and Canada from 2001 to 2007. In contrast to other studies, SORET et al. (2014) are not assuming a specific scenario, but rather compare the impacts of existing dietary patterns. This way they find that mortality rates for vegetarians and semi-vegetarians (meat 1 to 3 times per month) are 16-17% lower than for non-vegetarians. The authors argue that their observational approach allows for estimating the effect of realistic dietary patterns rather than theoretical and artificially created diets. However, in the sample average meat consumption is two times lower than in the average American diet, thus, the results might be of limited significance for the American population as a whole.

FRIEL et al. (2009) conduct a comparative risk assessment based on country-level health and population profiles from the Global Burden of Disease (GBD) database. Assessments of a 30% reduction in the consumption of livestock products in the UK and Sao Paulo City in Brazil show that local premature deaths from ischaemic heart diseases could decrease by 17% in 2030 compared to 2010 levels, which is estimated to be an effect of reduced intake of saturated fats from animal-source foods. Moreover, the study identifies changes in disability-adjusted life years and years of life lost, which fall by 15-16% and 16-17%, respectively. By using a similar methodological approach, ASTON et al. (2012) analyse the health impacts of lowering red and processed meat consumption by 42% for men and 44% for women. These figures result from doubling the number of vegetarians derived from the British National Diet and Nutrition survey from 2000-2001, while assuming that the remaining population will adopt meat consumption levels of the bottom fifth of non-vegetarians in the survey. As a result, the risk of coronary heart disease, diabetes and colorectal cancer from red and processed meat consumption could decrease by 10-12% for men and 6-8% for women.

Table 6. Overview of studies analysing the effects of reduced animal-based food consumption on health

Author	Method	Scenario	Reference year	Health Indicator (HI)	Result (Reduction in HI)
Scarborough et al. (2012)	DIETRON Model	- 50% consumption of all animal-source foods substituted by plant-based products UK	2008	Deaths delayed/averted	36,910
		Shift from ruminant meat to pig and poultry consumption UK	2008	Deaths delayed/averted	1,999
Biesbroek et al. (2014)	CPH Model	Meat consumption reduced by one third (35 g/day) Netherlands (NL)	1993-1997	All-cause mortality risk	4%
		Meat consumption reduced by one third (35 g/day) replaced by fish NL	1993-1997	All-cause mortality risk	19%
		Meat consumption reduced by one third (35 g/day) replaced by pasta, rice, couscous NL	1993-1997	All-cause mortality risk	11%
		Meat consumption reduced by one third (35 g/day) replaced by fruits, vegetable, nuts NL	1993-1997	All-cause mortality risk	6-9%
		Meat consumption reduced by one third (35 g/day) replaced by potatoes, cheese, milk NL	1993-1997	All-cause mortality risk	0%
Soret et al. (2014)	CPH Model	Vegetarian diet	2001-2007	All-cause mortality risk	17%
Friel et al. (2009)	Comparative Risk Assessment	30% reduction of saturated fat intake from livestock products UK and Sao Paulo City	2010	Premature Deaths	17%
		30% reduction of cholesterol intake from livestock products UK and Sao Paulo City	2010	Premature Deaths	4-6%
Aston et al. (2012)	Comparative Risk Assessment	44% and 42% reduction in red and processed meat consumption for women and men, respectively	2000-2001	Coronary heart disease risk	6-10%
				Diabetes mellitus risk	8-12%
				Colorectal cancer risk	8-12%
Tilman and Clark (2014)	Meta-Analysis of Cohort Studies	Global Vegetarian diet	Data from studies between 1984-2013	Type II Diabetes rate	41%
				Cancer rate	10%
				Coronary mortality rate	20%
				All-cause mortality rate	0%
		Global Mediterranean diet	Data from studies between 1984-2013	Type II Diabetes rate	16%
				Cancer rate	7%
				Coronary mortality rate	26%
				All-cause mortality rate	18%
		Global Pescetarian diet	Data from studies between 1984-2013	Type II Diabetes rate	25%
				Cancer rate	13%
				Coronary mortality rate	21%
				All-cause mortality rate	13%
Springmann et al. (2016)	Global Health + IMPACT Model	Implementation of international nutritional recommendations	2050	Deaths per year	6-10%
Springmann et al. (2018)	IMPACT	Progressive reduction in animal-source food consumption by 25-100%, substituted by plant-based foods	2030	Premature Mortality rate	4-12%
		Vegan diet	2030	Premature Mortality rate	22%
		Vegetarien diet	2030	Premature Mortality rate	19%
		Flexitarien diet	2030	Premature Mortality rate	19%

Note: CPH = Cox Proportional Hazard Model
Source: own representation of study results

TILMAN and CLARK (2014) compare conventional animal-based diets to three alternative diets: vegetarian (includes dairy products and eggs, but no meat or fish), pescetarian (vegetarian diet that includes fish) and mediterranean diets (rich in fruits, vegetables and seafood, includes also moderate amounts of meat). The analysed data was derived from 18 studies that in total compromise 10 million person-years of observations. Overall, the findings indicate that the alternative diets reduce the incidence of type II diabetes, cancer, mortality due to heart disease and all-cause mortality by 16-41%, 7-13%, 20-26%, 0-18%, respectively. The effects of individual product categories such as meat, fruit and vegetables or seafoods on health are not identified within the study. However, the authors mention that the positive impacts of alternative diets on health indicators mainly arise from a higher consumption of fruits, vegetables, nuts and lower intakes of meat and other energy-dense products such as sugars and alcohol.

SPRINGMANN et al. (2016) estimate the effects of a more plant-based diet on health by combining a health model with the economic model IMPACT. For this purpose, regional diets were adjusted according to international nutritional recommendations. This way the maximum intake of red meat is limited to 43 g/day (301 g/week), whereas fruit and vegetable consumption is increased to a minimum of five portions a day. The calorie intake is limited to 2,200-2,300 kilocalories, depending on age, sex and the general composition of the population. Based on domestic production, trade balances, stock losses and intended use (e.g. food/industrial), FAO statistics show that the worldwide available quantity of calories amounts to 2,917 kcal per capita and day (FAO, 2020). These figures are even higher for Europe, America and Oceania, at around 3,300 kcal per capita and day. Although, these statistics do not reflect actual calorie intakes as, for example, food losses at household level are not considered, they indicate that a scenario as in SPRINGMANN et al. (2016) could be accompanied by significant reductions in meat and calorie intake, particularly in high-income countries. Compared to the reference scenario in 2050, a global diet according to dietary guidelines could prevent 5.1 million deaths p.a. and preserve 79 million life years. Accordingly, a global vegetarian or vegan diet could prevent 7.3 and 8.1 million deaths p.a., respectively, corresponding to 6-10% fewer deaths compared to the reference scenario. More than half of these avoided deaths are based on a reduction in red meat consumption. SPRINGMANN et al. (2016) also emphasize that most deaths per capita could be avoided in industrialised countries which is mainly due to a relatively greater reduction in meat and calorie intake. In developing countries, by contrast, increased consumption of fruit and vegetables leads to reduced mortality. In addition, SPRINGMANN et al. (2016) make an attempt to monetize these health benefits in terms of savings from medical and informal care as well as days lost through premature death from diet-related diseases.

