

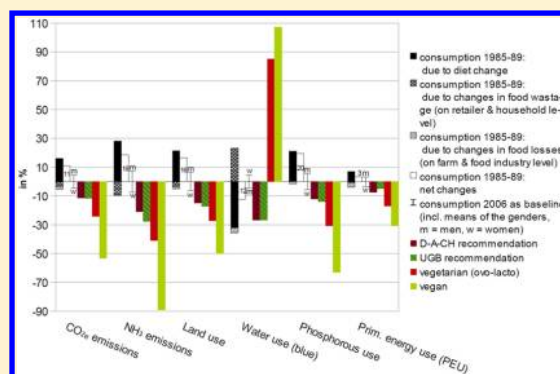
# Environmental Impacts of Dietary Recommendations and Dietary Styles: Germany As an Example

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## Supporting Information

**ABSTRACT:** Besides technical improvements and a reduction of food losses in the food chain, diet shifts offer practicable opportunities to reduce environmental impacts in the agri-food sector on a low-cost basis. In this paper we analyze the environmental impacts of nutrition in Germany in the year 2006. Based on an equalized daily energy uptake of 2000 kcal person<sup>-1</sup> day<sup>-1</sup>, we compared these impacts with those of four dietary scenarios (D-A-CH, UGB, ovo-lacto vegetarian, vegan) and with average nutrition from 20 years ago, differentiating between effects caused by altering food losses, food wastage, and changed diets. In the year 2006 gender-related impacts were considered separately. With regard to the scenarios analyzed, the highest impact changes would be expected from the vegan and the ovo-lacto vegetarian diet. The impact potentials of the recommendations of UGB and D-A-CH rank third and fourth, but are still significant. Concerning gender, the average female diet is already closer to the recommendations than men's. In comparison to the years 1985–1989, all indicators (with the exception of blue water) show lower impacts, due mainly to changes in diet. In comparison to this, impact changes resulting from food wastage were lower and mainly contrarian, which could be explained by higher food wastage in 2006 compared to 1985–1989.



## INTRODUCTION

Depending on the environmental indicator analyzed, human nutrition has a strong effect on environmental impacts, varying in Germany from contributing to 95% of all ammonia emissions, 50% of total land use, and even 25% of all greenhouse gas emissions.<sup>1,28</sup> Additionally global challenges, such as the disappearance of tropical forests, biodiversity loss, and excessive resource extraction are closely linked to nutrition—and most of all to prevailing diets in industrialized countries.<sup>4–10</sup> Moreover, western dietary patterns with an augmented intake of mono-saccharides, animal-based products and saturated fatty acids are linked to degenerative/noncommunicable diseases (adiposity, diabetes, gout, cancer, etc.).<sup>11</sup> Political considerations in the EU<sup>2</sup> imply the development of nutritionally acceptable and environmentally sound measures to cope with the above-mentioned agro-ecological challenges. According to the European Commission, “by 2020, incentives to healthier and more sustainable food production and consumption will be widespread and will have driven a 20% reduction in the food chain’s resource inputs. Disposal of edible food waste should have been halved in the EU.”<sup>3</sup>

To support environmental decisions various studies with a life cycle perspective have been conducted: (i) on a product level basis to identify hot spots in the life cycle or (ii) on a complete diet basis to identify the most polluting food items and to compare different dietary patterns.<sup>12–16</sup>

From a consumer viewpoint, a shift in diet and reduced food losses tend to be the most influential measures to reduce

nutrition-related environmental impacts.<sup>18–25</sup> From a producer perspective, technical solutions (efficiency gains in production, processing and trade) as well as a reduction of food losses could lower the environmental pressures of the agri-food sector. Considering different options and strategies, McMichael et al. (2007)<sup>26</sup> and Weidema et al. (2008)<sup>6</sup> concluded that the influence of bare production-driven measures (technical solutions and reduced food losses in the agri-food sector) is limited to about 20%.

In this paper we analyzed diet-related environmental impacts and possible alterations from a consumer perspective. In the main part we compare the impacts of dietary recommendations (D-A-CH & UGB) as well as of dietary styles (ovo-lacto vegetarian, vegan) with the average German nutrition profile from the year 2006. Novelty in this study could be found on the one hand in the environmental data used, and on the other hand in the nutritional data and the methodology applied to transform eating habits into environmental impacts. Regarding the environmental assessment of the German agri-food sector mainly representative inventory data (top-down) from the System of Environmental and Economic Accounting were used.<sup>35</sup>

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In comparison to Meier & Christen (2012)<sup>17</sup> detailed life cycle inventory (LCI) and impact assessment data (LCIA) are provided with this study (see the Supporting Information). Another innovative aspect could be seen in the ammonia emissions, which were examined besides other environmental indicators, related to distinct diets, dietary recommendations, and dietary styles.

Regarding the nutritional data and methodology applied it was in this study for the first time possible to draw a comparison of the average diet profile between the year 2006 and the diet profile from 20 years ago (in the years 1985–1989). For this we used the intake data from the last two German National Nutrition Surveys (NNS) from the years 1985–1989 and 2006 and embedded these in corresponding official food supply and consumption data. Hence it was possible to consistently examine the impact of varying food losses/wastage (on the farm and market level as well as on the retailer and household level). Thus both effects (variation in diet and in food losses) could be distinguished to explain the changes in the environmental impacts.

Previous studies with a similar scope used either an equal conversion factor for all food groups between intake and consumption<sup>8</sup> (therefore allowing no particular conclusions to be made concerning distinct food groups), or converted the intake into consumption data by using hypothetical conversion factors, generated econometrically on a household level.<sup>13,18</sup> Another new aspect of this study is the environmental analysis and comparison of a balanced, purely vegetable-based (vegan) diet. Other studies with a similar scope focused either on prevailing diets<sup>4,9,15,23</sup> or, in the scenario analysis, on less altered nutritional patterns.<sup>13,16,18</sup>

Moreover, in the year 2006 we distinguished between the typical nutrition patterns of men and women (age range 14–80). In contrast to Meier & Christen (2012),<sup>17</sup> where the differences of men's and women's dietary patterns were analyzed in more detail and compared on the basis of an equal weight (mass basis), we compare the different dietary profiles in this study based on an equalized energy uptake (energy basis) of 2000 kcal person<sup>-1</sup> day<sup>-1</sup>.

## MATERIALS AND METHODS

This study was carried out in accordance with ISO 14040/14044 (2006),<sup>40</sup> completing the four steps of a life cycle assessment (LCA): (i) goal and scope definition/system boundaries; (ii) life cycle inventory (LCI); (iii) life cycle impact assessment (LCIA); and (iv) sensitivity analysis and interpretation of results.

**Goal.** The goal of this study was to analyze the environmental impacts of the dietary pattern in the year 2006 (incl. genders) as well as in the years 1985–1989. These were compared with four dietary scenarios (two recommendations and two dietary styles) to examine the environmental benefits of possible dietary changes. Further, changes to environmental impacts caused by varying food losses between 2006 and 1985–1989 were considered separately.

