Food Production and Consumption in a 1.5°C World
Options for Germany

Methods brief

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Introduction

This paper describes the method used for calculating the carbon footprint of the current average German diet and for establishing food-footprint targets for 2030 and 2050 based on a fair approach that limits global warming to 1.5C. Both supply and demand side actions were identified and calculated and combined for a pathway to reach the 1.5C target.

In this report, the term 'carbon footprint' refers not only to CO_2 but also to other greenhouse gases: methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6), converted into CO_2-equivalents, using GWP100 values (IPCC, 2021). GWP100 is one metric to estimate the radiative properties of different GHGs, using the 100-year timeframe. GHGs have different atmospheric longevities: CO_2 can last for centuries, N_2O around one century and CH_4 only a decade (IPCC, 2021). GWP100 metric cannot convey all aspects of the GHGs climate impact because it does not consider continuous or evolving GHG emissions (Ocko et al., 2017). Agriculture and causes more CH_4 and N_2O emissions than other sectors, such as energy sector, and thus the challenge of estimating the warming impact is very present in the food domain.

Estimating the carbon footprint of German food consumption

The average diet: composition and amounts consumed

The current carbon footprint of German diets was estimated with consumption-based accounting which capture all the GHG emissions released in the supply chain of food, starting from the agricultural production until the final consumption and waste management. The calculations combine statistics on how much an average German resident consumes each year of all major kinds of food products with data on how much GHG emissions are generated by each product over its entire lifecycle. That enables us to analyse how changes in diets or in the emissions-intensity of the production system, or any combinations of such changes, affect the food-related carbon footprint.

To formulate the current average German diet, we used consumption data which includes all the food and beverages consumed at home and outside. Consumption data was obtained from the national food balance statistics provided by the German Federal Ministry for Food and Agriculture (BMEL, 2022a). The reference year was 2021 or 2020/2021 (some plant product categories use fiscal year instead of calendar year). Consumption data (the class "Nahrungsverbrauch kg/Kopf" was used, for meat products "Verzehr kg/Kopf") from BMEL food balance statistics are based on calculated estimates and refer to the total food amounts available for human consumption during the reference period (table 1, Annex A). For fish, the BMEL food balance sheet does not differentiate fish species. Since different fish and seafood species have substantially different climate impact (Gephart et al., 2021), the category was divided between various fish and seafood species using market share data from Fisch-Informationszentrum (2021).

BMEL food balance values were used instead of data from nutritional surveys for two reasons. First, the latest publicly available nutritional survey data is from the national nutrition survey NVS II which data was collected 2005-2007. The aim of this report was to examine the recent situation of German diets. Second, BMEL statistical data also refers to food supply amounts which can directly be combined with carbon intensities without conversion from food consumption to supply amounts.

The carbon footprint of the current diet

To calculate the GHG emissions of the current German diet, lifecycle emissions (carbon intensities) data for individual food products were taken from Agribalyse 3.1. - an open-source database with information on 2,500 food products. Agribalyse includes emissions from land use and land use change. The emissions of different GHGs are added up based on their respective heating effect over a 100-year period (GWP100) following the EF method. Where one kind of production generates multiple products Agribalyse mostly allocates the emissions based on economic value, except for dairy (biophysical allocation) and cheese (mass allocation). Agribalyse (version 3.1) was last updated in October 2022 (Asselin-Balençon et al., 2022).

Even though Agribalyse is tailored towards the French food production supply chain, we chose to use it due to a lack of an equally coherent database for Germany. The only existing dataset of carbon intensities for food products specific to Germany that we were able to identify was produced by the Institute of Energy and Environmental Research (Reinhardt et al., 2020), but it does not cover all the food categories needed for this study. Since methodological choices of system boundaries, allocation, cut-off criteria etc. within one LCA study may have substantial effects on the estimated carbon intensities, we chose to use one single LCA dataset instead of mixing and matching, thus, choosing consistency over geographical precision.

The most significant difference in French and German production markets lies in the energy mix, which is much smaller in France than Germany (EEA, 2021). However, for food products, most emissions come from agriculture (Crippa et al., 2021; Poore & Nemecek, 2018). In the Agribalyse database, these agricultural emissions contribute on average by 70% to a food product's life cycle. Although regional differences in agricultural practices exist between Germany and France, we conclude that the striking difference in the electricity grid mix will not lead to a drastic underestimation of the German food carbon footprints.

In the following analysis we use Agribalyse 3.1 carbon intensities that represent the cradle-to-store life stages (thus leaving out emissions from transporting food products to residential homes and from residential cooking and waste treatment, as the conditions that control the latter life stages emissions are highly specific to the consumer’s country). To account for emissions in Germany that arise from transportation from store to residents’ homes as well as from residential cooking and waste treatment, we add Germany-specific average values (uniform for all food products). The consumption stage includes transport from store to home and energy needed for cooking and cooling. End-of-life includes GHG emissions from biowaste (BMEL, 2022b) and food packing waste (Umwelt Bundesamt, 2023) management. Carbon intensities for waste treatment options are from ecoinvent 3.9.

In the consumption phase, transport from the grocery store to home was estimated to be 1 km one way and two shopping trips for groceries per week and household (a scenario based on Achen (2005) and Hardi & Wagner (2019)). Emissions were calculated only for transportation done by car, which constitute 60 % of all shopping trips (Hardi & Wagner, 2019). Cooking and the use of refrigerators and freezers in households require 40 050 GWh in Germany, with 97 % from electricity and the rest from natural gas (EuroStat, 2021). At the end-of-life-stage, all household food biowaste (data from BMEL, 2022b) was assumed to go to biowaste treatment. The amount and treatment options for food packaging were estimated using data from Umwelt Bundesamt (2022).

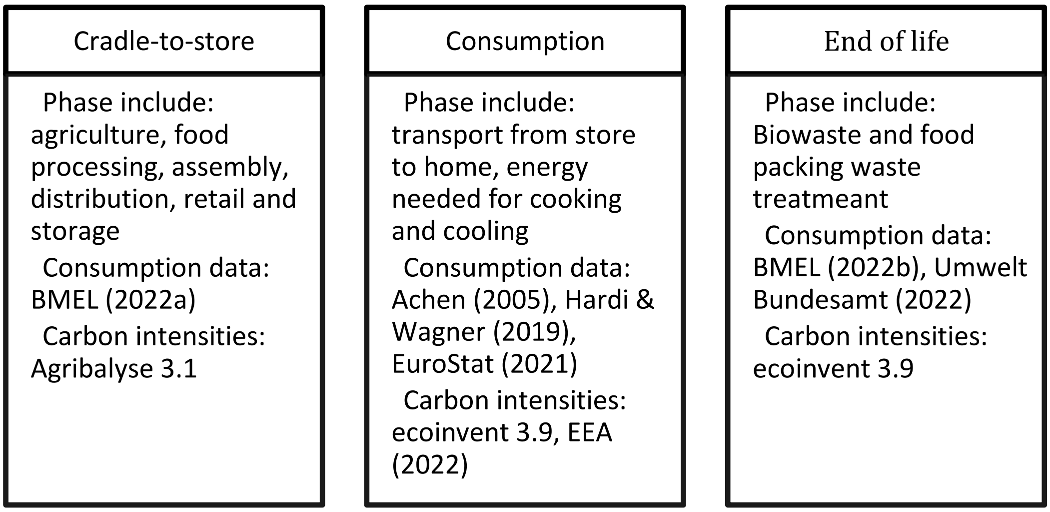

Figure 1. System boundary and sources used to calculate the carbon footprint of the current average German diet.

