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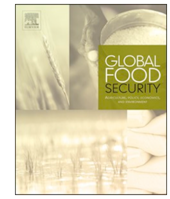

Methodological choices drive differences in environmentally-friendly dietary solutions

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ABSTRACT

Much scientific literature proposes reduction of animal-source foods to reduce environmental impacts of the food system. However, these dietary solutions differ regarding level and type of animal-source foods. We review this literature and our results show that these differences relate to differences in employed methodological approaches. Approaches that consider systemic consequences throughout the food system propose to limit livestock to low-opportunity-cost feed, where feed availability drives level and type of animal-source foods, resulting in poultry and pork being reduced most. Approaches with fixed impacts propose to reduce animal-source foods depending on current impact intensities, suggesting largest reductions for beef. By linking differences in dietary solutions to methodological approaches, our results contribute to informed choices of researchers, policy makers, and consumers.

1. Introduction

The current food system – that is all the processes involved in feeding the global human population – connects some of the most pressing environmental challenges of our times. It contributes significantly to approaching or transgressing planetary boundaries (Steffen et al., 2015), such as climate change or the biochemical flow of nitrogen and phosphorus (Campbell et al., 2017). In recent years reducing the environmental impact of the food system has received increasing attention. Next to studies comparing environmental impacts of different production systems (Poore and Nemecek, 2018; Seufert and Ramankutty, 2017), several studies reviewed the environmental impacts of various dietary scenarios (Aleksandrowicz et al., 2016; Hallström et al., 2015; Jones et al., 2016; Ridoutt et al., 2017). Willett et al. (2019) subsequently related environmental impacts of the food system to total resource and emission budgets. They proposed a safe operating space for food systems by defining targets for human diets and for food production. Further, Van Zanten et al. (2018) defined a land boundary for sustainable livestock consumption by reviewing studies that assessed scenarios based on low-opportunity-cost livestock (LOCL) – LOCL describes livestock raised on non-food competing feed, such as food processing by-products, food waste, and grass resources – and comparing them to studies assessing vegetarian or vegan diets.

Recent solutions for keeping the food system within the planetary boundaries often comprise a set of actions targeting both production and consumption aspects. On some dietary solutions, there is agreement among scientists regarding their environmental benefits. This is for example the case for the reduction of animal-source food (ASF) in high-income countries (Poore and Nemecek, 2018; Van Zanten et al., 2018; Willett et al., 2019). However, disagreement arises as soon as these dietary solutions are assessed in more detail, for example regarding which types of ASF should be reduced and by how much (Ridoutt et al., 2017; Schader et al., 2015; Van Zanten et al., 2018). Disagreement also prevails with regard to how production systems should look like (Muller et al., 2017; Poore and Nemecek, 2018). While some studies conclude that ASF from monogastric animals (mainly pork and poultry) should be favoured over ruminants, others argue that grassland-based ruminant production can contribute to food security by avoiding competition with resources that could be used for direct human food production. Understanding why these differences in dietary solutions for sustainable food systems and diets occur is highly relevant, as such dietary solutions based on scientific results serve as evidence base for environmentally-oriented dietary guidelines as well as policy making.

Therefore, we aim to investigate in which way these differences in dietary solutions can be explained by differences in methodological approaches. To this end, we reviewed scientific studies that compared environmental impacts of human diets in order to identify conformity as well as differences in dietary solutions. Further, choices that need to be taken to specify the type of dietary scenario and the modelling approach used to assess the environmental impact of human diets, hereafter denoted by approach-related choices, are assessed within the reviewed studies. These approach-related choices are then grouped to

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typical methodological approaches and related to dietary solutions in order to understand why different dietary solutions occurred.

2. Material and methods

We conducted a review of scientific literature to investigate how approach-related choices affect the differences in dietary solutions derived from assessments of the environmental performance of different diets. We applied keyword search, Boolean operators, and screened references of recent review articles to identify relevant articles. More information on the review approach can be found in the Supplementary Material S1.

Following the literature search, all articles were scanned and qualitative information on choices that are required in the process of calculating environmental impacts of dietary scenarios were collected. These approach-related choices were first deduced from the life cycle assessment (LCA) framework, as LCA was the most commonly used method to calculate environmental impacts in the papers reviewed (37 out of 56 studies). Seven choices are directly deduced from the LCA framework: definition of the 1) system boundary, 2) functional unit, 3) impact categories, 4) allocation, 5) inventory analysis, 6) impact assessment, and 7) treatment of consequences. Further, as in dietary scenarios also absolute restrictions on resource availability and on sink capacities become important, an additional approach-related choice was identified: 8) restrictions on resource availability and on sink capacities for emissions. Based on the qualitative information collected for the approach-related choices, the possible values for each choice were defined (thus, e.g. for the approach-related choice 'system boundary', the values are ‘cradle-to-farm-gate’, ‘cradle-to-distribution’, etc.; see Supplementary Material S2). In a next step, all studies were reviewed a second time, where the defined values of each approach-related choice were assessed (see Supplementary Material S2). Then, based on prevailing combinations of values of several approach-related choices, typical methodological approaches for scenario specification and environmental impact assessment were identified.