**System Boundaries.** The system boundaries are set cradle-to-store and include the processes (i) agricultural production (incl. upstream processes); (ii) processing; (iii) transport and trade; and (iv) packaging. The upstream processes of agricultural production include emissions from direct land use change and land use (dLUC, LU), emissions from fertilizer/pesticide production and emissions from the construction and use of buildings and machinery. Related emissions during food buying, in the use phase (cooking and storing in the household/

in restaurants, etc.) or in the waste phase have not been taken into consideration in the study.

**Functional Unit.** The functional unit in this study refers to diets with an energy uptake of 2000 kcal person<sup>-1</sup> day<sup>-1</sup>.

**Environmental Data.** The impact modeling in this study was done by way of an attributional Input-output LCA/hybrid-LCA.<sup>56</sup> The term reflects the origin of the LCI data sets used (top-down environmental extended input-output data and classical bottom-up LCA data). The environmental impact assessment of the domestically produced commodities was based mainly on the top-down input-output tables of SEEA (System of Environmental and Economic Accounting).<sup>35</sup> To disaggregate between different couple products (milk/meat, rapeseed oil/cake, sugar/molasses, etc.) we have applied an allocation based on the products' mass (mass basis).

To consider the impacts of food imports, agricultural upstream processes, emissions from direct land use change and land use (dLUC, LU), food processing, trade/transport and packaging, the SEEA data were complemented by several LCAs and other complementary data sets. For citrus fruits, life cycle inventory data were used from Sanjuan et al. (2005).<sup>45</sup> Blue water use and yields of imported products were derived from Mekonnen & Hoekstra (2012)<sup>39</sup> and FAO Stat (2012),<sup>48</sup> respectively. For the calculation of impacts from agricultural upstream processes we used data from Brentrup & Pallière (2008)<sup>44</sup> (concerning fertilizer production) and data from the above-mentioned SEEA data sets<sup>35</sup> for the rest of the upstream processes (pesticide production, emissions from the construction and use of buildings and machinery). For calculating emissions from dLUC, LU we used data from Leip et al. (2010).<sup>36</sup> Modeled with the system CAPRI (Common Agricultural Policy Regionalised Impact Modeling System) these provide by a Tier-1 approach for European and non-European countries product specific emissions from dLUC, LU. The Danish LCA Food database<sup>37</sup> was used for modeling the impacts of fish and shellfish landing/production. The environmental impacts from processing built upon official top-down energy consumption data from the German food industry in the year 2006,<sup>28</sup> which were modeled along with impacts from trade, transport and packaging with data from the Institute of Applied Ecology (2010).<sup>38</sup> For the years 1985–1989 the same production conditions (and therefore production efficiencies) as well as the same import shares and import countries were assumed as for the year 2006. For further specifications see Table 3 and the Supporting Information.

**Environmental Indicators.** As regards environmental impact assessment, global warming potential (GWP) according to IPCC<sup>54</sup> was assessed with a time interval of 100 years (GWP methane: 25, GWP nitrous oxide: 298)—including emissions from direct land use change and land use (dLUC, LU). Further, five inventory indicators (ammonia emissions, land use, blue water use, phosphorus use (as a pure nutrient) and primary energy use (PEU)) were considered—see specifications in Table 3.

Although different water impact methodologies are already established,<sup>49–51</sup> due to the scope and origin of the data in this study we analyzed the blue water footprint only. Blue water refers to ground and surface water, which is used for irrigation and during processing. Besides regionalized watershed-specific scarcity indicators, we argue that blue water use on the national level is a proper indicator for depicting water stress in a practical manner, rather than the nonweighted summation of blue and green water.<sup>52</sup>

**Nutritional Data.** For the study, representative data sets concerning German food production, food supply and food

consumption were used.<sup>27,28</sup> The term “supply” as used in this study is described by Formula 1:

$$\begin{aligned} \text{supply(HDU)} = & \text{production} + \text{imports} - \text{exports} \\ & + \text{changes in stock} - \text{nonnutritional use} \end{aligned} \quad (1)$$

Supply (HDU): supply for human domestic utilization

The term reflects the amount of food that was statistically used on the domestic market for human nutrition. This amount is defined as environmentally relevant and was used for the environmental assessment. Whereas farm and food industry losses (due to weight loss and spoilage) are included in the supply wherever corresponding data were available, these losses are excluded in the consumption. The term “consumption” reflects the amount of food that was statistically available on retail level.<sup>28</sup> The term “consumption” is described by Formula 2:

$$\begin{aligned} \text{consumption(URL)} \\ = \text{supply(HDU)} - \text{food losses}_{\text{on-farm, food industry}} \end{aligned} \quad (2)$$

Consumption (URL): utilization on retail level

The term “intake” reflects the amount of food that was actually eaten and is described by Formula 3:

$$\text{intake} = \text{consumption(URL)} - \text{food wastage}_{\text{retailer, household}} \quad (3)$$

Regarding food intake, subgroup-specific intake data were used, provided by both National Nutrition Surveys (NNS) from the years 1985–1989 and 2006.<sup>30,31</sup> Whereas the NNS I (1985–1989) was based on a sample size of 25 000 persons (4–94 years) in the former Federal Republic of Western Germany, the NNS II (2006) was based on a sample size of 19 000 persons (14–80 years) in the reunified country. Whereas the NNS I was representative of 59 million people, the NNS II is representative of 68 million people—or 83% of the total population. Representative subgroups in the NNS II were specified according to gender, age groups, social groups, and regions. In this study we include the results concerning the socio-demographic factor gender. With regard to accuracy and representativeness, the survey establishes a solid stock for further statistical research that can be used via scientific-use-files.

**Food Losses, Food Wastage.** In this study we distinguish between food losses and food wastage. Food losses refer to spoilage and weight losses on the producer level (on the farm and food industry level). To relate to retailers’ and consumers’ behavior, corresponding food losses at these stages in the supply chain are denominated as “food wastage”.<sup>32–34</sup> As a corresponding breakdown between food losses and food wastage—based on official agricultural statistics in Germany<sup>27,28</sup>—was possible, we use both terms in this study.

**Imports and Exports of Food.** Resulting from the manifold trade relations of the German agri-food sector, it was impossible to include all imports and exports and their related environmental impacts in the assessment. Nevertheless, to approach this issue in a practical manner we consider only trade relations in the year 2006 where Germany is a significant net importer. Therefore the import shares of vegetables, fruits, nuts/seeds, vegetal oils/fats, oil cakes, and vegan milk products were considered separately. According to data from national trade statistics<sup>28</sup> and the FAO,<sup>47</sup> the degree of self-sufficiency for these products is far below 100% (Table 3).

**Adjustment of the Food Groups Analyzed.** In the assessment 43 different commodities were considered: 12 animal-based foods, 23 plant-based foods, and 8 feeds. To enable a comparison of the diets in 2006 and 1985–1989 with the recommendations, these were aggregated into the following food groups: dairy products (including butter, high-fat dairy products like cheese and cream, and low-fat dairy products like milk and yoghurt), meat products (including pork, beef/veal, poultry, other meat), egg products, fish/shellfish products, grain products, vegetables, legumes, fruits, nuts and seeds, potato products, vegetal oils and margarine, sugar/sweets (Tables 2 and 3).