Table 1. Consumption amounts (kg/person/year) and carbon footprint (kgCO_2e/person/year) of the current average German diet.

Food group	**Amount, kg/person/year**	**Carbon footprint, cradle-to-grave, kgCO2e/person/year**
Meat	56	804
Dairy	121	474
Beverages	508	341
Grains	113	149
Sugars	36	122
Vegetables	107	98
Potatoes	72	76
Fruits	70	63
Oils	17	58
Fish	7	46
Eggs	15	44
Plant proteins	8	19
Total	1135	2293

Limiting global warming to 1,5C – determining the implications for German food consumption

Limiting global warming to 1.5C requires worldwide emissions to fall rapidly between now and 2030, reaching net-zero by mid-century. But it is unrealistic and unfair to expect all countries and all sectors to reduce their emissions equally. Countries with high current per-capita emissions, mainly high-income countries, will need to reduce faster than the global average. This will allow low-income countries, which currently emit very little and where many people are struggling to satisfy basic needs, room to increase their emissions for some time still. Similarly, with a rapidly shrinking room to emit greenhouse gases, priorities need to be set between different categories of goods to ensure the continued supply of essential products, such as food. Over time, it is thus reasonable to assume that emissions related to essential products will make up an increasing share of the total carbon footprint. The study applies these general principles using quantitative methods developed for the Hot or Cool 1.5-degree lifestyle report, which establishes targets for per-capita CO_2eq emissions for 2030 and 2050, then allocates emission shares for different lifestyle domains, such as food consumption.

The method follows the principle of "contraction and convergence", which implies that high-emitting countries need to slash their emissions faster than the world average so that all countries converge to the same level of per-capita emissions at some point in the future. After the convergence year, all countries need to reduce their emissions so that the combined global emissions reach net-zero around 2050. The 1.5-degree lifestyles report sets the convergence year to 2030. Requiring high-emitting countries to make deeper cuts until 2030 leaves room for low-emitting countries to make essential infrastructure investments and some more time for the transition to zero-carbon energy systems.

The emission reduction pathway to be followed globally is based on scenarios included in the assessments by the IPCC. The scientific literature documents over 1,000 modelling scenarios for how the world could keep warming to 1.5C or less by the year 2100 but most of these scenarios are problematic. First, most of them allow the increase in global temperature to substantially exceed 1.5C temporarily before falling to 1.5C or lower by the end of the century. According to the IPCC's sixth assessment report (IPCC, 2022), such temperature overshoot increases the risk of triggering multiple tipping elements in the Earth system. Second, most of the 1.5C scenarios depend on large-scale deployment of carbon dioxide removal (CDR), which is controversial. Many CDR techniques are unproven at scale, could have serious unintended consequences (such as biodiversity loss or negative impacts on food production), or could turn out to be exceedingly costly.

For these reasons, the 1.5-degree lifestyles method uses scenarios with small temperature overshoot and only limited use of CDR. The global emission levels that need to be reached by 2030 and 2050 are calculated based on the average of three such scenarios.[1] Per-capita carbon footprints for the target

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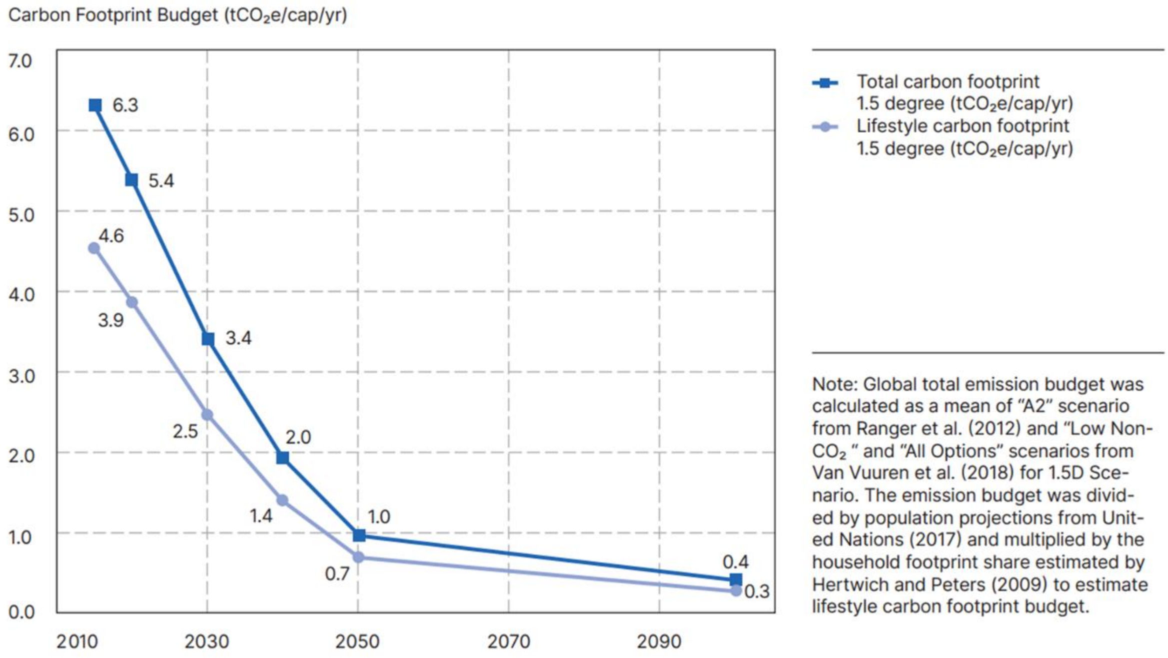
[1] Reference "A2" scenario (Ranger et al. 2012), "Low Non-CO_2" scenario from (van Vuuren et al. 2018), and "All Options" scenario from (van Vuuren et al. 2018). More details on these scenarios is available in the 1.5-degree lifestyles report (Akenji et al. 2021)

years were calculated by dividing the global emissions by projected world population numbers.[2] The resulting pathway for an average person's carbon footprint is shown in Figure 1 (Dark blue line). As can be seen, footprints would need to reach 3.4 t by 2030 and 1.0 t by 2050.



Note: Global total emission budget was calculated as a mean of "A2" scenario from Ranger et al. (2012) and "Low Non-CO_2" and "All Options" scenarios from Van Vuuren et al. (2018) for 1.5D Scenario. The emission budget was divided by population projections from United Nations (2017) and multiplied by the household footprint share estimated by Hertwich and Peters (2009) to estimate lifestyle carbon footprint budget.

Figure 1. Pathways for carbon footprints until 2100.