Depending on the extent to which the consumption of livestock products is restricted, USD 735-1,067 billion could be saved annually compared to the reference scenario with the largest savings being observed in industrialized countries, where the costs of health care are relatively high.

In a further modelling study, SPRINGMANN et al. (2018) analyse the effects of reducing the share of animal-source foods in diets on health and nutrient supply. Several scenarios are simulated where the amount of animal-based foods in country specific diets is gradually reduced by 25-100% and substituted by plant-based foods. In line with the available evidence on healthy diets, further scenarios with flexitarian, vegetarian and vegan diets are estimated. The simulations are based on the partial equilibrium model IMPACT. For nutrient supply assessments, 2010 levels serve as reference scenario, whereas for mortality estimates the year 2030 is used as baseline. Overall, the study indicates that a higher intake of plant-based foods can compensate for a reduced consumption of animal-source foods in high-income countries, thus, ensuring a sufficient supply of most nutrients. Increased consumption of fruit, vegetables and legumes can improve the nutrient supply for e.g. vitamin A, iron and potassium and also the protein supply in high-income countries can be kept above the recommended level of 52 g per capita and day in all scenarios. However, purely vegetarian and vegan diets and a strong reduction in the consumption of livestock products by 75-100% result in an undersupply of nutrients that are mainly taken from animal-based foods, such as riboflavin, vitamin B12 and calcium. These deficiencies are particularly high for vegan diets, but the reduced intake of animal-source products still leads to a decline in premature deaths. In the scenarios with a progressive reduction of animal-source foods, premature mortalities can be reduced by 4% for the 25% reduction scenario and by 12% for the 100% reduction scenario. However, more than half (51-58%) of these avoided deaths are due to a higher intake of vegetal products, further 30% can be attributed to a higher consumption of fruits. The decrease in red meat consumption accounts for 8-11% of avoided premature deaths. In scenarios with nutritionally balanced diets, positive health impacts are stronger. A flexitarian diet which allows for small intakes of meat and other animal-based products results in a 19% decrease in premature mortality. Vegan diet reduce mortalities by 22%. These results are consistent with many epidemiological studies which indicate that especially in countries with high per capita income, a vegetarian or vegan diet improves health status and reduces the risk of certain diseases such as cancer or diabetes (ORLICH et al., 2015; TONSTAD et al., 2009). An overview of the results is given in Table 6.

8 Discussion

This review summarised a total of 30 studies analysing the impact of dietary change on the agricultural economy, the environment, food security and public health. The results indicate that a reduction in the consumption of livestock products could be challenging for the agricultural sector and livestock farmers, while offering environmental and health benefits. Within these studies reductions in meat demand were implemented exogenously. In this way, it is assumed that consumer behaviour will change by itself without any external intervention and, thus, no costs will be incurred to bring about this change.

Although the studies analyse similar scenarios, there are differences between the results, which are mainly due to different methodological approaches**.** PE and CGE models are often used to analyse economic and environmental impacts. PE models simulate agricultural markets with relatively detailed and regionally differentiated agricultural demand and supply, whereas non-agricultural markets are assumed to be constant. Adjustments in the whole economy due to changes in the agricultural sector are not considered, thus, there are no feedback loops from other sectors to agriculture and vice versa. In contrast, CGE models simulate the economy as a whole with interactions between all sectors and feedback loops to household income, but this is done at the expense of a more detailed representation of the primary agricultural sector. Instead food processing sectors and processed foods are explicitly implemented in CGE models, which is not the case for partial equilibrium models. It can, therefore, be stated that PE and CGE models cover different aspect and levels of the agri-food system. This has implications for price and environmental effects. Furthermore, CGE models estimate the broader impacts of dietary change on GHG emissions across all sectors, while PE models capture emissions only from the agricultural sector, but in more detail. Further differences between the individual models are related to the use of different data sets, baselines, base years and functional forms of the supply and demand functions. In addition, the models vary in their time horizon. While CGE models are more often used for long-term analyses, it seems that PE models are generally employed for short- to medium-term assessments. Currently, PE models are mainly used to analyse the effects of dietary changes, but more CGE analyses could be helpful to estimate economy-wide effects on all sectors as well as possible rebound effects and their decomposition.

Health effects of dietary changes are mainly estimated by comparative risk assessments. However, the individual studies differ in the number of risk factors and health outcomes that are linked to specific diets. Moreover, uncertainty in comparative risk assessment results from the assumption of causal relationship between food risk factors and certain diseases as well as from the dependence of the estimated health outcomes on published risk parameters. Moreover, uncertainty can also arise from the analysed data sets as dietary data is often reported by the participants and cannot be fully controlled. An important driver of the results is the substitution of the consumption of meat and other animal-based foods. In particular, a simultaneous increased consumption of fruits and vegetables can double the positive health effects, whereas a substitution by potatoes and dairy products eliminates positive effects of a reduced meat consumption. In general, it should be mentioned that in addition to the studies shown here, there are many other studies that link far less a reduction in the consumption of animal-based foods to improved health. Several studies for example emphasize the positive effects of keto diets which aim to reduce carbohydrates mainly from staple foods and increase fat and protein intake from animal-source foods. However, the lack of long-term evidence prevents general recommendation both in the direction of keto diets as well as vegan diets (CASTELLANA et al., 2020; PAOLI, 2014).

The existing scientific evidence reveals shortcomings and limitations. The regional focus of the studies is rather narrow, since they consider the impact of dietary changes on EU and OECD countries and the average person with their nutritional needs. There seems to be a lack of literature addressing possible changes in diets in low- and middle-income countries. However, growth in consumption of livestock products is expected in these countries particularly and might significantly influence the impact of dietary change on environment, GHG emissions and agricultural markets (OECD/FAO, 2019). As shown by existing model-based analyses, demand from the rest of the world influences the effect of dietary change on beef, pork and poultry prices and production depending on the respective trade potential. Moreover, an increase in the consumption of animal-source foods in low- and middle-income countries could have other effects on public health than in high-income countries as malnutrition, nutrient deficiencies and scarcity of foods and animal-source products are more prevalent.

