Nutri2Cycle
Nurturing the Circular Economy

Nutri2cycle

D.5.3 Impacts of changes in consumer behaviour on nutrient and carbon flows, environmental and socio-economic

Deliverable: Impacts of changes in consumer behaviour on nutrient and carbon flows, environmental and socio-economic indicators

Author(s): Jörg Rieger[1], Alexander Gocht[1], Anoma Gunarathne[1], Davit Stepanyan[1], Bernhard Osterburg[1]

Contributors/Editors: Elizabeth O'Carroll[2], Zein Kallas[3]

Thuenen Institute, Germany[1]; Teagasc , Ireland[2]; IRTA-CREDA, Spain[3]

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Co-ordinator: Prof. Erik Meers, Ghent University

Contact details: Erik.meers@ugent.be

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Abbrevations

C	carbon
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regional Impact
CH_4	methane
CO_2	carbon dioxide
ETS	Emission Tradind System
EU	European Union
eq.	equivalent
FAO	Food and Agriculture Organization
GHG	greenhouse gases
ha	hectare
kcal	kilocalorie
kg	kilogram
IPCC	Intergovernmental Panel on Climate Change
Mt	million tonnes
N	nitrogen
N2C	Nutri2cycle
N_2O	nitrous oxide
NH_3	ammonia
P	phosphorus
t	ton
VCS	Voluntary coupled support
WP	Work package
UAA	utilised agricultural area

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Glossary

Agro-typology: Refers to the classification of agricultural systems based on their biophysical and socio-economic characteristics, including soil type, climate, farm size, production practices, market access, and other relevant factors.

Anaerobic digestion: A series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen and produce biogas.

Carbon leakage: Carbon leakage refers to the situation where efforts to reduce greenhouse gas emissions in one country or region result in increased GHG emissions in another country or region.

Coronary heart disease: Coronary heart disease (CHD) is a condition in which the blood vessels that supply the heart muscle with blood, oxygen, and nutrients become narrowed or blocked, leading to reduced blood flow to the heart. Risk factors for CHD include high blood pressure, high cholesterol, smoking, physical inactivity, obesity, diabetes, and family history.

Diabetes: Diabetes is a chronic metabolic disorder characterized by high levels of glucose (sugar) in the blood. This occurs when the body is unable to produce enough insulin (a hormone produced by the pancreas) or is unable to use insulin effectively, resulting in elevated blood glucose levels.

EAT-Lancet: The EAT-Lancet Commission is a group of international experts in the fields of nutrition, health, sustainability, and agriculture who were brought together to address the challenge of feeding a growing global population in a healthy and sustainable way. The Commission was formed in 2015 as a collaboration between the EAT Foundation, a non-profit organization that seeks to transform the global food system, and The Lancet, a leading medical journal.

Gross value-added: Concept used in economics to measure the contribution of an industry, sector, or region to the economy. It is calculated by subtracting the cost of intermediate inputs (such as raw materials or goods purchased from other businesses) from the total value of goods and services produced in a given period.

Nitrogen surplus at the soil level: Refers to the amount of nitrogen that exceeds the crop's demand and is left over in the soil after plant uptake. This can occur when nitrogen inputs from fertilizers or organic matter are greater than what the crop needs for optimal growth and development.

NUTS2 level: NUTS2 refers to the Nomenclature of Territorial Units for Statistics, which is a hierarchical system used by the European Union to divide regions for statistical purposes.

Premature mortality: Premature mortality refers to deaths that occur at a younger age than expected based on average life expectancy or in comparison to the age at which the majority of the population dies.

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Executive Summary

In this deliverable, we investigated the effects of three scenarios on the environment, agricultural production and trade in 2030 using the CAPRI model. The scenarios were based on the EAT-Lancet recommendations for dietary changes (Diet_Lancet), the implementation of a carbon tax to trigger the adoption of mitigation technologies (Tax_tech), and the combination of both (Diet_Tax_tech). The results showed that dietary changes led to reductions in animal-based production, increased production of fruits, vegetables, and legumes, and reductions in agricultural GHG emissions and nitrogen (N) surplus. The Tax_tech scenario resulted in higher reductions in GHG emissions, mineral fertilizer use, and N-surplus due to the carbon tax and the adoption of mitigation technologies. The Diet_Tax_tech scenario showed the highest reductions in all emission types and was the most positive for the environment. Policies that support the adoption of the EAT-Lancet diet and mitigation technologies in the agricultural sector could be useful tools for achieving national or EU-wide mitigation goals.

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1. Introduction

1.1 Background

The NUTRI2CYCLE project addresses the current nutrient flow gaps within European agroecosystems while balancing productivity, quality, and environmental impact by implementing optimized management systems. The main objectives of the NUTRI2CYCLE project are:

(i) Benchmark mass flows of nutrients, organic carbon, and, GHG emissions, across eight investigated agro-typologies over three major agricultural pillars, and, toolbox development.
(ii) Develop innovative funnel for optimizing farm systems.
(iii) Develop and test prototypes for different farm typologies, while considering different agro-climatological and socioeconomic factors.
(iv) Determine the environmental, economic and agronomic impact of innovative solutions for closing C, N, P loops and benchmarking these against the current baseline
(v) Calculate impact at regional & EU level.
(vi) Evaluate consumer preference for eco-labelling and consumer behaviour impact (e.g. dietary shifts) on flows, sustainability and agro-economics.

This report contains the main results of the research carried out within Task 5.6 (Consumer behaviour impact on flows, sustainability and agro-economics). The main objective is to analyse the dietary changes on the demand-side, particularly with regards to reduced consumption of animal products, which can improve the efficiency of nutrient and carbon cycles in the EU. In Work Package 5 (WP), Task 5.6 ties together previous work carried out as part of Nutri2Cycle, such as WP2, WP3, WP 4, and WP 6, which focused on supply-side measures. In this deliverable, 5.3, a quantitative model-based analysis is performed using the CAPRI model to evaluate the effects of demand-side changes. The objective is to enhance the efficiency of nutrient and carbon cycles within the EU agricultural sector through measures such as policy changes, awareness campaigns and modifying diets to decrease consumption of animal products. Given that agricultural commodities in Europe are closely connected with other regions of the world through trade flows, and that farm inputs such as feed concentrates are internationally traded goods, this deliverable will investigate how changes in the EU's agricultural commodity supply could impact international trade and land use. In addition, these demand-side scenarios will be combined with implementing and expanding innovative technologies for managing nutrients and carbon on the supply-side from deliverables 4.2 in WP4 based on the transferability assessment from deliverable 4.1. The goal is to determine the comprehensive effects of the different scenarios on nutrient loops and mitigating GHG emissions.

1.2 Literature review

The current food system is neither healthy, nor sustainable. It causes one third of worldwide anthropogenic GHG emissions (Crippa et al. 2021) and supports diets that are too low in fruits, vegetables, nuts and legumes and too high in red and processed meat and, hence, is therefore responsible for the greatest mortality burden in many regions (Roth et al. 2018; Willett et al. 2019). Animal products, particularly meat from ruminants, account for the majority of GHG emissions in current food systems and are a major driver of deforestation and biodiversity loss (IPCC 2019).

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Moreover, animal production systems alter the biogeochemical cycle of nitrogen, phosphorus, and carbon, which affects air, soil, and water quality (Sutton et al. 2011). The European livestock sector is responsible for 78% of terrestrial biodiversity loss, 80% of soil acidification, 81% of global warming, and 73% of water pollution (both N and P) (Leip et al. 2015). The livestock industry further contributes to the degradation of freshwater and coastal waters, increasing losses of nitrogen (N) and phosphorus (P). Authors also showed that the livestock sector is responsible for 23%–47% of the nitrogen river load to coastal areas and 17%–26% of the phosphorus river loads in Europe. According to (Westhoek et al. 2014), reducing meat, dairy, and egg consumption in the European Union by half would reduce nitrogen emissions by 40% and greenhouse gas emissions by 25%-40%. Globally, approximately 43 kg of meat and 88 kg of milk are consumed per capita and year. In Europe, these figures are twice as high, with 78 kg of meat and 216 kg of milk consumed per capita per year. As a result, Europeans consume an average of almost 800 kilocalories per day from animal-based foods (FAO 2020) which is well above nutritional recommendations (DGE 2017) and also exceeds an estimated healthy and sustainable amount of 300 kilocalories per day (Willett et al. 2019).

Several studies also focused on supply-side measures such as technological and management advances including anaerobic digestion, nitrification inhibitors, timing of fertilisation, precision farming, and changes in the composition of animal diets to assess economic and environmental mitigation potentials in the agricultural sector (Pérez Domínguez et al. 2016; Fellmann et al. 2020). According to a recent study anaerobic digestion can reduce GHG emissions by 10-13 percent through renewable energy generation, avoided emissions management, crop burning, deforestation, landfill gas, and fertilizer manufacturing emissions (World Biogas Association 2019). Balafoutis et al. 2017 showed that high-tech precision agriculture practices can reduce agricultural inputs through site-specific applications, which can reduce greenhouse gas emissions. Northrup et al. 2021 estimate that by combining digital agriculture, crop genetics, and electrification, greenhouse gas emissions could be reduced by 71%. However, these measures alone will not suffice to keep within planetary boundaries and reduce agricultural GHG emissions to the required level to meet 2°C targets (Springmann et al. 2018; Herrero et al. 2016).

