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Main Manuscript for

Eating Healthy or Wasting Less? Reducing Resource Footprints of Food Consumption

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Abstract

To feed future populations on ever-scarcer natural resources, policy initiatives aim to decrease resource footprints of food consumption. While adopting healthier diets has shown great potential to reduce footprints, current political initiatives primarily address strategies to reduce food waste, with the target of halving food waste at retail and consumption levels by 2030. Using Germany as a case study, we compare the resource-saving potential of this political target with three scenarios of nutritionally viable, plant-based dietary patterns and investigate interactions and trade-offs. By using the food and agriculture biomass input-output model, we capture biomass, cropland, and blue water footprints of global supply chains. The results show that dietary changes are particularly effective in reducing biomass and cropland footprints, showing a decrease of up to 61% and 48% respectively, whereas halving food waste decreases biomass and cropland footprints by 11% and 15% respectively. For blue water savings, halving food waste is more effective: water use decreases by 14% compared to an increase of 6% for dietary change with the highest water consumption.Subsequently, a combination of the scenarios shows the highest total reduction potential. However, our findings reveal that despite reduced footprints, a dietary shift can lead to an increased amount of food waste due to the rising consumption of products associated with higher food waste shares. Therefore, policy strategies addressing both targets might be contradicting. We conclude that international and national policies can be most effective in achieving higher resource efficiency by exploiting the reduction potentials of all available strategies while simultaneously considering strategy interactions.

1. Introduction

To feed future populations on a planet with dwindling resources and increasingly degraded ecosystems, societies need to decrease the pressures of food systems on land and resources worldwide (Gerten et al. 2020). Given global supply chains and demand-driven resource use, it is necessary to address consumption footprints (e.g. carbon, land, or water footprints), particularly in industrialized countries (International Resource Panel 2019; Steen-Olsen et al. 2012; Tukker et al. 2014). How to reduce these footprints is at the core of many current political and scientific debates related to the food sector. International policies aimed at decreasing resource pressures predominantly focus on food waste reduction. The Sustainable Development Goal (SDG) 12 on "sustainable production and consumption" calls for halving food waste in consumption and distribution by 2030 (UN 2015), a target that has been adopted, for instance, by the EU Action Plan for the Circular Economy (EC 2015). In this context, food loss and waste (FLW) comprise commodities that were intended for human consumption, including their non-edible parts, and removed from the food supply chain or thrown away in households (BMEL 2019; Champions 12.3 2017; EU 2008, 2018; WRI 2016). Given these supranational strategies, several countries have developed national strategies or initiatives to operationalize food waste reduction targets (Australian Government 2017; BMEL 2019; BMLRT 2019; Swedish Food Agency 2018). Next to FLW reduction, research on sustainable food systems increasingly points to the role of more plant-based and healthier diets to decrease resource footprints (Foley et al. 2011; Springmann et al. 2018; Tilman and Clark 2014; Vanham et al. 2018; Willett et al. 2019). Previous studies show similar or greater potential of dietary shifts to decrease environmental footprints than food waste reduction, depending on assumptions of FLW reduction potential, regional consumption habits, and dietary scenarios. The potential of dietary shifts is particularly large in high-income countries (Aleksandrowicz et al. 2016; Behrens et al. 2017; Shepon et al. 2018).

Because of the lack of political initiatives targeting dietary changes in comparison to the strong focus on FLW reduction, assessing the potential environmental benefits of these two strategies is crucial to support national policymakers in their prioritization efforts and target setting. There is a general scientific consensus that, for Western countries, an increase in plant-based diets is in most cases both healthier and more environmentally friendly (Bryngelsson et al. 2016; Clark et al. 2019; Gephart et al. 2016; Hallström et al. 2015; Lacour et al. 2018; Springmann et al. 2018; Tilman and Clark 2014). It has also been shown that for the US the resource losses in the conversion from plant-based feed to animal-based food products exceed those of FLW (Shepon et al. 2018). So far, the interaction between dietary changes and food waste strategies has received little attention. One study assesses food waste, the diet quality of various dishes, and environmental pressures for the US, indicating that healthy dishes are associated with greater amounts of food waste (Conrad et al. 2018). Yet, economy-wide analyses of the relationship between resource footprints, food waste reduction scenarios, and various dietary scenarios at a national level are few, and to our knowledge have only addressed the US so far (Birney et al. 2017). To ensure that policy targets accurately aim at the overarching goal of reducing resource footprints, the saving potentials of different policies and their interactions with other measures must be taken into account. For a policy target of reducing food waste, dietary changes may influence both the possibility of reaching the target and its environmental benefit (Conrad et al. 2018; Shepon et al. 2018). We aim to address these interactions between strategies related to food waste reduction and to dietary changes. To support policy target setting and prioritization, we compare the environmental benefits of dietary changes with those of food waste reduction. Specifically, we assess the cropland, biomass and blue water footprints of different food waste and dietary scenarios and discuss the implications for policy target setting, their potential risks and opportunities, and the accuracy of related indicators to reflect resource footprints.

This article focuses on Germany as a case study. The country constitutes a particularly relevant case with high potential to contribute to reducing global resource footprints, as it has Europe's highest carbon footprint related to food consumption (Kim et al. 2019). Germany is also perceived as a frontrunner in waste management and one of the few EU countries that particularly promotes food waste reduction as a means of achieving a more resource-efficient circular economy. It adopted a national strategy in 2019 to decrease food waste (BMEL 2019). A comparative analysis of German food waste and dietary change scenarios can provide insights for other industrialized countries on ways to implement effective resource-efficiency policies.