The dietary solutions in the studies were compiled as follows: on the one hand, dietary scenarios were quantitatively assessed, by extracting the consumed amount per food group per person. On the other hand, reduction of ASF was specifically assessed as follows: first, reduction solutions per ASF category were identified. Second, the suggested optimal range per ASF was classified as follows: as low as possible, intake based on LOCL, or a (nationally) recommended level. Third, the solutions for substitutes to compensate the reduction in nutrient intake were assessed.

Finally, congruent as well as differing dietary solutions among methodological approaches were identified, and their implications for possible food system states were discussed.

3. Results

We first describe general characteristics of reviewed studies. Subsequently, we introduce the approach-related choices and present results on their values as utilised in the reviewed studies. Following this, typical methodological approaches are proposed, and the dietary solutions for reducing the environmental impact of the food system presented. Then, congruent and differing dietary solutions are identified and related to typical methodological approaches.

3.1. General characteristics

In total, 56 studies were identified that fulfil all inclusion criteria (see Supplementary Material S2). The geographical scope of these studies varied; 32 performed a national, 11 a regional, and 13 a global assessment. Further, more than half of the studies (n = 33) performed an assessment for current circumstances, whereas 23 studies employed a future temporal scope.

3.2. Approach-related choices

3.2.1. System boundary

System boundaries describe the boundaries of the system studied; thus, the main focus is on which stages of the production process are included. In a wider context, also temporal and geographical scope contribute to the system boundaries. The studies covered the production stages as follows: 16 studies considered impacts from cradle-to-farm gate, 8 from cradle-to-distribution/retail, 15 from cradle-to-consumer, and 10 from cradle-to-grave. For 7 studies the system boundaries could not be detected in the description of the methods, or differing system boundaries were used for different food groups.

3.2.2. Functional unit

In the studies reviewed, the functional unit assessed is rarely mentioned explicitly. Implicitly, the functional unit can be derived from the temporal scope and the fraction of the population assessed. Different diets are thus compared on the basis of nutritional value per part of the population per time frame (e.g. kcal/person/day).

3.2.3. Impact categories

Resulting from our inclusion criteria, all studies assessed greenhouse gas (GHG) emissions (n = 49) and/or land use (n = 35). Further, 10 studies include indicators related to nitrogen and/or phosphorus surplus, 6 assess eutrophication and/or acidification, and 7 assess fossil energy use. Only 3 studies employ an indicator related to biodiversity (biodiversity damage potential (n = 2) and extinction rate (n = 1)).

3.2.4. Allocation

When a process has multiple outputs, the total resulting environmental impact needs to be allocated to each individual output. According to the ISO-guidelines (Finkbeiner et al., 2006), allocation should be avoided whenever possible, by increasing the level of detail or using system expansion. If it is unavoidable, physical or economic relations should be employed to allocate.

For the assessment of diets, it is not only relevant which allocation method is applied, but also how co-products, i.e. products that result from the same process (such as milk and ruminant meat), are treated in the assessment after allocation has taken place. Two approaches are prevailing: first, to follow a product, and second, to follow nutrients. Approaches that follow products allocate the total resulting environmental impact based on the chosen allocation method (mostly economic allocation). Then, products that are not of primary interest are allocated out of the system boundary of the study; thus, they are allocated a share of the environmental impact, but are not included in the subsequent analysis. An example for this would be a vegetarian scenario, where human diets contain milk produced by ruminants, but the associated meat is not considered in the consumption. Even though the environmental impact of dairy farming is also partly allocated to the associated meat, it is not included in the total environmental impact of a vegetarian diet, and is thus allocated out of the system. In literature, approaches that follow products mainly base their environmental impacts upon factors from single product LCAs (n = 41). Approaches that follow nutrients, however, steer their analysis not on product, but on nutrient level, and therefore, after allocation, trace nutrients and thus keep all products with relevant nutrients in the system. Following nutrients complicates the modelling, as links between co-products have to be considered throughout the assessment. Following nutrients (n = 15) is employed for example in mass- and nutrient-flow models.

3.2.5. Inventory analysis

In the inventory analysis, resource use and emissions to air, water, and soil of all inputs and outputs of processes that fall into the previously defined system boundary are inventoried. Thus, inventory analysis refers to the data that are used as basis for the calculation of environmental impacts. Here, the approaches reviewed differ in their

Table 1
Approach-related choices that are considered for the definition of typical methodological approaches on scenario specification and environmental impact assessment (in italics: values per approach-related choice).

