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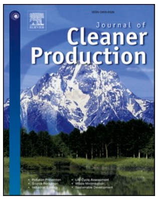

How diet portfolio shifts combined with land-based climate change mitigation strategies could reduce climate burdens in Germany

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ABSTRACT

Many studies have analysed the environmental impact of vegan, vegetarian, or reduced meat diets. To date, literature has not evaluated how diet shifts affect environmental impacts by utilising portfolios which reflect personal nutrition preferences. Further, changing diets could alter the available land for non-food uses. This paper defines novel diet portfolios to outline alternative diet transitions and choices within the population and finds their effect on greenhouse gas (GHG) emissions, primary energy use, and land use in Germany. The aim of this study is to capture how these diet shifts affect land availability and increase the options for land-based climate change mitigation strategies. To do so, a contextualisation is made to compare the use of freed-up land for afforestation or biomethane production (with and without carbon capture and storage). The investigated diet portfolios lead to a reduction of the investigated impacts (GHG emissions: 7–67%; energy use: 5–46%; land use: 6–64%). Additionally, afforestation of freed-up land from each diet portfolio leads to further emission removals of 4–37%. In comparison, using the land to produce energy crops for biomethane production could lead to 2–23% further CO^2-eq emission reductions when replacing fossil methane. If biomethane production is paired with carbon capture and storage, emission abatement is increased to 3–34%. This research indicates various short-term pathways to reduce GHG emissions with portfolio diet shifts. Utilising freed-up land for climate change mitigation strategies could prove essential to meet climate targets, but trade-offs with, e.g. biodiversity and ecosystem services exist and should be considered.

1. Introduction

With a growing global population and the increasingly adverse effects of climate change, sustainable transitions within the agricultural sector are important to reduce greenhouse gas (GHG) emissions, lower energy consumption, reduce land use for food production, and secure food supply. Bajželj et al. (2014) propose food-demand management to reduce GHG emissions in the agriculture sector through reducing over-consumption, food waste, and livestock product consumption. The Intergovernmental Panel on Climate Change (IPCC) special report ‘Climate Change and Land’ also emphasizes demand-side mitigation to reduce the environmental impacts of the food sector, also highlighting a decrease in food waste, reducing over-consumption, and changing diets (Mbow et al., 2019). Indeed, Hayek et al. (2020) find that global shifts towards plant-based diets are crucial to preserve a chance of limiting warming to 1.5 °C above pre-industrial temperatures, a climate change mitigation target outlined by the Paris Agreement (United Nations / Framework Convention on Climate Change, 2015). Theurl et al. (2020) also find that diets are the primary determinant of emissions within the food system, where ruminant meat and dairy have the highest emissions.

Currently, 60% of agricultural land in Germany is used for feed crops, and 49% of agricultural GHG emissions come from livestock (FNR, 2020; Rösemann et al., 2021). A large amount of feed is needed to raise livestock specifically. If crops used for livestock feed were instead used for food products, current global production could adequately feed a projected population of 9.7 billion in 2050 (Berners-Lee et al., 2018). To put this in context, approximately 2.8 kg and 3.2 kg of human-edible feed converts to 1 kg of ruminant (ex. cattle and sheep) and monogastric

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meat (ex. pigs and poultry), respectively (Mottet et al., 2017). Furthermore, cereals used to feed livestock have higher energy densities than meat. For example, barley contains 332 kcal/100g, while beef contains <250 kcal/100g (FAO, n.d.). Using Mottet et al.'s (2017) food-feed conversion, 100 g of beef would require approximately the equivalent of 320 g of barley. Thus, the direct consumption of barley instead of beef would, on average, be 4.25 times more energy efficient.

The difference in energy densities is reflected in the GHG emissions per gram of protein when comparing ruminant meat to protein-rich crops, i.e. legumes. For example, Tilman and Clark (2014) found that ruminant meat can emit 250 times more GHGs than legumes. The authors compared data from life cycle assessments (LCA) covering 150 studies with a system boundary of cradle to farm gate, which included emissions from pre-farm activities but excluded emissions from land-use change. Another study by Clune et al. (2016) found that the global average of beef emissions was 32 times more than legumes[1]—they analysed 369 studies with a system boundary of farm to regional distribution centre, including pre-farm activities. Nijdam et al. (2012) also reviewed 52 LCA studies to compare the carbon footprint of animal products to legumes, from cradle to farm gate. They found the average emissions from beef products were 50 times higher than the average GHG emissions of legumes. They also compared land use and found that producing beef used 40 times more land than legumes. Additionally, another study by Poore and Nemecek (2018) analysed 570 LCA studies from cradle to retail, including farming inputs. They found that beef had 25 times more GHG emissions and used 75 times more land than tofu, a commonly consumed legume. Therefore, while results may vary from study to study due to differences in, for example, system boundaries, regional conditions set in the LCAs, or conversion factors used to obtain a standard functional unit, each study came to the same conclusion—ruminant meat emits higher GHG emissions and requires more land than legumes when comparing grams of protein.

Meat diets generally are more emission- and resource-intensive than comparable vegetarian diets (Harris et al., 2020; Marlow et al., 2015; Meier and Christen, 2013). Thus, land, a finite and scarce resource, should be comprehensively managed to not only secure the provision of food but also to jointly supply material and energy, preserve biodiversity, and protect the climate (WBGU, 2021). When more land is devoted to food production, conflicts with several non-food sustainability dimensions increase. Indeed, one strategy, land-based climate change mitigation—e.g. afforestation/reforestation—specifically requires land to sequester or abate carbon and is an approach that combats climate change but also may contribute to land scarcity (Humpenöder et al., 2014). In Germany, 51% of land is already used for agriculture (Statistisches Bundesamt, 2019). Therefore, considering Germany's political aims of achieving carbon neutrality by 2045 and fulfilling international biodiversity targets (Müller et al., 2020), the competition between land use for food, afforestation, and other non-food uses will significantly increase and require new solutions and compromises (UBA, 2021a).

Another important aspect is Germany's current diet mix and the potential for change. Of the population of 83 million, 39% consume meat regularly, 55% identify as flexitarian—that is, meat-eaters that consciously abstain from eating meat on occasion, 5% identify as vegetarian, and 1% as vegan (BMEL, 2020a; Statistisches Bundesamt, 2020). Looking at meat consumption within the population, 57% of meat consumed is pork, 23% is poultry, 17% is beef and veal, and 2% is other meat, amounting to 57.3 kg of meat consumption per capita in 2020, or 1099 g/week (BLE, 2021). In comparison, the German Nutrition Society (Deutsche Gesellschaft für Ernährung- DGE) recommends only 300–600 g of meat per week in a healthy diet, 27–55% less than what is currently being consumed (DGE, 2020). Consequently, there is ample room to reduce meat consumption in the German diet.