2. Methods

We modeled the global supply chain of German food consumption and its associated resource footprints, accounting for cropland use, total harvested biomass, and blue-water use. Cropland and blue water, given their uses in different economic activities, are considered scarce, and at the same time are vital for food production (Hoekstra and Wiedmann 2014; Steffen et al. 2015). Total harvested biomass captures the material footprint and thus helps to compare resource intensity among product groups. To assess the potential of dietary changes towards a healthier general nutrition, we develop three nutritionally viable scenarios of average dietary patterns, referred to simply as "diets": 1) a *guideline diet* based on German dietary guidelines (DGE 2020; Oberritter et al. 2013), 2) a *sustainable diet* meeting several environmental and health requirements (Willett et al. 2019), and 3) a low-dairy *vegetarian diet* adapted from the sustainable diet. Our food waste reduction scenario reflects the current political targets of halving food waste in consumption and distribution. We assess this scenario both separately and in combination with the dietary scenarios. We present the resource footprints for each scenario and provide a deeper understanding of the system dynamics by showing product characteristics in terms of footprints and food waste shares. Figure 1 shows the modeled supply chain of German food consumption, the system boundaries, and the consumption-oriented scenarios that feed into the model.

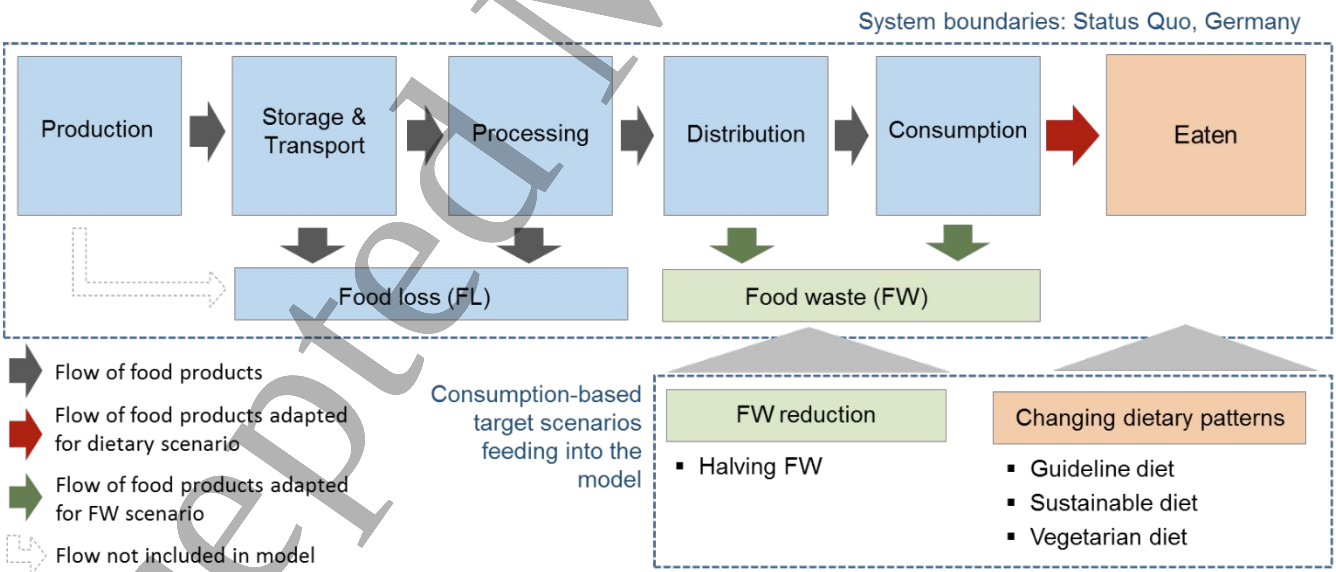

Figure 1. System definition and boundaries. The supply chains are global and defined based on the food consumed and eaten in Germany. The system processes are defined according to FAO (2011).

2.1 Modeling national consumption footprints

We map the food supply chain and its resource footprints using the Food and Agriculture Biomass Input-Output Model (FABIO; Bruckner et al. 2019). FABIO is an environmentally extended multi-regional input-output (EE-

MRIO) model covering physical flows and associated inputs of harvested biomass, land, and water for 130 food and agricultural products in 191 countries (Bruckner et al. 2019). Using the latest available data for FABIO, we map the supply chains and biomass flows associated with German food consumption for the reference year 2013. We account for FLW along the supply chain from post-harvesting to final human consumption.

Footprints are commonly used indicators of human pressure on the environment (Galli et al. 2013; Hoekstra and Wiedmann 2014) and generally refer to a supply-chain or consumption-based perspective (Giljum et al. 2013; Tukker et al. 2014). The biomass footprint shows the primary plant biomass harvested or grazed, according to the conventions of economy-wide material flow accounting (EUROSTAT; EUROSTAT 2013; OECD 2008). The land-use footprint refers to cropland, including both arable land and permanent crops (FAOSTAT 2019). The blue water footprint measures the consumption of freshwater (surface and groundwater), including both direct and indirect water use (Hoekstra and Mekonnen 2012). Following the EE-MRIO methodology, the footprints were calculated as $\boldsymbol{f} = \hat{\mathbf{e}}\mathbf{L}\mathbf{y}$, where $\boldsymbol{f}$ is the total footprint of German food consumption, $\hat{\mathbf{e}}$ is a diagonalized vector giving the environmental input of the addressed resource per unit of output of each product, $\mathbf{L}$ gives the Leontief inverse matrix, and $\mathbf{y}$ the final demand vector for Germany. Final demand, in the case of FABIO, comprises food use for 130 commodities and 191 source regions including those amounts of food that are wasted at the distribution and consumption stages. We implement the scenarios in the form of adapted final-demand vectors, applying the assumed changes to food consumption and waste (Section 2.3). Due to a lack of data, the model does not cover environmental inputs for fish. This increases the uncertainty of the results, in particular for water footprints. We consider this uncertainty acceptable as the scenarios contain relatively low levels of fish. A discussion of the implications of this limitation is found in Section 4.2.