However, these footprint targets are based on societies' total emissions of greenhouse gases, including emissions from public spending and infrastructure investments – activities that are not closely related to the lifestyles of individuals and their consumption choices. The 1.5-degree lifestyles method accounts for emissions associated with six "lifestyle domains": food and beverages, housing, mobility, consumer goods, services, and leisure. It does not include emissions from other activities. This means that targets for future carbon footprints need to be adjusted by excluding these other emissions.

To determine the share of total carbon footprints that are linked to individual lifestyles, the 1,5-degree method relies on findings from input/output analyses of carbon footprint for multiple countries. Hertwich and Peters (2009) show that household consumption forms an average of 72% of the total carbon footprint. The remaining 28% is divided between government consumption (10%) and investments (18%).[3] The lifestyle carbon footprint targets were thus calculated as 72% of the total carbon footprint targets. The resulting pathway for lifestyle carbon footprint targets is shown in the light blue line in Figure 1, reaching 2.5 t CO_2eq per person by 2030 and 0.7t CO_2eq per person by 2050.

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[2] Based on the median projection of the 2017 Revision of the World Population Prospects (United Nations 2017).

[3] Examples of government consumption include road and infrastructure repairs and national defence; examples of investments include factories, transport equipment, and materials used for the future production of goods.

Consequently, by 2030, all countries are expected to have converged to the same 2.5 t/capita lifestyle carbon footprint. For wealthy European countries, this implies reducing their residents' footprints by around 70-75% (e.g., UK by 71%, Finland by 74%). Meanwhile, countries with smaller current footprints will need to make less drastic cuts. For example, Turkey would need to reduce by 49% and Brazil by 22%. Countries at lower levels of economic development, such as Indonesia and India, currently have carbon footprints that are close to or below the 2030 target.

The share of food in lifestyle carbon footprints in 2030 and 2050

When the overall footprint is reduced, the share allocated to each consumption domain will differ as compared to today's contributions. Some domains, such as nutrition, are essential for human survival and health, while for other categories, such as housing, leisure, consumer goods, and mobility, reduced consumption has less serious implications for wellbeing. Hence, larger cuts will be required in such non-essential forms of consumption. This means that emissions from food systems will need to be reduced, but their share of the total carbon footprint will increase over time.

Numerical targets for each consumption domain were established based on the current variability among households. A consumption domain where some households have remarkably high emissions while others have close to zero, is considered more discretionary (more like a "want" than a "need"). Such a domain is therefore allocated a decreasing share of the overall footprint. In contrast, a domain where households emit roughly the same amount is considered more essential (a true "need") and is therefore given a larger share of the overall footprint. The method for allocating the total lifestyle carbon budget to consumption domains was developed for the 1.5-degree lifestyles report and is based on a prediction model using household expenditure data from Japan (Akenji et al., 2021; Koide et al., 2019). Table 1 shows the resulting shares of total lifestyle emissions for the six consumption domains. Food is allocated 29% of the total in 2030, increasing to 50% in 2050.

Table 2. Predicted lifestyle carbon footprint shares of six consumption domains (from Akenji et al., 2021).

Year	Predicted lifestyle carbon footprint share of domains (%)					
	Food	Housing	Mobility	Goods	Leisure	Services
2030	29%	31%	17%	10%	4%	8%
2050	50%	26%	9%	5%	3%	7%

In this method, the food domain considers GHG emissions from cradle-to-store, while emissions from the food consumption phase are considered to be part of other domains, such as housing and mobility. To include the consumption phase to the 1.5 target, we estimate the share of cooking and grocery shopping from the housing and mobility domains using Eurostat data for Germany in 2020 and %-share was assumed to stay the same in 2030 and 2050. The 1.5 target for cradle-to-store is globally the same for everybody but the consumption phase is specific to Germany because the share of cooking for total household energy consumption varies between countries.

The resulting 1.5C target for the whole food related GHG emissions is 775 kgCO_2eq/person/year in 2030 and 360 kgCO_2eq/person/year in 2050. The consumption phase for Germany is 50 kgCO_2eq/person/year in 2030 and 10 kgCO_2eq/person/year in 2050 and the 1.5C global targets for cradle-to-store are 725 kgCO_2eq/person/year in 2030 and 350 kgCO_2eq/person/year in 2050. Targets are similar to Broekema et al. (2020) who estimate the food-related per capita targets align with IPCC's 1.5°C report (IPCC, 2018), using the same equity approach but also consumption phase is the same to everybody globally. Broekema et al. (2020) targets are 745 kgCO_2eq/person/year in 2030 and 402 kgCO_2eq/person/year in 2050.

The climate change mitigation actions of the German diet

A range of climate change mitigation actions at both the demand and the supply-side were identified through a literature review. The mitigation potential for each action was calculated by modifying either the amounts of consumption or the carbon intensity of food product categories. These potentials are based on the current carbon footprint of German food consumption and illustrate the impact that each action could have on the food footprint. Thus, mitigation potentials do not predict likely changes in the future (a business-as-usual scenario) based on estimated interactions between demography, technology, economy, and consumption. Subsequently, a set of supply and demand side actions were combined into one scenario, 1.5 pathway, which shows how the German food-related footprint could be reduced in line with the 1.5-degree target for 2030.

Demand-side actions

Shifting to more plant-based diets is one of the most effective ways to reduce food-related GHG emissions (Bajželj et al., 2014; Hallström et al., 2015; Poore & Nemecek, 2018; Springmann et al., 2018). In this study, we examined how much dietary shifts reduce the current CF. In addition to diet options, we chose four other demand-side options. Two of these consider shifts from individual food categories with high climate impact to others with lower impact: shift from red meat to low-impact fish and shifting dairy products to plant-based alternatives. These actions are not additional to dietary options. The other two options consider reducing the amount of food consumption: reducing household food waste and reducing the consumption of sugars and beverages.

Our analysis excludes some new and interesting actions because of the lack of data. These actions include for example novel protein sources, such as plant-based meat analogues, micro- and macroalgae, insects, cultured meat (meat produced from live animals' stem cells in a laboratory), mycoprotein (protein derived from fungi) or ovalbumin (egg white protein produced using fungi) (Järviö et al., 2021; Mazac et al., 2022; Scherer et al., 2023). All the novel protein sources do not provide climate mitigation possibilities yet, for example cultured meat does not currently have smaller carbon footprint than conventional ones (Scherer et al., 2023). More LCA research is needed to understand their environmental impacts and impact on human health (Marac et al., 2022).

The mitigation potentials are calculated using 25, 50, 75 and 100 % adaptation rates. Adaptation rates describes how many people will do the action from entire German population or how much individually each person must implement the action. For example, 50 % adoption of the action "shifting from red meat to low-impact fish products" means either 50 % of the population adopt the action or each individual will shift 50 % of red meat consumption to low-impact fish products.

Dietary options

Dietary options include diet models from the EAT-Lancet report (Willet et al., 2019), diet following the German nutritional guidelines (DGE, 2022) and a German-specific vegan diet (Weder et al., 2018). These models ensure that the diets are healthy and nutritionally adequate. The EAT-Lancet report has a flexitarian reference diet that includes minor amounts of animal products (“Flexitarian diet'' in our work). The EAT-Lancet report also includes vegetarian and pescetarian diet options, which are used in this report as well. One more dietary option was created to explore the impact of plant-based diet which also includes low climate impact fish and seafood (“vegan + low impact fish”). For this diet option, meat was substituted as in the pescetarian diet, and the substitution of dairy and eggs followed the vegan diet from EAT-Lancet report. The two first mentioned diet (DGE, 2022; Weder et al., 2018) are specific to German context and they provide diet model for flexitarian and vegan diets. For other dietary options there are not German specific models available. Thus, we used diets from EAT Lancet report although they only provide global models (Willet et al., 2019). The composition of dietary models is presented in Annex A.