Approach-related choices	Typical methodological approaches: scenario specification		Typical methodological approaches: environmental impact assessment	
	Consumption-oriented	Resource-oriented	Fixed impact assessment (FIA)	Systemic consequences analysis (SCA)
System boundary				
Functional unit	X	X		
Allocation				
Follow products	X		X	
Follow nutrients		X		X
Inventory analysis				
Product level			X	
Systems level				X
Impact assessment				
Consequences				
No			X	
Yes				X
Restrictions on resource use and sink capacities				
No	X		X	
Yes		X		X

starting level, i.e. whether they conduct a bottom-up or a top-down inventory.

On the one hand, we identified studies that conducted a bottom-up inventory (n = 43), using a product level approach. Then, by assuming a linear relationship, the product level inventories are scaled up to the level of the functional unit (e.g. inventory made for 1 kg of carrots; then, if the assessment is done for the population of Germany, the inventory for 1 kg of carrots is scaled up to the amount that is consumed in the diet of the German population). On the other hand, studies that conduct a top-down inventory analysis (n = 13) start from aggregated values and allocate based on nutrient requirements, for example (thus, they take e.g. the total emissions attributed to fertiliser application on agricultural areas in a certain region and distribute them to the single crop products based on the relative nutrient requirements of the different crops).

3.2.6. Impact assessment

Impact assessment is conducted by applying characterisation factors to the emission and resource inventories. Thus, for e.g. GHG emissions, factors are applied to bring all different GHGs to a common unit. These commensurable values are then added up. For GHG emissions, global warming potential over a time frame of 100 years is most often used, but there is some discussion on whether or not this is the most appropriate measure, in particular for methane which shows considerably different warming dynamics over time than CO_2 (Persson et al., 2015).

3.2.7. Consequences

When assessing diets on a national, regional or global level, changes in diets are likely to cause a cascade of changes in production systems and trade patterns. As a result, the environmental impacts per reference unit may change as well. In the modelling process, one has to decide how such consequences of changes on environmental impacts are treated. One possibility – which is abundant in literature (n = 38), is to ignore the consequences and thus keep environmental impacts per reference unit constant (mostly by using attributional LCA factors). Another approach is to follow consequences of changes for single products by applying consequential LCA (n = 2). The third option how to deal with consequences is to apply a modelling approach that captures the interlinkages between relevant processes and calculates the environmental impacts per reference unit endogenously (n = 16). By this, it is possible to trace the resulting consequences. However, such an approach requires more modelling complexity, which then might require simplifications in other aspects (e.g. regarding the level of detail in crop coverage). Examples for such modelling approaches are biophysical models (e.g. (Bajželj et al., 2014; Erb et al., 2016; Muller et al., 2017) or material flow analysis (Thaler et al., 2015).

3.2.8. Restrictions on resource availability and on sink capacities for emissions

Absolute restrictions on resource availability and on sink capacities for emissions and the resulting scarcities (called 'restrictions on resource use and sink capacities' in the following) become relevant when diets are assessed for a broader spatial scope. Thereby, restricted resource availability refers to water scarcity or availability of land of a certain quality, for example, while the limitations on sink capacities become relevant in the context of carrying capacities of ecosystems, e.g. for nutrient inflows. However, estimating the contributions of the food system for a broader spatial scope and therein also in relation to other activities and how to include those in the assessment can be complex. Taking the example of land use, land quality differs drastically between regions, which implies differing comparative advantages for different crop and livestock varieties (Zabel et al., 2014). Feed produced on arable land competes with direct crop production for humans, while feed sourced from grassland unsuitable for human food production can contribute to food security by allowing to use additional area and associated biomass for the production of human-edible ASF. Of the studies reviewed, 17 consider resource scarcities and limited sink capacities in relation to the food system in their assessment, while 39 do not.

3.3. Typical methodological approaches

The approach-related choices identified above potentially affect the outcome of the studies regarding solutions for environmentally-friendly diets. Thereby, we can discern two broad areas where the choices can become relevant, either via the way how scenarios are specified (not to be confused with specific scenario assumptions, e.g. the level of bioenergy use), or via the way how the environmental impact assessment is undertaken. Based on prevailing combinations of values of approach-related choices in the studies reviewed, typical methodological approaches for scenario specification and for environmental impact assessment were identified, see Table 1. These typical methodological approaches can be applied to most of the studies, but not all; for scenario specification, four studies do not fit into the proposed typical methodological approaches, and for the environmental impact assessment, seven studies (see Supplementary Material S1). We will first present the case of the approach-related choices regarding functional unit, impact categories, allocation, and restrictions on resource use and sink capacities that become effective via the way how scenarios are specified. Subsequently, we present the case of the choices regarding allocation, inventory analysis, consequences, and restrictions on resource use and sink capacities that become effective via the environmental impact assessment. Choices regarding system boundaries and impact assessment are not further pursued, due to a lack of indication to affect the outcome of the studies.