As entries concerning alcoholic beverages (beer, wine, spirits) as well as coffee, tea and cocoa do not exist in most of the recommendations and diets, these product groups were omitted in the assessment. Nevertheless, as all recommendations consider the intake of fruits and sugar via soft drinks and juices, we considered this intake pathway, too. Furthermore, grains in beer were reallocated to the corresponding main group “grain products”. As far as statistical information about the composition of heterogeneous and complex food groups in the National Nutrition Surveys was available, the related food groups were taken apart and the raw products reallocated to the corresponding main group. Besides the above-mentioned drinks (beer, soft drinks, juices) this taking apart and reallocation was done in the case of grain products, vegetal oils/margarine, and sugar/sweets. To give an example: Besides bread and pasta, grain products include pastries and sweet bakery products (and therefore sugar). To produce in the year 2005/2006 a total of 8585 kt grain products also 524 kt sugar was used.<sup>28</sup> In the mass flow matrix, which underlies this study, these 524 kt were taken from the grain products group and reallocated to the product group “sugar, sweets”. Limitations are caused by ingredients for which no statistical information was available (e.g., nut/seed usage in sweet bakery production).

**Dietary Scenarios.** For the comparison with dietary recommendations and diet styles the quantifiable food-related dietary profiles in Table 1 were examined. When determining the dietary scenarios analyzed, the following points were of major interest: (i) the recommendations should be expressed in clearly defined quantifiable food groups, (ii) the food groups should be sufficiently distinguished to allow an environmental assessment.

There generally exist two types of recommendations: nutrient-based dietary recommendations (NBDR) and food-based dietary recommendations (FBDR). Whereas NBDR are suited to health impact analysis, FBDR are more consumer-friendly and can be used for environmental assessments, if they are sufficiently determined (ample, consistent and standardized product categories). In this study we analyzed exclusively FBDR. For this we chose two recommendations from Germany (D-A-CH, UGB). Furthermore, an ovo-lacto vegetarian and a vegan dietary style were selected to analyze the impacts of more drastic dietary shifts. Since in Germany there are no FBDR for vegetarian and vegan dietary patterns from official institutions, we used the ones from USDA/USDHHS (2010),<sup>43</sup> Table 1. To allow a comparison between the different dietary scenarios all were adjusted to an energy uptake of 2000 kcal person<sup>-1</sup> day<sup>-1</sup>.

Table 2 gives an overview of the intake amounts analyzed based on 2,000 kcal person<sup>-1</sup> day<sup>-1</sup>.

**Intake-Supply Conversion and Environmental Assessment.** To allow an environmental analysis, the intake amounts were converted to the corresponding food supply (for human domestic utilization, see Formula 1), using statistically derived



**Table 1. Types of Dietary Recommendations and Diet Styles Analyzed**

	description	reference
dietary recommendations	D-A-CH (official recommendations of the German Nutrition Society, valid for Germany, Austria and Switzerland)	41
	UGB (alternative recommendations by the Federation for Independent Health Consultation with less meat, but more legumes and vegetables). Besides health considerations these recommendations are also based on ecological and social constraints (e.g., preferably the intake of organically produced food). These process-specific recommendations have not been considered in the analysis.	42
dietary styles	ovo-lacto vegetarian (plant-based diet with egg and dairy products, no meat or fish)	43
	vegan (totally plant-based diet, with no meat, dairy, fish or egg products and instead greater amounts of fortified soy-based milk products, more legumes, nuts and seeds)	43

**Table 2. Intake Amounts Analyzed in g person<sup>-1</sup> day<sup>-1</sup> (based on 2,000 kcal person<sup>-1</sup> day<sup>-1</sup>)**

	intake 1985–89	intake 2006 mean	intake 2006 men	intake 2006 women	D-A-CH	UGB	ovo-lacto vege-tarian	vegan
	g person <sup>-1</sup> day <sup>-1</sup>							
butter	20	12	13	11	11	10	8	–
high-fat dairy products (cheese, cream)	38	46	42	51	55	75	732 <sup>a</sup>	–
low-fat dairy products (milk, yoghurt)	169	207	191	223	225	375	–	–
vegan milk products	–	–	–	–	–	–	–	732 <sup>a</sup>
meat products	158	103	121	84	64	40	–	–
beef, veal	41	19	22	15	12	7	–	–
pork	93	57	68	45	35	22	–	–
poultry	21	24	27	22	15	9	–	–
other meat	3	3	3	2	2	1	–	–
egg products	31	18	18	19	9	9	16	–
fish products	17	25	25	25	26	25	–	–
grains	293	278	299	258	362	403	295	295
vegetables	145	231	192	270	400	500	245	245
legumes	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	52	124	128
fruits	134	347	276	419	250	200	250	250
nuts, seeds	2	3	3	4	– <sup>c</sup>	– <sup>c</sup>	21	26
potato products	108	80	80	80	112	82	107	107
vegetal oils, margarine	22	15	15	15	24	30	27	34
sugar	54	70	71	69	32	32	32	32
sum	1192	1437	1345	1528	1571	1833	1857	1850

<sup>a</sup>In whole milk equivalents. <sup>b</sup>Legumes are included in vegetables. <sup>c</sup>D-A-CH & UGB do not have quantifiable recommendations for nuts and seeds.

supply, processing and composition data<sup>27,28</sup> for the years considered (2006 and 1985–1989). For the years 1985–1989 the average mean of supply and consumption was used. For the conversion the intake data were divided by the corresponding supply amounts. Thus it was possible to embed the intake consistently in official supply data. The product-specific conversion factors (CF = intake/supply) derived in this manner as well as the environmental impact factors used in the assessment are outlined in Table 3. To give an example: A CF of 0.71 (butter in 2006) means that just 71% of the statistically available amount of butter on the domestic market (=supply) was actually eaten (=intake). On the other hand, a CF higher than 1 indicates that more products were actually eaten than were available on the domestic market. Normally this is not the case, but it can occur, for example, for fruits. Fruits are also produced extensively in home gardens or occur naturally in forests. These fruits are eaten, yet their availability does not appear in national statistics.

The following formulas were used to calculate the environmental impacts on diet level (EI<sub>diet</sub>)(4,5).

$$CF = \frac{\text{intake (national mean)}}{\text{supply (national mean)}} \quad (4)$$

$$EI_{\text{diet}} = \sum_{n=1}^{18} \frac{\text{intake}_n}{CF_n} EF_n \quad (5)$$

CF: conversion factor; EI: Environmental impact of the supply of the complete diet; EF: environmental factor of the corresponding food/food group; *n*: food group.

First, product group-specific conversion factors (CF) were calculated by dividing the means of the national intake amounts by the corresponding supply amounts. Second, these were used to convert the specific intake into supply amounts. Then, these were multiplied with the corresponding environmental factor (EF) (to determine the individual impact of food group in the whole diet) and summed up with the environmental impacts of the other food groups (to calculate the impact of the whole diet).