Calory intake was adjusted to 2250 kcal for all the diet options. This value was packed up by German Nutritional Society’s guidance on caloric intake (DGE, 2015). Currently Germans eat more calories and 60 % of men and 43 % of women are overweight (Stehle, 2014). Thus, dietary options also address overconsumption of food and reduce the caloric intake to healthy level and.

Dietary options do not include beverages, which were explored as a separate consumption option. The GHG reduction potentials are calculated as the difference between emissions from the current diet and those from each dietary options. The consumption phase activities and the related emissions were assumed to stay the same as for the current diet.

Reducing food waste in households

Reduction of food waste was assumed to help reduce GHG emissions in two ways: lower need for food production and less biowaste sent for waste management. Data for household food waste is taken from the most recent food waste survey produced by the Federal Ministry of Food and Agriculture (BMEL, 2022b). The data only include food wasted at home and not when eating outside of the home. Only edible food waste is reduced and inedible waste, such as coffee grains and vegetable peels, are assumed to stay the same. Household food waste data is differentiated between different food categories such as fresh vegetables, meat, and dairy. These categories were combined with BMEL food consumption data to calculate the reductions in food amounts and the related effects on GHG emissions. The GHG emissions from reduced waste management were estimated based on values from the database ecoinvent 3.9.

Reduction of sweet and beverages

Reducing beverages and sweet snacks lowers the carbon footprint without harming the nutritional quality of the diet (Mazac et al., 2022). Currently Germans also overconsume sugar and alcoholic beverages (Ernst et al. 2019; RKI, 2017) and reducing these would lead to co-benefits for climate and health. In addition to sugars, soft drinks and alcoholic beverages, the action also includes other beverages, such as coffee, that have a high carbon footprint. The reduction of sweets, confectionery, and alcohol and non-alcohol beverages was assumed to lead reduction in the production of these foods. Alcohol beverages include beer, wine, sparkling wine, and spirits. Non-alcohol beverages consider coffee, tea, fruit juices and soft drinks. Sweets include sugar and chocolate.

Shift from dairy products to plant-based milk substitutes

In general, plant-based milk products have a lower carbon footprint than dairy (Geburt et al., 2022; Poore & Nemecek, 2018). Data on the carbon intensity of plant-based milk is from Switzerland, an area close to Germany (Geburt et al., 2022). For other dairy products, Germany-specific carbon intensities were used to replace cream, fermented milk products and butter (Kolbe, 2020) and cheese (Scheelbeek et al., 2020).

Replace red meat with low impact fish

Red meat has a much higher climate impact than some fish and seafood products (Poore & Nemecek, 2018). The option considers replacing red meat (beef, mutton, goat, and pork) with fish and seafood which has a low climate impact (low-impact fish, see the section below). Red meat is not possible to completely replace with low-impact fish because of the availability of it, but even partly implementation of this action provides large mitigation potentials.

Low climate impact fish and seafood

The climate impact of fish and seafood varies greatly because of many different production practises (Gephart et al., 2021). Two demand-side options consider “low-impact fish” which means fish and seafood products that have a low climate impact per kilogram of product within this category. These are, for example, small pelagic fish such as mackerel, herring, and sardines or fish farmed in low-to-no-input aquaculture systems.

Small pelagic fish has a low climate impact because of low fuel use per kilogram of captured fish. Fisheries targeting small pelagic fish deploying surrounding nets or pelagic trawling reported the lowest fuel consumptions per kilogram of captured fish whereas fish captured by bottom-trawling needs much more fuel per yield (Parker et al., 2018). For aquaculture, the amount and ingredients of feed strongly affects the carbon footprint and thus no-input or restorative systems, such as coastal farms growing seaweed and molluscs or brackish/freshwater systems growing shrimp and carp, may provide blue foods with small carbon footprints (Gephart et al., 2021; Ritchie & Roser, 2021).

In the analysis, low-impact fish has a carbon intensity of 2.1 kgCO_2eq/kg based on Agribalyse 3.1 and Gephart et al., (2021).

Supply-side actions

Supply-side actions include action in agriculture, in the following food supply chains such as in food processing and retail and food loss prevention from agriculture to stores.

Action in agriculture

Changes in agricultural production practises have the potential to reduce GHG emissions and to enhance carbon sequestration capacity of agricultural soils. However, quantification of these potentials involves many uncertainties and thus supply-side actions included in this report should be seen as indicative examples of their mitigation potential. The range of the mitigation potentials of different agricultural actions are shown in the Annex B.

The German food demand is met with domestically produced and imported food products. The mitigation potentials of production actions differ depending on the geographical area and were calculated with country-specific values for the German domestic production and global average values for imported food. The global scenario is not as detailed as the German scenario reflecting differences in availability of data and significant uncertainties of estimates.

The German and the global scenarios were combined to have one estimate for the mitigation potential of agricultural management actions. In Germany, imports from total domestic food supply are 35% while 29% of domestic production is exported, in the mass values (FAOStat, 2022), but these shares differ between food groups. The following shares (table 3) were used to calculate the mitigation potential of agricultural management of German food consumption.

Table 3. Import %-shares from German food supply and export %-shares from domestic food production in different food groups (mass values). Numbers are calculated using FAOStat, reference year is 2020.

	Imports	Exports
Grains	31%	29%
Vegetables	72%	30%
Fruits	77%	31%
Potatos	18%	38%
Dairy	28%	32%
Fish	72%	4%
Plant protein	90%	5%
Oil and animal fat	32%	33%
Beverages	31%	20%
Beef	40%	31%
Pork	33%	47%
Poultry	49%	39%

In the analysis, supply-side actions were combined with different dietary options. Mitigation potential of supply-side action is calculated assuming that agriculture produce food consumed currently in Germany. Different diet options affect food composition and thus change the mitigation potential of supply-side actions. For example, the mitigation potential of animal husbandry actions decreases when consuming less animal-based products. The mitigation potential of agricultural actions in different dietary options is estimated based on food composition and the reduction and increase of grassland and cropland area.

The analysis considers conservative values for estimating the mitigation potential of technological and land-based solutions. For example, the potential to reduce methane from enteric fermentation is 6 times higher if the total technical potential is considered instead of plausible and cost-effective estimate (Roe et al., 2021). Reaching the total technical potential of enteric fermentation would require new drug innovations which have to pass animal drug legislation and become economically profitable to farmers (Roe et al., 2021). Reduction potentials are calculated for 2030, which is under a decade from now, and it is unlikely that many new innovations would reach a large-scale implementation. In the future, technological and land-based solutions can have bigger mitigation potential, but the low-carbon pathways should not rely too much on them.