2.2 Composition of dietary scenarios

The composition of the three dietary scenarios and the current average German dietary pattern are shown in Figure 2. The current diet represents the average per capita food consumption pattern in Germany based on the demand vector available in FABIO (adjusted for FLW) and its related supply chains for the reference year 2013. The data is generally given in fresh weights of primary food product equivalents (e.g. oats, olive oil, milk) for 130 products. We use dietary recommendations or principles, specifying the amount of food consumed for different product categories (e.g. vegetables, fruit, and meat) to develop the final demand vectors for three reference dietary patterns. As the dietary recommendations forming the basis of our scenarios are given in quantities of food from different product categories, we translate these into primary food products (e.g. oats, onions, bananas, pork). We split product categories into primary food products according to the proportions of the product categories in the current German dietary pattern. The alternative dietary patterns are standardized to meet the average energy demand of 2796 kcal per day, i.e. 311 kcal less than the current diet. The average energy demand was estimated by Vásquez et al. (2018) and is based on the demographic composition of the German population in the reference year 2013. To ensure that the scenarios are “nutritionally viable” in terms of providing the population with an adequate supply of proteins and fats, the dietary scenarios are controlled against German official recommendations. As the study aims to assess general nutrition patterns and their main resource flows, we refrain from addressing individual diets, including for instance aspects of micronutrients, human uptake, fortified foods, supplements, or particular preparation practices. Information on the nutritional content of the analyzed diets and the recommendations of the German Nutrition Society (DGE) on nutrient intake can be found in the supplementary information (SI), Table S1.

The guideline diet is based on the nutrition circle scheme recommended by the DGE, showing the proportions of different food groups (DGE 2020; Oberritter et al. 2013). Due to consumer convenience, the proportions are given in terms of the weight of prepared food. However, as the form of preparation largely determines the weight, we assume fresh weights as given in FABIO. The assumed moisture contents are given in the supplementary dataset ('H. Moisture_content'). The sustainable diet is based on the reference diet suggested by the EAT Lancet Commission (Willett et al. 2019). This diet is developed taking into account health, biophysical limits of the planet, and political targets for climate change limitation, which include indicators for greenhouse gas emissions, nitrogen and phosphorus application, consumptive water use, extinction rate, and cropland use. This reference diet provides more detailed product categories than the guideline diet and its composition is given in grams per day. Given the substantial scientific evidence of balanced vegetarian diets as nutritionally adequate, healthy, and beneficial to prevent certain chronic diseases (Craig and Mangels 2009; Key et al. 2006; Sabaté), we develop a low-dairy vegetarian diet as an additional illustrative scenario. Since the EAT Lancet reference diet reflects a generally balanced and low-meat reference diet, we adapt this scenario by excluding meat and fish products and assess protein and fat levels against German recommended levels (see Table S1). As the resulting diet exceeds the recommended levels for proteins and fats, there was no reason to increase protein-rich or high-fat foods. We conclude that the dietary pattern reflects balanced vegetarian dietary habits, offering a broad variety of vegetables, fruits, whole grains, legumes, nuts, seeds, soy foods and oils (USDA 2015). Finally, the dietary composition is scaled to the same energy demand as the other scenarios. Similar to the other dietary pattern scenarios, this does not aim to represent an average vegetarian diet in Germany, but rather an appropriate explorative scenario to investigate possible resource use reduction potential. As this first analysis of German diets does not cover all nutritional factors, future studies need to delve into the specific micronutrient requirements of the plant-based scenarios to ensure their viability and adjust their food composition. As the DGE does not provide any recommendations for sugar, sweeteners, and alcoholic beverages, we assume this product group to comprise 10%[1] of the total diet in the guideline diet. This corresponds to a halving compared to the current diet, but still allows the consumption of these product groups. The EAT Lancet Commission does not specify alcoholic beverages. Therefore, we apply the same quantity of alcohol products as in the guideline diet scenario for the sustainable diet and vegetarian diet scenarios.

The assessed dietary patterns represent variant diets with an increased plant base (Figure 2). The current average energy intake is calculated based on the IO-data provided by FABIO whereas the other diets correspond to an intake of 2796 kcal a day as explained above. The guideline diet involves a significant decrease in meat products (98 grams as compared to the current 249 grams per day), which are partially replaced with dairy products. The sustainable diet replaces large shares of meat and dairy products with plant-based products, such as pulses, beans, and nuts as well as vegetable oils. This diet involves less potatoes and roots than the guideline diet. The vegetarian diet is identical to the sustainable diet except for the replacement of meat and fish with a proportional increase of other product groups. The latter two dietary patterns meet the energy requirements of 2796 kcal per day with about 500 grams less of food per day than the guideline diet. The current diet corresponds to an average energy intake of 3107 kcal, with the uncertainty interval of 2646 kcal to 3567 kcal (supplementary dataset 'J. Uncertainty_SQ_Food_Intake'), because of uncertainties in FLW levels (see Section 2.3). The dietary scenarios all exceed the national recommendations for protein and fats (not accounting for micronutrients). Given that recommended individual energy intakes for adults vary between 1700 kcal and 3100 kcal depending on age, sex and physical activity level (DGE 2020), the estimated status quo average energy intake of 3107 kcal per capita and day appears high. The plausibility and the implications of this estimation are further discussed in section 4.2.

[1] Based on the average recommendations for intake of added sugars from USDA (2015)

However, the difference of 311 kcal between the status quo scenario and the alternative dietary scenarios is within reasonable uncertainty levels, i.e. the resulting impact of food intake reduction (only) in our dietary scenarios stays within accepted uncertainty levels. All dietary patterns are provided in detail together with nutritional data per product in the supplementary dataset ('G. Diets_analysis').