Against this background, the question is how diet transitions could affect land availability and thus, increase the options for land-based climate change mitigation strategies in Germany. One such strategy is afforestation. Benefits of afforestation are carbon sequestration, increased biodiversity, reduced frequency of climate extremes, e.g. heat waves, through net changes in the biophysical effects—i.e. changes in, for example, albedo and evapotranspiration—and improved water quality (Cunningham et al., 2015; Krause et al., 2017; Smith et al., 2019). Another example of a land-based climate change mitigation strategy is bioenergy production. Biomass is, thus far, the dominant resource for producing renewable transport fuels. The European Union has prioritised advanced biofuels from residues and waste materials (Das Europäischen Parlament und der Rat der Europäischen Union, 2018, Annex 9), and it is expected that advanced biofuels could play a role in reducing the environmental impact of transport modes that are hard to electrify, such as aviation and long-haul commercial shipping (EASAC, 2019; Kahn Ribeiro et al., 2012). However, a complete shift to advanced biofuels is considered more of a long-term expectation. Chiaramonti et al. (2021), for example, reviewed different energy transformation scenarios of biofuels and found that advanced biofuels will play a prominent role in 2050, contributing an average of 36.5 Mtoe (million tonnes of oil equivalent). To put this to scale, Germany's overall energy consumption in the transport sector was 54 Mtoe in 2019 (Baumgarten et al., 2022). Additionally, under the EU RePower Action, a growth in biomethane production to save 650 PJ of imported gas has been recently announced (EC, 2022), which will drive the increase in generation in Germany.

Several previous studies have shown the potential of diet changes—especially decreased meat consumption—to reduce environmental impacts (Stehfest et al., 2009; Meier and Christen, 2013; Hedenus et al., 2014; Van Dooren et al., 2014; Westhoek et al., 2014; Hallström et al., 2015; Bryngelsson et al., 2016; Mertens et al., 2019; González-García et al., 2020). However, these studies focus on environmental impact reductions based on individual diets rather than diet portfolios. Additionally, Springmann et al. (2018) found that several mitigation strategies must be combined to keep the food system within planetary boundaries. They analysed diet change, food loss and waste reduction, and technology improvements and management in combinations. In this study, coupling diet shifts with land-based climate change mitigation options for GHG abatement is assessed. While there is a lack of research which analyses this coupling, one study by Zech and Schneider (2019) investigated the GHG mitigation potential of transitions to a healthy diet in the EU and then utilised the freed-up land for biofuel production. However, they focused on only one diet and only analysed biofuel production. Strapasson et al. (2020) also modelled the interconnected system effects of land-use dynamics, including utilising freed-up land for afforestation and bioenergy with diet changes. However, they did not define diet portfolios but focused on the general reduction of meat consumption, categorised in two scenarios. As well, instead of comparing afforestation and bioenergy production, they only used a combination of the two options.

Herein, 12 different diets with varying meat consumption are defined and utilised to determine 8 mixed diet portfolios with reduced percentages of the Business As Usual (BAU) diet. Next, the GHG emissions, land use, and primary energy use (PEU) impacts of these 8 diet portfolios are found. As diets richer in plant protein increase within the German population, land use for livestock production decreases, leading to freed-up or surplus land (Harwatt et al., 2017; Reijnders and Soret, 2003). Within this study, it is contextualised that this newly available land from the diet portfolio transitions can be used for afforestation, biomethane production, or biomethane production paired with carbon capture and storage. The effectiveness of each strategy to abate GHG emissions is compared. This study is novel because it defines a broad spectrum of individual diets and composite diet portfolios to simulate realistic rather than idealistic diet transitions. Alternative diet portfolios are important to reflect the heterogeneous personal nutrition preference

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[1] own calculation of emissions per g of protein based on beef and legume protein content from BNF (2018) and USDA (2019).

of the German population and, thus, better understand their consequences. Additionally, coupling land-based climate change mitigation strategies with diet shifts can aid in understanding the complex land-use dynamic driven by food and non-food uses. Here, afforestation and bioenergy production are compared as two strategies for land-based climate mitigation. Carbon capture and storage (CCS) is included in addition to bioenergy generation as a variation for further GHG abatement. The strengths and limitations of bioenergy and CCS (or BECCS) have been well researched (Azar et al., 2010; Fajardy and Mac Dowell, 2017; Fridahl and Lehtveer, 2018; Rosa et al., 2021), including a lack of policy incentives, the need for CO_2 transportation networks, and the benefit of BECCS in reaching GHG emission targets.

The German population (83.8 million) is incorporated to estimate whole-country impacts. GHG emissions, PEU, and land use impacts of agriculture abroad are implicitly included in the base data, which accounts for food product imports. The effects of diet transitions on German food trade exports are excluded to emphasise the contextual impact of diet change. It should be noted that Germany is a net importer of food commodities, though 33% of Germany's agricultural products are exported, mainly to the Netherlands, France, and Italy, and outside of the EU to the USA and China (BMEL, 2022a, 2020b). Focusing on Germany, this study aims to answer the following questions: (1) How could changes in diet portfolios, consisting of individual diet mixes, affect GHG emissions, PEU, and land use? (2) What is the potential for further GHG abatement when freed-up land from diet shifts is utilised for afforestation or bioenergy production?

2. Materials and methods

2.1. Definition and impact evaluation of diet portfolios

In total, 12 different diets were quantified. All diets were adjusted to 2000 kcal capita^{-1} day^{-1} to be comparable, based on the average German recommended kcal of adults ages 19–65 and older, in the 1.4 physical activity level (DGE, 2015). A physical activity level (PAL) is a standard unit used to express physical activity as a number. A PAL of 1.4 stipulates sedentary to light activity (FAO, 2004). Protein amounts in g capita^{-1} day^{-1} were also quantified for each diet to include an additional functional unit of comparison that addresses each diet's nutritional aspect (Table A3 and Fig. A1 in Appendix A). The quantified diets include 5 vegetarian diets, 5 meat-restricted diets, a Business as Usual (BAU) diet, and the Average German Recommended diet (AGR). A vegan diet and a flexitarian diet are included in the vegetarian diet mix and the meat-restricted diet mix, respectively. Please see Appendix A for detailed descriptions of the diet quantifications.