3.3.1. Scenario specification

The choices regarding functional unit and impact categories affect scenario specification in a general way, and are thus explored first. Then, two typical approaches for the specification of scenarios, based on the choices regarding allocation and restrictions on resource use and sink capacities, are proposed: **resource-oriented scenario specification** and **consumption-oriented scenario specification**.

The functional unit employed differs between studies, but can also differ within studies, by varying amounts of foods and thus micro- and macronutrients. In scenarios that are not isocaloric, effects of changes in dietary patterns are mixed with total reductions or increases in caloric intake, and thus cannot be straightforwardly interpreted anymore. Examples for this are comparisons of dietary patterns that follow dietary guidelines (n = 16) – and accordingly limit caloric intake to the recommended levels – with current diets, where the caloric intake exceeds the recommended levels. Another example is food waste reduction (n = 18); in scenarios that assume less food waste along the production chain, less food has to be produced to provide the same amount of food for human consumption, and thus, also the absolute environmental impacts are scaled. When interpreting results from studies assessing scenarios that include different amounts of caloric intake or different food waste reduction rates, the effects of changes in dietary compositions need to be interpreted carefully and disentangled from effects resulting from differing caloric levels. To facilitate interpretation, the impact of dietary composition can be isolated by normalising the caloric content of the modelled dietary scenarios. Next to the functional unit, impact categories can affect scenario specification, if scenarios are defined based on performance of specific impact categories. This is the case in studies that employ diet optimisation (Gazan et al., 2018), where dietary scenarios are derived endogenously based on constraints on, for example, GHG emissions (e.g. (Donati et al., 2016)).

Further, how allocation is treated (i.e. whether co-products are allocated out of the system, thus products are followed, or whether nutrients are followed) can influence the dietary composition in scenarios; if nutrients are followed, consistent proportions between co-products are used in the diets. On the contrary, if co-products are allocated out of the chosen system boundary, dietary compositions that are inconsistent from a production perspective can result. Furthermore, how restrictions on resource use and sink capacities are treated affects the dietary composition. If biomass resources are treated differently depending on suitability for human consumption, production systems that focus on animals that are able to convert biomass streams unsuitable for human consumption into human-edible foods perform better than those that cannot. Examples for this are ruminants raised on grassland unsuitable for arable farming and pork raised on food waste (Van Zanten et al., 2018). On the other hand, when suitability for human consumption is not considered, ASF is included in the diet according to the lowest intensities (e.g. land or GHG emissions) per kg of output; then, intensive grain-fed poultry systems perform better compared to grass-fed beef cattle, as the total land used for the production is lower (Van Zanten et al., 2018). Thus, in the latter case, competition for arable land between feed and food cannot be disclosed, which poses an important limitation and needs to be considered when interpreting such results.

Resource-oriented scenario specification (n = 14), on the one hand, is hence characterised by following nutrients in the allocation and considering restrictions on resource use and sink capacities in the specification. Thus, production restrictions, such as co-product links and scarcity of resources, are taken into account, and the suitability of resources is considered in the production systems and dietary composition. Consumption-oriented scenario specification (n = 38), on the other hand, is characterised by following products in the allocation, and absolute restrictions on resource use and sink capacities are not specifically related to in the framing of the scenario. This can then lead to scenarios that are inconsistent from a production perspective (see example on vegetarian diets in Section 3.2).

3.3.2. Environmental impact assessment

Two typical approaches for environmental impact assessment can be defined according to how the identified choices allocation, inventory analysis, consequences, and restrictions on resource use and sink capacities are treated: **fixed impact assessment (FIA)** and **systemic consequences analysis (SCA)**.

FIA is characterised by applying fixed impact factors per food product when assessing dietary scenarios. More precisely, studies applying FIA (n = 36) follow products in the allocation – thus, co-products are allocated out of the system. Further, inventory analysis is done on product level, and then, linear scaling is applied to reach the level of interest (i.e. a diet for a certain part of the population). Consequences are not considered in the assessment. Lastly, restrictions on resource use and sink capacities are not considered according to suitability (e.g. land). In contrast to this, studies performing a SCA (n = 13) consider systemic changes and boundaries in the modelling, and by this, typically generate impact factors per product within a consistent food system state endogenously. For the identified choices, this can be depicted as follows: allocation is treated such that nutrients are followed and all co-products are thus kept in the system. Further, inventory analysis is often done on an aggregate level, and inputs, such as fertiliser, are e.g. allocated based on relative nutrient requirements of different crops. Consequences are included by considering level-induced changes for production systems (i.e. assuming that the way how products can be produced depends on how much is produced, for example limiting ASF to non-food competing feed) and consequential implications for environmental impacts per unit output. Alongside with this, restrictions on resource use and sink capacities are captured where relevant.

3.4. Solutions for reducing environmental impacts of the food system

In the following, the solutions of reviewed studies regarding changes in human diets and production-side measures are presented, and congruent as well as differing solutions between studies are identified.