Additionally, the studies share the assumption that the consumption of all meat categories (beef, pork and poultry) is decreasing. However, developments and projections for meat consumption show that in Europe the consumption of beef and pork is decreasing, while the consumption of poultry meat is increasing (OECD/FAO, 2019). Scenarios considering such developments could be helpful as this substitution could be positive from an environmental and health perspective. Particularly, the consumption of beef seems to be a key driver in the GHG emission impact of different diets as pig and poultry meat cause 80-90% less GHG emissions per kilogram. Moreover, when estimating the health effect of diets, reductions in red and processed meat consumption are primarily linked to positive health effects, while poultry meat is often excluded. In addition, the studies do not differentiate with respect to other product characteristics like organic meat, meat with animal welfare labels, processed products, etc. Such varying trends in demand could have different effects on the livestock sector and GHG emissions as they can vary considerably from farm to farm (RIVERA-FERRE et al., 2016; POORE and NEMECEK, 2018). The same argument is true for consumers, who are also treated homogeneously from a socio-economic and nutrient perspective. Different diets might be more or less suitable for certain groups in society, such as children, pregnant women or physically very active people who might have different nutritional needs than the average person (ALEKSANDROWICZ et al., 2016). Moreover, the affordability of diets needs to find more consideration for socio-economic reasons as certain diets and their components may not be available and affordable to all countries and social groups.

Another limitation of existing studies is that the impact of dietary change is only estimated on one or two dimensions. In reality, however, various interactions and feedbacks from agriculture to the environment, health and vice versa can occur. These possible interlinkages and feedbacks between agriculture, environment and health and comparisons between the different effects could be subject to future research. For example, dietary changes can improve the environment by reducing emissions and pressure on resources, which in turn could have also a positive impact on agricultural production. In addition, improved health and, thus, lower costs for the health care system and higher productivity of the labour force due to less diseases and sick days, could lead to positive feedbacks on agriculture and the economy. Positive environmental-health interactions are also possible.

However, consumption and dietary preferences are difficult to change, and so far, statistics do not indicate a widespread shift towards vegetarian diets, as meat consumption in the EU has remained constant at around 80 kg p.a. over the last 10 years (FAO, 2020). Thereby a variety of barriers prevents changes in individual behaviour, some of them are lack of knowledge about climate impact of consumption, unconsciousness behaviour such as routines, social and psychological barriers such as lack in interest, economic barriers, cultural barriers and lack of governmental support (STANKUNIENE et al., 2020). Therefore, reductions in meat consumption are not immediately feasible and policy measures might be necessary. Frequently suggested measures include fiscal measures (e.g. meat tax), information instruments (e.g. labels, information campaigns, education policy) and behavioural economic approaches (e.g. "nudging") (BONNET et al., 2020). In a similar vein, the Scientific Advisory Board for Agricultural Policy, Nutrition and Health-related Consumer Protection (WBAE) in Germany recommends the establishment of a holistic nutrition policy that integrates environmental, health, animal welfare and social goals to achieve progresses and changes towards sustainable diets which include also the reduction in animal-source food consumption (WBAE, 2020). Moreover, there is evidence that dietary patterns depend to a significant extent on the cultural and social environment as well as certain socio-demographic indicators. In particular female, younger individuals (18-34 years) and people with a higher level of education and socio-economic status, living in urban areas as well as in single households seem to be more likely to choose a diet with smaller or no shares of meat (MENSINK et al., 2016; KOCH et al., 2019). In addition scientific evidence indicates that environmental measures are more likely to be implemented if an additional positive side effect on health can be expected (Amelung et al., 2019; Stankuniene et al., 2020). Policy makers and scientists could take advantage of existing evidence, expand on it and contribute to the development of appropriate tools to change diets.

9 Conclusion

In conclusion, based on the scientific results presented it is evident that a transition towards more plant-based diets would bring about major changes for the entire agri-food system. While the agricultural sector and livestock producers may face price and production declines if demand for livestock products decreased, the environment as well as consumer health could benefit from more plant-based diets. This literature review indicates that the following improvements are needed to increase the relevance of scientific work on the effects of dietary change. First, scenario analysis estimating the impact of dietary change could gain in depth if more precise data on dietary patterns of consumers were available and implemented. This refers particularly to the specifications of actual vegetarian, vegan and flexitarian diets, which reveal the potential substitution between different food products by consumers, but also the impact of socio-demographic indicators on diets as well as the nutritional needs of different groups in society. Second, analyses of current diets and potential dietary changes in middle- and low-income countries are required to assess local economic, environmental, food security and public health effects as well as to achieve a more holistic picture of the overall global effects of dietary change. Third, multi-dimensional approaches are needed to estimate interlinkages and trade-offs between economic, environmental and public health objectives. Future developments in diets and meat consumption, can have significant impacts on climate, environment and health. Therefore, there is a need for further development of scientific evidence on the impacts and potential changes in diets and animal-source food consumption.

References

Afshin, A., …, C.J.L. Murray (2019): Health effects of dietary risks in 195 countries, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017. In: The Lancet 393 (10184): 1958-1972.

Aguiar, A., M. Chepeliev, E L. Corong, R. McDougall and D. van der Mensbrugghe (2019): The GTAP Data Base: Version 10. In: Journal of Global Economic Analysis 4 (1): 1-27.

Aleksandrowicz, L., R. Green, E.J.M. Joy, P. Smith and A. Haines (2016): The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. In: PLoS ONE 11 (11): e0165797.

Alexandratos, N. and J. Bruinsma (2012): WORLD AGRICULTURETOWARDS 2030/2050. The 2012 Revision. ESA Working paper No. 12-03. Food and Agriculture Organization of the United Nations, Rome.

Alfredsson, E.C. (2004): "Green" consumption—no solution for climate change. In: Energy 29 (4): 513-524.

Amelung, D., H. Fischer, A. Herrmann, C. Aall, V.R. Louis, H. Becher, P. Wilkinson and R. Sauerborn (2019): Human health as a motivator for climate change mitigation: results from four European high-income countries. In: Global Environmental Change 57: 101918.

Araujo-Enciso, S.R., I. Pérez-Dominguez, F. Santini and S. Hélaine (2015): Documentation of the European Comission's EU module of the Aglink-Cosimo modelling system. JRC SCIENCE AND POLICY REPORTS. European Commission Joint Research Centre, Luxembourg.