Rewetting drained peatlands used as agricultural soils

Of all drained peatland in Germany, one million hectares are used as grassland and 0.3 million hectares as croplands, which are around 70% of the total peatland area in Germany (Tegetmeyer et al., 2021; Tiemeyer et al., 2021) and 6% of the total agricultural area (Don et al., 2018; Grethe et al., 2021). These fields cause 40% of the GHG emissions from agriculture (Grethe et al., 2021) and 5.4% of total GHG emissions in Germany (UBA, 2019). Drainage of peatland lowers the water levels which increases the decomposition of biomass, releasing carbon into the atmosphere. Rewetting peatlands prevents CO_2 losses, but CH_4 flux increases after raising water levels. However, carbon sequestration in rewetted peatlands is expected to compensate the warming role of CH_4 in the temperate climate zone over a long timescale (Abdalla et al., 2016; Jacobs et al., 2018). Nevertheless, CO_2 and NH_4 fluxes after rewetting are highly variable depending on the peatland vegetation type and previous anthropogenic management and land use (Abdalla et al., 2016).

Rewetted peatlands cannot be used as farmland for common agriculture, but paludiculture can be practised in rewetted peatlands. Paludiculture is the agricultural use of soils in wet conditions. In Europe, it mainly addresses growing biomass for fodder, fuel production, and raw materials for construction but also for grazing with cattle adapted to wet conditions (Ziegler et al., 2021).

The calculation scenario for rewetting agricultural peatlands assumes that, in 2030, 25% of the drained agricultural peatland are rewetted and used for paludiculture or they are out of production use for example as natural conservation areas (table 4). An additional 50% of the current agricultural organic soils are turned into extensive grasslands when water levels can be raised but not as much as in natural peatland which is the case of out-of-production-use and paludiculture areas (table 4).

Table 4. Values and sources used in estimating the climate change mitigation potential of rewetting drained agricultural peatlands.

Rewetting peatlands	**Current area Mha**	**Source**	**Current GHG emissions, tCO_2e/ha/year**	**Source**
Grasslands in organic soils	969100	Tiemeyer et al., 2021	26.32	Average from Tanneberger et al., 2021; Tiemeyer et al., 2021; Günther et al., 2020
Croplands in organic soils	356700	Tiemeyer et al., 2021	36.89	Average from Tanneberger et al., 2021; Tiemeyer et al., 2021; Günther et al., 2020
	Rewetted area in the analysis		**Reduction potential**	
	%-share from total drained agricultural peatlands	**Area, Mha**	**tCO2e/ha/year**	**Source**
Paludiculture & out of production areas	25%	331450	5.88	Category "rewetted peatland", average from Tanneberger et al., 2021; Tiemeyer et al., 2021; Günther et al., 2020
Extensive grassland	50%	662900	17.81	Change from deep drained peatland to shallow drained peatland, average from Tanneberger et al. 2021 and Günther et al. 2020

Nitrogen management

Application of nitrogen fertilizers can increase the release of N_2O from soils. Also, the production of mineral nitrogen fertilizers is highly energy intensive and thus causes GHG emissions. Emissions can be reduced by optimising and reducing the total fertilizer application by the best practices such as split fertilization, crop residue incorporation and nitrification inhibitors. The scenario assumed that current use of 90 kg N/ha/year reduced to 70 kg N/ha/year in 2030 and this reduction is entirely from mineral nitrogen fertilizers (table 5). The calculations consider both direct and indirect N_2O emissions from soils and GHG emissions from mineral fertilizer production.

Table 5. Values and sources used in estimating the climate change mitigation potential of nitrogen fertilizer management.

	N fertilizer reduction, current to 2030	Source	Mitigation potential of N_2O from soil	Source	Mitigation potential of fertilizer production	Source
Nitrogen management	20 kgN/ha/year	Grete et al., 2021; Prognos, Öko-Institut & Wuppertal Institute 2020	10 $kgCO_2e/kgN$	BMEL 2016	4.64 $kgCO_2e/kgN$	ecoinvent 3.9

Enteric fermentation

The enteric fermentation process causes CH_4 emissions from ruminators digestion. The estimation of reduction potential for this option considers both rumen modifiers, which inhibit CH_4 production, and actions to improve animal production efficiency (total CH_4 emissions will be decreased if fewer cows are needed to produce the same amount of milk or meat) (table 6). The highest estimations (Knapp et al., 2014; Roe et al. 2021 “technical potential”) of the CH_4 reduction potentials were excluded in the analysis, because many actions to reduce emissions from enteric fermentation are very costly and not applicable to farms for practical and economic reasons in the upcoming years (Knapp et al., 2014; BMEL, 2016).

Manure management

Livestock manure releases CH_4 and N_2O emissions into the atmosphere and these GHG emissions can be prevented through improved collection, storage and spreading technics. Further on livestock manure can be used to produce biogas and after biogas treatment the digestate could be applied into fields as fertilizer (Prognos, Öko-Institut & Wuppertal Institute, 2020). The calculation scenario is based on Roe et al. (2021) “cost-effective” estimate (table 6). Higher reduction potentials would require large investments on the small and large-scale anaerobic digesters (Roe et al., 2021).

Table 6. Values and sources used in estimating the climate change mitigation potential of enteric fermentation and manure management.

	Mitigation potential, $MtCO_2eq/year$	Source
Enteric fermentation	0.47	Roe et al. 2021
Manure management	1.22	Roe et al. 2021

Energy efficiency

Energy use in agricultural sector can be reduced through energy-saving practises and technologies such as energy efficient machines and buildings. The main areas of energy reductions are greenhouses, pigsties, poultry houses and facilities for milk production (BMEL, 2016). The reduction potential is based on BMEL (2016) number which was the only estimation founded for Germany (table 7). This action only considers the energy reduction gains and not take into account the changes in energy sector such as the lower carbon intensity of grid electricity in 2030.

Table 7. Values and sources used in estimating the climate change mitigation potential of energy efficiency.

	Energy related GHG emissions of German agriculture	**Source**	**Potential for energy consumption reduction from current**	**Source**
Energy efficiency	6.2 $MtCO_2eq$/year	Prognos, Öko-Institut & Wuppertal Institute, 2020	20%	BMEL, 2016

Actions to increase agricultural soils' capacity to sequestrate carbon in Germany

In addition to GHG reductions, changes in agricultural production practises can increase the carbon stocks of agricultural soils. For the analysis, these actions only consider carbon sequestration potential, although some actions also decrease the use of fertilizers, but this is reflected in the nitrogen management option. These actions do not endlessly increase carbon stocks, because after the soils reach a new equilibrium stage, carbon gains will be increasingly smaller. Carbon sequestration potential was modelled in the topsoil (30 cm). All actions were assumed to be implemented in mineral soils, not organic soils, which should be rewetted. Agroforestry option considers both soil organic carbon (SOC) and aboveground woody biomass while cover crops and crop rotation only the changes in SOC.

The analysis considers that in temperate climate, climate change will decrease SOC stocks (Riggers et al., 2021). To keep SOC stocks unchanged, 5% more organic carbon input is needed yearly according to RCP2.6 scenario (Riggers et al., 2021).