3.4.1. Changes in human diets

Solutions for changes in human diets point at food groups, i.e. ASF and plant-source food, and absolute reduction of food intake until caloric intake is at the recommended level (solutions for studies not falling into the proposed typical methodological approaches can be found in Supplementary Material S1). Studies agree that in high-income countries, ASF needs to be reduced; more precisely, in Fig. 1 we see that all studies agree on a reduction of pork and beef, while for a reduction of poultry, the majority of studies agrees. To a lesser extent also reductions of dairy, eggs, and fish and seafood are proposed. However, which ASF should be reduced most and how the remaining (if any) ASF should be produced, remains inconclusive.

Studies following a consumption-oriented scenario specification and fixed impact assessment either suggest to reduce beef, pork, and poultry as low as possible, or they propose to keep a certain level of ASF as part of a recommended healthy diet (Fig. 1). Studies employing a resource-oriented scenario specification and systemic consequences analysis mostly propose a reduction of all ASF to the level that can be sustained based on LOCL. In LOCL scenarios, resulting amounts per capita per day

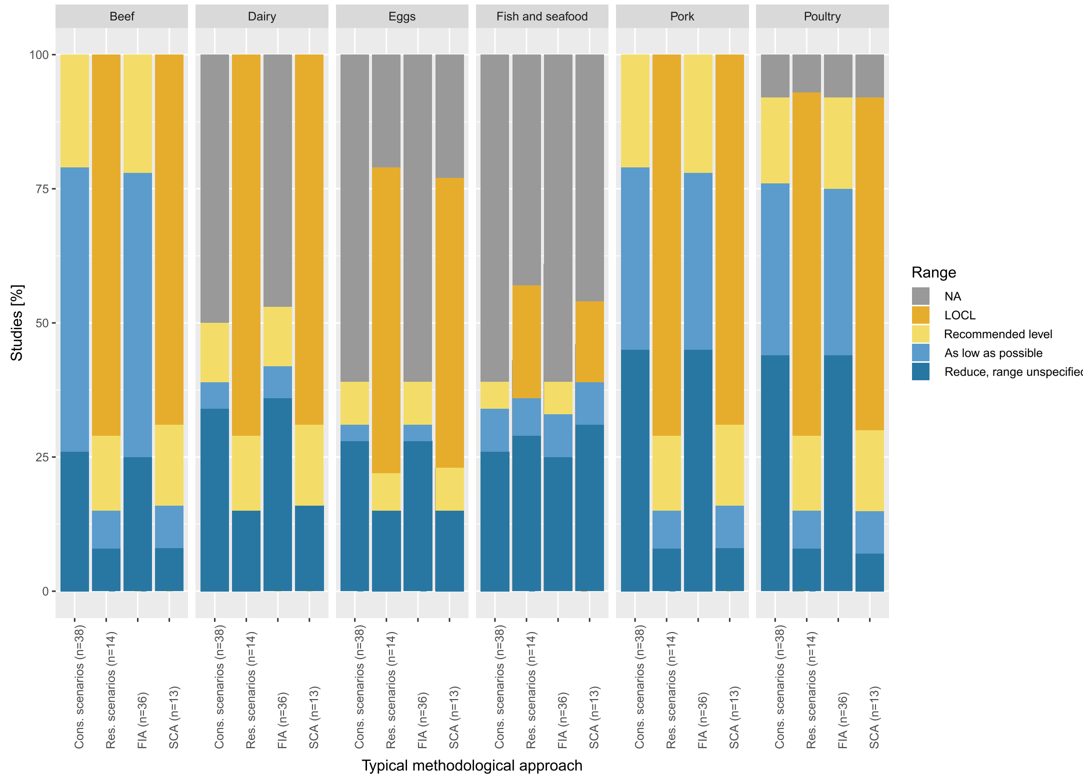

Fig. 1. Inventory of optimal ranges for animal-source food reduction solutions to achieve reduced environmental impacts of the food system (% of the studies per typical methodological approach; consumption-oriented scenario specification (Cons. scenarios), resource-oriented scenario specification (Res. scenarios), fixed impact assessment (FIA), and systemic consequences analysis (SCA)). Colors indicate the proposed range; low-opportunity-cost livestock (LOCL), recommended level, as low as possible, reduce with unspecified range, and not assessed (NA). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for beef range between 10 and 55 g, for pork between 7 and 46 g, and for poultry, between 0 and 26 g per person per day.

Another point for discussion is how to substitute for the reduction in ASF – be it by other types of ASF, such as dairy, or by plant-based protein sources, such as legumes. Fig. 2 shows the proposed food groups per methodological approach. All studies agree to take plant-source food as substitute for the reduction in ASF. Further, some studies employing consumption-oriented scenario specification and FIA also include dairy, fish and seafood, and to a lower extend eggs, poultry, and pork as possible substitutes.