## RESULTS

**Overall Results Due to Recommendations and Dietary Styles.** Table 4 presents overall results for the nutrition scenarios analyzed. In comparison to the dietary recommendations and the dietary styles, which can be mainly characterized by an increasing share of legumes, nuts/seeds and vegetables in the profiles, instead of meat, butter, egg and fish products as well as fruits (D-A-CH > UGB > vegetarian > vegan), both genders could

Table 3. Conversion Factors, Environmental Impact Factors, and Degree of Self-Sufficiency of the Food Groups Analyzed

	meat products											modeled as						
	high-fat dairy products (cheese, cream) butter	low-fat dairy products (milk, yoghurt)	vegan milk products (in whole milk)	beef, veal	pork	poultry	other meat products	egg products	fish products	grains	vegetables		legumes	fruits	nuts & seeds	potato products	vegetable oils, margarine	sugar
conversion factor 1985–89	0.91	0.83	0.59	0.70	0.61	0.53	0.69	0.47	0.69	0.48	0.87	0.66	0.66	0.54	0.18	0.45	0.57	0.47
conversion factor 2006	0.71	0.75	0.70	0.70	0.61	0.40	0.56	0.40	0.54	0.61	0.79	0.76	0.76	0.97	0.32	0.36	0.39	0.56
degree of self-sufficiency of German food supply in 2006	81	117	116	36	126	96	86	61	71	25	109	36	77	11	9	137	30	123
CO <sub>2</sub> e emissions	19.7	10.0	2.7	0.7	18.6	7.9	5.9	17.2	3.1	2.4	1.5	0.8	1.1	0.8	0.8	0.5	3.4	1.9
NH <sub>3</sub> emissions	82.5	39.4	9.7	0.2	75.2	33.4	24.1	100.5	19.7	0.2	1.9	0.7	0.6	0.6	0.6	0.3	3.3	1.5
land use	20.7	9.9	2.4	0.7	25.4	8.9	6.2	19.9	3.8	0.2	1.8	0.5	2.1	0.9	2.9	0.3	4.1	1.2
water us (blue)	86.0	44.3	15.6	6.4	84.6	29.7	15.2	96.6	8.8	14.7	5.2	27.4	8.8	87.6	1425	5.7	15.7	9.5
phosphorus use	70.0	33.5	8.2	1.3	97.9	22.2	16.0	68.1	10.3	4.4	5.3	2.7	3.7	1.4	1.4	0.9	9.7	3.6
primary energy use (PEU)	64.2	38.5	13.8	7.5	78.0	49.3	42.8	69.5	24.4	13.1	11.9	11.2	8.0	12.6	12.6	5.1	19.9	18.6

data concerning food supply from 27; data concerning food intake from 30; data concerning food supply from 28; data concerning food intake from 31 according to official agricultural statistics 28; degree of self-sufficiency of vegan milk products was adapted from vegetables

data concerning domestic agriculture and upstream processes from 35 and 44; data concerning fish from 37; data concerning fruits partly from 45; data concerning DLUC, LU from 36; data concerning processing from 28; data concerning trade/transport from 46 and data concerning packaging from 38. If no data for imported products were available, domestic conditions were assumed. Global warming potentials were calculated according to 54.

data concerning domestic agriculture from 35; data concerning fish from 37; data concerning processing from 28; data concerning trade/transport from 46 and data concerning packaging from 38. If no data for imported products were available, domestic conditions were assumed.

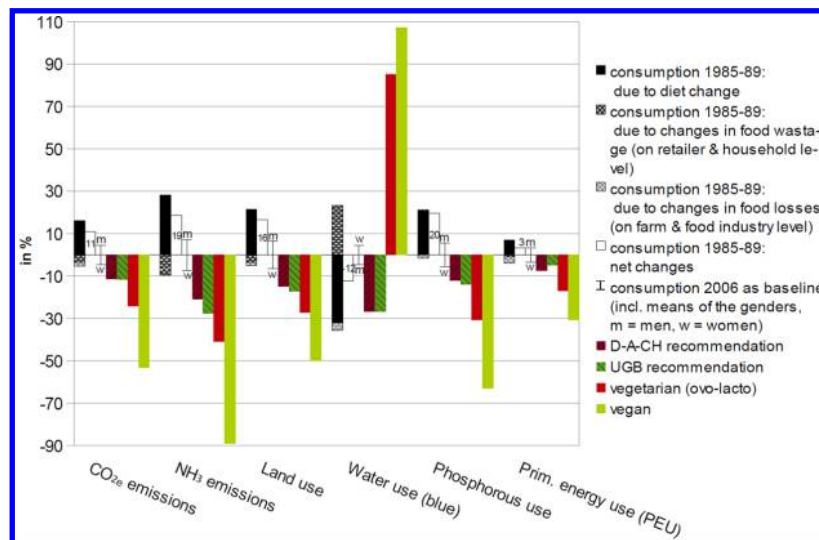
data concerning domestic agriculture from 35; data concerning packaging from 38. data for imported products from 39.

data concerning domestic agriculture from 35. Phosphorus use during processing was not examined.

data concerning domestic agriculture and upstream processes from 35 and 44; data concerning fish from 37; data concerning fruits partly from 45; data concerning processing from 28; data concerning trade/transport from 46 and data concerning packaging from 38. If no data for imported products were available, domestic conditions were assumed.

**Table 4. Environmental Impacts of Food Consumption in the Years 1985–89 and 2006 (Incl. Genders) in Germany As Well As of Several Dietary Recommendations and Dietary Styles Based on 2000 kcal person<sup>-1</sup> day<sup>-1</sup>**

		1985–89 mean	2006 mean	2006 men	2006 women	D-A-CH	UGB	ovo-lacto vegetarian	vegan
CO <sub>2e</sub> emissions	t person <sup>-1</sup> year <sup>-1</sup>	2.28	2.05	2.13	1.98	1.82	1.81	1.56	0.96
NH <sub>3</sub> emissions	kg person <sup>-1</sup> year <sup>-1</sup>	7.7	6.5	6.9	6.0	5.1	4.7	3.8	0.7
land use	m <sup>2</sup> person <sup>-1</sup> year <sup>-1</sup>	2444	2098	2209	1984	1786	1740	1527	1052
water use (blue)	m <sup>3</sup> person <sup>-1</sup> year <sup>-1</sup>	24.9	28.4	25.8	31.0	20.9	20.8	52.5	58.8
phosphorus use	kg person <sup>-1</sup> year <sup>-1</sup>	7.7	6.5	6.8	6.1	5.7	5.6	4.5	2.4
primary energy use (PEU)	GJ person <sup>-1</sup> year <sup>-1</sup>	14.0	13.5	13.7	13.4	12.5	12.9	11.2	9.4

**Figure 1.** Environmental impacts of food consumption in 2006 in Germany as a baseline scenario in comparison to 1985–1989, gender and dietary recommendations based on 2000 kcal person<sup>-1</sup> day<sup>-1</sup>.

reduce the impacts of their diets if they were to be more in line with the recommendations or dietary styles.