Diet portfolios were defined based on these 12 different diets to portray a plausible societal shift towards less meat consumption, along with three 100% portfolios to represent two contrasting diets (BAU and Vegan) and what can be considered a moderate diet (AGR). Mixed portfolios include 25% or more of the BAU diet and a combination of vegan, vegetarian, and restrictive meat diets to represent the diversity of consumer preferences. In the portfolios, the "vegetarian" and "restrictive meat" portions comprise an equal percentage of each of the 5 meatless diets or each of the 5 restricted meat diets, respectively. See Table 1 for descriptions and Table A1 for diet types.

Table 1
Diet portfolio names and descriptions.

Names	Descriptions
BAU	100% Business As Usual
10Vegan	90% BAU +10% Vegan
25RM	75% BAU +25% Restricted Meat
25Veg	75% BAU +25% Vegetarian
25Veg25RM	50% BAU +25% Vegetarian +25% Restricted Meat
50Veg25RM	25% BAU +50% Vegetarian +25% Restricted Meat
100AGR	100% Average German Recommended diet
100Vegan	100% Vegan

German environmental food impacts, compiled by Meier and Christen (2013) through life cycle inventory and life cycle assessment, were used to find CO_2-eq emissions, primary energy use (PEU), and land use for each diet. They define the system boundaries from cradle-to-store, which includes agriculture production, processing, transport and trade, and packaging. CO_2-emissions include direct land-use change, land use, and agricultural direct and upstream processes. PEU includes direct and upstream agricultural processes. Direct agricultural energy consists of fuels and electricity usage on the farm. Upstream processes are fertiliser and pesticide production, construction, and use of machinery and buildings. Land use impacts include domestic and abroad use, including arable land and grasslands. Additionally, Meier and Christen (2013) take into account the effects of food product imports by including environmental impacts of agriculture production abroad for food products with a degree of self-sufficiency far below 100%. The degree of self-sufficiency is defined as the extent to which domestic agriculture production can meet domestic demand. For more detailed descriptions of data compilation, please see Meier and Christen (2013) and the supporting information therein.

Each portfolio was defined based on decreasing the BAU diet percentage. These transitions could occur over time, based on the social norm effect, as Eker et al. (2019) describe. That is, with increasing vegetarian and restricted meat diets in the population, a shift to vegetarian and restricted meat diets becomes more prevalent.

2.2. Contextualisation: Land-based climate change mitigation

With resource-friendly diet changes, agricultural land in Germany can be freed-up if food trade volumes remain unchanged. Surplus land from diet changes is due to a shift in food products towards products rich in plant protein, which require less land for cultivation, as outlined in section 1. This land can be allocated to alternative land uses. Here, two land-based climate change mitigation options are compared: afforestation of cropland to sequester carbon and maize crop growth (for maize silage) for biomethane production to replace natural gas leading to GHG abatement. As a variation of biomethane production, carbon capture and storage (CCS) was included with biomethane generation as an additional option for further GHG abatement. As well, the contextualisation of land-based mitigation strategies is not based on a temporal development but rather on comparing fixed CO_2-eq removals through afforestation and CO_2-eq abatement through bioenergy production and biomethane production paired with CCS (henceforth BECCS-bioenergy, carbon capture and storage).

Freed-up land ($land_{freed-up,\ i}$) (where i refers to each diet portfolio) was determined using the BAU scenario as a base. As data from Meier and Christen (2013) included land use for each food product, freed-up land was calculated by computing the total land use of each diet portfolio and then subtracting this from the reference scenario. As the data included a distinction of land use for domestic and abroad agriculture, it was possible to solely utilise domestic land for the land-based mitigation strategies. Grasslands are not considered for afforestation or biomethane production, as Germany has committed to maintaining the 2012 amount of total grassland area (UBA, 2021b). As livestock production in Germany decreases, it is assumed that these grasslands can be extensively managed through occasional mowing, an alternative to grazing (Vogt et al., 2019).

Carbon sequestration through afforestation represents a relatively straight-forward approach for GHG abatement through carbon (C) removal. Here, afforestation data from Riedel et al. (2019) was used to represent CO_2-eq sequestration of biomass above and below ground. They estimate C sequestration from afforestation with mixed-species stands based on Germany's 2012 and 2017 National Forest Inventory, averaged over 20 years. Riedel et al. (2019) also assume the forests are managed. Their data, however, is not exclusively for afforestation of cropland. Thus, to overcome this discrepancy, soil organic carbon (SOC) data from cropland (Poeplau et al., 2020) and forests (Grüneberg et al., 2019) from Germany was used. A 30-year SOC equilibrium time frame is assumed (Nave et al., 2013; Brunn et al., 2017), in which the SOC of cropland changes to that of forest soils. Deadwood is not included in the analysis—in Germany's managed forest, deadwood accounts for ≤1% of the total stored C (BMELV, 2009; Wellbrock et al., 2017). The effects of harvesting woody biomass for bioenergy are not included. Total CO_2-eq emission removals ($Removals_{GHG_{Aff},\ i}$) of each diet profile i were found using freed-up land from diet shifts ($land_{freed-up,\ i}$) and annual average CO_2-eq sequestration per hectare (GHG_{seq}) (Eq. (1)). Please see Table 2 for data, symbols, and sources.

$$Removals_{GHG\_Aff,i} = land_{freed-up,\ i} \cdot GHG_{seq} \tag{1}$$

For simplicity, only biomethane was examined as a bioenergy product. Biomethane can be used as a natural gas replacement and can be directly infused into the natural gas network in Germany. Biomethane is very competitive among different biofuels in the German transport sector (Lauer et al., 2022; Millinger et al., 2017) and, therefore, a prominent example for contextualisation. The GHG abatement method of replacing fossil methane (natural gas) with biomethane was chosen due to the competitiveness of biomethane as a biofuel and its efficiency of being a one-to-one replacement with fossil methane (natural gas), which facilitates its injection into the natural gas network in Germany (Scholwin et al., 2020). Eq. (2) is used to find the yield of biomethane ($Y_{biomethane,\ i}$) of each diet profile i, based on the production of maize for maize silage. Maize was chosen for an energy crop due to the high methane content (52%) in the biogas produced therefrom (FNR, 2020). Biomethane emissions ($GHG_{biomethane,\ i}$) of each diet profile i were calculated based on Millinger et al. (2018). Details of the calculation can be found in Appendix A. Fossil emissions from natural gas stem from Exergia S.A (2015), where upstream and midstream emissions were included. For BECCS, a 40% CO_2 ratio was assumed in the gas mix. Details of the calculation can be found in Appendix A. The reduction of GHG emissions, $Reduction_{GHG,\ i\_m,c}$ of each diet profile i was calculated using Eq. (3), where m is biomethane and c is BECCS. Please see Table 2 data, sources, and symbols.