Regarding land use, in Fig. 3, relative land use (differentiated by land type) per additional g of ASF-based protein in the human diet is presented. For values below 30 g of ASF-based protein, there is no clear trend as to which level of ASF and which products perform best regarding total land use. For cropland only and studies employing SCA, these results look different; two of these studies found that less cropland is required if some livestock, based on the LOCL principle, remains in the system, compared to a vegan scenario (Röös et al., 2017; Van Kernebeek et al., 2016). In contrast to this, studies operating with FIA find increased land use for all land types with increased levels of ASF in the human diet. For values above 30 g of ASF-based protein, both SCA and FIA studies find increased land use.

For GHG emissions (see Fig. 3), the results are clearer, meaning that according to currently available estimates, scenarios with less ASF generally perform better. Also for LOCL scenarios, one study finds that GHG emissions are higher than for purely plant-based diets (Röös et al. (2017)).

To sum up, when looking at total land use and GHG emissions, scenarios with ASF as low as possible – down to vegan, in the most extreme case – perform best. When looking at cropland use only, scenarios with ASF from LOCL perform best according to SCA studies, while FIA studies do not find different results compared to total land use.

3.4.2. Changes in production systems

Generally, solutions identified in the studies reviewed focus on changes in food consumption, resulting from our inclusion criteria. Next to these solutions, some studies also include different production systems in their assessment, leading to additional solutions regarding how the recommended foods should be produced. Such changes in food production systems can for instance be to follow existing trends, such as sustainable intensification (n = 10) and closing yield gaps (n = 6). Another possibility is to include well-defined production standards, such as organic farming (n = 8). A third option is to highlight single management options in the production process (which however can require substantial changes in the system), regarding animal production (n = 16), or plant production (n = 12). Management options for animal production systems often focus on feed that avoids competition with direct food production (n = 11), previously defined as LOCL (Van Zanten et al., 2018), or then, to reduce feed conversion ratio (n = 3). Specific options named to improve plant production are e.g. crop rotations. Lastly, 18 studies assess the effects of a reduction in food waste, which takes effect on all actors along the value chain.

Although diverse changes in production systems are included in several scenarios, mainly scenarios based on LOCL propose consistent large-scale changes of food production linked with food consumption. These studies propose to limit animal numbers to the amount that can be sustained based on the local productive capacity, i.e. that ruminants should mainly be raised on available grasslands (with or without temporary meadows as part of crop rotations). Further, the recommended levels for pork, poultry, and eggs are mostly based on locally available by-products and, in some studies, on food waste. The optimal mix and

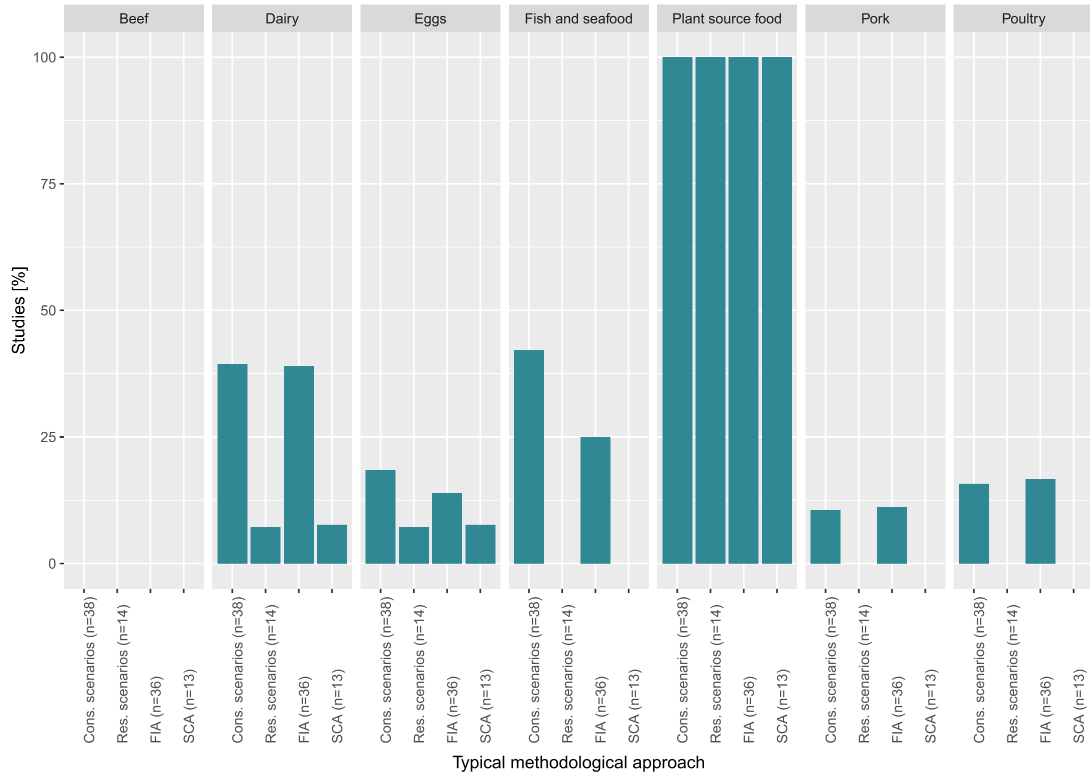

Fig. 2. Inventory of substitution solutions (% of the studies per typical methodological approach; consumption-oriented scenario specification (Cons. scenarios), resource-oriented scenario specification (Res. scenarios), fixed impact assessment (FIA), and systemic consequences analysis (SCA)).