Aston, L.M., J.N. Smith and J.W. Powles (2012): Impact of a reduced red and processed meat dietary pattern on disease risks and greenhouse gas emissions in the UK: a modelling study. In: BMJ Open 2 (5): e001072.

Barnard, N., S. Levin and C. Trapp (2014): Meat consumption as a risk factor for type 2 diabetes. In: Nutrients 6 (2): 897-910.

Behrens, P., J. . Kiefte-de Jong, T. Bosker, J.F.D. Rodrigues, A. de Koning and A. Tukker (2017): Evaluating the environmental impacts of dietary recommendations. In: Proceedings of the National Academy of Sciences of the United States of America 114 (51): 13412-13417.

Bennett, M.K. (1941): International Contrasts in Food Consumption. In: Geographical Review 31 (3): 365.

Benton, T.G., C. Bieg, H. Harwatt, R. Pudasaini and L. Wellesley (2021): Food System Impacts on Biodiversity Loss. Three levers for food system transformation in support of nature. Chatham House, London.

Berners-Lee, M., C. Kennelly, R. Watson and C.N. Hewitt (2018): Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation. In: Elementa Science of the Anthropocene 6 (1): 52.

Biesbroek, S., H.B. Bueno-de-Mesquita, P.H.M. Peeters, W.M. Verschuren, Y.T. van der Schouw, G.F.H. Kramer, M. Tyszler and E.H.M. Temme (2014): Reducing our environmental footprint and improving our health: greenhouse gas emission and land use of usual diet and mortality in EPIC-NL: a prospective cohort study. In: Environmental health : a global access science source 13 (1): 27.

Blanco, M. (2019): Support for Policy Relevant Modelling of Agriculture (SUPREMA). D.1.5 Documentation of the SUPREMA model tools. European Union's Horizon

2020. https://www.suprema-project.eu/images/Deliverable_D15_-_final_version.pdf, accessed June 2, 2021.

BOHRER, B.M. (2017): Review: Nutrient density and nutritional value of meat products and non-meat foods high in protein. In: Trends in Food Science & Technology 65: 103-112. https://doi.org/10.1016/j.tifs.2017.04.016.

BONNET, C., Z. BOUAMRA-MECHEMACHE, V. RÉQUILLART and N. Treich (2020): Viewpoint: Regulating meat consumption to improve health, the environment and animal welfare. In: Food Policy 97: 101847. https://doi.org/10.1016/j.foodpol.2020.101847.

BOUVARD, V., D. LOOMIS, K.Z. GUYTON, Y. GROSSE, F E. GHISSASSI, L. BENBRAHIM-TALLAA, N. GUHA, H. MATTOCK and K. STRAIF (2015): Carcinogenicity of consumption of red and processed meat. In: The Lancet Oncology 16 (16): 1599-1600.

BREUER, B., L. MARTIN, M. WIERIG and E. SAGGAU (2019): Drivers of change and development in the EU livestock sector. Meta-Analysis as basis for future scenario building. German Federal Office for Agriculture and Food, Bonn.

BRITZ, W. and H.P. WITZKE (2014): CAPRI Model Documentation 2014. University of Bonn. http://www.capri-model.org/docs/capri_documentation.pdf, accessed April 14, 2021.

BZL (2019): Versorgung mit Fleisch in Deutschland seit 1991. https://www.ble.de/DE/BZL/Daten-Berichte/Fleisch/fleisch_node.html;jsessionid=84D90275799AAC74449E50294034167E.1_cid325#doc9091258bodyText1, accessed April 14, 2021.

CARLSSON-KANYAMA, A., R. ENGSTRÖM and R. KOK (2005): Indirect and Direct Energy Requirements of City Households in Sweden: Options for Reduction, Lessons from Modeling. In: Journal of Industrial Ecology 9 (1-2): 221-235.

CASHMAN, K.D. and A. HAYES (2017): Red meat's role in addressing 'nutrients of public health concern'. In: Meat science 132: 196-203. doi: 10.1016/j.meatsci.2017.04.011.

CASTELLANA, M., E. CONTE, A. CIGNARELLI, S. PERRINI, A. GIUSTINA, L. GIOVANELLA, F. GIORGINO and P. TRIMBOLI (2020): Efficacy and safety of very low calorie ketogenic diet (VLCKD) in patients with overweight and obesity: A systematic review and meta-analysis. In: Reviews in endocrine & metabolic disorders 21 (1): 5-16.

CLUNE, S., E. CROSSIN and K. VERGHESE (2017): Systematic review of greenhouse gas emissions for different fresh food categories. In: Journal of Cleaner Production 140: 766-783. https://doi.org/10.1016/j.jclepro.2016.04.082.

CORDTS, A., N. DUMAN, H. GRETHE, S. NITZKO and A. SPILLER (2014): Potenziale für eine Verminderung des Fleischkonsums am Beispiel Deutschland und Auswirkungen einer Konsumreduktion in OECD-Ländern auf globale Marktbilanzen und Preise für Nahrungsmittel. In: Proceedings “Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaues e.V., German Association of Agricultural Economists 49.

CORDTS, A., N. DUMAN, H. GRETHE, S. NITZKO and A. SPILLER (2013): Auswirkungen eines verminderten Konsums von tierischen Produkten in Industrieländern auf globale Marktbilanzen und Preise für Nahrungsmittel. Sicherung der Welternährung bei knappen Ressourcen. Rentenbank, Frankfurt/M.: 103-135.

COX, D.R. (1972): Regression Models and Life-Tables. In: Journal of the Royal Statistical Society: Series B (Methodological) 34 (2): 187-202.

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

EHRMANN, M. (2016): Modellgestützte Analyse von Einkommens- und Umweltwirkungen auf Basis von Testbetriebsdaten. Dissertation. Thünen Report No. 48, Braunschweig.

EZZATI, M. (2000): Methodology for assessment of Environmental burden of disease. Annex 4.1.: Comparative risk assessment in the global burden of disease study and the environmental health risks. World Health Organization, Buffalo.

FAO (2003): Measurement and Assessment of Food Deprivation and Undernutrition. Keynote Paper: FAO methodology for estimating the prevalence of undernourishment. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/3/y4249e/y4249e06.htm#b m06.

FAO (2006): Livestock's long shadow. Environmental issues and options. Food and Agriculture Organization of the United Nations, Rome.

FAO (2017): Livestock solutions for climate change. Food and Agriculture Organization of the United Nations, Rome.