$$Y_{biomethane,\ i} = land_{freed-up,\ i} \cdot Y_{maize\ silage} \cdot \eta_{conversion} \tag{2}$$

$$Reduction_{GHG\_m,c} = \left(GHG_{fossil} - GHG_{biomethane,\ i}\right) \cdot Y_{biomethane,\ i} \tag{3}$$

2.3. Sensitivity of the system

In order to analyse the sensitivity of the system, diets portfolios of varying BAU diet percentages and meat intake were defined, as previously mentioned in section 2.1 (see Table 1). In determining a range of different diets, the effect each food product has on the defined diets and diet portfolios can be analysed. Three 100% diet portfolios (BAU, 100AGR, and 100Vegan) were defined to include the effects of two polar opposite portfolios (BAU and 100Vegan) and a moderate portfolio (100AGR).

For the contextualisation, the 95% confidence interval (CI) was used for the CO_2-eq sequestration of above and below biomass and SOC to depict the 95% interval range of values for CO_2-eq removals from afforestation. For biomethane production, ranges based on minimum and maximum values are given. The ranges for low and medium maize silage yields were used to depict a comparable range to the 95% CI used for afforestation. The same method is applied for BECCS. Due to this differentiation, data ranges from afforestation GHG removals and GHG abatement from biomethane production and BECCS are depicted separately.

3. Results and discussion

3.1. Impact evaluation of diet portfolios

Fig. 1 depicts the relative impacts based on the BAU portfolio. Absolute values of GHG emissions, primary energy use (PEU), and land use

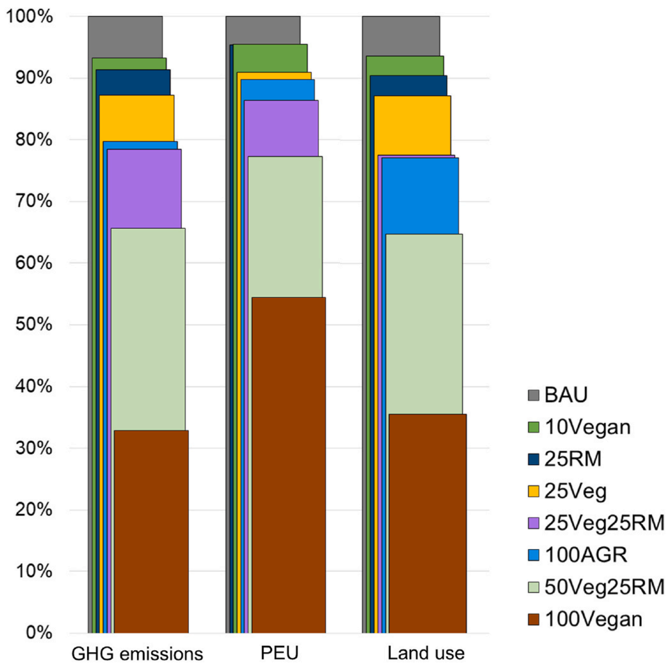

Fig. 1. Relative GHG emissions, primary energy use (PEU), and land use for each diet portfolio with BAU as a basis. Diet portfolio impacts are expressed as percentages of the Business as Usual (BAU) portfolio. See Table 1 and section 2.1 for further portfolio quantifications and descriptions. Impacts are based on data from Meier and Christen (2013), with a system boundary from cradle to store. Further information regarding sectors included in the system boundary can also be found in section 2.1. RM = Restricted Meat, Veg = Vegetarian, and AGR = Average German Recommended.

Table 2

Data and sources for calculating afforestation CO_2-eq removals and biomethane production (including CCS).

Symbol	Type	Unit	Value	Source
GHG_{seq}	CO2-eq removals	tCO2-eq/(ha·a)	14.35 ± 11.91	Grüneberg et al. (2019); Riedel et al. (2019); Poeplau et al. (2020)
$Y_{maize\ silage}$	Yield, FM, medium	GJ_{feed}/ha	268–327	KTBL (2012)
	Yield, FM, low	GJ_{feed}/ha	208–268	KTBL (2012)
$\eta_{conversion}$	Conversion efficiency	eta	0.56–0.70	Millinger et al. (2017)
$GHG_{biomethane}$	Biomethane GHG emissions	g CO2-eq/ kWh_CH4	33–85	Own calculation, see Oehmichen et al. (2016), Millinger et al. (2018), and Appendix A
GHG_{fossil}	Fossil methane GHG emissions	g CO_2.eq/ kWh_CH4	241	Exergia S.A (2015)
$Reduction_{GHG,\ i\_m}$	GHG abatement from biomethane replacing fossil methane	tCO_2.eq/(ha·a)	5.0–13.2	Own calculation, see Eq. 3
	GHG abatement incl. CCS	tCO_2.eq/(ha·a)	7.9–18.7	Own calculation with 40% CO_2 in the gas mix, Eq. 3

of each portfolio can be found in Table 3. 100Vegan provides the lowest relative impacts in all categories. It should be noted that 10Vegan, in which only 10% more of the German population switches to a Vegan diet, has a relative reduction of 7% GHG emissions, 5% PEU, and 6% land use, compared to the 100% BAU portfolio. As a middle ground scenario, 100AGR gives relatively lower impacts for each category (20% GHG emissions, 10% energy, and 23% land reduction). The 100AGR, thus, shows the effect of a more balanced diet, moving away from heavy meat, dairy products, and oil/margarine/butter intake, without the necessity of restricting any food products to reduce impacts. Indeed, Röös et al. (2018) also found that if meat consumption in Sweden were reduced by 50% and replaced with legumes, GHG emissions and land use would be reduced by 20% and 23%, respectively.