With the exception of blue water, the reduction potentials for men are twice as high as women's. In other words, the average female diet is already closer to the recommendations. Nevertheless, women's average diet is associated with increased blue water use, mainly caused by higher consumption of fruits as well as of nuts and seeds, which are often produced in water-scarce areas in foreign countries. According to FAO trade statistics,<sup>47</sup> fruits imported in 2006 into Germany were mainly produced in Spain and Italy, whereas nuts and seeds were mainly imported from China, the U.S., Turkey, and Iran. Related to the mean in 2006, the strongest reduction potentials were determined for the vegan (−31% PEU to −89% NH<sub>3</sub>) and the ovo-lacto vegetarian diet (−17% PEU to −41% NH<sub>3</sub>), with the exception of blue water (vegan: +107%, vegetarian: +85%). Here we have to bear in mind that for the recommendations (D-A-CH, UGB) quantifiable intake amounts for nuts and seeds do not exist, although an increased intake in these scenarios is probable.

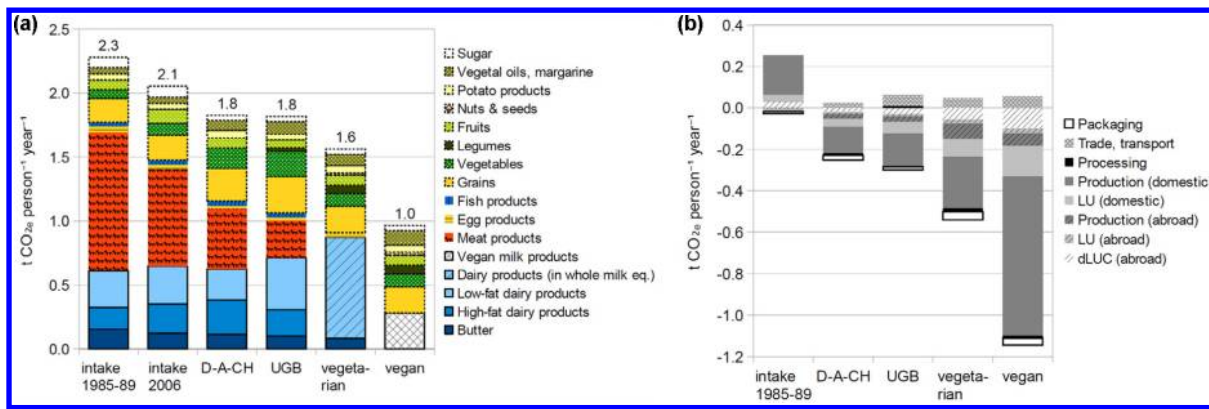
**Comparison with the Years 1985–1989.** In comparison with the environmental impacts caused by average nutrition in the years 1985–1989, almost all indicators, with the exception of blue water, show a reduced impact. Due to different diets and different conversion factors (and therefore food losses/wastage) in 2006 and 1985–1989, the differences observed could be caused either by variations in the average diet or varying food losses/wastage (Figure 1).

For the reductions observed the main driver was a shift in diets, with the exception of blue water. Here, mainly caused by

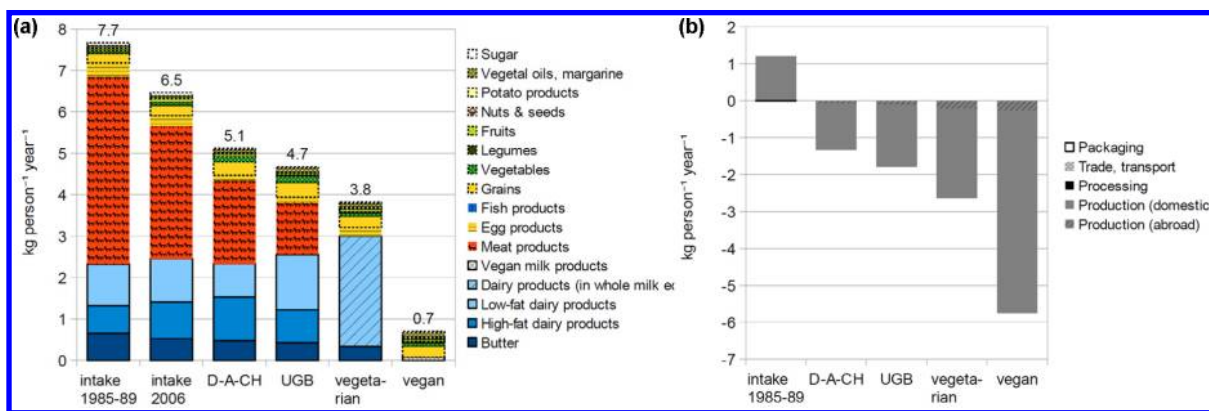
an increased intake of fruits, blue water also increased accordingly. But this rise was almost compensated by less food wastage of fruits on the retail and household level in 2006, compared to 1985–1989. On the one hand this strong decline can be explained by a reduced overproduction due to reforms of the Common Agricultural Policy of the EU (CAP) with beginning of the 1990s. On the other hand, the catastrophe of Chernobyl in April 1986 leads to a below average intake of fruits, vegetables and milk products.<sup>30</sup> For the other indicators (GHG, NH<sub>3</sub>, land use, P use, PEU), which are more driven by animal products, increased food losses, but mainly increased wastage, partially countervailed gains achieved through shifting diets.

**Specific Results Based on Product Groups and Process Stages.** Figures 2a–7b show the environmental impacts of the nutrition scenarios analyzed according to product groups and process stages. The impacts of the process stages are compared absolutely to the average impacts in the year 2006 as a baseline scenario. Differences due to gender are not presented in these figures. As no further specification concerning dairy products was available, impacts in the vegetarian and vegan scenario are presented in whole milk equivalents.

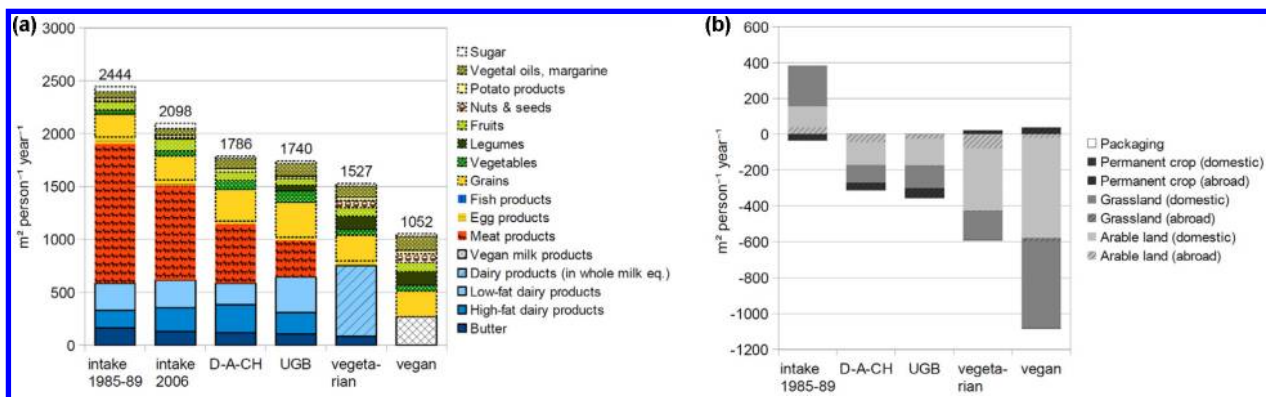
**Greenhouse Gas (GHG) Emissions (Figure 2a,b).** With regard to the nutrition scenarios analyzed, in the scenarios GHG emissions related to the consumption of dairy products are increasing (with the exception of the vegan diet), whereas GHG emissions of meat products are on the decline. GHG emissions related to the consumption of plant-based foods vary marginally in comparison to animal-based foods. Figure 2b shows that most GHG reductions would be expected in domestic production.