Despite this, since livestock emissions account for most agricultural non-CO_2 emissions (EPA 2012; Tubiello et al. 2013), demand-side solutions may also significantly contribute to GHG savings, and to lessen diet-related diseases, such as diabetes and coronary heart disease (Clark et al. 2020; Creutzig et al. 2016; Bajželj et al. 2013). In particular, the importance of dietary shifts toward smaller shares of animal-based foods is increasingly emphasised in social and political debates (Bonnet et al. 2020; Willett et al. 2019; Spiller et al. 2020; Bryngelsson et al. 2016). Model-based studies indicate that food-related GHG emissions can be reduced by up to 29 % when national dietary guidelines with less calorie intake and smaller shares of animal-based foods are implemented (Springmann et al. 2016; Behrens et al. 2017). Global vegetarian or vegan diets have the potential to reduce food-related GHG emissions by even 60-70 % (Springmann et al. 2016). Considering future income and population growth, dietary change has significant potential to mitigate emissions from the food and agricultural sector (Tilman and Clark 2014; Godfray et al. 2018). Against this background, the EAT-Lancet Commission on Food, Planet and Health derived a healthy and sustainable diet that aims to protect the health of people and the planet. Adopting this diet would require strong adaptations of our current diet. In most regions,

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the consumption of animal-based foods, in particular red meat, would need to be reduced significantly while the consumption of fruits, vegetables, legumes, whole grains and nuts would need to be strongly increased. Estimations of the EAT-Lancet commission indicate that such a dietary change could reduce GHG emissions by up to 80 %, while premature mortality could be decreased by 19 % (Willett et al. 2019).

One possible effective policy to address the mentioned environmental challenges for the agricultural sector is to implement a pricing mechanism for greenhouse gas (GHG) emissions based on the polluter-pays-principle. For example, a carbon tax would establish a price for GHG emissions, requiring emitters to pay for the harm they cause, addressing the market failure behind global warming. However, agriculture has been excluded from such pricing instruments and emission trading schemes (Jansson et al. 2023). A carbon tax for the agricultural sector may also trigger investment and implementation into mitigation technologies with positive environmental effects, e.g. using less mineral fertilizer through precision farming (Perez Dominguez et al. 2020). However, the introduction of a carbon tax in a single country or small region, such as the EU, may lead to carbon leakage. This means that while GHG emissions may be reduced in the region, international competitiveness may be weakened, leading to increased production and emissions in countries not adopting the tax, potentially offsetting the emission reductions, partly or completely (Elliott et al. 2010).

While the implications for environment and health of large dietary changes, have already been explored to a large extent, the consequences for the agricultural sector are less researched. The importance of complementing dietary and environmental analysis with economic models has already been emphasised by Marette and Réquillart (2020). Existing studies have mainly focused on one part of diets, namely reductions in meat consumption, but have not thoroughly addressed the need to largely increase the consumption of fruits, vegetables, nuts and legumes (Cordts et al. 2014; Santini et al. 2017; Jensen and Perez Dominguez 2019; Geibel et al. 2021). A recent study by Rieger et al. (2023) investigated the implementation of the EAT-Lancet diet in the European Union focusing on the economic impacts on the agricultural sector. The study concludes that the agricultural sector could benefit from a dietary shift, though the results are mixed at country, regional and farm levels. In particular, countries and regions that are highly specialised in animal farming are likely to lose income, at least in the short run, while regions with higher shares of vegetable and fruit farms can expect income gains. The economic and environmental effects of mitigation technologies including carbon pricing mechanisms in the agricultural sector have also been investigated by several studies (Fellmann et al. 2021; Himics et al. 2018; Perez Dominguez et al. 2020) . However, the combined analysis of supply-side and demand-side changes is not sufficiently addressed in the literature.

In this deliverable, we add to the literature by combining the effect of dietary changes on the demand-side following EAT Lancet recommendations and the use of mitigation technologies on the supply-side triggered by a carbon tax in order to analyse the overall environmental effects for the agricultural sector.

2. Methodology

The scenarios are analysed with the CAPRI model (Britz and Witzke 2014), combining regional supply models and a global market model. The supply module is based on programming models for each of

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the approximately 280 NUTS2 regions of the EU (or similar administrative units in auxiliary countries). The production decision of a farmer is modelled based on mathematical programming models depicting the supply at the regional level by approximately 50 primary and processed agricultural products including the current ceilings and financial support implemented by the Common Agricultural Policy (CAP) after 2014. This includes the greening measures, premium schemes, entitlements and voluntary coupled support (VCS). Animal products are highly interlinked via the young animal market, the heard flow model and fodder ratios to depict animal production adjustments in the EU and its interlinkage to global markets. The interaction between animal and crop production is established via the feed module. It defines how many kg of certain feed categories or single feedstuffs are used per animal, depending on its prices. It thus accounts for the nutrient requirements of animals. Total feed use might be produced regionally (grass, fodder root crops, silage maize and other fodder from arable land) or bought from the market at fixed prices. These prices, however, change with each iteration with the market module of CAPRI. The supply model uses positive mathematical programming for calibration. Supply not observed or small in the baseline stay zero or relatively small, even if higher price changes occur. The market model is defined by a system of behavioural equations differentiated by commodity and geographical units. Food consumption is derived at the country level based on FAO food balance sheets and Eurostat (Britz and Witzke 2014). Consumer food demand is based on generalized Leontief expenditure functions (Ryan and Wales 1999), and the resulting indirect utility functions depend on prices and changes in income. International trade in the CAPRI market model is implemented following the Armington assumption (Armington 1969). Market equilibria in CAPRI are reached by iterations between the supply and market modules. These two modules iteratively exchange information on prices, supply and feed demand until convergence is reached.

CAPRI endogenously calculates EU agricultural GHG emissions based on the inputs and outputs of production activities in the supply module. The CAPRI model incorporates a detailed nutrient flow model per activity and region (which includes explicit feeding and fertilising activities, i.e. the balancing of nutrient needs and availability) and calculates yields per agricultural activity. With this information GHG emissions are calculated following the IPCC guidelines (IPCC 2014). The activity-based emission factors are calculated using the Tier 2 approach, but where the respective information is missing a Tier 1 approach is applied (e.g. rice cultivation). The quantification of methane emissions from enteric fermentation and manure management follows a Tier 2 approach for cattle activities and a Tier 1 approach for swine, poultry, sheep and goats. Feed digestibility is calculated endogenously on the basis of the feed ration. Nitrogen fluxes (e.g. N_2O emissions) are calculated according to a mass flow approach developed for the MITERRA-EUROPE model using data from the GAINS database.

GHG emissions are a global issue, and restricting the analysis of emissions to just one world region does not give the complete picture of the mitigation effects of specific policies. In particular, the effects of changing trade patterns on global emissions are of relevance, as climate action in one region can give rise to emissions in another region (i.e. can lead to emission leakage). The emission accounting for non-EU regions is done on a product basis, where the estimated emission factors per commodity are multiplied by production to calculate the total emissions for each non-EU region. Within the EU emission accounting is undertaken by utilising detailed emission inventories that are

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computed directly into the supply model in each simulation, which allows for the emission intensities per commodity to change endogenously with changing input use and regional distribution of production (Pérez Domínguez et al. 2016).

Nutrient surpluses and nutrient balances are computed on the NUTS2 level for each group of crops , and, for each of the three nutrients Nitrate (N), Phosphorus (P_2O_5) and Potassium (K_2O). The NPK needs of plants are covered via different fertilisers available from three different sources, namely from purchased mineral fertiliser, animal manure and crop residues. Fertilisers in animal manure produced per-animal-per-head-per-year depend on the type of animal, the raising period in number of days and the kg live weight at the start and the end of the raising period. The nitrogen emission factors from animal activities are coupled with crude protein intake. In CAPRI, each crop has a requirement per hectare, calculated based on the yield. Yields are exogenous from the vantage point of the producer, but there are alternative technologies available for each cropping activity, letting the producer choose between a higher input and higher yield technology and a lower input and lower yield technology. (Britz and Witzke, 2014). (For more detailed information about the computation of nutrient balances and fertilisation in CAPRI, see Jansson et al. (2019)).

In the CAPRI model, a number of already existing or innovative mitigation technologies for the European agricultural sector are available. A detailed description of the modelled technological options can be found in Perez Dominguez et al. (2020). The main assumptions related to implementation costs, cost savings, implementation limits and mitigation potential are mainly taken from the GAINS database. Based on a non-linear mitigation cost function the implementation share of each mitigation technology is determined endogenously for each region as an economic decision by farmers. The scope and degree of adaptation of a mitigation technology in each region is an endogenous variable. This variable is determined by the cost of the technology (annual investment cost and operational costs), the revenue generated by it (e.g. anaerobic digestion), cost savings (e.g. using less mineral fertilizer through precision farming), and other incentives such as subsidies or taxes. Hence, as the agents in the CAPRI regional programming models are assumed to be profit maximisers, farmers will only apply a mitigation option if the marginal profit (according to a gross value-added concept) increases.

In Nutri2cycle, the list of mitigation technologies is extended with new innovative technologies developed in WP2. In this report, we include modelled technologies from WP4 such as “Farm-scale anaerobic digestion of manure to increase local nutrient cycling & improve nutrient use efficiency” and “Sensor technology to assess crop N status” which will be analysed more in detail in deliverable 4.2. In addition, we include already existing technologies in CAPRI such as precision farming, nitrification inhibitors, feed additives and fallowing of histosols (see Perez Dominguez et al. 2020 for more details).

3. Scenarios description

For this deliverable, three scenarios are analysed in comparison to a reference scenario (see Table 1), which reflects the state of the art of the EU agricultural sector in 2030 all the future developments as well as policy changes already foreseen by the current legislation. In the first scenario “Diet_Lancet” demand changes based on EAT-Lancet recommendations are applied in the EU-27 in 2030.

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Table 1: Simulated scenarios

	Ref	Reference scenario
1.	Diet_Lancet	Dietary changes based on EAT-Lancet recommendations are applied in the EU-27 in 2030 with the effect of mitigation technologies.
2.	Tax_tech	100€/t CO_2 eq. tax is applied to agricultural activities in the EU-27 with the effect of mitigation technologies.
3.	Diet_Tax_tech	Dietary changes based on EAT-Lancet recommendations and 100€/t CO_2 eq. tax is applied in the EU-27 with the effect of mitigation technologies.