Behrens et al. (2017) also analysed emissions, eutrophication potential, and land use differences between BAU country diets and national recommendations. Comparatively, they found relatively higher impacts of approximately 14% reduction for GHG emissions and 16% for land use. The difference in values could be due to their methods, in which they scaled the national recommended diets up to the caloric intake of the average country diets, whereas herein, the caloric intake was scaled to the average recommended calories from the DGE (2000 kcal day^{-1}). Additionally, it could be due to the difference in source data, where they used FAO data for the BAU diet and EXIOBASE 3.3 (Wood et al., 2014) to find the environmental impacts. Energy use was not included in their study.

25Veg25RM has similar relative impact reductions to 100AGR (22% GHG emissions, 14% energy, and 23% land). This shows that a diet portfolio, which still consists of 50% of the BAU diet, can also lead to relevant reductions in the investigated impacts. To put this into context, these relative reductions can be compared to Germany’s overall GHG emissions (739 Mt CO_2-eq), electrical consumption (569 TWh), and land use (35.8 Mha) (Hein et al., 2020; Statistisches Bundesamt, 2019; UBA, 2021a). 25Veg25RM would lead to a decrease of 4% GHG emissions, 5% electrical consumption, and 9% land use. While these overall reductions for Germany may seem minor, it is important to note that these results are based on a scaled BAU diet of 2000 kcal day^{-1}. However, without kcal scaling, the BAU diet would have a caloric intake of 2983 kcal day^{-1}. Thus, further reductions could be found when comparing GHG emissions, electricity consumption, and land use without scaling the caloric intake of BAU. Indeed, Ranganathan et al. (2016) identify reducing per capita caloric intake as one method to reduce GHG emissions and land use.

3.2. Contextualisation

With a transition away from 100% BAU towards more plant-based diets, agricultural land is freed-up, as seen in section 3.1. As a contextualisation, this newly available land can be used for either afforestation or to grow maize crops for biomethane production, with or without carbon capture and storage (CCS). It is found that using the freed-up land from diet transitions can lead to further GHG abatement. Compared to the BAU portfolio emissions, using the freed-up land for afforestation achieves 4–37% GHG emission reduction through forest uptake of atmospheric carbon (negative emissions). In comparison, biomethane production and replacing fossil methane achieves 2–23% GHG emission reduction, and when paired with CCS, 3–34% reduction (Fig. 2a, Table 3 for absolute values). These reductions also reflect how increasing land is freed-up as meat consumption is reduced within the population.

It is found that afforestation can achieve almost double the GHG

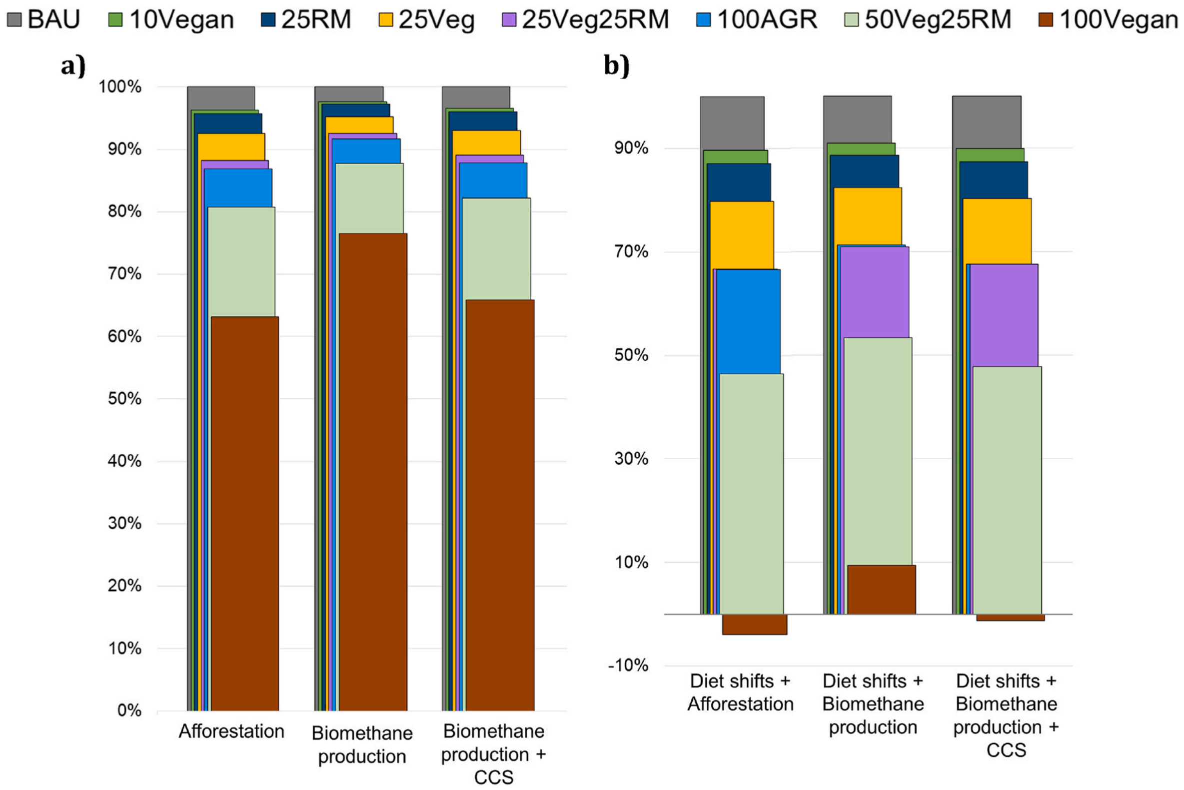

Fig. 2. a) Relative GHG emissions of the diet portfolios considering afforestation, biomethane production and BECCS. Portfolio GHG emissions are expressed as percentages of the Business as Usual (BAU) portfolio. Biomethane reductions are based on replacing natural gas. No losses are assumed for CCS. **b) Total relative emission abatement of diet shifts, afforestation, biomethane production, and BECCS.** Total emission abatement is found by combining GHG reductions of both diet shifts of each portfolio and land-based climate change mitigation from afforestation, biomethane production, and biomethane production with CCS. No losses are assumed for CCS. RM = Restricted Meat, Veg = Vegetarian, AGR = Average German Recommended, CCS = Carbon Capture and Storage, and BECCS = BioEnergy Carbon Capture and Storage (in this case, biomethane production).