**Figure 2.** (a) GHG emissions in t CO<sub>2e</sub> per person per year, caused by food intake in 1985–89, 2006 and four dietary scenarios. LU: Emissions from land use. dLUC: Emissions from direct land use change. (b) GHG emissions in t CO<sub>2e</sub> per person per year in 1985–89 and four scenarios compared to 2006 intake (according to process stages).



**Figure 3.** (a) NH<sub>3</sub> emissions in kg per person per year, caused by food intake in 1985–89, 2006 and four dietary scenarios. (b) NH<sub>3</sub> emissions in kg per person per year in 1985–89 and four scenarios compared to 2006 intake (according to process stages).



**Figure 4.** (a) Land use in m<sup>2</sup> per person per year, caused by food intake in 1985–89, 2006 and four dietary scenarios. (b) Land use in m<sup>2</sup> per person per year in 1985–89 and four scenarios compared to 2006 intake (according to process stages).

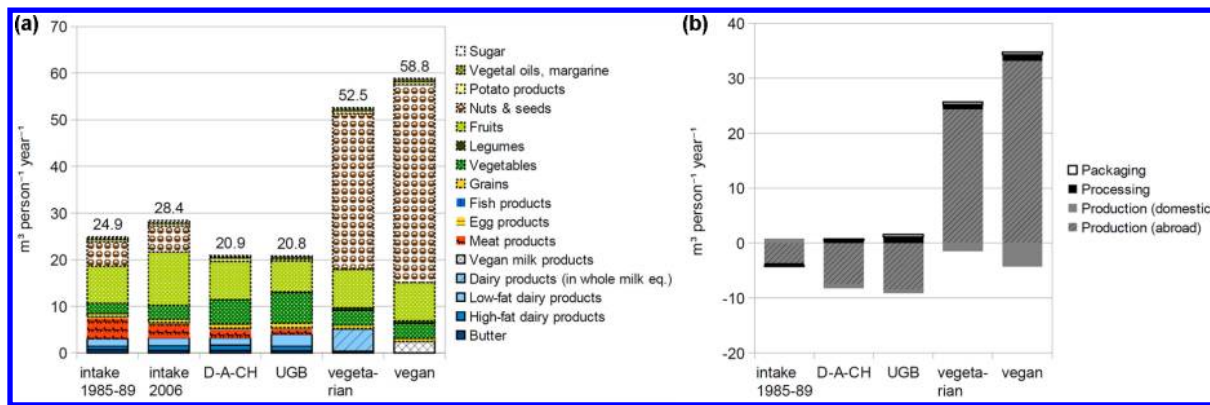
Second-order emission reductions come from direct land use change (dLUC) and land use (LU) varying for the recommendations and dietary scenarios between –11% (D-A-CH) and –53% (vegan).

**Ammonia Emissions (Figure 3a,b).** As ammonia emissions occur mainly as a pollutant in livestock production, consumption-related emissions are dominated by dairy and meat products. Emissions from processing, transport/trade and packaging are irrelevant. In comparison to the other impact indicators analyzed, the highest reduction potentials in view of the recommendations and dietary styles are observed for ammonia (up to 90% for the vegan diet).

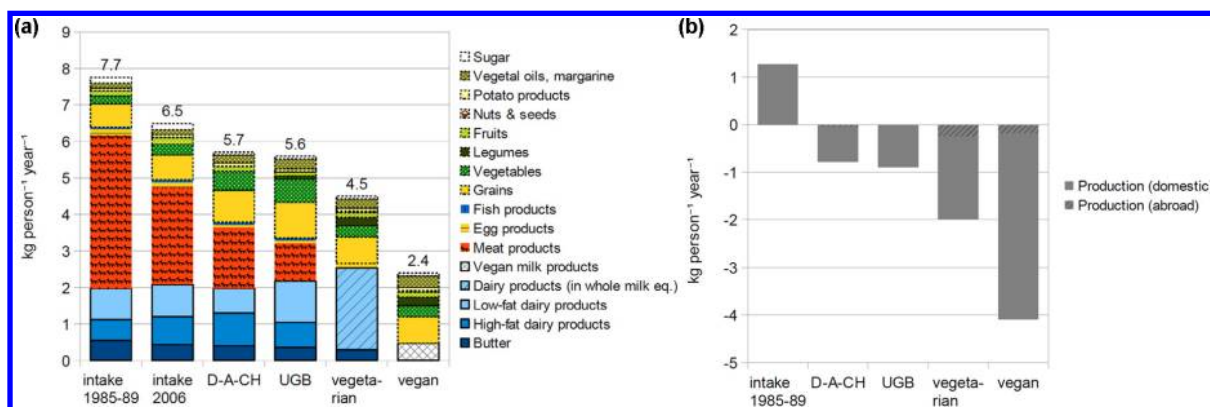
**Land Use (Figure 4a,b).** The impact profile of land use is similarly as pronounced as that of GHG emissions (Figure 2a). With regard to land releases, if the recommendations or dietary styles were to be pursued, the most land freed up would be domestic arable land, followed by domestic grassland and arable land abroad. With the implementation of a vegan diet, up to 1000 m<sup>2</sup> person<sup>-1</sup> year<sup>-1</sup> could be freed up, with a slight increase of permanent crops abroad.

**Blue Water Use (Figure 5a,b).** The results concerning blue water use differ remarkably from the others. Here we have to bear in mind that for the dietary recommendations





**Figure 5.** (a) Blue water use in  $m^3$  per person per year, caused by food intake in 1985–1989, 2006 and four dietary scenarios. (b) Blue water use in  $m^3$  per person per year in 1985–1989 and four scenarios compared to 2006 intake (according to process stages).



**Figure 6.** (a) Phosphorus use in kg per person per year, caused by food intake in 1985–1989, 2006 and four dietary scenarios. (b) Phosphorus use in kg per person per year in 1985–1989 and four scenarios compared to 2006 intake (according to process stages).

(D-A-CH, UGB) quantifiable intake amounts for the water-intensive product group nuts and seeds do not exist, although an increased intake in these scenarios is probable. Therefore, the results concerning the vegetarian and vegan diet are of higher relevance. As shown in Figure 5a, the strong increase compared to the year 2006 would be driven by nuts and seeds. With regard to the process stages, besides a slight increase in blue water during processing, the biggest impact would be expected in agricultural production abroad.