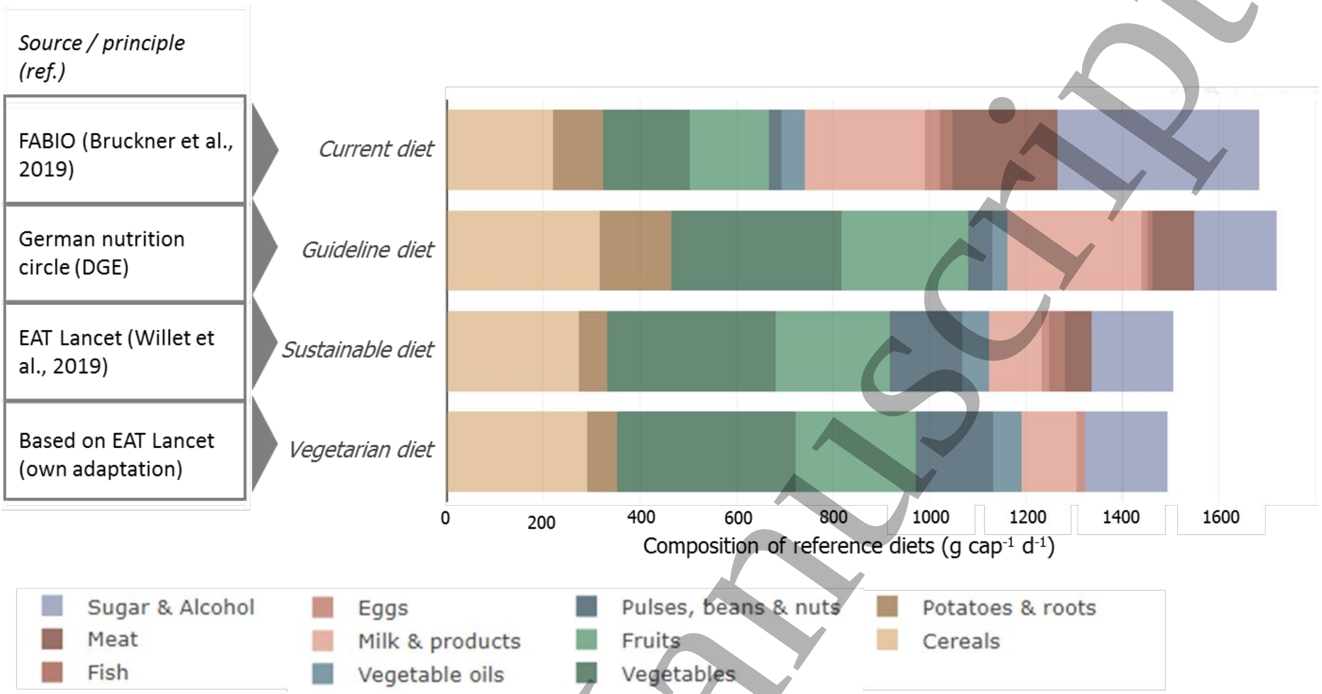

Figure 2. Composition of assessed reference dietary patterns (gram cap^{-1} d^{-1}). Weights are generally given in fresh weights; cereals, pulses and beans are dry, raw.

2.3 FLW estimations

For the assessments of a 50% food waste reduction, we follow the FLW reporting standard (WRI 2016) and the proposed interpretation of SDG 12.3 (Champions 12.3 2017) and define FLW as commodities that were intended for human consumption, including their non-edible parts. We use shares of FLW per product group at each step along global supply chains and applied these to all products in a respective product group. For supply chain processes within Germany, we use data from the national food waste baseline report (Schmidt et al. 2019) and from a study by WWF Germany (2015). The latter is used to fill data gaps of sufficiently disaggregated data in consumption and distribution in the baseline report. For supply chain processes outside of Germany, we use data from FAO (2011), following the methodology outlined by SIK (2013). However, this data excludes inedible parts of plant-based products and eggs from the FLW estimations and is therefore likely to underestimate the FLW. To account for the uncertainties in post-harvest FLW data, an uncertainty analysis was conducted by assuming a range of variation of +/- 50% of the FLW ratios. In cases where we found estimates in the literature diverging by more than 50%, we use these values as the respective maximum divergence. For more details on the FLW data used, the uncertainty analysis and the considered literature, see the SI.

3. Results

3.1 Healthy diets mostly more effective than food waste reduction

Our results show that dietary changes are particularly effective to decrease biomass and cropland footprints, whereas blue water footprints are less responsive to dietary change (Figure 3). Halving food waste corresponds to a decrease in resource footprints of 11–15% (shown as FW↓ in Figure 3). The error bars indicate uncertainty related to the assumed food waste shares in the status quo. Therefore, scenarios with reduced food waste show a smaller uncertainty range.

A change in dietary patterns to the sustainable diet, i.e. the EAT Lancet Commission's reference diet, would result in reductions of the biomass, cropland, and blue water footprints by 54%, 43%, and 7% respectively. For cropland and biomass footprint reductions, this scenario turns out to be three to five times more effective than halving food waste with no dietary changes. The latter has a biomass and cropland saving potential of 11% and 15%, respectively. For decreasing the blue water footprint, however, food waste reduction is more effective than dietary changes (14% compared to up to 7%, depending on dietary scenario). This is due to the particularly high consumption of blue water in fruit and vegetable growing, the proportion of which increases in the alternative dietary scenarios. We enlarge upon this in Section 3.3. For the more conservative guideline diet, the water footprint even increases by 6% if not combined with food waste reduction measures. This dietary pattern reduces biomass and cropland footprints by 19% and 22% respectively, compared to 11% and 15% for the food waste reduction scenario. With a vegetarian diet, the biomass footprint can be decreased by up to 61%, the cropland footprint by 48%, and the blue water footprint by 7%. This implies that a mainly plant-based diet reduces cropland and biomass footprints three to six times as much as the food waste reduction scenario. To reduce water footprints, however, reducing food waste is twice as effective as changing diets to the sustainable or vegetarian diets, and even more compared to the guideline diet.