The analysis gives rough estimates of the carbon sequestration potentials, and the impact depends on a range of factors, including the soil properties, climate conditions and implementation of actions.

Cover crops

Cover crops means the cultivation of temporary fast-growing plants to cover the soil between arable crops typically over winter (Poeplau & Don, 2015). Cover crops show a potential to increase SOC, especially if biomass remains and are used as green manure (Poeplau & Don, 2015; Jacobs et al, 2018) (table 8). However, in some cases, cover crops may decrease the yields (Abdalla et al., 2019) or change soil microbial activity (priming effect) and enhance the rate of decomposition thus decreasing the reduction potential (Jacobs et al., 2018).

Crop rotation

Crop rotation, for example cultivation of legumes, crops with a dense and deep root systems and perennial crops, may increase SOC stocks. The increase is however highly variable depending on the crop species (Wiesmeier et al., 2020). Crop rotation may also reduce agricultural productivity when main crops are replaced in rotation (Wiesmeier et al., 2020). In the analysis, it was assumed that crop rotation increases SOC in poor rotation fields. These field means areas where plants, which decrease SOC, are cultivated in several years in a row. The area was estimated to be at least 17 % of the total cropland area in Germany (based on Wiesmeier et al., 2020, table 8).

Agroforestry

Agroforestry has the potential to sequester carbon in the aboveground woody biomass as well as into the soils (Golicz et al., 2021). Agroforestry systems in temperate climate zone can be classified into three groups: silvoarable systems (trees/shrubs + crops), silvopastoral systems (trees/shrubs + pastures and/or animals) and hedgerows (tree/shrub fences around the fields). The scenario for C sequestration potential assumes that 10% of current croplands in mineral soils are converted to silvoarable systems and 2% to hedgerows and 10% of grasslands to silvopastoral systems (table 8). Currently agroforestry has very minor role in Germany (Wiesmeier et al., 2020).

Table 8. Values and sources for agricultural management actions to increase the C sequestration potential of agricultural fields.

Action	Current area, Mha	Source	Area in 2030, Mha	Source	Reduction potential, kgC/ha/a	Source
Cover crops	1.70	Don et al., 2018	3.39	Seitz et al., 2022	305	Seitz et al., 2022
Crop rotation			1.92	Estimation of poor crop rotation area based on Wiesmeier et al., 2020	725	Bolinder et al., 2012; West & Post, 2002
Agroforestry						
Silvoarable	0.06	Own estimation	1.14	Own estimation	680	Wiesmeier et al., 2020
Silvopastural	0.02	Own estimation	0.38	Own estimation	680	Wiesmeier et al., 2020
Hedgerows	0.03	Drexler et al., 2021	0.31	Aertsens et al., 2013	2100	Drexler et al., 2021

Actions excluded in the German supply side scenario

Among all possible actions, we only investigated mitigation actions with quantitative data available in the context of German food consumption. Accordingly, some mitigation actions could not be considered. The actions excluded are for example the adoption of alternative food systems, which emphasizes small scale farming, holistic food production approaches and alternative institutions such as food cooperatives, farmers' markets, and community-supported agriculture (El Bilali et al., 2019).

Reduced tillage, biochar, organic fertilizers, organic agriculture and alternative grazing practises are often mentioned as actions to reduce agriculture's GHG emission. They were excluded in the German production management scenario for the reasons described below.

Reduced / No tillage

In reduced or no-tillage systems, manual soil disturbance is done with less intensity or shallower depth compared to conventional farming. The effect of reduced or no tillage on SOC has been studied in several studies, revealing either a positive (Jacobs et al., 2018; Jordon et al., 2022; Krauss et al., 2022) or non-significant effect (Powlson et al., 2014; Haddaway et al., 2017; Meurer et al., 2018). Reduced tillage systems may not result in a significant net increase in the total soil profile, as SOC in the topsoil increases but soils below loose carbon because of decreased organic carbon input. Because of the inconsistency of current data, reduced tillage was excluded in the analysis.

Biochar

Biochar has the potential to increase agricultural soils' carbon stocks, but a clear positive effect has only been shown in tropical and sub-tropical soils, not in temperate regions like in Germany (Jeffery et al., 2016; Don et al., 2018). For climate change mitigation, the stability of biochar against degradation is a key factor for whether biochar increases SOC long-term or releases carbon back into the atmosphere through degradation (Don et al., 2018). Don et al. (2018) also noted that an evaluation is needed to assess the availability and quality of biomass for biochar production in Germany and if biochar is the most effective way to use biomass for climate change mitigation purposes. The AGRI Committee's report on European Union's agricultural soil management does neither recommend biochar as a climate mitigation action in EU until better understanding of biochar's long-term potential to increase carbon stocks (Andres et al., 2022). In conclusion, although biochar may have a role to increase SOC stocks in the future, there are currently no long-term studies available to quantify the possible C sequestration potential in Germany (Haubold-Rosar et al., 2016; Don et al., 2018; Wiesmeier et al., 2020).

Organic fertilizers

Unlike mineral fertilizers, organic fertilizers return organic material back to soil. Nevertheless, they do not lead to a net CO_2 uptake from the atmosphere (Wiesmeyer et al., 2020; Öko-Institut, 2021) why this option is excluded in the analysis. Relocation can contribute to climate protection if organic fertilizers from regions with nutrient surpluses are transferred to other regions (Don et al., 2018). The production of organic fertilizers does not cause GHG emission unlike mineral fertilizers. The mitigation potential of the mineral fertilizer production is reflected in the nitrogen fertilizer management option.

Organic agriculture

Organic farming is the most practised alternative to conventional agriculture in Germany. The organically farmed agricultural area currently covers 11% of farmland and Germany is aiming to increase the share of organic farmland area to be 30% in 2030 (BMEL, 2023).

Studies have shown that although organic farming can have a range of environmental benefits, there are no clear climate mitigation gains (Clark & Tilman, 2017). Organic farms have lower footprint per area, but this is cancelled out by higher yields of conventional farming (Clark & Tilman, 2017). The climate impact of German organic and conventional diets is also about the same (Treu et al., 2017). These research findings challenge a commonly held belief that organic food is also climate friendly. It should be noted that the currently used methods for studying the environmental impacts of our diet's lack the complexity to consider important ecosystem services such as biodiversity and habitat provision, which organic farming has been proven to promote over conventional farming (Stein-Bachinger et al., 2021).

Alternative ruminant production systems

There is a large variability of meat production systems which vary in their environmental impacts depending on factors such as region, climatic conditions, and management practices. Case studies indicate that an optimized grazing system (i.e., grass-fed beef) may lead to a temporary soil organic carbon build up that may partially or fully offset the greenhouse gas emissions (CH_4 and N_2O) from ruminants (Rowntree et al., 2020; Stanley et al., 2018). However, large uncertainty exists about the extent of applicable land area and the permanency of the favorable conditions (Garnett et al., 2018). Thus, for this report, we did not consider a large-scale shift to grass-fed ruminant production as a viable option. Other important aspects in the debate on grass-fed meat production such ass societal benefits are outside the scope of this work.