Source: Own depiction

The EAT-Lancet diet (Willett et al. 2019) is a global reference diet providing the first evidence-based indications for a healthy and environmentally friendly diet. This reference diet allows for an intake of 2,500 kcal per capita per day and is rich in fruits and vegetables while being low in animal-sourced food. The main source of fats and proteins are plant-based foods, and unsaturated oils, while carbohydrates are mainly provided by whole grains. Combined with improved agricultural production practices and a reduction of food waste and loss, the EAT-Lancet Commission estimated that this diet would permit feeding 10 billion people in 2050 within planetary boundaries.

We assume that the adjustment of consumption patterns follows a linear trend which can be extrapolated from the base year in CAPRI to the EAT-Lancet recommendations in 2050. Following the linear trend projection to 2030, we first calculate the differences in product-specific consumption (in kcal per capita) between the reference scenario and the Lancet diet for all EU- 27 countries in the year 2030. If the EAT-Lancet proposition figure in kcal per capita per day is lower than the consumption in the reference scenario, e.g. for beef, then consumer demand will be reduced by the previously calculated changes in calorie intake; and vice versa for food products for which the Lancet diet recommends an increased consumption, e.g. for fruits (see Figure 1). In the CAPRI model, the differences between the reference diet and the Lancet diet in 2030 are implemented as preference shocks in the demand system.

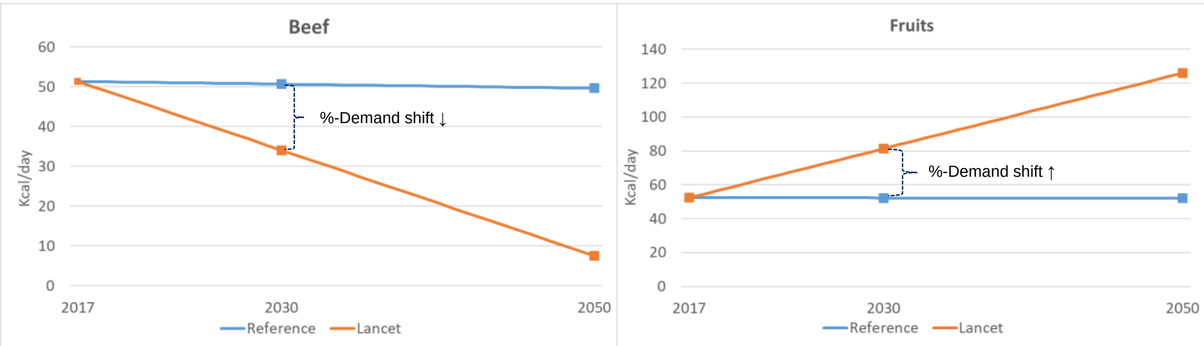

Figure 1: Demand changes towards the recommendations of EAT-Lancet for beef and fruits in the EU-27

Source: Own calculation with CAPRI model

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Table 2 provides an overview of the average consumption (in kcal/day) and consumption changes of different product groups in the EU for the "Diet_Lancet" scenario. The food demand patterns reveal that the demand for red meat (pork, beef) and dairy products as well as sugar show the largest declines due to high levels of consumption for these products in the reference scenario compared to the EAT-Lancet recommendations. For fruits, cereals, pulses, soya, and nuts, the consumer demand in the scenarios show the largest increases.

Table 2: Reference diets and range of absolute and percentage changes for the diet scenario in the EU-27

	Simulation Year	2030	2030	2030	2030
		Reference (kcal/day)	Diet_Lancet (kcal/day)	Diet_Lancet %-Change	Diet_Lancet Abs. Change
EU-27	Poultry	81.0	70.2	-13.4%	-10.9
EU-27	Beef	50.7	34.8	-31.4%	-15.9
EU-27	Lamb	6.4	5.8	-9.4%	-0.6
EU-27	Pork	218.3	156.5	-28.3%	-61.8
EU-27	Eggs	38.8	30.9	-20.3%	-7.9
EU-27	Dairy	394.7	299.8	-24.1%	-94.9
EU-27	Vegetables	80.0	88.3	10.3%	8.3
EU-27	Fruits	52.3	79.1	51.4%	26.9
EU-27	Soya	3.7	17.1	367.0%	13.5
EU-27	Pulses	16.6	75.3	352.9%	58.7
EU-27	Cereals	525.9	656.6	24.9%	130.7
EU-27	Sugar	249.4	211.0	-15.4%	-38.5
EU-27	Vegetable Oils	393.6	368.3	-6.4%	-25.4
EU-27	Palm Oil	43.6	48.7	11.7%	5.1
EU-27	Fish	62.3	49.6	-20.4%	-12.7
EU-27	Nuts	24.0	69.7	190.6%	45.7
EU-27	Total	2311.3	2285.9	-1.1%	-25.4

Source: Own calculation with CAPRI model

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

For the scenario, Tax_tech, a carbon price of 100€/tCO2eq is integrated in order to trigger the implementation of mitigation technologies as the uptake of the mitigation technologies is driven by the model's profit maximization framework. Therefore, farmers will only implement the technologies if their competitiveness is improved by reducing their production costs. This may happen with the introduction of the carbon tax linking the GHG emissions involved in the production of commodities to production costs (Himics et al. 2018). When a carbon tax is in place, the cost of emitting greenhouse gases is factored into the production costs of farmers. This can make adopting mitigation measures

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more economically viable, as the cost savings from reduced emissions can offset the cost of implementing the measures. The carbon price in 2022 of the EU ETS (Emissions Trading System) has been fluctuating between 50 and 100€/tCO2eq. Hence it is reasonable to assume that the average carbon price in 2030 in the EU ETS will be around the upper limit of the 2022 carbon price. In CAPRI the carbon price is applied to the CO_2 equivalents of all emissions from agriculture, assuming that farmers have carbon permits corresponding to their emissions observed in the reference scenario. The simulated tax is applied to the difference between their actual emission levels and permits. Therefore, the tax becomes a subsidy if the regional emissions decrease. For the scenario Diet_Tax_tech, the changes in dietary patterns based on the EAT-Lancet recommendations are combined with the implementation of a carbon price in the EU-27 in order to analyse the combined effect of supply-side mitigation technologies and demand-side changes.

In all scenarios the available mitigation technologies consist of already existing technologies in CAPRI ("Ecampa") and new technologies from the Nutri2cycle project which can be explicitly modelled with CAPRI ("Nutri2cycle") (see Table 3). Further description of the technologies and how they are implemented in CAPRI is provided in deliverable 4.2 of the Nutri2cycle project. Considering also the already existing technologies in CAPRI ("Ecampa") in all scenarios provides a more realistice picture about the relevance of mitigation technologies in 2030 for the different scenarios as the uptake of the technologies is driven endogeneously by the model's profit maximization framework.

Table 3: Considered technologies for all scenarios

Ecampa	Nutri2cycle
Low nitrogen feed Linseed as feed additive Nitrate as feed additive Antimethagon vaccination Better timing of fertilization Nitrification inhibitors Precision farming Increasing legume share on temporary grassland Rice measures Fallowing histosols Low emission housing Manure storage with basin in concrete Storage cover Low ammonia application Buffer Strips Winter cover crops No tillage Conservation tillage	Farm-scale anaerobic digestion of agro residues/pig manure to increase local nutrient cycling & improve nutrient use efficiency (**"Pocket anaerobic digestion")** Adapted stable construction for separated collection of solid manure and urine in pig housing **("Adapted stable construction"**) Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain **("NIRS sensor for manure"**) Sensor technology to assess crop N status ("**Yara N-Sensor"**)

Source: Own depiction

The expected impact of all scenarios on producer prices and produced quantity exemplified for animal products based on economic theory is depicted in Figure 2.

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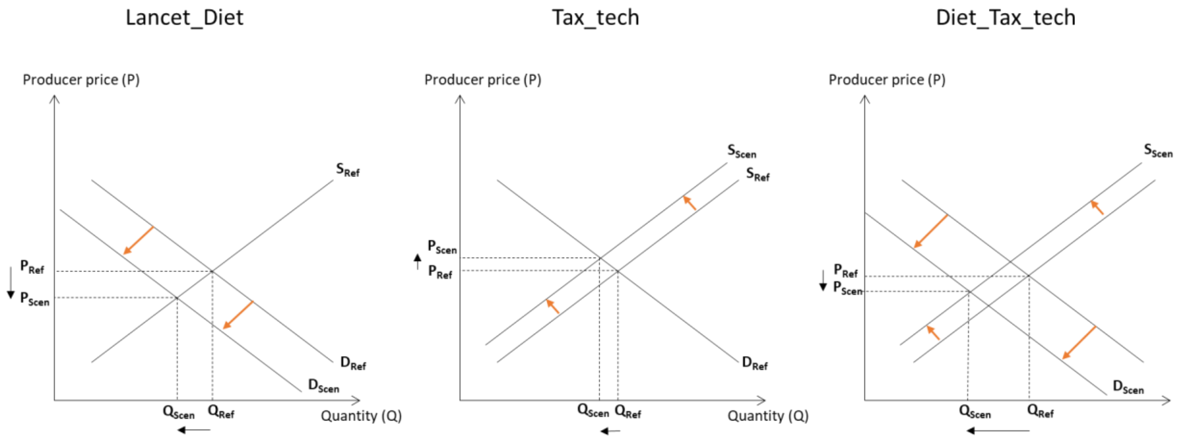

Figure 2: Theoretical assumptions about the impacts on supply (S), demand (D), producer prices (P) and production of animal products (Q) of the scenarios (Scen) compared to the reference (Ref)

Source: Own depiction

In the Lancet_Diet scenario, the demand in animal products (D_{Scen}) decreases (see Table 2) compared to the reference (D_{Ref}) resulting in lower producer prices (P_{Scen}) and reduced production of animal products (Q_{Scen}). For the scenario Tax_tech the production costs for farmers increases as the carbon tax links the marginal cost of production of agricultural activities to the emissions, resulting in a reduction of supply (S_{Ref}) and consequently higher producer prices (P_{Scen}) and less production of animal products. However the effect of the carbon tax is lowered by the triggered adoption of mitigation technologies, improving the emission efficiency and therefore reduce marginal costs in the presence of a carbon tax. Here we expect comparably lower production reductions compared to the Diet_Lancet scenario. In the combined scenario, Diet_Tax_tech induced supply reductions by the carbon tax and the reduced demand in the Diet_Lancet scenario is expected to be additive. Therefore, we expect the producer price (P_{Scen}) to decrease but to a lower extent than in the Diet_Lancet scenario. Similar to the assumed producer price effects, the production changes are assumed to be achieved by an accumulation of the supply effects from the other scenarios resulting in the highest decline in production for animal products.