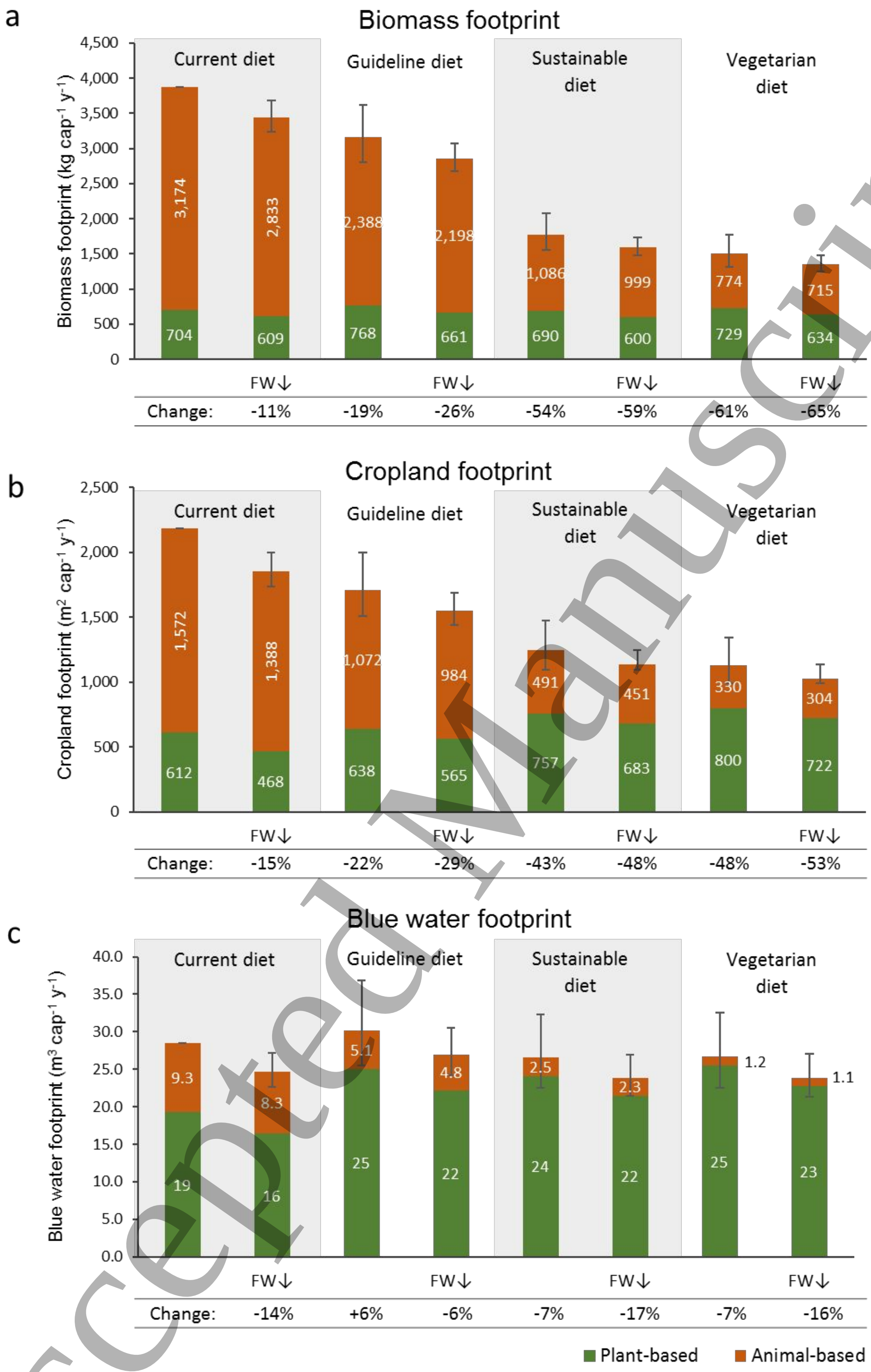

Figure 3. Resource footprints by scenarios. a) Biomass footprints in kg cap^{-1} y^{-1}, b) cropland use footprints in m^2 cap^{-1} y^{-1}, c) Blue water footprints in m^3 cap^{-1} y^{-1}. FW↓ = food waste reduction by 50%. The green parts describe the share of footprints generated by plant-based food, orange represents the contribution of animal-based food. The error bars show the results of the uncertainty analysis.

3.2 Product footprints and composition of food explain outcomes

While the total biomass and cropland footprints related to animal-based products plummet with dietary changes, those of plant-based products increase by up to 41%. The overall decrease of footprints, thus, is related to the reduction of animal-based products in diets, which are the most resource-intensive foodstuffs. Today, 72% and 82% of the total cropland and biomass footprints, respectively, are associated with the consumption of animal products. For water footprints, only 32% of the current total footprint comes from animal products (supplementary dataset, 'C. SQ_Analysis').

A look at the peculiarities of individual foods provides further insights. Figure 4a shows the relation between footprints per unit of mass and per unit of energy content (y-axes) and food waste shares (x-axes) for ten food categories. Meat has particularly high footprints per mass unit for all three resources, but most prominently for biomass and cropland use (Figure 4a). For water, the difference between animal-based products and plant-based products is not as pronounced, which also explains the smaller difference for water footprints between the scenarios in comparison to biomass and cropland. Plant-based products generally show lower footprints per unit of energy content, with vegetables and fruit being the exceptions in terms of water footprints.