allocation of low-opportunity-cost feedstuff to different livestock systems is subject of current research (Van Hal et al., 2019).

In conclusion, all studies agree on a reduction for ASF for the geographical scope considered in this review. Further, studies that employ a consumption-oriented scenario specification and FIA either recommend a maximum reduction of ASF, or if some ASF remains, this should mainly be sourced from dairy, eggs, fish and seafood, pork, and poultry. For these, often, no specific recommendation with regard to production systems is given. On the other hand, studies that employ a resource-oriented scenario specification and SCA mostly recommend a remaining low level of ASF based on the LOCL principle, and thus come with clearer solutions how this remaining ASF should be produced.

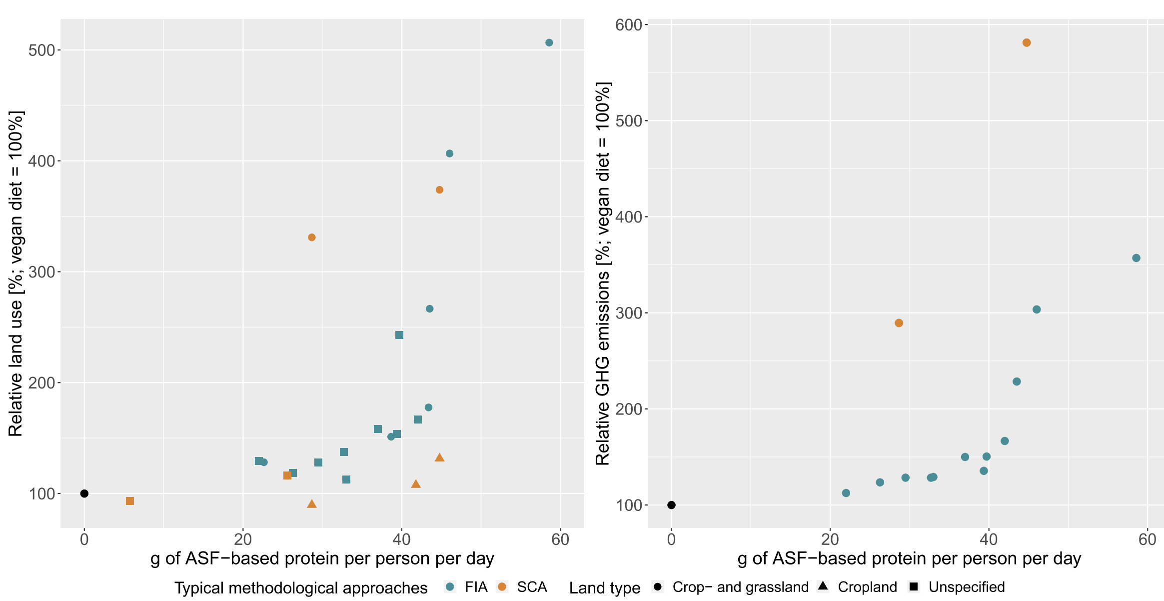

Fig. 3. Left: relative land use per g of animal-source food (ASF)-based protein per person per day (land type is indicated by shape). Right: relative greenhouse gas (GHG) emissions per g of ASF-based protein per person per day. Each dot represents one dietary scenario. Colors indicate typical methodological approaches; fixed impact assessment (FIA) and systemic consequences analysis (SCA). Land use and GHG emissions of dietary scenarios are presented relative to vegan scenarios of the same studies (black dot) in percentage. Caloric consumption across scenarios is normalised to 2000 kcal to facilitate comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Additionally, the solutions in studies that do not fit into the identified typical methodological approaches for scenario specification resemble those of the consumption-oriented scenario specification, and solutions in those that do not fit in the typical methodological approaches on environmental impact assessment, are mixed, thus, could be part of both FIA and SCA.

4. Discussion

4.1. Suitability of typical methodological approaches

Generally, the methodological approach should be chosen according to the aim of the study. With regard to typical methodological approaches on scenario specification, we can conclude that consumption-oriented scenarios are suitable for small-scale changes, where either the geographical scope is restricted, or only part of the population is assessed. For large-scale changes, and especially global assessments, resource-oriented scenarios are suitable, as they include consistent proportions between products that originate from the same production process.