4. Results

The dietary changes described above are implemented as preference shocks of the demand system in the CAPRI market module. The carbon tax, including the adoption of mitigation technologies, has been integrated into the supply module of CAPRI. In the following section of this report the effects of all scenarios on producer prices, agricultural production, as well as import and exports, are discussed first to provide a better understanding of the resulting environmental effects.

4.1 Producer prices, production and trade

Impacts on producer prices are directly related to the magnitude of simulated consumer demand changes for respective products in the Diet_Lancet scenario. The producer prices in this scenario for red meat products and milk show the highest declines in the EU-27 resulting from the comparably high level of simulated demand reductions of European consumers (see Figure 3). The average

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producer price in the EU-27 for beef in Diet_Lancet declines by 22% in 2030 and for pork and milk by 12% and 27% respectively. For other animal products such as poultry or lamb meat, the producer prices are less affected as the consumption levels in the reference scenarios are closer to the EAT-Lancet recommendations. For the product category 'vegetables, fruits and legumes (pulses, soya)' the producer prices in the EU-27 increase strongly as the daily kcal intake in most EU countries is much lower compared to the EAT-Lancet diet. On average, the producer price in the EU-27 for fruits and vegetables increases by 27.6%. In the Diet_Lancet scenario the implementation share of modelled mitigation technologies stays within the levels of the reference scenario for 2030 as there are no financial and policy incentives to trigger an increase in the uptake of technologies as in most cases adoption is not profitable for the farmers.

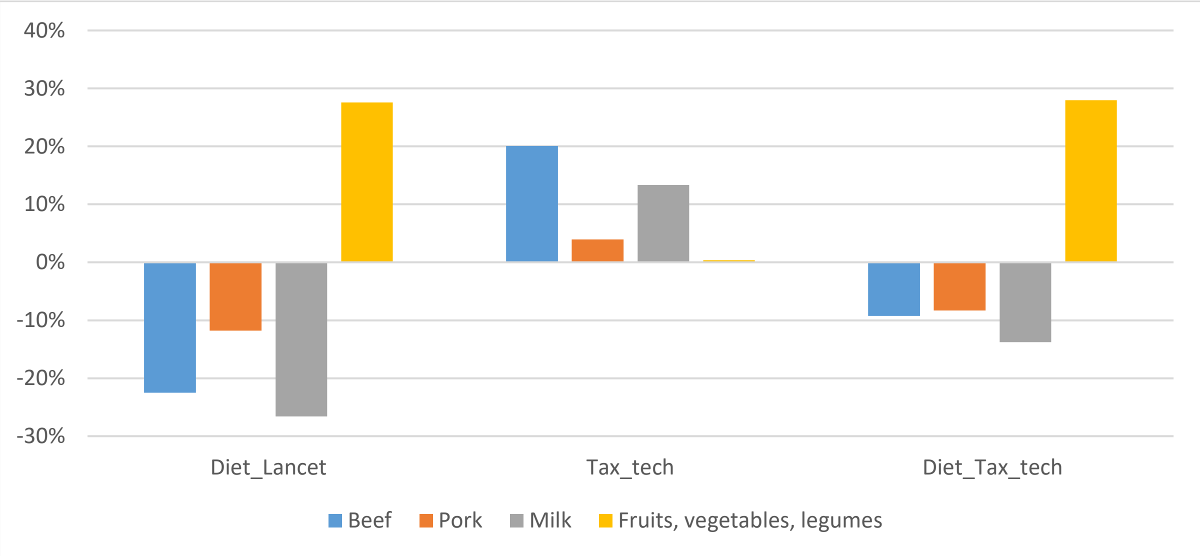

Figure 3: Percentage changes in producer prices for the scenarios compared to the reference for selected products in the EU-27

Source: Own computations with CAPRI

In the Tax_tech scenario the carbon tax of 100€/tCO_2eq. links the marginal cost of production of agricultural activities to the emissions, resulting in higher producer prices for all food categories due to the higher costs for farmers. However, the effect of the carbon tax is lowered by the triggered adoption of mitigation technologies, improving the emission efficiency and therefore reducing marginal costs in the presence of a carbon tax. Mitigation technologies such as precision farming or the Yara-N-Sensor can improve the nitrogen use efficiency, generating cost savings in mineral fertiliser use. Producer prices increases are highest for beef (20%) and milk (13%) to their high emissions intensities, as they are the main contributor to methane emissions from agriculture. The impact of the Tax_tech scenario on producer prices for pork and the product category fruits, vegetables, and legumes is more modest, since the emission intensities of these products are considerably lower compared to beef production.

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In the combined scenario Diet_Tax_tech, the effects on producer price ranges between the two previously discussed scenarios, resulting in reduced producer prices for animal products and higher prices for fruits, vegetables and legumes. This consequential effect from the Diet_Lancet and Tax_tech scenarios is plausible, as, the effect on producer prices from the demand changes based on the EAT-Lancet recommendations are reduced by higher production costs for farmers resulting from the impact of the carbon tax being alleviated by cost savings related to the implementation of mitigation technologies in the EU-27. In this combined scenario, producer prices for beef and milk decline by 9.3% and 13.8% respectively. The increase in producer prices for vegetables, fruits and legumes (28%) is mainly triggered by the increased demand in the Diet_Lancet scenario, as the carbon tax affects the crop sector less due to low emissions intensities compared to the livestock sector.

The production changes in the EU-27 that result from the different scenarios are shown in Figure 4. For the Diet_Lancet scenario, it can be observed that, in principle, the changes in production are smaller than those in demand (see Table 2) due to international trade effects. The Diet_Lancet scenario increases the utilized agricultural area (UAA) by 0.69 million ha in the EU-27 mainly due to more arable land for production of fruits, vegetables and legumes. In 2030 the largest production decreases in the EU-27 are projected for animal products such as beef (-9.5%), milk (-10%) and pork (- 9.2%). Accordingly, the production of feed is also declining by 4% in the EU-27. For fruits, vegetables, and legumes the production in the EU-27 is expanded by 7.5%, driven by higher producer prices in the Diet_Lancet scenario.

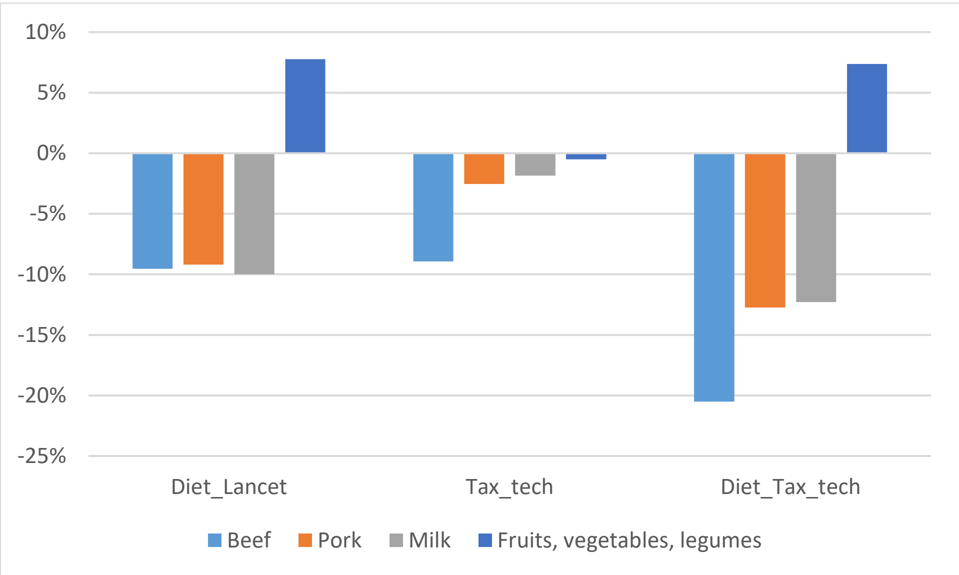

Figure 4: Percentage changes in production for the scenarios compared to the reference for selected products in the EU-27

Source: Own computations with CAPRI

In the Tax_tech scenario the UAA in Europe decreases by 1.4 million ha and set aside and fallow land increases by about 14% (1.3 million ha). The reductions in UAA are mainly triggered by arable land taken out of production since pasture land cannot be converted due to CAP obligations for biodiversity

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conservation. As a consequence, under Tax_tech scenario, grassland extensification is observed which is also the case for the other scenarios. Following the reduction of overall UAA the production of cereals and oilseeds reduces by 3.3% and 2.8% respectively. The highest reduction in the Tax_tech scenario is observed for beef production by 8.9% as the main contributor of methane emissions from agriculture. The production declines for pork (-2.6%) and poultry (-0.4%) are modest since the impacts on European GHG emissions are minor as the emission intensity of pork and poultry is relatively low compared to beef production activities. Accompanied by the reduced number of animals in the European agricultural sector, feed production declines by 10.2%.

Similar to the observed producer price effects in Figure 3, the production changes in the Diet_Tax_tech scenario are achieved by an accumulation of the supply effects observed in Diet_Lancet and Tax_tech scenarios. Accordingly, the impacts on pork and the product category fruits, vegetables and legumes are more driven by the changes in consumer demand (Diet_Lancet), due to their lower emissions intensities compared to beef production. The highest production decreases in 2030 are observed for animal products such as beef (-21%) followed by pork (-13%) and milk (-12%) as well as fodder production (-17%). Also, in the Diet_Tax_tech scenario the combined production increases from Diet_Lancet and the small decreases in the Tax_tech scenario for vegetables, fruits and legumes add up resulting in 7.4% higher production.