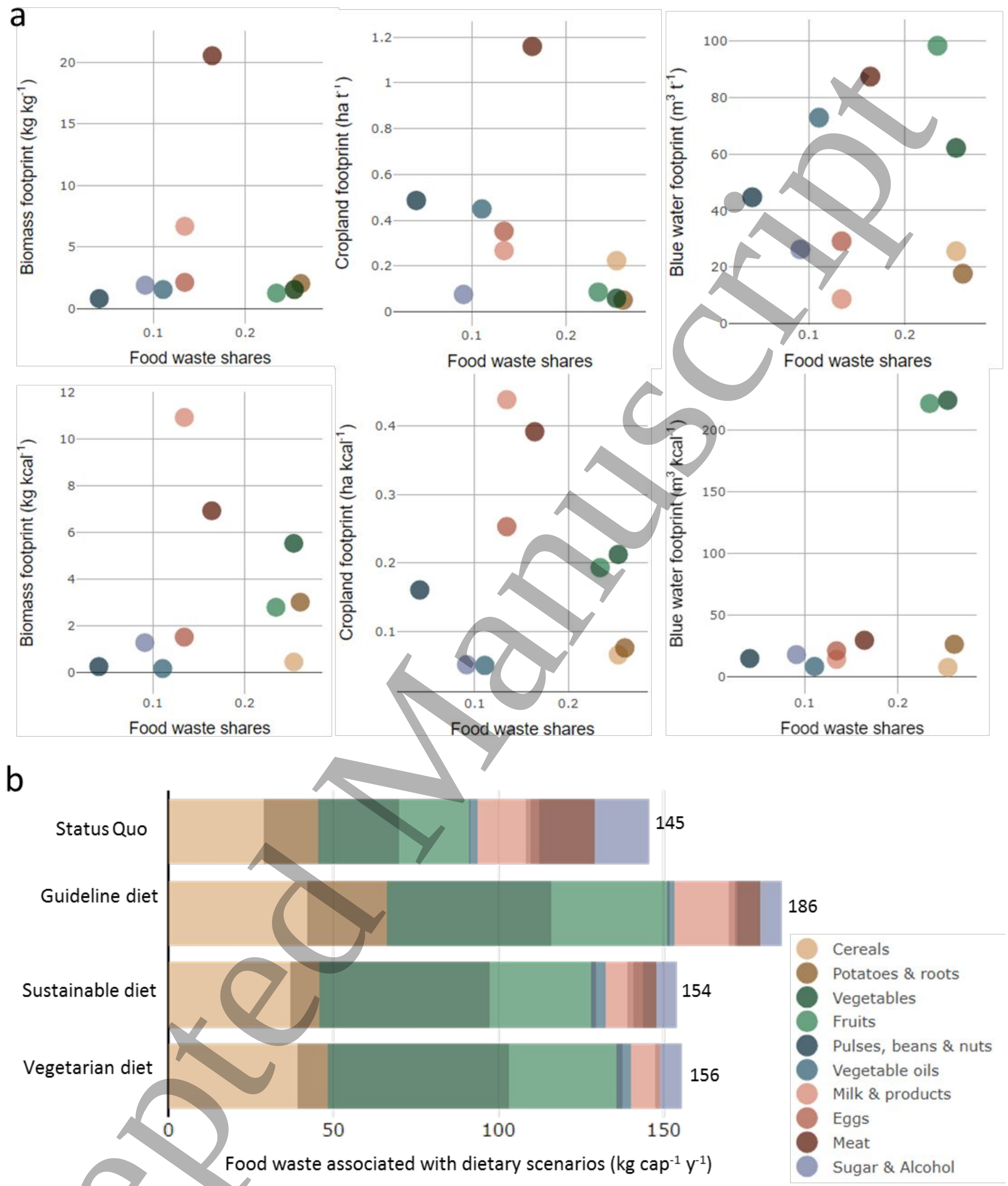

Figure 4. Interactions between diets and food waste quantities. a) Resource intensities and waste shares of 10 product groups. Y-axes show biomass, cropland, and blue water footprints per Million calories of energy content of eaten food, x-axes show food waste shares. b) Absolute amounts of food waste associated with each dietary scenario based on the dietary composition and respective food waste shares. The figure reflects the main FLW estimates, uncertainty intervals for FLW data is found in the supplementary dataset 'I. Food_waste_shares'.

3.3 Product characteristics determine strategy trade-offs

Based on the food waste estimates for each product group underlying this study, we can expect interactions and even goal conflicts between the strategies of dietary change and food waste reduction. Vegetables, cereals, fruit, potatoes, and roots are associated with higher levels of food waste (Figure 4a). Subsequently, an increased share of these product groups in the dietary pattern might cause the overall amounts of food waste to grow, which may hamper the possibility of reaching the political target of halving food waste. Figure 4b shows the composition and amounts of food waste for the assessed dietary scenarios and the current diet. Given that food waste shares of each product remain the same, this shows that changes according to the dietary scenarios would increase the amounts of food waste, in particular for the guideline diet.

The main question here is how this interaction affects the total footprints of food consumption. Plant-based products that are associated with relatively high levels of food waste are particularly relevant in this context. If a dietary shift includes greater amounts of such products, there is a risk of increased amounts of food waste. At the same time, larger shares of these products decrease the overall footprints of food consumption, with the water footprint in the case of the guideline diet as the only exception. Thus, in terms of both total consumption footprints and food waste footprints, scenarios of dietary change would be beneficial. In combination with decreased food waste, in particular for fruit and vegetables, also water footprints decrease for all scenarios. Because of the simultaneous reduction in footprints and increase in food waste associated with dietary changes, total resource losses are not reflected in the amount of food waste. Resource footprint indicators, which embed the overall resource use and loss associated with final consumption (from food losses in agriculture to conversion rates in processing and food losses along the whole supply chain), would thus be better suited for political target setting. These losses are much higher than what is addressed as food waste (Shepon et al. 2018).