abatement per land unit compared to biomethane replacing fossil methane. With that, Riedel et al. (2019) report that CO_2-eq sequestration is at its highest between 20 and 40 years, whereas in this study, an average of the first 20 years of CO_2-eq sequestration is used. For GHG abatement from biomethane production, further reductions could be found if compared directly to other fossil fuels, instead of only natural gas. For the case of this study, natural gas is replaced as this could be considered the most realistic benchmark. However, GHG abatement could also be achieved by replacing other liquid or gaseous fossil fuels (Ferreira et al., 2019; Pääkkönen et al., 2019), shale oil or gas (Ogunsola et al., 2010; Heath et al., 2014). If CCS is utilised with biomethane production, similar GHG emission abatement to afforestation can be achieved. These results are comparable to Humpenöder et al. (2014), who found that afforestation and bioenergy generated from lignocellulosic biomass paired with CCS results in similar GHG abatement for their time horizon. Harper et al. (2018) found that carbon savings from BECCS is highly dependent on energy crop type, bioenergy produced, and the type of fossil fuel replaced. They suggest that afforestation/reforestation may result in more effective carbon sequestration if BECCS involves replacing ecosystems with high carbon stocks. Cronin et al. (2020) also found that afforestation achieves 5 $GtCO_2$ a^{-1}, compared to 4 $GtCO_2$ a^{-1} for BECCS in their core scenario. They utilise a combination of bioenergy resources, including biogas, bioliquid, and woody biomass. Literature results comparing bioenergy production and afforestation are, however, limited and usually include CCS technologies.

Another interesting aspect is the amount of biomethane that could be used in the transport sector. The Renewable Energy Directive 2018/2001/EU defines a 14% renewable energy fuels mandate in the transport sector by 2030 (EC, 2021). From the contextualisation herein, the share of biomethane could increase from its current 0.1% (FNR, 2020) to a range of 3–29%. As mentioned in section 1, Zech and Schneider (2019) investigated healthy diet transitions in the EU and the effect on biofuel production. They found that biofuel amounts could increase 8-fold, and 14% of GHG emissions in the EU transport sector could be abated.

When coupling emission reductions from diet shifts with GHG abatement gained from afforestation, biomethane production, and BECCS, an overall decrease of 10–104%, 9–90%, and 10–101% is found, respectively (Fig. 2b, Table 3 for absolute values). Most interesting is the 100Vegan portfolio coupled with afforestation, which results in negative emissions, i.e. a net uptake of atmospheric carbon. Similar results can be achieved with BECCS. These reductions can also be compared to Germany's total GHG emissions, 739 Mt CO_2-eq (UBA, 2021a). Diet shifts coupled with afforestation achieves an overall 2–18% net GHG emission reduction, while diet shifts connected with biomethane production replacing fossil methane can achieve a 2–16% net GHG emission reduction. BECCS attains a 2–18% emission abatement. To compare, diet shifts alone achieve a 1–12% reduction in Germany's total GHG emissions.

These results can also be compared to Strapasson et al. (2020). They defined a low emission scenario of land use, which included reduced meat consumption and used surplus land (freed-up land) for 40% energy crop production and 60% afforestation through natural regrowth. Their scenario also included net self-sufficiency of plant and meat foods and a reduction of food calories consumed. They found a reduction in emissions by 29% for the EU. While this outcome cannot be directly compared to the results herein, considering calorie reduction and system self-sufficiency were not included, and Germany is the focus, similar net emission reductions are found for the middle ground portfolio, 100AGR, considering GHG abatement from diets shifts in addition to afforestation or biomethane production. These reductions are based on the GHG emissions from the BAU portfolio. They are 33% for afforestation with diet shifts and 29% for biomethane production coupled with diet shifts (Fig. 2b). As Strapasson et al. (2020) do not include CCS, BECCS results cannot be compared.

Coupling land-based climate change mitigation strategies with demand-managed diet shifts could be an effective mixed strategy to reach climate targets set in Germany and globally. However, trade-offs exist; for example, changes in albedo (the portion of light/radiation reflected from the Earth's surface) could occur, though reforestation/afforestation has a higher warming potential than energy crop production (Smith et al., 2015). Albedo changes are emphasised in northern latitudes due to changes in reflection during winter months when snow cover would typically reflect large amounts of radiation (Smith et al., 2015). Additionally, risks of increasing the cost of food could also occur, especially if negative emission technologies are more incentivised (Kreidenweis et al., 2016; Popp et al., 2014; Reilly et al., 2012).

3.3. Sensitivity of the system

When analysing the system's sensitivity, a range of 43–131 Mt CO2-eq a^{-1}, 117–215 TWh a^{-1}, and 5–14 Mha a^{-1} is found for the diet portfolios between no diet shift (BAU) to a progressive shift (100Vegan). The moderate diet shift (100AGR) gives 104 Mt CO2-eq a^{-1}, 193 TWh a^{-1}, and 11 Mha a^{-1}. From the results, dairy products have the highest effect on the diet portfolio impacts, followed by ruminant meat products. This can be gathered from the relatively high impact of 100AGR, which does not restrict dairy or meat products, compared to 100Vegan, which only includes plant products. Also, data used for food impacts is only from farm-to-store. Thus, further household impacts could impact each product's GHG emissions and energy use.

Sensitivity results from afforestation show that with higher GHG removals, there is higher uncertainty (Fig. 3a). In the case of 100Vegan, GHG removals could range from 8 to 88 Mt CO_2-eq ha^{-1} a^{-1}, almost a factor of 10. Afforestation results depend on the soil organic carbon (SOC) data used in this study from Poeplau et al. (2020) and Grüneberg et al. (2019) and afforestation values from Riedel et al. (2019). This data is based on statistical information specific to Germany. It does not include deadwood and litter, though deadwood was found to store $\leq$1% of forest carbon in German (BMELV, 2009). Additionally, SOC results are based on the assumption that crop soil will reach forest soil equilibrium after 30 years (Nave et al., 2013; Brunn et al., 2017). However, other studies have found that, after afforestation, SOC is stagnant or undergoes initial losses in the first 30 years before any gains occur (Li et al., 2012; Bárcena et al., 2014).

Nonetheless, the rate of C-sequestration in soil is less than in biomass

Table 3
Absolute values of impacts from diet shifts and CO_2-eq emission abatement due to afforestation, biomethane production, and BECCS.