FAO (2020): FAOSTAT Statistical Database. New Food Balances. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/faostat/en/#data/FBS.

FRIEL, S., …, A. HAINES (2009): Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. In: The Lancet 374 (9706): 2016-2025.

GERBER, P.J., H. STEINFELD, B. HENDERSON, A. MOTTET, C. OPIO, J. DIJKMAN, A. FALCUCCI and G. TEMPIO (2013): Tackling climate change through livestock - A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations, Rome.

GODFRAY, H.C.J., P. AVEYARD, T. GARNETT, J.W. HALL, T.J. KEY, J. LORIMER, R.T. PIERREHUMBERT, P. SCARBOROUGH, M. SPRINGMANN and S.A. JEBB (2018): Meat consumption, health, and the environment. In: Science (New York, N.Y.) 361 (6399).

GRABS, J. (2015): The rebound effects of switching to vegetarianism. A microeconomic analysis of Swedish consumption behavior. In: Ecological Economics 116: 270-279. https://doi.org/10.1016/j.ecolecon.2015.04.030.

HAENEL, H.-D., …, R. FUß (2020): Berechnung von gas- und partikelförmigen Emissionen aus der deutschen Landwirtschaft 1990 - 2018: Report zu Methoden und Daten (RMD) Berichterstattung 2020. Thünen Report 77. Johann Heinrich von Thünen-Institute, Braunschweig.

HAß, M., …, M. ZIRNGIBL (2020): Thünen-Baseline 2020 - 2030: Agrarökonomische Projektionen für Deutschland. Johann Heinrich von Thünen-Institute, Braunschweig.

HEDENUS, F., S. WIRSENIUS and D.J.A. JOHANSSON (2014): The importance of reduced meat and dairy consumption for meeting stringent climate change targets. In: Climatic Change 124 (1-2): 79-91.

IPCC (Intergovernmental Panel on Climate Change) (2019): Climate Change and Land: an Intergovernmental Panel on Climate Change (IPCC) special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In: Shukla, P.R.,…, J. Malley (eds.). In press.

JENSEN, H. and I. PÉREZ DOMÍNGUEZ (2019): Scenario: A protein shift in the EU. EU agricultural outlook for markets and income, 2019-2030. European Commission, DG Agriculture and Rural Development, Brussels.

JOHANSSON, D.J.A. (2011): Temperature stabilization, ocean heat uptake and radiative forcing overshoot profiles. In: Climatic Change 108 (1-2): 107-134.

KAVALLARI, A. (2008): Agricultural policy reforms and trade liberalisation in the Mediterranean Basin : A partial equilibrium analysis of regional effects on the EU-27 and on the Mediterranean Partner Countries. Inaugural-Dissertation. Fachbereich Agrarwissenschaften, Ökotrophologie und Umweltmanagement, Justus-Liebig Universität, Gießen.

KLÜMPER, W. (2014): Das Problem der Welternährung: Simulationen zu Einflussfaktoren, die Bedeutung von Agrartechnologien und gesellschaftliche Einschätzungen in Deutschland. Dissertation. Georg-August-Universität Göttingen, Göttingen.

KOCH, F., T. HEUER, C. KREMS and E. CLAUPEIN (2019): Meat consumers and non-meat consumers in Germany: a characterisation based on results of the German National Nutrition Survey II. In: Journal of nutritional science 8 (21): 1-13.

LENZEN, M. and C.J. DEY (2002): Economic, energy and greenhouse emissions impacts of some consumer choice, technology and government outlay options. In: Energy Economics 24 (4): 377-403.

LOCK, K., R.D. SMITH, A.D. DANGOUR, M. KEOGH-BROWN, G. PIGATTO, C. HAWKES, R.M. FISBERG and Z. CHALABI (2010): Health, agricultural, and economic effects of adoption of healthy diet recommendations. In: The Lancet 376 (9753): 1699-1709.

LOFGREN, H., R.L. HARRIS and S. ROBINSON (2002): A STANDARD COMPUTABLE GENERAL EQUILIBRIUM (CGE)MODEL IN GAMS. International Food Policy Research Institute, Washington, D.C.

MARQUES, A.C., J.A. FUINHAS and D.F. PAIS (2018): Economic growth, sustainable development and food consumption: Evidence across different income groups of countries. In: Journal of Cleaner Production 196: 245-258. https://doi.org/10.1016/j.jclepro.2018.06.011.

MAYEN, F. (2016): Livestock in protracted crises: The importance of livestock for resilience-building and food security of crisis-affected populations. Food and Agriculture Organization of the United Nations, Rome.

MEKONNEN, M.M. and A.Y. HOEKSTRA (2012): A Global Assessment of the Water Footprint of Farm Animal Products. In: Ecosystems 15 (3): 401-415.

MENSINK, G.B., C.L. BARBOSA and A.-K. BRETTSCHNEIDER (2016): Verbreitung der vegetarischen Ernährungsweise in Deutschland. In: Journal of Health Monitoring 1 (2).

MERCIAI, S. and J. SCHMIDT (2018): Methodology for the Construction of Global Multi-Regional Hybrid Supply and Use Tables for the EXIOBASE v3 Database. In: Journal of Industrial Ecology 22 (3): 516-531.

MRI (Max-Rubner-Institut) (2008): Verzehrsstudie II. Ergebnisbericht, Teil 2. Die bundesweite Befragung zur Ernährung von Jugendlichen und Erwachsenen. Max-Rubner-Institut, Bundesforschungsinstitut für Ernährung und Lebensmittel, Karlsruhe.

OECD (2012): OECD-Umweltausblick bis 2050. Die Konsequenzen des Nichthandelns. OECD publications, Paris.

OECD/FAO (2015): Aglink-Cosimo Model Documentation. A partial equilibrium model of world agricultural markets. Paris.

OECD/FAO (2019): OECD-FAO Agricultural Outlook 2019-2028. OECD Publishing, Paris/Food and Agriculture Organization of the United Nations, Rome.

ORLICH, M.J., …, G.E. FRASER (2015): Vegetarian dietary patterns and the risk of colorectal cancers. In: JAMA internal medicine 175 (5): 767-776.

PAIS, D.F., A.C. MARQUES and J.A. FUINHAS (2020): Reducing Meat Consumption to Mitigate Climate Change and Promote Health: but Is It Good for the Economy? In: Environmental Modeling & Assessment 25 (6): 793-807.

PAOLI, A. (2014): Ketogenic diet for obesity: friend or foe? In: International journal of environmental research and public health 11 (2): 2092-2107.