4. Discussion

The results show that changes in dietary patterns have significantly higher potential to decrease resource footprints than halving food waste (up to 65% in comparison to 15%). There is also a risk of counteractive interactions between the strategies, which is associated with product characteristics. These findings are of particular significance for policies addressing footprints and the sustainability of our food system. Next to significantly reducing resource footprints, political strategies promoting more sustainable diets also have positive side effects on human health, which is relevant for policies aimed at improving people's health, especially in an aging society such as Germany (Clark et al. 2019; Tilman and Clark 2014).

4.1 New evidence on resource footprints and strategy interactions

Few studies have addressed the implications of the circumstance that cereals, potatoes, roots, fruit, and vegetables are associated with greater food waste shares but generally lower footprints (Conrad et al. 2018). This study adds new evidence to the challenging trade-off between healthier diets and food waste. The importance of the resource efficiency of food products themselves in comparison to losses was underlined by Shepon et al. (2018), showing that the "conversion loss" of animal products by far exceeds total food losses. Our results confirm that including biomass footprints in resource efficiency assessments allows capturing all types of resource losses in one indicator and thereby reflects resource efficiency more adequately than the amount of food waste.

The results of this study substantiate other research findings regarding the high potential of dietary changes to decrease resource footprints (Aleksandrowicz et al. 2016; Behrens et al. 2017; Bryngelsson et al. 2016; Conrad et al. 2018; Vanham et al. 2018). A literature review across countries (the majority European) shows average land savings of 20% for diets following dietary guidelines, 51% for vegetarian diets, and 55% for vegan diets (Aleksandrowicz et al. 2016). This is very much in line with our results of 22% land savings for the guideline diet and 48% for the low-dairy vegetarian diet. For blue water footprints, previous studies show an average decrease of 37% for vegetarian diets and 22% for diets following the local dietary guidelines (Aleksandrowicz et al. 2016; Vanham et al. 2018). Our results show a smaller impact of dietary changes on the blue water footprint, ranging between +6% and -7%. Particularly the blue water footprint of diets varies among studies (Aleksandrowicz et al. 2016; Meier and Christen 2013; Rehkamp and Canning 2018; Tom et al. 2016). Our results differ from a study focusing on Germany that shows a tripling in blue water use for vegan and vegetarian diets, with more than two-thirds of the footprint being associated with nuts and oilseeds (Meier and Christen 2013). Although the authors do not further explain the deviation from other studies, the inventory data of 1,425 liters of blue water per kilogram of nuts and oilseeds (Meier and Christen 2013) indicate a particularly water-intensive composition of this product group (cf. Mekonnen and Hoekstra 2011). Differences in the reduction potentials among different countries can be explained by differences in consumption patterns, supply chain structures, and production methods (Kim et al. 2019).

4.2 Limitations and future research needs

Limitations of this study mainly include the previously discussed uncertainty of FLW data and the resulting high average energy intake. Additionally, the lack of environmental data related to fish and the absence of other indicators such as a scarcity-weighted water footprint, pastures, nutrient loss, and greenhouse gas emissions leave room for improvement. Complementing nutrition studies need to delve into the nutritional viability of dietary patterns.

The current average energy intake of 3107 kcal appears high in comparison with survey-based data on German food consumption habits, which has several possible reasons. A comprehensive German survey showed an average energy intake of 2159 kcal per person and day from 2005 to 2013 (Gose et al. (2016), average from table 4, converted to kcal). The product groups mainly contributing to the difference to the FAO data used in our study are meat and alcohol. The survey acknowledges an expected underreporting of energy intake of 11-17%, which would imply a total energy intake of 2396-2526 kcal per person and day. Heseker et al. (1994) came to a similar average energy intake of 2414 kcal (p.123, converted to kcal). The difference to our resulting average energy intake is about 650 kcal, with an uncertainty interval of 185 to 921 kcal. The most possible sources of error of our estimate involve uncertainties in FLW data and a detected discrepancy in the product energy content in FAO data. The high uncertainty in FLW data is mainly due to the lack of proper monitoring possibilities, as well as the exclusion of inedible parts of plant-based products and eggs as waste flows, which may contribute to an underestimation of FLW. Given the high uncertainty of FLW data, the uncertainty intervals are highly relevant for the interpretation of the results. Additionally, we noted a discrepancy in FAO energy content data. In this study, we used the energy content data given in the Food Balance Sheet (FBS) handbook (FAO 2001) (see supplementary dataset 'G. Diet composition'). However, our estimations are, on average, 12% higher than the energy content derived from the FBS for Germany (reported in kcal and kg per capita). Diverging data within FAO or possible moisture content inconsistency of product group reporting constitute ambiguities. We keep to the data provided by FAO (2001) while assessing the implications of possible data faults. With the maximum waste levels in our uncertainty range, this study estimates the current diet to consist of 2646 kcal (see supplementary dataset ‘J. Uncertainty SQ Food Intake’). Assuming these higher levels of FLW and a more conservative estimation of current food intake, the effects of food waste reduction in the current diet would be 17% for biomass, 20% for cropland, and 21% for blue water (the lower bound of our uncertainty range). The possibly lower energy content of all diets does not alter the main conclusions of the study.