Figure 5 examines the balance of land use changes in the EU-27 across the different scenarios. It is evident that in the Diet_Lancet scenario, the land devoted to arable crops (excluding fodder or fallow) notably rises by 2.7 million hectares, primarily driven by heightened demand for pulses and soy. Consequently, due to decreased demand for animal products and lower producer prices, the arable cropland utilized for fodder or fallow diminishes by 1.5 million hectares.

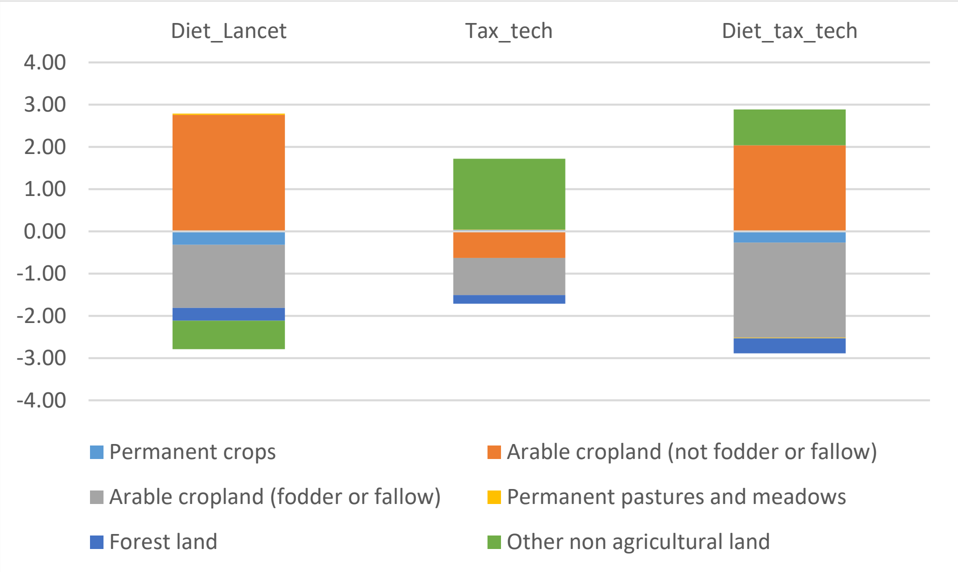

Figure 5: Absolute land use changes in 1000ha in the EU-27 for the scenarios compared to the reference

Source: Own computations with CAPRI

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In the Tax_tech scenario, there is an expansion of non-agricultural land and a reduction in land dedicated to agricultural production, stemming from increased costs for farmers due to the carbon tax. The combined scenario (Diet_Tax_tech) shows a cumulative effect from both Diet_Lancet and Tax_tech scenarios, resulting in a 2 million hectare increase in arable cropland (excluding fodder or fallow) and a reduction in land used for fodder or fallow by 2.3 million hectares.

Particularly for the modelled dietary changes based on the EAT-Lancet recommendations (Diet_Lancet) the magnitude of demand changes in the EU member states on agricultural production is dampened by international trade as the respective producers of these products in non-EU countries are also affected by the dietary changes in the EU (see Table 4). In non-EU countries, the demand changes in the EU based on the EAT-Lancet recommendations and the corresponding price changes for the European agricultural sector result in lower producer and consumer prices for animal products and higher prices for vegetables, fruits and legumes. These price effects induce the adoption of supply and demand in non-EU countries, resulting in lower supply and higher demand for animal products and vice versa for vegetables, fruits and legumes. The increased demand for goods like fruits and vegetables in the EU-27 is, hence, to some extent, satisfied by increased imports from non-EU countries where producer prices increase; while products for which domestic demand is decreasing, like meat, are increasingly exported to non-EU countries facing lower producer prices and higher demand (see Table 4). In the Diet_Lancet scenario imports of beef to the EU-27 would decrease by around 0.18 million tonnes (71%) and the exports increase by 0.56 million tonnes (126%). The changes in trade flows are particularly large for fruits, vegetables and legumes where imports more than double (203%) and exports decline by 26% as a result of the increases demand from European consumers.

Table 4: Percentage and absolute changes (1000 tons) in trade for the EU-27 with Non-EU countries compared to the reference 2030

	Imports						Exports					
Products	Diet_Lancet		Tax_tech		Diet_Tax_tech		Diet_Lancet		Tax_tech		Diet_Tax_tech	
	%-Δ	Abs. Δ	%-Δ	Abs. Δ	%-Δ	Abs. Δ	%-Δ	Abs. Δ	%-Δ	Abs. Δ	%-Δ	Abs. Δ
Beef	-71	-178	24	62	-47	-118	126	565	-49	-218	39	174
Pork	-61	-12	19	4	-53	-11	58	2371	-15	-602	38	1561
Dairy	-55	-207	13	50	-52	-196	34	1936	-5	-270	28	1552
Fruits, vegetables, legumes	203	86948	-1	-274	202	86227	-26	-4965	0	-5	-26	-4978

Source: Own computations with CAPRI

In the Tax_tech scenario the reduction in European supply for all considered products due to the carbon tax is partially substituted by increased imports from the rest of the world, as many non-EU countries increase their agricultural production to compensate for supply changes in the EU-27 leading to a negative net trade position for the EU, particularly for beef. Accordingly exports for animal products in this scenario decline due to the higher production costs of European farmers and less competitiveness in the world market, resulting in higher production of animal products in Non-EU countries which are more cost-efficient in this scenario due to the European exclusive carbon tax.

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In the combined scenario (Diet_tax_tech) the impacts on trade for the EU-27 are an accumulation of the trade effects from the previous scenarios which is consistent with changes in producer prices and agricultural production previously discussed. In this scenario, dietary changes, implementation of the carbon tax, along with increased adoption of mitigation technologies decrease the imports for animal products and rise for vegetables, fruits and legumes. For the latter product category, the changes in imports and exports are dominated by the Diet_Lancet scenario due to their comparably low emission intensities and hence, the minor impact of the carbon tax (Tax_tech).

4.2 Environmental effects

The mitigated GHG emissions in the EU-27 agricultural sector as a result of simulated scenarios are presented in Table 5. The implementation of the EAT-Lancet dietary recommendations decreases the total agricultural emissions in the EU-27 by 24.5 MtCO_2eq (-6.3%) mainly triggered by the production decreases for animal products (see Figure 4). The EU-wide 100€/t CO_2eq carbon tax with the consideration of the impact of mitigation technologies (Tax_tech) reduces the emissions in the EU by about 89 Mt CO_2eq. (-22.8 %) compared to the reference scenario. A combination of both scenarios results in the highest emission reductions by -109 Mt CO_2eq, which is equivalent to an approximate 28% reduction in emissions within the EU when compared to the reference.

Table 5: Mitigated emissions from the EU agricultural sector under the simulated scenarios

	Diet_Lancet		Tax_tech		Diet_Tax_tech	
	Abs. change (Mt CO_2 eq.)	%-change	Abs. change (Mt CO_2 eq.)	%-change	Abs. change (Mt CO_2 eq.)	%-change
Total	-24.5	-6.3%	-89.3	-22.8%	-109.2	-27.9%
N_2O	-9.7	-5.3%	-46.0	-25.2%	-53.3	-29.1%
CH_4	-14.8	-7.3%	-42.7	-21.1%	-55.3	-27.4%
CO_2	-0.1	-1.0%	-0.7	-9.1%	-0.7	-9.2%

[1]Includes CO2 emission related to liming and urease application

Source: Own computations with CAPRI

In the Diet_Lancet, Nitrous oxide (N_2O) and Methane (CH_4) emissions decrease mainly due to reduced production of animal products due to lower producer prices arising from reductions in meat consumption (see Table 5). For the Tax_tech scenario, CH_4 emissions decrease mainly due to lower production of beef and milk due to the comparably high impact of the carbon tax, as well as the increased uptake of mitigation technologies triggered by the tax. The reductions in N_2O emissions are much higher compared to the Diet_Lancet scenario due to the effect of mitigation technologies in place which are specifically targeting N_2O emissions. For the Diet_Tax_tech scenario, all considered emission types decrease as a result of the cumulative effects of the carbon tax, mitigation technologies and dietary changes based on the recommendation of EAT-Lancet.

In Figure 6, the changes in GHG emissions across regions of the European Union are depicted to account for regional differences resulting from the scenarios. In line with the previously discussed findings in the EU-27, a clear trend is visible, in that, reductions in GHG emissions increase from

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scenario Diet_Lancet to Diet_Tax_tech. In all scenarios the regions with a high share of animal production activities show the highest emission reductions. The emissions decrease in all member states for all scenarios, with the largest mitigation observed in France, Germany, Ireland, Poland and Spain, which is not surprising considering their livestock production levels particularly for beef within these listed countries. In the Diet_Lancet scenario the impact on GHG emissions is dominated by production changes whereas for the other scenarios the higher implementation of mitigation technologies triggered by the carbon tax further reduces emissions from the European agricultural sector.