POORE, J. and T. NEMECEK (2018): Reducing food's environmental impacts through producers and consumers. In: Science (New York, N.Y.) 360 (6392): 987-992.

POPKIN, B.M. (1993): Nutritional Patterns and Transitions. In: Population and Development Review 19 (1): 138.

RANGANATHAN, J., D. VENNARD, R. WAITE, P. DUMAS, B. LIPINSKI, T. SEARCHINGER and GLOBAGRI-WRR AUTHORS (2016): Shifting Diets for a Sustainable Food Future. Working Paper, Installment 11 of Creating a Sustainable Future. World Resources Institute, Washington.

REVELL, B.J. (2015): One Man's Meat … 2050? Ruminations on Future Meat Demand in the Context of Global Warming. In: Journal of Agricultural Economics 66 (3): 573-614.

RIVERA-FERRE, M.G., F. LÓPEZ-I-GELATS, M. HOWDEN, P. SMITH, J.F. MORTON and M. HERRERO (2016): Re-framing the climate change debate in the livestock sector: mitigation and adaptation options. In: Wiley Interdisciplinary Reviews: Climate Change 7 (6): 869-892.

ROBINSON, S., D. MASON-D'CROZ, S. ISLAM, T.B. SULSER, R. ROBERTSON, T. ZHU, A. GUENEAU, G. PITOIS and M. ROSEGRANT (2015): The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). Model Description for Version 3. IFPRI Discussion Paper No. 01483. International Food Policy Research Institute, Washington.

ROHRMANN, S., …, J. LINSEISEN (2013): Meat consumption and mortality-results from the European Prospective Investigation into Cancer and Nutrition. In: BMC medicine 11: 63. http://www.biomedcentral.com/1741-7015/11/63.

RÖÖS, E., B. BAJŽELJ, P. SMITH, M. PATEL, D. LITTLE AND T. GARNETT (2017): Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. In: Global Environmental Change 47: 1-12. https://doi.org/10.1016/j.gloenvcha.2017.09.001.

RÖÖS, E., C. SUNDBERG, P. TIDÅKER, I. STRID AND P.-A. HANSSON (2013): Can carbon footprint serve as an indicator of the environmental impact of meat production? In: Ecological Indicators 24: 573-581. https://doi.org/10.1016/j.ecolind.2012.08.004.

ROSEGRANT, M.W., N. LEACH and R.V. GERPACIO (1999): Alternative futures for world cereal and meat consumption. In: The Proceedings of the Nutrition Society 58 (2): 219-234.

SANS, P. and P. COMBRIS (2015): World meat consumption patterns: An overview of the last fifty years (1961-2011). In: Meat science 109: 106-111.

SANTINI, F., T. RONZON, I. PEREZ DOMINGUEZ, S.R. ARAUJO ENCISO and I. PROIETTI (2017): What if meat consumption would decrease more than expected in the high-income countries? In: Bio-based and Applied Economics 6 (1).

SCARBOROUGH, P., S. ALLENDER, D. CLARKE, K. WICKRAMASINGHE and M. RAYNER (2012): Modelling the health impact of environmentally sustainable dietary scenarios in the UK. In: European Journal of Clinical Nutrition 66 (6): 710-715.

SCHMITZ, M. (2019): Globale Auswirkungen einer rein pflanzlichen Ernährung. Konsequenzen für Wirtschaft, Umwelt und Welternährung. Studie erstellt auf Anregung und mit finanzieller Unterstützung der Dr. Alhard von Burgsdorff-Stiftung (Bonn). Institut für Agribusiness, Gießen.

SEARCHINGER, T., R. WAITE, C. HANSON and J. RANGANATHAN (2019): Creating a sustainable food future. A Menu of Solutions to Feed Nearly 10 Billion People by 2050. Final report. World Resources Report. World Resources Institute, Washington D.C.

SORET, S., A. MEJIA, M. BATECH, K. JACELDO-SIEGL, H. HARWATT and J. SABATÉ (2014): Climate change mitigation and health effects of varied dietary patterns in real-life settings throughout North America. In: The American journal of clinical nutrition 100 (100 Suppl 1): 490S-5S.

SPRINGMANN, M., H.C.J. GODFRAY, M. RAYNER and P. SCARBOROUGH (2016): Analysis and valuation of the health and climate change cobenefits of dietary change. In: Proceedings of the National Academy of Sciences of the United States of America 113 (15): 4146-4151.

SPRINGMANN, M., L. SPAJIC, M.A. CLARK, J. POORE, A. HERFORTH, P. WEBB, M. RAYNER and P. SCARBOROUGH (2020): The healthiness and sustainability of national and global food based dietary guidelines: modelling study. In: BMJ 2020:370:m2322.

SPRINGMANN, M., K. WIEBE, D. MASON-D'CROZ, T.B. SULSER, M. RAYNER and P. SCARBOROUGH (2018): Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. In: The Lancet Planetary Health 2 (10): 451-461.

STANKUNIENE, G., D. STREIMIKIENE and G.L. KYRIAKOPOULOS (2020): Systematic Literature Review on Behavioral Barriers of Climate Change Mitigation in Households. In: Sustainability 12 (18): 7369.

STEHFEST, E., L. BOUWMAN, D.P. VAN VUUREN, M.G.J. DEN ELZEN, B. EICKHOUT and P. KABAT (2009): Climate benefits of changing diet. In: Climatic Change 95 (1-2): 83-102.

TILMAN, D. and M. CLARK (2014): Global diets link environmental sustainability and human health. In: Nature 515 (7528): 518-522.

TONSTAD, S., T. BUTLER, R. YAN and G. E. FRASER (2009): Type of vegetarian diet, body weight, and prevalence of type 2 diabetes. In: Diabetes care 32 (5): 791-796.

UMWELTBUNDESAMT (2019): Beitrag der Landwirtschaft zu den Treibhausgas-Emissionen. ttps://www.umweltbundesamt.de/daten/land-forstwirtschaft/beitrag-der-landwi rtschaft-zu-den-treibhausgas#massnahmen-in-der-land-wirtschaft-zur-senkung-der-treibhausgas-emissionen.

UN (2019): World Population Prospects 2019. Highlights. New York.

UNFCCC (United Nations Framework Convention on Climate Change) (2011): Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010. Decisions adopted by the Conference of the Parties. Decision 1/CP.16 The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention. COP 16 Report: FCCC/CP/2010/7/ Add.1. United Nations. Available at: https://unfccc.int/ documents/6527, accessed April 14, 2021.