Fish is considered to be an environmentally friendly substitute for meat (Willett et al. 2019). However, while fish is shown to be preferable over meat in terms of greenhouse gas emissions and land-use change, fish from pond aquaculture has a remarkably high blue water footprint (Kim et al. 2019). The dietary patterns in this study only include small amounts of fish, the sustainable diet being the one with the largest share of fish. Thus, the water footprint for this diet may be slightly underestimated. However, the environmental relevance of water footprints depends on the water scarcity at the point of withdrawal (Ridoutt and Huang 2012), which is not accounted for in the present study. Scarcity-weighted national water footprints are relatively high in the case of nuts, fish, red meat, chicken, and olive oil (Clark et al. 2019). Thus, a closer look into the scarcity-weighted water footprint of these products would be useful. Similarly, increased nuances of dietary assessments can be achieved by also accounting for pastures, land-use suitability, and availability. Based on this perspective, a study of US food consumption concludes that some balanced omnivore diets have a higher carrying capacity than vegan diets (Peters et al. 2016). To get a more holistic view of the environmental impacts of different target scenarios, studies on carbon footprints and nutrient cycles is needed. Indirectly, these aspects are partly captured as the sustainable diet scenario is based on a reference diet that considers environmental requirements including nutrients and greenhouse gas emissions. Moreover, this study assumes as a baseline for all scenarios the German food supply chains of 2013. In reality, supply chains change to some degree when dietary patterns are altered and the product composition changes. Changing dietary patterns would also provide opportunities to change production patterns accordingly. For instance, reduced demand for certain crops in some parts of the world can ease the pressure on valuable ecosystem services in other parts, but at the same time, demand can increase the production of more sustainable alternatives in the country of consumption.

4.3 Expanding the scope of political actions

The potential of dietary changes for resource savings and public health opens up a broader scope of policy options. We reveal that dietary changes could be up to six times more effective in decreasing resource footprints than halving food waste. These findings urge policymakers to consider consumption-oriented political actions. Political instruments to implement targets of healthier and increasingly plant-based dietary patterns can comprise a mix of approaches. These include legal tools such as changing macro-economic policies, fiscal measures, and stricter marketing rules for unhealthy food, as well as promotion and supportive strategies such as nudging through changing store layouts, education, empowering community initiatives, and offering healthy and sustainable food in schools (Garnett et al. 2015; UNEP 2016). At the same time, effective political instruments for food waste reduction are still not in place. So far, the German strategy mainly relies on a dialog forum for stakeholders, workshops, and information campaigns (BMEL 2019). Thus, even reaching the comparatively small potential to reduce the footprint by halving food waste is still in the distant future. Presumably, it is easier to suggest food waste reduction than dietary changes, as the latter invokes individual food consumption habits which are often a sensitive topic. However, research on food waste causes and reduction measures shows that food waste reduction also requires considerable behavioral changes, such as shopping and cooking habits (Hebrok and Boks 2017; Schanes et al. 2018; Stancu et al. 2016). However, the responsibility is perceived as more clearly shared with food supply stakeholders and the individual changes seem less intrusive. Nevertheless, the obscure necessity of behavioral change to decrease food waste may hinder successful implementation.

4.4 Risks from current political targets and indicators

Based on our findings, we conclude that focusing solely on targets and indicators for food waste may be misleading in achieving the overarching goal of significantly reducing the resource footprints of food consumption. However, policies addressing dietary shifts would lead to an increased proportion of cereals, roots, potatoes, fruit, and vegetables in the diet -- this will lead to an increase in food waste as these products have higher food waste ratios, although they will still reduce overall resource footprints.

We show that footprint indicators could help political prioritization and target setting. At present, footprint indicators are entirely lacking in policy strategies and target monitoring tools for the food sector. The SDG 12 indicators in the proposed list as of 2016 (IAEG-SDGs 2016) do include the material footprint, although not specifically for the food sector. Indicators that capture the trade-offs between resource use and food waste reduction are lacking. The EU action plan for the Circular Economy (EC 2015) has similar shortcomings. The first monitoring framework lacks footprint indicators and instead focuses largely on the quantification of waste (EC 2018). The basic deficiencies in this monitoring approach (EC 2018) are highlighted by Helander et al. (2019). In the recently updated Circular Economy Action Plan (EC 2020), an update of the monitoring framework is foreseen, which intends to include indicators on resource use and material footprints. To monitor strategies related to the food sector particularly, we suggest including resource footprints of food consumption in the updated version of the monitoring framework. The possible trade-offs between goals revealed by this study emphasize the necessity of including such indicators if a circular economy is tod help avoid the irreversible damages caused by the high rate of resource consumption, as the action plan suggests (EC 2015).

5. Conclusion

Food waste is currently a predominant issue in policies aimed at reducing the resource use of food production and consumption. However, our results reveal that, for Germany, attaining the SDG 12.3 target of halving food waste is by far a less effective strategy to achieve actual resource savings than dietary changes. Adopting healthy dietary patterns – like the reference diet from the EAT Lancet Commission – would alone decrease biomass, land, and water footprints of German food consumption by around 54%, 43%, and 7%, respectively, whereas halving food waste yields only up to 20% resource-saving potentials (including uncertainty range). A combination of the two strategies has evidently the highest potential. However, we reveal potentially conflicting outcomes of a dietary change on food waste and resource use. Dietary shifts towards healthier and more sustainable diets may impede reaching the goal of halving food waste, as the change implies an increase in products associated with higher food waste shares. Subsequently, policies addressing dietary shifts may find themselves at cross-purposes to policies addressing FLW. Therefore, policies should be complemented with resource footprint indicators capturing the overall resource use rather than separate measures of FLW or dietary shifts. We conclude that an exclusive focus on food waste would potentially mislead policymakers and prevent them from addressing diets, despite being the more effective strategy for reducing resource use. Thus, complementing food waste reduction targets with measures to change dietary patterns as well as targets for the related resource footprint reduction can yield much larger benefits for the environment. Thereby the SDGs, EU and national policies, particularly in high-income countries like Germany, could be more effective to address global resource and environmental challenges that are currently jeopardizing the future food supply.

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Author contributions

H. Helander conceived the first research idea, carried out the analyses and footprint calculations as well as took the lead in writing the manuscript. A. Petit-Boix, S. Leipold and S. Bringezu contributed to the development of research questions and research design. M. Bruckner supported the analysis. M. Bruckner, A. Petit-Boix, S. Leipold and S. Bringezu reviewed various versions of the manuscript and wrote/contributed to specific passages with literature. All authors gave their final approval to the manuscript.

Ethics declarations

The authors declare no competing interests.

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