**Phosphorus Use (Figure 6a,b).** The impact profile of phosphorus use is similarly as pronounced as that of GHG emissions (Figure 2a) and land use (Figure 4a). With regard to the nutrition scenarios analyzed, phosphorus use related to the consumption of dairy products is increasing (with the exception of the vegan diet), whereas phosphorus use caused by meat products is on the decline in the scenarios. Nevertheless, the meat-related decline is more strongly pronounced than the dairy-related increase. Phosphorus use related to the consumption of plant-based foods varies marginally in comparison to animal-based foods.

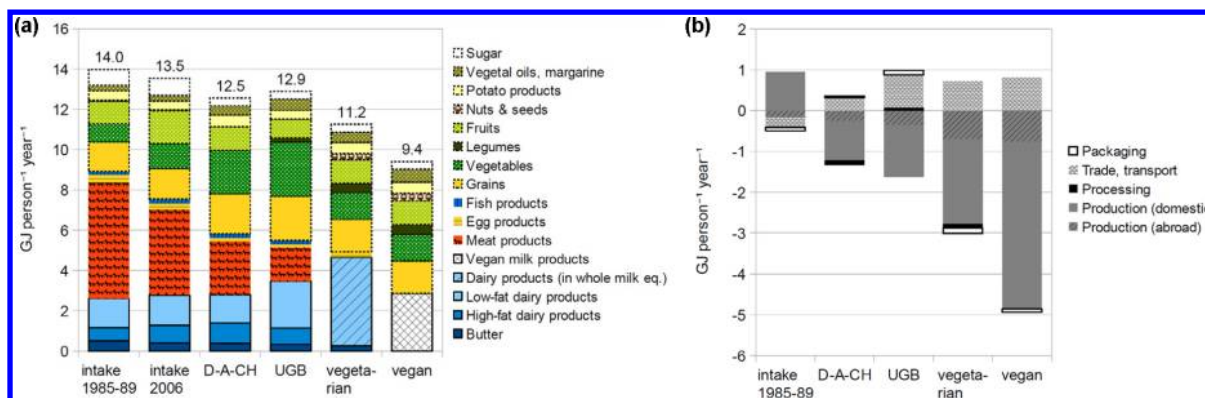
**Primary Energy Use (PEU) (Figure 7a,b).** Compared to the impact profiles of most indicators (GHG,  $NH_3$ , land and P use), PEU in the nutrition scenarios varies similarly: There is declining intensity toward the vegan diet. Nevertheless, the total differences between the scenarios are less pronounced and the PEU of the UGB recommendation is higher when compared to the other recommendation and the dietary styles.

## DISCUSSION

In this paper we analyzed diet-related environmental impacts and possible alterations from a consumer perspective. Taking different reference years, countries, system boundaries and methodological approaches into consideration, our results are comparable to those of other studies. For the consumption of food in Germany, using a multiregional input–output model (MRIO) Hertwich and Peters (2009)<sup>7</sup> calculated an average value of  $1.96 \text{ t CO}_2e \text{ person}^{-1} \text{ year}^{-1}$  (reference year 2001). In comparison to this study, with  $2.05 \text{ t CO}_2e \text{ person}^{-1} \text{ year}^{-1}$  (reference year 2006), the difference is almost negligible. Nevertheless, it was not possible to scrutinize the results further, since Hertwich and Peters (2009)<sup>7</sup> do not describe the system boundaries of the food sector sufficiently. Excluding emissions from direct land use change and land use, Jungbluth et al. (2011)<sup>9</sup> and Muñoz et al. (2010)<sup>15</sup> calculated the nutrition-related greenhouse gas emissions for an average Swiss and an average Spaniard to be  $2.0$  and  $2.1 \text{ t CO}_2e \text{ person}^{-1} \text{ year}^{-1}$ , respectively. While both studies considered emissions in the household (storing, preparing, cooking), Muñoz et al. (2010)<sup>15</sup> additionally determined emissions in the waste phase (treatment of sewage sludge, etc.). In this study, emissions from direct land use change and land use were calculated to be  $0.34 \text{ t CO}_2e \text{ person}^{-1} \text{ year}^{-1}$  ( $0.14 \text{ t CO}_2e \text{ person}^{-1} \text{ year}^{-1}$  from direct land use change and  $0.2 \text{ t CO}_2e \text{ person}^{-1} \text{ year}^{-1}$  from land use).

With a focus on Germany, Taylor (2000)<sup>13</sup> compared the dietary greenhouse gas emissions of various nutrition patterns





**Figure 7.** (a) Primary energy use (PEU) in GJ per person per year, caused by food intake in 1985–1989, 2006 and four dietary scenarios. (b) PEU in GJ per person per year in 1985–1989 and four scenarios compared to 2006 intake (according to process stages).

and two production styles (conventional/organic). Within the nutrition patterns analyzed, Taylor (2000)<sup>13</sup> distinguished between standard nutrition (based on the National Nutrition Survey I<sup>27</sup>), whole food nutrition<sup>42</sup> and ovo-lacto vegetarian nutrition. In comparison to our study, emissions from direct land use change and land use were omitted, whereas emissions in the household were included. The fact that Taylor (2000) used classical LCA data may explain why the results differ considerably in absolute terms. If, in order to compare the results within the same system boundaries, we exclude emissions from dLUC, LU and the household, then on the one hand we have 1.33 t CO<sub>2e</sub> person<sup>-1</sup> year<sup>-1</sup> according to Taylor (2000)<sup>13</sup> and on the other—in this study—we have 1.71 t CO<sub>2e</sub> person<sup>-1</sup> year<sup>-1</sup> (2.05 minus 0.34 t CO<sub>2e</sub> person<sup>-1</sup> year<sup>-1</sup>). In relative terms the results vary roughly by half: minus 29% with whole food nutrition (in this study: minus 12%) and minus 45% with ovo-lacto vegetarian nutrition (in this study: minus 24%). These differences are mainly due to methodological issues. When converting intake into consumption amounts Taylor (2000)<sup>13</sup> used an econometrical approach on the household level. With regard to dairy product modeling, an allocation based solely on fat content was applied. In comparison to our results this allocation method leads to a higher environmental load for fatty dairy products (like butter) and to an underestimated load for dairy products that also have other nutrients (e.g., cheese with proteins). In this study we allocated dairy products based on officially documented protein and fat content.

Jungbluth et al. (2012)<sup>19</sup> compared in a meta-analysis the reduction potentials of an ovo-lacto vegetarian diet. For greenhouse gas emissions the results ranged from 26%<sup>20</sup> to 55%.<sup>21</sup> In terms of primary energy use (PEU) the results in the studies analyzed fluctuated between minus 8%<sup>22</sup> and minus 52%.<sup>19</sup> In this study we observed a reduction potential for PEU with a shift to an ovo-lacto vegetarian diet of minus 17%. The strong variation may be explained by different assumptions concerning the degree of processing.