Global scenario for actions in agriculture

Global scenario is based on Griscom et al. (2017), Searchinger et al. (2018), Roe et al. (2019) and Roe et al. (2021), which analysed globally the climate change mitigation potential of agricultural management actions. Roe et al. (2019) maximum estimates for mitigation potentials were excluded because achieving these kinds of GHG reductions would require large scale implementation of technologies and innovations that do not exist yet and thus these are not likely to happen in 2030. Selected actions were mentioned in all the studies (Table 9).

Table 9. Supply side actions included in the global scenario to estimate the climate mitigation potential of supply side actions for imported food consumed in Germany.

Action	Description
Nitrogen management	Changes in nitrogen fertilizer application amounts and management practices which decrease GHG emissions from fertilizer production and released N_2O and NH_4 emissions from agricultural soils.
Biochar	Option is excluded from German scenario but included in global scenario. Biochar has probably a clear positive effect on soil organic carbon in tropical and sub-tropical climate zone.
Agroforestry	Increases both soil organic carbon and aboveground woody carbon stocks.
Enteric fermentation	Reduction of CH_4 emissions through improved feed and feed additives and animal welfare.
Carbon sequestration for agricultural land	Combination of action that increase agricultural soils' (both cropland and grassland) capacity to increase soil organic carbon stocks.

Decarbonization and food waste reduction in the food supply chain

Supply side actions described above consider only action in farms. Decarbonizing the supply chain considers all the needed actions to mitigate the climate impact on the downstream supply chain, including industrial processes, food packing, retail, transport, and waste management. In the analysis, the supply chains of German food consumption were assumed to be totally in Germany because of the lack of data to make other estimations. The GHG emissions are estimated using the production-based value for food supply chain emissions in Germany (Crippa et al., 2021). This value does not include supply chain emission occurring abroad, but it includes emissions related to the processing of re-exports. The reduction potential from current to 2030 is based on KN2045 scenario (Prognos et al., 2021).

Supply-side food waste option considers food losses occurring in agriculture, food processing, retail, and restaurants. Only avoidable food waste amounts (from Schmidt et al. 2019) are prevented and the scenario assumes 50% reduction from current levels. The shares of the edible and thus avoidable food waste in Germany per life circle stage are 86% for agriculture 55% for the food industry, 84% for retail, 72% for restaurants, and 41% for households (Schmidt et al., 2019).

Reforestation potential of dietary options

Animal-based foods have large land footprints and shifting towards plant-based diets frees up agricultural land (Chan et al., 2022; Dräger de Teran & Suckow 2021; Hayek et al., 2021). In these areas, native vegetation regrowth (reforestation) or planting forests (afforestation) offer a potential to enhance carbon sequestration. In the analysis, reforestation potential was estimated for different dietary options because the reforestation potential is dependent for the dietary change.

First, the land use (both cropland and grassland) of the current diet was assessed based on Bringezu et al. (2021) report of the agricultural land area in Germany and abroad (imports), excluding the area of non-food crops. The cropland areas of different diets were estimated by reducing land area of those food categories that decrease in dietary options compared to the current diet and increasing land area of food categories that exceeds the current consumption. Cropland areas of different food groups were taken from Umweltbundesamt (2017) publication which gives similar results to Paris et al. (2022) and Meier & Christen (2012). For grasslands, the reduction of ruminant meat and dairy was assumed to correlate directly to the reduction of grassland area.

In the analysis, 50% of freed cropland area is reforested, and the other half of the area is used for non-food crop cultivation or is located on land not suitable for forestation. For grasslands, areas that have earlier been forest were expected to be reforested again (table 10). The share of native grassland from all grasslands is from Hayek et al. (2021). These shares are rough estimates but in the scope of this project it was not possible to make more detailed estimates of the reforestation potential of the current agricultural areas.

Table 10. The %-share of grasslands that have been forest before the area was converted to grassland (from Hayek et al., 2021). This %-share was used to estimate the grassland area that was assumed to be reforested in the analysis.

Region	%-share of native forest
North America	15%
Latin America	38%
Europe	55%
Central Asia, Middle East, Nort Africa	2%
Sub Saharan Africa	28%
South Asia	19%
Eastern Asia	19%
Southest Asia and Oceania	4%

The potential of carbon sequestration of freed land area was estimated for Germany and abroad. The estimation includes above-ground as well as below-ground carbon. There is no available data on the carbon stock changes from arable land or grassland to forest in Germany. Above-ground carbon sequestration potential is based on Öko-Institute (2021) estimation excluding deadwood which have only very minor role in Germany’s managed forest (Wellbrock et al., 2017). The increase of SOC in croplands was estimated according to Poeplau et al. (2011) and for grassland, there are no major changes in SOC (Poeplau et al., 2011). Conversion of cropland to forest increases the carbon stock by 7.3 tCO_2/ha/year and for grasslands by 5.7 tCO_2/ha/year. For imported food and other agricultural inputs, such as animal feed, the carbon sequestration potential was estimated based on Hayek et al. (2021) study.

Reforestation potential estimates have many uncertainties, and they demonstrate the scale of the impact instead of giving exact values. The increase of carbon stocks in reforestation areas is highly variable, especially in the litter and soils (Hayek et al., 2021). Also, changes in diets do not automatically lead changes from land use, as it is assumed in the analysis.

The 1.5 pathway

Supply and demand-side actions were combined to one scenario, the 1.5 pathway, that describes the needed actions to achieve the 1.5 target in 2030. The magnitude of the impacts of different actions depends on their adoption rates. The 1.5 pathway considers achievable adoption rates which still enable German diets to stay within the 1.5 target (table 11). However, the adoption rates considered in the pathway are one example of different possible combinations of adoption rates to achieve the 1.5 target.

Table 11. Actions included in the 1.5 pathway scenario, their adoption rates and reasonings for the rates.

Actions	Adoption rate	Reasoning for the adoption rate
Actions in agriculture	80% of the maximum potential of all the agricultural actions included in this report	To avoid too huge estimates, 80% adoption of actions was expected to be realistic
Decarbonization of supply chain	German will achieve the climate targets for 2030 for energy and transport sector	It is assumed that Germany will reach it climate targets in 2030
Dietary shifts	80% of population will change to flexitarian diet	Flexitarian diet includes minor amounts of animal-based products and thus it was assumed to be easier to adopt by Germans than other dietary options
Decrease of beverages and sweets	30% reduction of the consumption of alcoholic and non-alcoholic beverages and sugar	30% reduction of beverages and sweets do not lead calorie deficiency or harm the quality of nutrition (Mazac et al. 2022).
Prevention of food waste	50% reduction of both supply chain and household food waste	Food waste reduction target in the National Strategy for Food Waste Reduction (BMEL, 2019)
Reforestation	Based on the dietary change	50% of the cropland area and grassland, which used to be forest before agricultural use, are reforested, as it is in our reforestation scenario

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Annex A

The composition and carbon footprint of the current average German diet.