For the environmental impact assessment of dietary and associated food system change, we identified two typical methodological approaches: FIA and SCA. On the one hand, FIA is characterised by using status-quo intensities, and therefore, this approach is well suited to assess small-scale dietary changes for the current situation. On the other hand, SCA considers systemic consequences of dietary changes on processes in the system and resulting environmental intensities; therefore, SCA is well suited to assess large-scale dietary changes for the future situation.

4.2. Sustainability strategies

Results from identified methodological approaches have several implications for how environmentally sustainable food systems would look like. On the one hand, when consumption-oriented scenario specification and FIA are applied, major changes of food consumption are proposed; either a maximum reduction of ASF, or small amounts of ASF that are mainly sourced from dairy, eggs, fish and seafood, pork, and poultry. However, on the production side, often no changes are assumed, and thus, also the environmental impacts per unit output stay constant. If changes in production systems are assumed, then sometimes in form of efficiency increases and thus higher yields per area or per animal head. Relating this to sustainability strategies on food system level (Huber, 2000; Schader et al., 2014), with such a system, two sustainability strategies are covered; efficiency and sufficiency. Efficiency by altering the diet towards products exhibiting lower impacts per unit output, or by assuming efficiency increases in the production chain. Sufficiency is covered as the dietary change assumed requires behavioural shifts that change humans' choices towards reduced ASF.

On the other hand, in studies that apply SCA, define scenarios from a resource perspective, and conclude that a low amount of ASF remaining in the food system should be based on LOCL, the resulting food system state does not only assume changes on the consumption side, but also proposes a coherent change of the production system. With this, the sustainability strategies efficiency, sufficiency, and consistency can be covered. Efficiency however is not covered per product (i.e. lower impacts per amount of inputs), but on food system level, by accounting for efficient resource use for the whole system. An example for this is that ASF produced with non-food competing feed might be less efficient from an impacts – inputs perspective, since animals have to cope with suboptimal diets and therefore might not be able to follow optimal growth rates (Van Zanten, 2019). However, from a food systems perspective, such a feeding regime can be even more resource efficient, because feed that cannot be used for direct human consumption is used to produce human-edible products. The same argument can be used to explain why the consistency strategy is covered; the resulting system links to concepts such as optimal resource use from a systemic perspective, related to closed and circular nutrient flows and waste reduction (hence the focus on utilising by-products for feed, for example).

4.3. Other environmental impacts

Next to GHG emissions and land use, the production of our food causes other adverse impacts on the environment, such as biodiversity loss, eutrophication, pollution, and water scarcity. Due to lack of adequate evidence across reviewed studies, these impacts were not included in the present analysis. Nevertheless, considering these impacts is important and future research should focus on improving quantification and standardisation of these impacts. Then, a more complete view on the environmental impacts of dietary scenarios could be obtained.

5. Conclusion

We draw conclusions for three target groups: researchers, policy makers, and civil society.

First, for researchers, we note that in studies assessing future food system states resulting from dietary change, the modelling approach used should be able to capture the resulting consequences. Large-scale dietary changes will cause a cascade of effects, and require cautious consideration of co-product links and suitability and scarcity of resources. To assess such changes and propose suitable solutions, systemic consequences analysis (SCA) studies are adequate, while fixed impact assessment (FIA) studies are not able to capture the full consequences of such changes. FIA is however adequate to assess the impacts of the current food system or of relatively small systems, where changes have negligible effects only beyond narrowly chosen boundaries.

Second, solutions from the two typical methodological approaches result in different implications for policy makers. Results from studies applying a consumption-oriented scenario specification and FIA could generally be implemented with policies targeting at consumption-side and efficiency measures. Thus, with regard to production, no large-scale changes are proposed. On the contrary, with resource-oriented scenario specification and SCA, a sophisticated policy mix would be required, to provide incentives and resources to restructure food systems towards systems where resources are allocated such that humans fed per hectare are again in focus. In total, this would require a focus on closed nutrient flows and circular economy concepts. For animal-source food (ASF), this would mean a focus on low-opportunity-cost livestock (LOCL), leading to requirements for breeding programmes, feed processing, etc. These differing implications are of particular importance, because choosing an inadequate methodological approach for the problem of interest (see first point above) could result in inadequate recommendations for policies.

Third, for civil society, our results give insights into congruent and differing dietary solutions, and for the latter offer possible reasons by making underlying – and often implicit – assumptions transparent. Although all reviewed studies agree on a reduction of ASF, differences occur: while studies operating within current settings generally recommend to reduce beef most, followed by pork and chicken, studies considering consequences of dietary change, co-product links, and restrictions on resource use and sink capacities tend to recommend a role for livestock based on the LOCL principle. Thus, for researchers, policy makers, and civil society, implications differ between methodological approaches. Choosing the correct methodological approach is therefore central for avoiding confusion, and for effective communication and policy design.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2019.100333.

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