USDA-NASS (2017): Overview of U.S. Livestock, Poultry, and Aquaculture Production in 2017. National Agricultural Statistics Service and U.S. Department of Agriculture. http://www.aphis.usda.gov/animal_health/nahms/ downloads/Demographics2017.pdf.

VELTHOF, G.L., D.A. OUDENDAG and O. OENEMA (2007): Development and application of the integrated nitrogen model MITERRA-EUROPE. Alterra, Wageningen UR. https://edepot.wur.nl/30636, accessed April 14, 2021.

WBAE (Wissenschaftlicher Beirat für Agrarpolitik, Ernährung und gesundheitlichen Verbraucherschutz beim BMEL)(2020): Politik für eine nachhaltigere Ernährung: Eine integrierte Ernährungspolitik entwickeln und faire Ernährungsumgebungen gestalten. Gutachten. Berlin.

WESTHOEK, H., J.P. LESSCHEN, T. ROOD, S. WAGNER, A. DE MARCO, D. MURPHY-BOKERN, A. LEIP, H. VAN GRINSVEN, M.A. SUTTON and O. OENEMA (2014): Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. In: Global Environmental Change 26: 196-205. https://doi.org/10.1016/j.gloenvcha.2014.02.004.

WILKINSON, J.M. (2011): Re-defining efficiency of feed use by livestock. In: Animal: an International Journal of Animal Bioscience 5 (7): 1014-1022.

WILLETT, W., …, C.J.L. MURRAY (2019): The EAT-Lancet Commission Summary Report. No. 10170. https://eat-forum.org/eat-lancet-commission/eat-lancet-commission-summary-report/, accessed April 14, 2021.

WOLTJER, G. and M. KUIPER (2014): The MAGNET model. Module description. LEI Report 14-057. LEI Wageningen UR (University & Research centre), Wageningen.

WOOD, R., …, A. TUKKER (2015): Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. In: Sustainability 7 (1): 138-163.

WWAP (United Nations World Water Assessment Programme) (2018): The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. UNESCO, Paris.

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Appendix

Appendix A: Supplementary Material - Method

1) Aims and Research Questions of Literature Review

In the context of climate change mitigation, dietary changes and in particular the renouncement of animal-source foods are often mentioned as an effective measure to reduce greenhouse gas emissions (IPCC, 2019). This literature review aims to summarize existing studies that analyze the effects of changing eating habits towards less consumption of animal foods. The main focus is on the effects on the agricultural sector (prices, production, trade, income), greenhouse gas emissions, food security and health outcomes. The review contains summary tables that provide a quick overview of the results and the analysed scenarios. The aim is also to illustrate as far as possible the complex relationships between demand, supply, international trade, environment, health and food security, as well as the state of the art in order to incentives for future research. Primarily the following questions are answered:

I. ***What are the various scenarios and underlying assumptions for dietary changes proposed in the literature?***

II. ***What are the current and future impacts of those assumed scenarios on the agricultural sector, greenhouse gas emissions, food security and health?***

2) Search Strategy

The following search concepts were used:

1. **Section Impacts on Agricultural Markets:** (“meat” OR “meat consumption” OR “dairy” OR “animal foods” OR “livestock products” OR “vegetarian” OR “vegan” OR “diet change” OR “diet pattern” OR “diet behavior” OR “sustainable diet” OR “Mediterranean diet” OR “diet” OR “food consumption” OR “dietary guidelines” or “food choice”) AND (“effects/impacts on” OR “modelling study”) AND (“economy” OR “agriculture” OR “agricultural markets” OR “farms/farmers” OR “livestock production” OR “animal husbandry” OR “trade” OR “GDP”)
2. **Section Impact on Greenhouse Gas Emissions:** (“meat” OR “meat consumption” OR “dairy “ OR “animal foods” OR “livestock products” OR “vegetarian” OR “vegan” OR “diet change” OR “diet pattern” OR “diet behavior” OR “sustainable diet” OR “Mediterranean diet” OR “diet” OR “food consumption” OR “dietary guidelines” or “food choice”) AND (“effects/impacts on” OR “modelling study”) AND (“environment” OR “greenhouse gas emissions” OR “climate/climate change” OR “sustainability” OR “global warming”)
3. **Section Rebound Effect:** (“meat” OR “meat consumption” OR “dairy” OR “animal foods” OR “livestock products” OR “vegetarian” OR “vegan” OR “diet change” OR “diet pattern” OR “diet behavior” OR “sustainable diet” OR “Mediterranean diet” OR “diet” OR “food consumption” OR “dietary guidelines” or “food choice”) AND (“rebound effect”)
4. **Section Food Security:** (“meat” OR “meat consumption” OR “dairy” OR “animal foods” OR “livestock products” OR "vegetarian" OR “vegan” OR “diet change” OR “diet pattern” OR “diet behavior” OR “sustainable diet” OR “Mediterranean diet” OR “diet” OR “food consumption” OR “dietary guidelines” or “food choice”) AND (“effects/impacts on” OR “modelling study” OR “developing countries/low income countries”) AND (“food security” OR “nutrition” OR “malnutrition” OR “hunger” OR “undernourishment”)
5. **Section Health:** (“meat” OR “meat consumption" OR “dairy” OR “animal foods” OR “livestock products” OR “vegetarian” OR “vegan” OR “diet change” OR “diet pattern” OR “diet behavior” OR “sustainable diet” OR “Mediterranean diet” OR “diet” OR “food consumption” OR “dietary guidelines” or “food choice”) AND (“effects/impacts on” OR “modelling study”) AND (“health” OR “vitamins” OR “nutrients” OR “public health” OR “diseases” OR “mortality” OR “cancer” OR “diabetes”)

These word combinations were entered on Google Scholar, PubMed and Science Direct. The studies found were also searched for relevant references. Additionally, it was searched for publications of several Non-governmental organizations such as OECD and FAO. Peer-reviewed studies were included, as well as appropriate grey literature such as dissertations, working papers and reports, which meet the inclusion criteria described below.