Food category	Amount, kg/cap/year	Carbon footprint, kgCO2e/person/year
Meat		
Pork	31.0	368
Beef	9.4	316
Poultry	13.2	79
Other meat	1.6	41
Dairy		
Milk and buttermilk	52.3	99
Semi-hard/hard cheese	12.4	89
Fermented milk prodcts	30.2	82
Soft cheese	10.9	71
Milk powder	3.5	61
Butter	6.1	55
Cream	5.3	17
Beverages		
Coffee	169.0	110
Beer	91.6	106
Soft drinks	118.4	61
Wine + sparkling wine	23.9	29
Juices	28.5	24
Spirits	5.2	6
Tea	71.5	5
Grains		
Wheat	88.9	103
Rice	6.8	23
Oats	6.2	10
Rye	6.8	7
Corn	4.4	6
Vegetables		
Tomatoes	31.5	29
Other vegetables	27.8	27
Onions, leek	10.2	10
Carrots, beets	11.5	8
Cabbages	7.1	7
Leafy vegetables	7.4	6
Cucumbers	7.5	6
Cauliflower, broccoli	2.0	2
Mushrooms	2.0	1
Potato	59.6	47
Potato strach	12.5	29
Fruits		

Other fruits	26.7	24
Apples	24.4	18
Bananas	11.6	11
Berries	7.6	10
Sugars		
Chocolate	2.7	76
Sugar	32.5	44
Honey	0.9	1
Vegetable oils	17.1	58
Fish	6.5	46
Eggs	14.7	44
Plant proteins		
Legumes	2.5	3
Nuts and seeds	5.5	15
Total	1135	2293

Annex B

Composition of current diet and the six dietary models, g/day/person.

Food category	Current diet	DGE guidelines	Vegan diet. German guidelines	Flexitarian diet	Pescetarian diet	Vegetarian diet	Vegan+ low impact fish diet	Vegan diet
Grains	232	275	250	209	209	209	209	209
Potatoes	144	220	120	45	45	45	45	45
Vegetables	214	350	400	270	344	344	402	420
Fruits	141	225	225	180	210	229	268	280
Dairy	261	265	0	225	225	225	0	0
Beef	27	43	0	9	0	0	0	0
Pork	85		0	9	0	0	0	0
Poultry	36		0	26	0	0	0	0
Eggs	31	26	0	12	12	12	0	0
Fish	35	21	0	25	79	0	79	0
Legumes	4	65	90	60	60	72	72	84
Nuts	10	25	50	44	44	53	53	61
Oils	23	15	40	42	42	42	42	42
Sugars	59			28	28	28	28	28
Source	BMEL, 2022b	DGE, 2022	Weder et al., 2018	Willet et al., 2019	Willet et al., 2019	Willet et al., 2019	Own model based on Willet et al., 2019	Willet et al., 2019

Annex C

The table presents data that was found to estimate the agricultural management actions' impacts on climate change in Germany. All the sources are not used in our analysis of the mitigation potentials of agricultural actions, but the table gives an overview of the range of different estimates.

Action	Value	Description	Source
Nitrogen management			
	20 N kg/ha/year	N fertilizer reduction, N kg/ha/year	Grethe et al. 2021
Enteric fermentation			
	15% from NH_4 emissions	Technical reduction potential	Knapp et al. 2014
	0.32 MtCO2e/year	Cost-effective reduction potential in Germany	Martineau et al. 2016
	3.2 MtCO2e/year	Technical reduction potential in Germany	Roe et al. 2021
	1.32 MtCO2e/year	Cost-effective reduction potential in Germany	Roe et al. 2021
Manure management			
	3.74 MtCO2e/year	Technical reduction potential in Germany	Roe et al. 2021
	1.22 MtCO2e/year	Cost-effective reduction potential in Germany	Roe et al. 2021
	3.4 MtCO2e/year	Reduction potential in 2030 in Germany, including high investments to manure biogas plants	Prognos et al. 2021
Rewetting of peatlands	Reduction potential		
	31 tCO_2e/ha/year	Rewetted cropland	Günther et al. 2020
	23 tCO_2e/ha/year	Rewetted grassland, deep drained	Günther et al. 2020
	11 tCO_2e/ha/year	Rewetted grassland, shallow drained	Günther et al. 2020
	35 tCO_2e/ha/year	Rewetted cropland	Tiemeyer et al. 2020
	26 tCO_2e/ha/year	Rewetted grassland	Tiemeyer et al. 2020
	29 tCO_2e/ha/year	Rewetted cropland	Tannenberg et al. 2021
	18 tCO_2e/ha/year	Rewetted grassland in organic soils, deep drained	Tannenberg et al. 2021
	12 tCO_2e/ha/year	Rewetted grassland, shallow drained	Tannenberg et al 2021
Cover crops	CO_2 sequestration rate		
	1.18 tCO_2/ha/year	Global meta-analysis	Poeplau & Don. 2015
	2.06 tCO2/ha/year	Global meta-analysis	Abdalla et al. 2019

Crop rotation	CO_2 sequestration rate		
	0.55 tCO_2/ha/year	Global meta-analysis	West & Post 2002
	1.02 tCO_2/ha/year	Study from Sweden	Bolinder et al. 2012
	0.9 tCO_2/ha/year	Estimation in Germany	Mengis et al. 2022
Agroforestry	CO_2 sequestration rate		
	40% change in SOC stock	Agriculture to agrisilviculture	De Stefano and Jacobson. 2018
	15% change in SOC stock	Grassland to agrosilvopastural system	De Stefano and Jacobson. 2018
	2.57 tCO_2/ha/year	Grassland to agrosilvopastural system	Shi et al. 2018
	3.30 tCO_2/ha/year	Windbreaks	Shi et al. 2018
	2.50 tCO_2/ha/year	Estimation for silvoarable and silvopastural systems for Bavaria region, in Germany	Wiesmeier et al. 2020
	0.77 tCO_2/ha/year	Cropland to hedgerows	Drexler et al. 2021
	2.75 tCO_2/ha/year	Estimation of agroforestry's C sequestration potential in Europe	Andrés et al. 2022
	2.50 tCO_2/ha/year	Estimation for cropland to agroforestry in Germany	Mengis et al. 2022
Reduced tillage			
	0.55 tCO_2/ha/year	C increase from conventional farming to no-tillage system	Jacobs et al. 2018
	0.99 tCO_2/ha/year	C increase in organic farming systems when tillage is reduced	Krauss et al. 2022
	no clear effect on SOC increases in the whole soil profile		Andrés et al. 2022
			Wiesmeier et al 2020
			Haddaway et al. 2017

The table shows global climate change mitigation potentials ($GtCO_2e$/year) of different agricultural action and domains. All the values are not used in our analysis, but the table gives overview of the range of different potentials.

	Griscom et al. 2017	**Searchinger et al. 2018**	**Roe et al. 2019 min value**	**Roe et al. 2019 median value**	**Roe et al. 2019 max value**	**Roe et al. 2021 technical value**	**Roe et al. 2021 cost effective value**
Nitrogen management	0.71	0.44	0.03	0.10	0.71	0.26	0.22
Biochar	1.10		0.03	1.50	6.60	2.36	1.82
Agroforestry	1.04		0.11	1.50	5.65	5.61	1.12
Enteric fermentation		0.61	0.12	0.40	1.20	0.18	0.10
Soil carbon sequestration for croplands			0.25	1.80	6.78	1.02	0.92
Soil carbon sequestration for grassland			0.13	0.90	2.56	1.49	0.89