		Unit	BAU	10Vegan	25RM	25Veg	25Veg 25RM	50Veg 25RM	100AGR	100Vegan
Diets	GHG	Mt CO_2-eq/a	131	122	119	114	102	86	104	43
	Energy	TWh/a	215	205	205	195	185	166	193	117
	Land use	Mha/a	14	13	12	12	11	9	11	5
Afforestation		Mt CO_2-eq/a	0	1–9	1–10	2–18	3–28	4–46	3–31	8–88
Biomethane production		Mt CO_2-eq/a	0	2–4	2–5	3–9	5–14	9–23	6–16	17–44
BECCS		Mt CO_2-eq/a	0	3–6	3–7	5–13	8–20	14–33	9–22	26–63

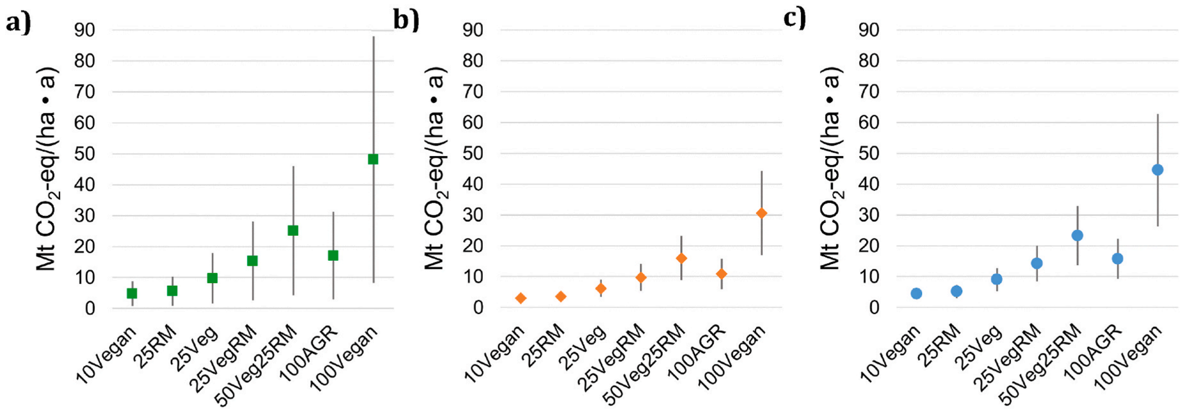

Fig. 3. a) Afforestation minimum, maximum, and mean GHG sequestration values, based on the 95% confidence interval in Mt CO_2-eq/(ha · a). The green square point represents the mean. Lines below the mean point represent the minimum 95% confidence interval. Lines above the mean point represent the maximum 95% confidence interval. b) Biomethane production minimum, maximum, and mean GHG abatement values in Mt CO_2-eq/(ha · a). The orange diamond point represents the mean. Absolute minimum and maximum values were used to depict a value interval. c) BECCS minimum, maximum, and mean GHG abatement values in Mt CO2-eq/(ha · a). The blue circle point represents the mean. Absolute minimum and maximum values were used to depict a value interval. No losses are assumed for CCS. RM = Restricted Meat, Veg = Vegetarian, AGR = Average German Recommended, CCS = Carbon Capture and Storage, and BECCS = BioEnergy Carbon Capture and Storage (in this case, biomethane production).

of temperate forests (Lal and Lorenz, 2012). Afforestation data of above and below-ground biomass from Riedel et al. (2019) is not specific to cropland area but to all afforested areas in Germany between 2012 and 2017. This is due to the lack of studies specific to Germany for cropland afforestation. This data is also an average of the first 20 years of afforestation. While Riedel et al. (2019) have found that afforestation is at its peak C-sequestration between 20 and 40 years, Luyssaert et al. (2008) have also found that forests, age 15–800, continually sequester carbon and remain net carbon sinks throughout their lifetime. Furthermore, afforestation data used within this study also includes the effects of forest management according to Article 3.4 of the Kyoto Protocol (UN, 1998). Different forest management regimes, including no management, will impact the amount of carbon sequestered. To date, there is a lack of literature consensus regarding the effects of forest management (Bellassen and Luyssaert, 2014). While there is evidence that unmanaged forests achieve higher sequestration than managed forests (Borys et al., 2016; Noormets et al., 2015), others find that forests of a certain age cease to be net carbon sinks (Gower et al., 1996; Lippke et al., 2014). Due to the uncertainty of forest management impacts, it is challenging to ascertain optimal scenarios for carbon sequestration.

The GHG emissions of energy crop production depend to a large extent on yields and, e.g. area-based field emissions of e.g. N_2O, which may differ substantially (Skenhall et al., 2013; Millinger et al., 2017), though maize silage achieves among the highest yields of energy crops in Germany (KTBL, 2012). Moreover, the anaerobic digestion of maize silage attains relatively high conversion efficiencies compared to other biofuel production processes (Millinger et al., 2021). The process of upgrading biomethane has been well developed, is state-of-the-art, and efficient (Abdalla et al., 2022). Furthermore, upgrading biogas to biomethane involves the separation of CO_2, which enables carbon dioxide removal (CDR) if the captured carbon is stored long-term (CCS). The upgraded biomethane can directly substitute fossil methane. Thus, biomethane produced through anaerobic digestion of maize silage achieves a very high GHG abatement per land unit compared to other biofuel options. Still, this study's results show that the GHG abatement of biomethane is clearly lower than that of afforestation, though it achieves more comparable results when paired with CCS.

The uncertainty ranges of the GHG sequestration of afforestation and the GHG abatement of biomethane overlap (Fig. 3). However, both similarly depend on soil and location-specific conditions affecting yields; thus, afforestation and biomethane yields are correlated. Thereby, for a given plot of land, afforestation would achieve more GHG abatement than would maize silage-based biomethane production.

3.4. Limitations and further research

Findings within this study are intended as approximations of real-world diets, and thus, GHG emissions, PEU, and land use of these diets. They are meant to outline short-term climate change mitigation strategies through the demand-side of the food sector and emphasise how land use within the agriculture sector is affected by consumer preference. However, the defined diets and diet portfolios are not based on population statistics, limiting the reality of the German personal preference within the study. Specifically, diet portfolios are proposed to represent diet transitions away from the BAU diet while also incorporating a more realistic diet mix. They are based on random assimilation of the 12 diets defined within this study. These diets represent the social norm effect within the population; that is, the extent of a particular diet within a society further increases a shift to that specific diet, as Eker et al. (2019) describe. However, for more realistic diet representations, further studies should strive to incorporate survey results, as in Heuer et al. (2015). Further, the methods used to define each diet do not consider all macronutrients and micronutrients. Due to this, some of the defined diets could be unbalanced in this regard. Incorporating this aspect, such as in Hallström et al. (2014) or Payne et al. (2016), would bring additional value to further studies by analysing the health benefits or lack thereof for such diet transitions.