Inclusion Criteria

– Defining a dietary scenario and quantifying the rebound effect OR the effect on economic (price, production, trade, welfare, GDP), environmental (greenhouse gas emissions), food security (mal-

nutrition, undernourishment, nutrient deficiencies) and health (risk/rate of cancer, diabetes, mortality, other diseases) indicators
- Modelling study with scenarios on dietary change with less livestock products or regression analysis using food balance sheets or dietary surveys
- Modelling studies with reference scenario between 2010-2100, studies conducted from 1990 onwards, studies using consumption or intake data from 1990 onwards
- English and German language

Exclusion Criteria
- Studies implementing scenarios with non-quantified changes in animal-based food consumption
- Studies comparing the impact of individual food items or meals rather than diets

Appendix B: Supplementary Material - Model Description

The **MAGNET** model (Modular Applied GeNeral Equilibrium Tool) is a comparative-static multi-regional, general equilibrium model that captures the global economic activity of the world, but also of individual countries and regions. It models the interactions between primary agriculture and food industries as well as other sectors. It takes into account the intra- and interregional linkages of markets and actors including the resulting feedback effects. The MAGNET model is based on the GTAP model. Compared to the standard GTAP model, MAGNET is extended in the areas of cereals and oilseeds, differentiated meat products, agricultural factor markets and products of the bio-based economy as well as associated policies. In total, 115 sectors are considered. MAGNET enables long-term analyses and a more detailed mapping of the common agricultural policy in the EU (WOLTJER and KUIPER, 2014).

FARMIS is a comparative-static, nonlinear programming model that maps agricultural activities in detail at the farm group level. The core of the model is a standard optimization matrix, which includes 27 cropping activities and 21 livestock production practices. Profit maximization is performed using the Positive Mathematical Programming approach. FARMIS is used in short-term analyses to estimate the operational effects of different policy scenarios (EHRMANN, 2016; HAß et al., 2020).

The **CAPRI** model (Common Agricultural Regionalised Impact Analysis) is a comparative-static, global, spatial, partial equilibrium model. It was designed to estimate the impact of agricultural policy decisions on production, income, market, trade and the environment globally and regionally in the short- to medium-term. This is achieved by coupling regional or farm type-specific supply models with a global market model. It covers different scales ranging from global, EU and national states to Nuts2 regions and farm types. It covers 70 countries, 40 trading blocks and 50 agricultural primary and processed goods for the EU (BRITZ and WITZKE, 2014).

GTAP (Global Trade Analysis Project) is a global network of researchers and decision makers who developed a global data base including bilateral trade patterns, production, consumption and intermediate use of commodities and services. The network developed the corresponding CGE model GTAP. The standard GTAP model is a comparative-static multi-regional general equilibrium model that can be used for long-term assessments. The 10th Version includes and 141 countries/regions and 65 sectors of which approximately one third are related to agriculture, forestry and aquaculture (AGUIAR et al., 2019).

AGLINK-COSIMO is a recursive-dynamic, partial equilibrium model of world agriculture. It is used to project global and regional annual market balances and prices for the production, consumption and trade of the main agricultural commodities for up to 10 years. It is also used for the annual EU Agricultural Outlook. As it is recursive-dynamic the results of each individual year depend on previous years. Moreover, each year is modelled over the respective projection period, so that pathways can be described. Aglink-Cosimo covers 44 countries, 12 regions, 93 commodities (agricultural primary goods) and 40 world market clearing prices (OECD/FAO, 2015; ARAUJO-ENCISO et al., 2015).

IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) is a comparative static multi-market partial-equilibrium model that simulates national and international markets. It was designed by the International Food Policy Research Institute (IFPRI) for analysing agricultural markets, developments in food security and poverty as well as impacts on natural resources in the long-run. The model covers 62 primary agricultural goods and 159 countries (ROBINSON et al., 2015).

AGRISIM (Agricultural Simulation Model) is a static multi-regional partial equilibrium model. It is based on non-linear supply and demand functions. It covers the whole world with 56 countries that can be modelled separately and 29 primary agricultural commodities (KAVALLARI, 2008).

IFPRI standard CGE model is a comparative-static single country open economy model developed by the International Food Policy Research Institute (IFPRI). The model was designed for the application at the country level and to facilitate the use of CGE models in developing countries. The code of the model is provided, however, datasets must be contributed by the users. The model is particularly distinctive in that it considers many of the characteristics of developing countries such as the consumption of non-marketed commodities (LOFGREN et al., 2002). LOCK et al. (2010) used for the application the GTAP database from 2004 which captures 66 regions and 57 commodities, including 20 agricultural commodities.

EXIOBASE3.3 is a global, multi-regional input-output database which describes the economy of 49 countries with 200 product groups including 12 foods in 2011. EXIOBASE was developed to conduct economic, social and environmental analysis at the sectoral, national or global level. It accounts for CO_2, nitrous dioxide and methane emissions by activities (MERCIAI and SCHMIDT, 2018).

MiMiC is a climate-economic multi-gas mitigation climate (MiMiC) model. The model determines CO_2, nitrous dioxide and methane emissions endogenously and enables to model emission abatements as well as emission pathways. It allows for analysis up to 2060 and uses the period 1880 to 2004 to calibrate the model (JOHANSSON, 2011; HEDENUS et al., 2014).

GlobAgri-WRR is a global agriculture and land-use accounting model. It is used to analyse the effects of changes in population, diets, waste or production technologies on emissions, land-use and agricultural production quantities. GlobAgri-WRR includes 11 regions and 117 agricultural products at the country level which are derived from FAOSTAT. The base year is 2010 and analyses are mainly conducted until 2050. Dietary change scenarios are implemented by adjusting FAO food balance sheet data. The model allows for CO_2, nitrous oxide, and methane estimations from livestock, rice, nitrogen, aquaculture, energy use and land-use (SEARCHINGER et al., 2019).

MITERRA-EUROPE is a deterministic and static biophysical model which estimates CO_2, CH_4 and as well as nitrogen emissions (N_2O, NH_3, NO_x and NO_3) and nitrogen leaching to ground and surface waters. It was designed to assess the effects of agricultural policies on emissions and nitrogen losses in the European Union at Nuts2-Level. The reference year of the model is 2000 (VELTHOF et al., 2007; BLANCO, 2019).

The **DIETRON** model estimates mortality from coronary heart disease, stroke or cancers of the mouth, larynx and pharynx, oesophagus, stomach and lung. The model allows to estimate the impact of one or multiple risk factors such as age, sex, diets on diseases and mortality. Risk parameters are derived from existing studies such as meta-analyses and cohort studies (SCARBOROUGH et al., 2012).

Comparative Risk Assessments systematically estimate changes in public health. These assessments include different diseases which are assumed to be caused by certain risk factors. Changes in population health are derived by adjusting the exposure to one or multiple risk factors (EZZATI, 2000).

Cox proportional-hazards model is a regression model that estimates the survival time of individuals or all-cause-mortality as a function of one or multiple independent variables (COX, 1972).