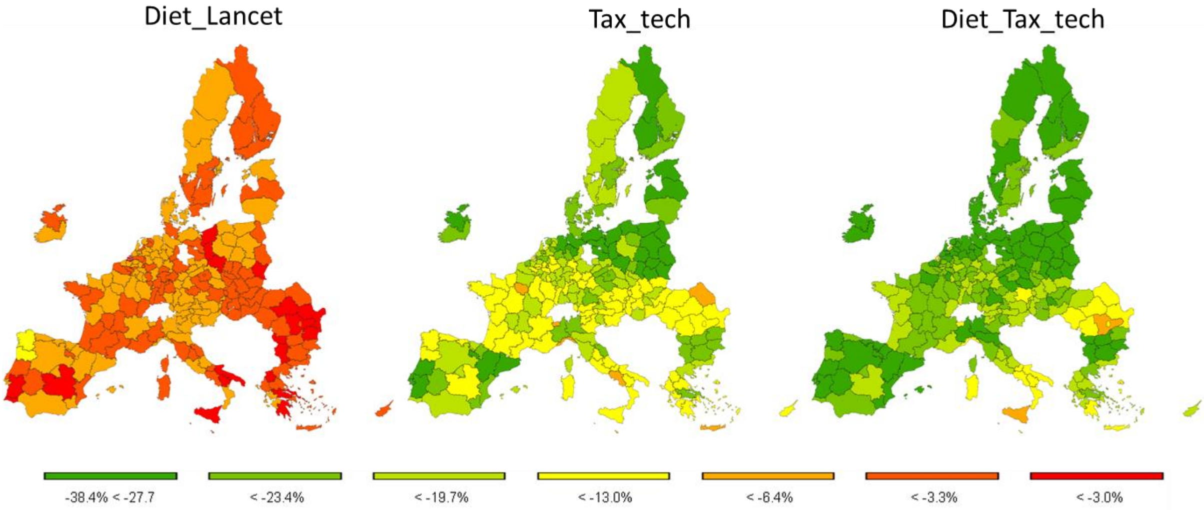

Figure 6: Relative changes of GHG emissions from agriculture at NUTS 2 level compared to the reference scenario

Source: Own computations with CAPRI

To further investigate the role of mitigation technologies, Figure 7 shows the overall contribution of modelled technologies already existing in CAPRI ("Technologies_ecampa") and the added technologies in Nutri2cycle ("Technologies_Nutri2cycle") to the total EU-27 emission reductions for the different scenarios. In the Diet_Lancet scenario around 84% of mitigated emissions are due to production effects resulting from the dietary changes based on EAT-Lancet recommendations. The total share of mitigated emissions by technologies is only 16% as there are no financial and policy incentives to trigger an increase in the uptake of technologies as in most cases adoption is not profitable for the farmers. For the Tax_tech scenario the provided carbon tax clearly triggers the adoption of mitigation technologies throughout the EU-27, contributing to 56% of the total GHG mitigation whith a considerably impact of mitigation technologies developed in Nutri2cycle (21%). In the combined scenario (Diet_Tax_tech) the contribution of mitigation technologies slightly decreases due to the relatively high impact of production changes in the Diet_Lancet scenario (see Figure 4). In addition, livestock numbers are lower due to the modelled demand changes which reduce the implementation share of animal related mitigation technologies, including improved fertiliser technologies focused on manure application.

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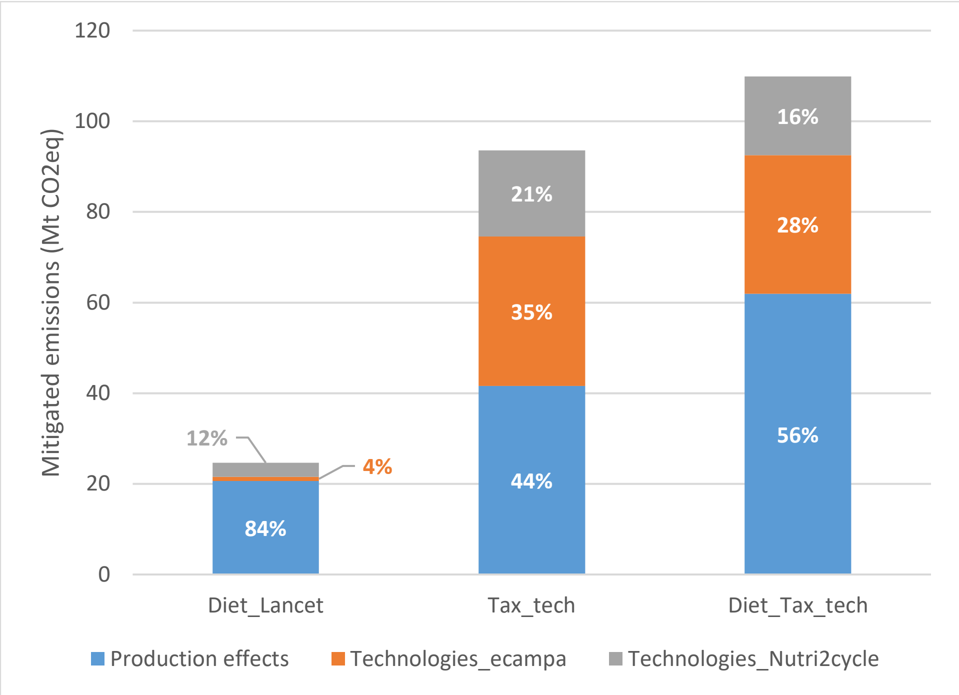

Figure 7: Contribution of mitigation technologies already exisiting in CAPRI ("Technologies_ecampa") and new technologies from Nutri2cycle ("Technologies_Nutri2cycle") to total mitigation in EU-27 for the scenarios

Source: Own computations with CAPRI

As indicated in Table 5 the emission reductions in the Diet_Lancet scenario are dominated by reductions in methane (CH_4) emissions due to the comparably high decline in beef and dairy related production activities induced via the consumer demand changes. For the Tax_tech and the Diet_Tax_tech scenarios the mitigated emissions in the EU-27 are also mainly due to reductions in CH_4 emissions as on the one hand the carbon tax reduces the production of animal related activities, particularly beef, and on the other hand the comparably high implementation share of "Farm-scale anaerobic digestion of manure to increase local nutrient cycling & improve nutrient use efficiency" ("Pocket anaerobic digestion") further increases CH_4 savings related to manure management. The higher share of saved emissions via production effects compared to the Diet_Lancet scenario is mainly caused by the high reduction in UAA by 1.4 million ha in the EU-27. In Figure 8 it can be seen that "Pocket anaerobic digestion" from the Nutri2cycle project is the most uptaken mitigation option in all scenarios, due to their high mitigation cost efficiency considering that it generates additional cost savings by producing renewable energy, and therefore has the highest mitigation impact. In the Tax_tech and the Diet_Tax_tech scenario it contributes to 17.9 million tonnes (20% compared to the total reduction) and 16,2 million tonnes of mitigated GHG emissions (15% compared to the total reduction) in the EU-27 respectively. The Tax_tech results align with (Stepanyan et al. 2023), who simulated a similar €100/t CO_2 carbon tax for the EU using the CAPRI model and established mitigation technologies (ECAMPA technologies) based on Perez Dominguez et al. (2020). Their study also identified farm-scale anaerobic digestion as the most widely adopted mitigation measure, contributing to a substantial reduction of 15 million tonnes of CO_2eq emissions. The high uptake of

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anaerobic digestors is due to their high mitigation cost efficiency considering that it generates additional revenues by producing renewable energy. In our study, the emission reduction attributed to 'pocket anaerobic digestion' is higher (17.9 million tonnes CO2eq) because we assume that this technology is economically viable even for smaller farms, a contrast to the farm-scale anaerobic digestion proposed by Perez Dominguez et al. (2020). In addition, the reduced N_2O emission from mineral fertiliser application plays an important role which are triggered the reduction in UAA and the higher nitrogen use efficiency via precision farming, nitrification inhibitors and the YARA N-sensor technology to assess crop N status.

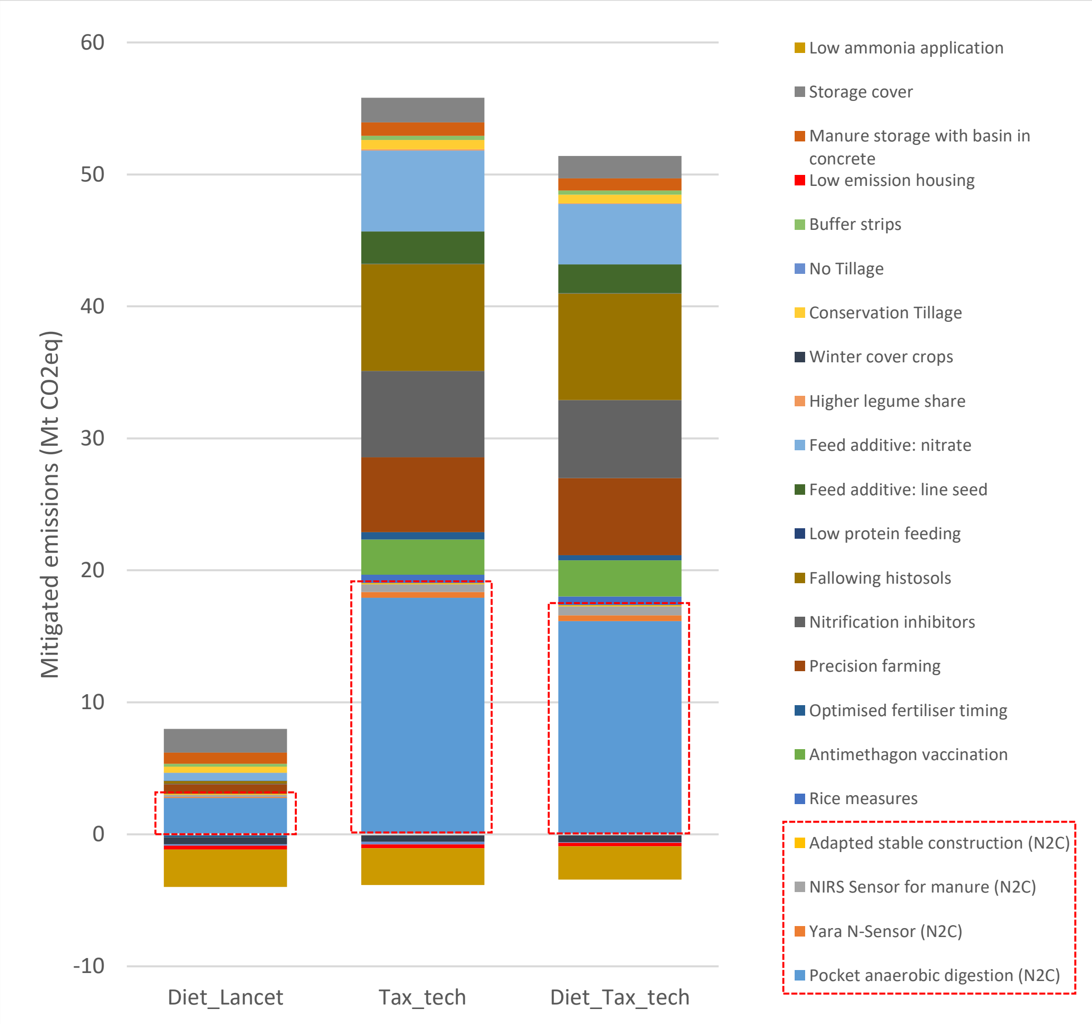

Figure 8: Contribution of each technological mitigation option in the EU-27 for all scenarios

Source: Own computations with CAPRI

By solely examining the technological mitigation options of Nutri2cycle (see Figure 9), the significant impact of "pocket anaerobic digestion" is even more evident. The relatively low impact of other Nutri2cycle technologies in terms of reducing greenhouse gas emissions is primarily attributed to their

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comparatively lower implementation rates resulting from endogeneous modelling approach. This can be attributed to the higher cost efficiency of other technologies like precision farming and the utilization of nitrification inhibitors.