Additionally, focusing on the over-consumption of the BAU diet could gain a more realistic result of its impact by comparing its total caloric intake to a diet shift which reduces overconsumption. The German BAU diet has an average consumption of 2983 kcal day^{-1} (own calculation from BZL (2019), excluding sugar, beverages, and stimulants). This is 33% more than the average recommended intake (considering an average recommended intake of 2225 kcal day^{-1}). Reducing over-consumption is one option for demand-side management to reduce the environmental footprint of the food sector (Mbow et al., 2019). Thus, incorporating the reduction of over-consumption into the analyses could provide additional insights into the effect of food-demand management while including a more realistic assessment of the BAU diet. In general, examining total food system GHG abatement measures could lead to a better understanding of reduction potentials, as in Clark et al. (2020). Future work should not only include food-demand management or caloric reduction but also improved management and technologies, reducing food loss and waste, and sustainable production.

In general, diet shifts would not only affect GHG emissions, land use, and PEU but other environmental impacts and ecosystem services. In particular, the interconnectivity of the food sector with biodiversity is an increasingly important relationship to understand due to the complex synergies and trade-offs. For example, negative drivers from agricultural production have been found to affect pollinators and soil-dwelling organisms, which, in turn, would affect crop production (FAO, 2019). Livestock grazing, specifically, can have a negative impact on species such as pollinators and herbivores (Alkemade et al., 2013; Filazzola et al., 2020; Outhwaite et al., 2022). However, livestock grazing can also maintain grasslands and positively affect plant biodiversity (Chabuz et al., 2019; Tälle et al., 2016). Additionally, water use is another aspect that would be impacted by shifts towards plant-based diets. Studies have found that meat products use higher amounts of green water (rainwater) compared to plant products (Harris et al., 2020; Kim et al., 2020). Additionally, Leip et al. (2015) found that livestock production accounts for more than half of the environmental impacts of the agricultural sector—for example, 78% of terrestrial biodiversity loss, 80% of soil acidification, and 73% of water pollution. Thus, further research should also include the effects of diet change on other environmental impacts and ecosystem services to gain a more robust insight.

The contextualisation in this study depicts idealistic land-use scenarios, which, in the case of biomethane production with only maize silage, would be detrimental to other environmental aspects. Monocultures generally negatively impact aspects such as biodiversity, pesticide use, and soil health (Bunzel et al., 2014; Franzluebbers et al., 2014; Figuerola et al., 2015; Crews et al., 2018). In addition, complete afforestation may not be realistic with the growing population and food security due to the large amount of land required (Doelman et al., 2020). On the other hand, maximising afforestation can benefit regional biodiversity and water quality (Cunningham et al., 2015). Further studies should focus on balancing the synergies and trade-offs of these land-based climate change mitigation strategies with regard to food security and environmental sustainability.

Another critical aspect of the interconnected system of the food and land-based climate change mitigation strategies is the effect of diet change on secondary agricultural products, such as waste products and residues. Transitions towards more plant-based diets could lead to reduced manure and slurry availability and increased agricultural residues. Changes in the amount of available waste and residue resources could significantly impact bioenergy generation, considering that 67% of wastes and residues (including trade and industrial residues) in Germany are used by the energy sector (Szarka et al., 2021). To the best of the authors' knowledge, this system relationship has yet to be examined in the literature. An additional facet of this system is the connection between afforestation and bioenergy, where woody biomass from afforestation could be utilised to also produce bioenergy. With the appropriate policies to protect forests from being intensively managed, woody bioenergy could lead to further net GHG abatement (Favero et al., 2020).

Lastly, in a globalised world, and especially within the EU, diet shifts limited to the German population would more likely lead to increased exports, for example, of meat and dairy products. In 2021, Germany was a net importer of live animals and a net exporter of meat, meat goods, and dairy goods (excluding butter) (BMEL, 2022b, 2022c). With reduced meat and dairy consumption in Germany, imports of live animals could decrease, while exports may increase to compensate for reduced domestic demand. Results from Tukker et al. (2011) reflect this effect with reduced meat diet changes in the European region, leading to increased meat exports. Thus, further studies should examine agricultural trade relationships of the EU or globally in order to obtain a comprehensive view of the effects of country and region-specific diet portfolio shifts.

4. Conclusions

This study's findings outline different portfolios, representing holistic diet mixes of the German population, which could reduce GHG emissions, energy use, and land use compared to the current diet mix. It is found that the defined portfolios lead to GHG emission reductions of 7–67%, primary energy use reductions of 5–46%, and reductions in land use for food production of 6–64% when compared to the Business as Usual portfolio. A general trend of increasingly lowered GHG emissions, primary energy use, and land use is found with a move away from the current German diet mix towards diets with higher plant protein shares. Additionally, using the freed-up land for afforestation achieves a further GHG abatement of 4–37% compared to the current diet mix. In contrast, using the land for maize silage cultivation to produce biomethane and replace fossil methane achieves a 2–23% GHG abatement. Afforestation, thus, results in approximately twice the GHG abatement per unit of land compared to biomethane. However, if biomethane production is combined with carbon capture and storage, a 3–34% emission abatement can be attained. While these strategies could be beneficial in their own way—that is, biomethane production as fuel replacement in aviation and long-haul shipping and afforestation for long-term carbon storage—both also have their trade-offs. Land competition could lead to increased food costs, and large-scale energy crop cultivation which could negatively impact the surrounding ecosystems, and afforestation could lead to reduced ecosystem services and changes in albedo. Thus, further studies should examine these effects to investigate the balance of trade-offs and synergies. Nevertheless, this study's results convey how consumer diet preference affects land use within the agricultural sector. This work is important to understand demand-side effects on the food system and coupled land-based climate change mitigation strategies for further GHG abatement.

CRediT authorship contribution statement

Katrina Chan: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Markus Millinger:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Supervision. **Uwe A. Schneider:** Methodology, Writing – review & editing, Supervision. **Daniela Thrän:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134200.

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