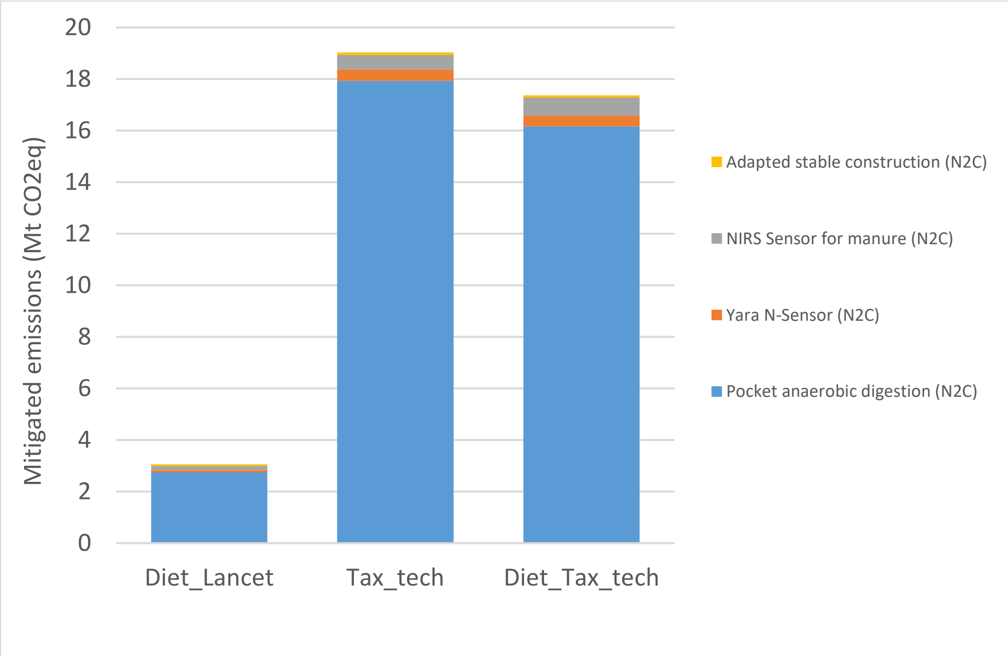

Figure 9: Contribution of each technological mitigation option from Nutri2cycle in the EU-27 for all scenarios

Source: Own computations with CAPRI

For all scenarios, mineral fertiliser use is reduced in most European regions (see Figure 10), resulting in lower Nitrogen surplus (N-Surplus) (see Figure 11). In the Diet_Lancet scenario, the nutrient balances are minimally affected, as the changes due to production are smaller than those in demand due to international trade effects (see Table 4). In this scenario the total use of mineral fertiliser in the EU-27 decreases by 3% (0.3 million tonnes of N) as well as the use of manure by 8% (0.6 million tonnes of N) due to the reduced UAA and the lower animal production activities. Biological fixation increases by 8% due to the higher production of legumes based on EAT-Lancet recommendations and the total N-Surplus in the EU-27 is reduced by 7% (0.7 million tonnes of N).

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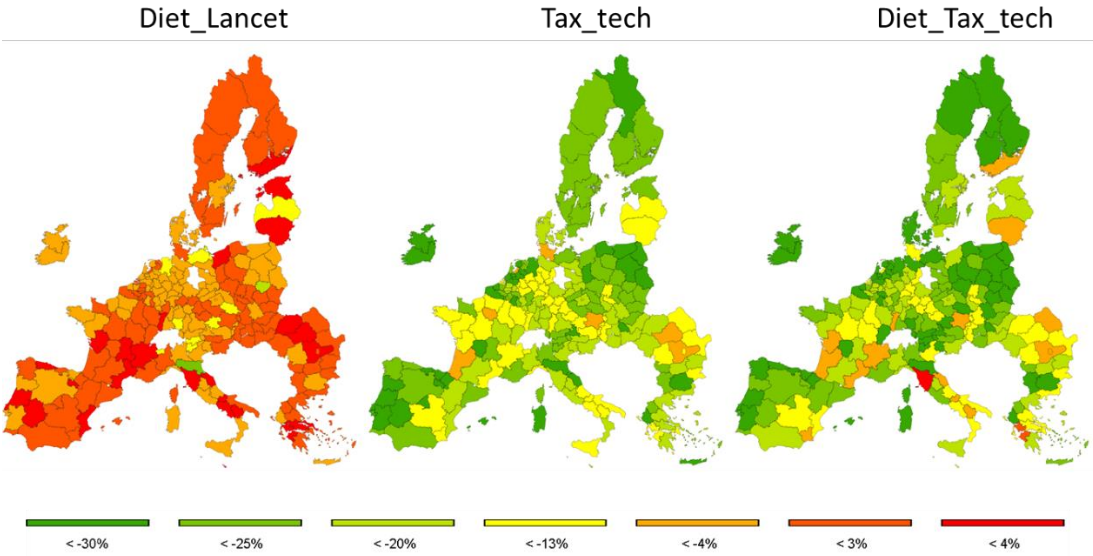

Figure 10: Relative changes in mineral fertilizer use compared to the reference scenario

Source: Own computations with CAPRI

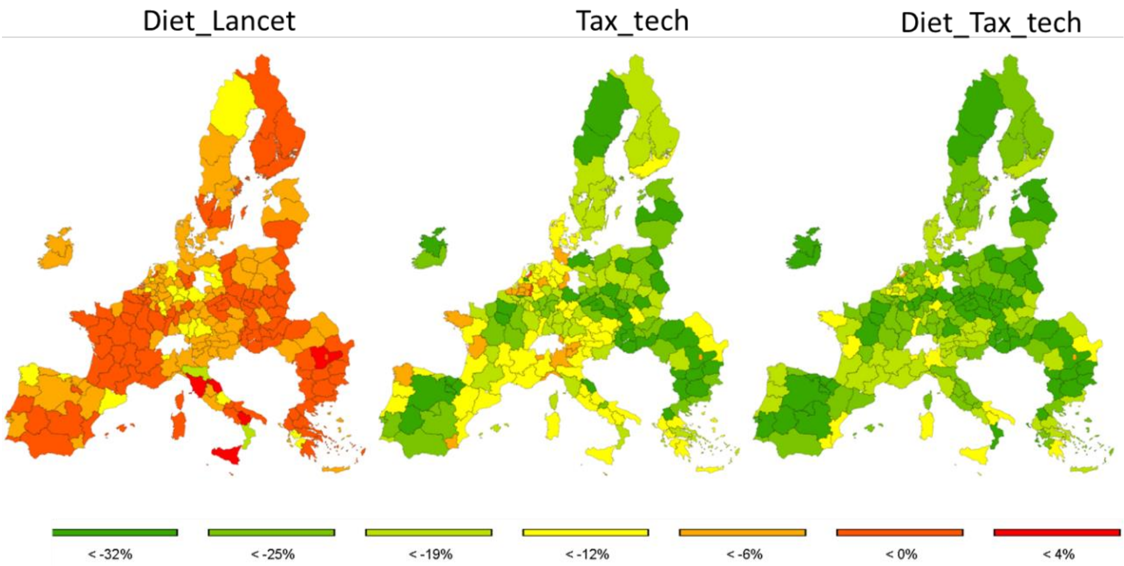

Figure 11: Relative changes in N-Surplus compared to the reference scenario

Source: Own computations with CAPRI

In the Tax_tech scenario the effects on nutrient balances in the EU-27 are considerably higher mainly due to higher nutrient use efficiency via the mitigation technologies triggered by the carbon tax. Here the total input with mineral fertiliser is reduced by around 23% (2.3 million tons of N) and the N-Surplus by 22% (-2.5 million tons of N). Compared to the Diet_Lancet scenario, biological fixation is reduced by 14% as the UAA declines and no demand shift increases the production of legumes. The

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combined scenario is an accumulation of environmental effects from the two previous scenarios which are in line with previous findings in this report. Accordingly, the total input of mineral fertiliser in the EU-27 would be reduced by 25% (2.5 million tonnes of N) and the N-surplus would decrease by 28% (3.3 million tons of N).

Overall, the combination of consumers dietary changes with mitigation technologies, triggered by the carbon tax, show the most promising positive environmental impacts related to GHG emissions, mineral fertiliser use and nitrogen surplus within the European agricultural sector. However, as shown in Table 4 all scenarios also induce changes in trade as well as agricultural production in non-EU countries as it is of major importance to assess net emission changes globally. To account for potential carbon leakage effects we analysed the impact of all scenarios on GHG emissions from the agricultural sector of the EU, non-EU countries and on a global level (see Figure *12*).

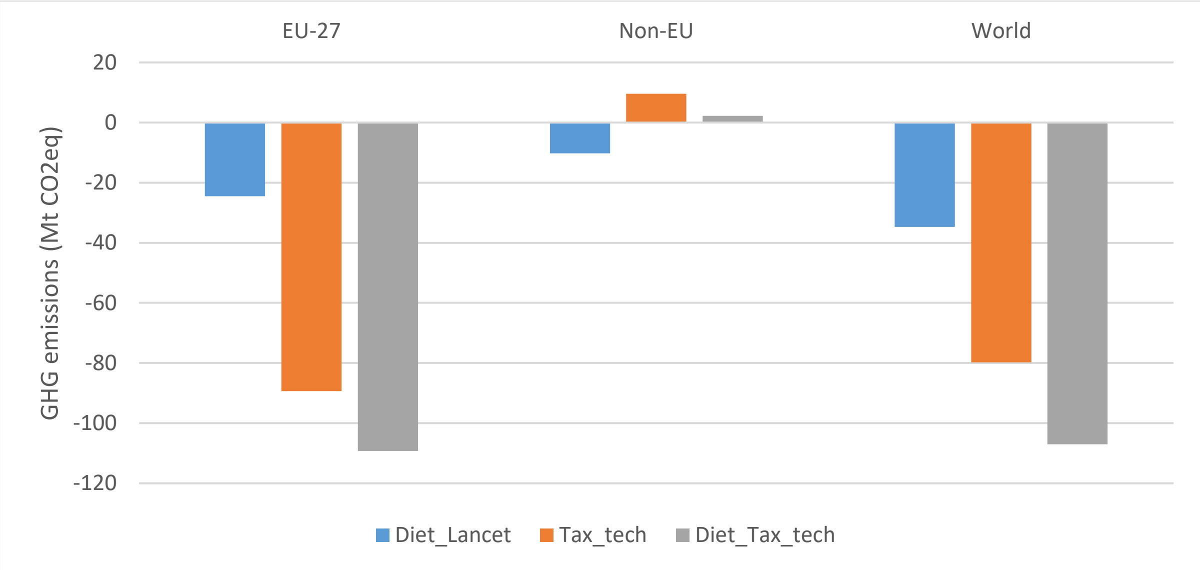

Figure 12: Absolute changes in total greenhouse gas emissions from agricultural sector for the scenarios in the EU-27, Non-EU countries and on a global level compared to the reference scenarios

Source: Own computations with CAPRI

In the Diet_Lancet scenario as already shown in Table 5 the GHG emissions of the European agricultural sector decline by 24.5 million tonnes of CO_2 equivalents (6.3%), mainly due to a reduction in animal based production activities resulting from the comparably high level of simulated demand reductions of European consumers. Interestingly, reductions in GHG emissions occur also in non-EU countries (10.1 million tonnes CO_2 equivalents; 0.2%) due to a replacement of non-EU production with higher emission intensities (more GHG emissions per kg produced) by European exports. The European emission reductions resulting from the Diet_Lancet scenario are in a sense exported, resulting in a further decrease of GHG emission in non-EU countries and positive emission leakage. In non-EU countries, the demand changes in the EU based on the EAT-Lancet recommendations and the corresponding price changes for the European agricultural sector result in lower producer and consumer prices for animal products and higher prices for vegetables and fruits. These price effects

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induce supply and demand adjustments in non-EU countries, resulting in lower supply and higher demand for animal products and vice versa for vegetables and fruits. On a global level, the further emission reduction in non-EU countries results in 34.7 million tonnes CO_2 equivalents (0.6%) less emissions from the agricultural sector.

In the Tax_tech scenario GHG emission reductions in the EU-27 are higher (89.3 million tonnes CO_2 equivalents) compared to the Lancet_Diet scenario, mainly as a consequence of lower production of beef and milk and the uptake of mitigation technologies which account for 56% of reduced emissions triggered by the carbon tax. Figure ***12*** shows that emission leakage indeed happens in the Tax_tech scenario as production is shifted to more cost-efficient non-EU regions which are assumed to be less efficient from a GHG emission perspective. Many non-EU countries increase their agricultural production particularly for beef to compensate for supply changes in the EU-27, resulting in increasing GHG emissions in the Tax_tech scenario by 9.6 million tonnes CO_2 equivalents (0.2%). The biggest increase in emissions is shown for Asia and Central and South America, which is related to beef production activities. Consequently, the EU mitigation effort under the Tax_tech scenario is partially offset resulting in a global reduction of GHG emission by 79.7 million tonnes CO_2 equivalents (1.4%) with a leakage rate of 11%.

The highest reductions in GHG emissions can be observed in the Diet_Tax_tech scenario due to the cumulative effects of the both previous scenarios. In this scenario a comparatively small reallocation effect on domestic agricultural supply from the EU-27 to more competitive non-EU producers, i.e. the substitution of own domestic production with imports, can be observed (see Table 4). Hence, the increase in emissions related to the agricultural sector in non-EU countries of 2.2 million tonnes CO_2 equivalents (0.04%) is minor when compared to the Tax_tech scenario. Compared to the other scenarios the reduced emissions by the EU-27 are highest (109.2 million tonnes CO_2 equivalents; 27.9%) where technology related mitigated emissions account for 44%. Here the leakage rate is only 2%, resulting in globally reduced emissions by 107 million tonnes CO_2 equivalents which is equivalent to a reduction of global agricultural GHG emissions by 1.9%.

5. Conclusion

More plant-based diets, as well as improvements in mitigation technologies, are important drivers towards a more ecologically sustainable planet. In this deliverable we specify three different scenarios to investigate the effects of changed diets based on i) EAT-Lancet recommendations (Diet_Lancet), ii) the implementation of a carbon tax to trigger adoption of mitigation technologies (Tax_tech), and, iii) the combination of the previous scenarios (Diet_Tax_tech), in order to analyse the overall effect on the environment as well as agricultural production and trade in 2030 using the well-established CAPRI model.

The results indicate that with dietary changes in the Diet_Lancet scenario, production and prices of animal-based products decrease, while production and prices for fruits, vegetables and legumes are increasing. The implementation of available mitigation technologies remains at the same level as the reference scenario for 2030 as there are no financial or policy incentives to encourage farmers to increase their adoption of these technologies. In most cases, the adoption of such technologies is not financially profitable for farmers. However, international trade buffers the impact on agricultural

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markets, by increasing imports of fruits, vegetables and legumes as well as exports of meat and dairy products. Dietary changes are also accompanied by reductions in agricultural GHG emissions as well as Nitrogen surplus. Globally the modelled dietary changes in the EU-27 result in positive leakage effects due to a replacement of non-EU production with higher emission intensities (more GHG emissions per kg produced) by European exports. In non-EU countries supply of animal products decreases and rises for vegetables, fruits and legumes due to higher import demands of the EU-27 resulting in a reduction of GHG emissions in those countries. This further increases the mitigated emissions in the EU-27 (24.5 34.7 million tonnes CO_2 equivalents) leading to 34.7 million tonnes CO_2 equivalents (0.6%) less emission from the agricultural sector on the global level.

The introduction of a carbon tax in the EU-27 triggered the implementation of mitigation technologies in the Tax_tech scenario. The reductions in GHG emissions, mineral fertiliser use and N-Surplus in the EU-27 are considerably higher than in the Diet_Lancet scenario. This is mainly due to the comparably high reduction in utilised agricultural area (UAA) via the carbon tax, the CH_4 reductions through reduced beef production and the higher implementation share of mitigation technologies particularly "Farm-scale anaerobic digestion of manure to increase local nutrient cycling & improve nutrient use efficiency". In this scenario the overall uptake of mitigation technologies accounts for 56% and the technologies developed in Nutri2cycle account for 21% of reduced emissions in the EU-27. However, in this scenario negative emission leakage is observed, as production shifts to more cost-efficient non-EU regions, particularly for beef, which is assumed to be less efficient from a GHG emission perspective. Consequently, the EU mitigation efforts (89.3 million tonnes CO_2 equivalents) are partially offset resulting in a global reduction of GHG emission by 79.7 million tonnes CO_2 equivalents (1.4%) with a leakage rate of 11%.

The most positive environmental effects are observed in combined the scenario Diet_Tax_tech. In this scenario all considered emission types, mineral fertiliser use and N-Surplus show the highest reductions as a result of the cumulative effects of the carbon tax, mitigation technologies and the dietary changes based on recommendations of EAT-Lancet. Even though there is negative emission leakage the effects are much smaller compared to the Tax_tech scenario with a leakage rate of only 2%. In the EU-27 agricultural GHG emissions are reduced by 27.9% (109.2 million tonnes CO_2 equivalents) where technology related mitigated emissions from Nutri2cycle technologies account for 16% and already existing technologies in CAPRI for 28%. On a global level, emissions in this scenario are reduced by 107 million tonnes CO_2 equivalents, which is equivalent to a reduction of global agricultural GHG emissions by 1.9%.

The findings of this study imply that policies should support the adoption of the EAT-Lancet diet due to its positive effects on the environment and health. A combination of monetary instruments, like taxes and subsidies, and non-fiscal measures, such as information campaigns and products, could be used to achieve this. Additionally, agricultural and trade policies are often insufficient in delivering public goods and should be redesigned to promote healthy and sustainable practices. As we have shown in this study, supply-side efforts, including technological and management improvements to increase agricultural yields, fertilizer efficiency, and feed conversion rates, in combination with policy instruments like a carbon tax, can play an important role. We can conclude that a carbon pricing

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scheme in the agricultural sector to enhance the implementation of mitigation technologies could be a useful and cost-effective tool for achieving national or EU-wide mitigation goals particularly in combination with more sustainable dietary patterns in the EU-27. In order to further decrease the leakage rates adequate policy instruments such as border carbon adjustment mechanisms could be a promising option with further research needed.

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