Regarding diet-related land requirements, Wiegmann et al. (2005)<sup>18</sup> calculated for average nutrition in Germany 2396 m<sup>2</sup> person<sup>-1</sup> year<sup>-1</sup> in the year 2000. Similar studies with different reference countries have yielded comparable results. Peters et al. (2007)<sup>14</sup> analyzed the land use of 42 different diets in New York State, whereby the area ranged from 1800 m<sup>2</sup> to 8600 m<sup>2</sup> person<sup>-1</sup> year<sup>-1</sup>, depending on meat and egg consumption as well as calories from fat. Gerbens-Leenes & Nonhebel (2005)<sup>23</sup> calculated an area of 1909 m<sup>2</sup> for the average diet in The Netherlands in 1990. In this study we have

calculated an average diet-related land area in the year 2006 of 2089 m<sup>2</sup> person<sup>-1</sup> year<sup>-1</sup>. When comparing results we have to bear in mind that in this study all results are adjusted to a daily energy uptake of 2000 kcal person<sup>-1</sup> year<sup>-1</sup> to allow a comparison of the different diets.

Focusing on the diet-related use of phosphorus (P) Cordell et al. (2009)<sup>16</sup> calculated, on a global level, for an average meat-based diet a P content stored in the required plants (as a pure nutrient) of 8.0 kg person<sup>-1</sup> year<sup>-1</sup>. For a vegetarian diet, this was 1.8 kg person<sup>-1</sup> year<sup>-1</sup>. These numbers are hardly comparable to our results (average diet 2006: 6.5 kg person<sup>-1</sup> year<sup>-1</sup>, ovo-lacto vegetarian: 4.5 kg person<sup>-1</sup> year<sup>-1</sup>), since P use in this study refers to the gross input to produce the crops, also including P run-offs. Exact data concerning the vegetarian the meat-based diet (specific composition, energy intake) is missing in Cordell et al. (2009).<sup>16</sup>

**Limitations and Uncertainties.** A quantitative uncertainty analysis was not conducted in this study because there was a lack of relevant uncertainty information concerning the input data. Therefore this part of the study has been done qualitatively. Considering the fact that this study builds in the core upon consistent environmental extended input-output data for the agricultural sector in Germany (for the year 2006), related results could, when compared to purely bottom-up LCA studies on a national scale, be regarded as relatively robust. Higher sensitivities would in general be expected in the scenario analysis, for the impacts of the years 1985–1989 and for the input variables, which were modeled with classical bottom-up LCA data (imports, packaging, etc.).

Nevertheless, statistical top-down data could also be flawed by uncertainties, mainly due to sample size, the methodology of extrapolation, and cutoff criteria.<sup>35</sup> For instance, in the German Farm Accounting Data Network, which forms the baseline for the environmental assessment of the agricultural sector in the year 2006 in this study, only farms with a contribution margin (profit) of more than 12 000 euros per year are considered (at the beginning of the fiscal year 2010/2011 this number was increased to 25 000 euros).<sup>29</sup> Smaller enterprises and their environmental impacts are therefore ignored. The cutoff criterion for statistically relevant plants in the food-industry (mills, slaughterhouses, etc.) is defined by the amount of employees. As a result, generally only plants with 20 or more employees are covered.<sup>28</sup> With regard to the National Nutrition Surveys (NNS) data gaps concerning the composition of the analyzed food groups must be mentioned. As far as statistical data allow, multi-ingredient food groups (like grain products incl. sweet bakery

products, sweets including vegetal fats, juices/soft drinks including sugar etc.) were taken apart and the corresponding ingredient was reallocated to the related main group (see the Supporting Information). Nonetheless, it was not possible to apply such a procedure where no statistical composition data was available (mainly for ready-made meals, convenience foods, etc.), which might therefore lead to biased results.

A further general source of uncertainty was found in the characterization factors in the impact assessment. In this study an impact assessment was conducted for global warming potential (GWP), applying a GWP of 25 for methane and a GWP of 298 for nitrous oxide (over a time interval of 100 years) according to IPCC (2006).<sup>54</sup> Taking different characterization factors into account, related results can vary for methane by 30–50% and for nitrous oxide by 35–230%.<sup>55</sup>

In particular the following limitations should be noted, in order to facilitate the proper interpretation of the results. Due to a lack of data, the system boundaries were set cradle-to-store (not cradle-to-grave). Although an attributional LCA approach was chosen in this study, the data for fish were generated by way of a consequential approach.<sup>37</sup> In the scenario analysis (comparison with recommendations and diet styles) a consequential approach would have been more appropriate to calculate rebound effects (e.g., market effects). For GHG emissions, ammonia emissions, P use and PEU of imported products, due to a lack of data we had to use classical bottom-up LCA data or, if no separate data were available, these were modeled as domestically produced. Multiregional impact assessment databases have since been published, and these would be more adequate to cope with the goal of this study.<sup>57,58</sup> Inconsistency in our analysis may result from the fact that emissions from dLUC/LU, adopted from Leip et al. (2010),<sup>36</sup> were allocated on the basis of the N content of the derived products. In this study we allocated the couple products on a mass basis. Although different intake, consumption and supply data were used, for the years 1985–1989 the same production conditions (and therefore production efficiencies) as well as the same import shares and import countries were assumed as for the year 2006. Furthermore, it must be considered that the basic population of both National Nutrition Surveys (NNS) was adjusted to the same age group (14–80 years), but that the first NNS (1985–1989) was compiled in the former West Germany (with just 80% of the total German population<sup>59</sup>). Therefore the specificity of food consumption in the former East Germany was not considered in the comparison. Besides the fact that specific intake data for the East were not available, the official supply data vary depending on the food group considered. Whereas the consumption of animal-derived products (exception: fish) and margarine was almost equal, the consumption of grain products and potatoes was higher and the consumption of fruits was lower in the East. Nonetheless, due to methodological differences the comparability of the supply data of both countries is limited. Presumably the actual consumption of grain products and potatoes in the East was lower, since usage as feed was included there.<sup>61</sup>

Nuts and seeds were omitted in the scenario analysis of the recommendations (D-A-CH, UGB), since related recommendations do not exist. Due to the ongoing discussion about how best to deal with water in LCAs<sup>49–51</sup> we just analyzed blue water. We argue that, besides regionalized watershed-specific scarcity indicators, which need huge data input for a complete diet model, blue water use on the national level is a proper indicator for depicting water stress in a practical manner, rather than the nonweighted summation of blue and green water.<sup>52</sup>

To allow a comparison of the different dietary scenarios, luxury goods (coffee, chocolate/cocoa, wine, etc.) were omitted from the analysis, because special, quantifiable recommendations do not exist. Due to a lack of data we did not consider environmental effects of products fortified with essential nutrients, which are commonly used in a vegan and vegetarian diet.

**Outlook.** In light of the EU's political goals of fostering sustainable food production and consumption, reducing the food chain's resource input by 20% by 2020 and of decreasing the amount of edible food waste by half (see Introduction and EC (2011)<sup>3</sup>), this study provides some meaningful insights about the extent to which these goals are within reach. As regards resource inputs (and related emissions), the results show that, from a diet perspective, developments within the last 20 years have been in line with the set target. In contrast, nutrition-related environmental pollution increased over the same period due to augmented food losses, mainly on the retailer and the household level. Therefore, besides efficiency gains in the whole food chain and the promotion of less resource-intensive dietary patterns, increased attention should be paid to food wastage on consumer level. Considering alterations from efficiency gains and rebound effects in the whole supply chain would be desirable for further studies from a research perspective. Another point is of paramount importance: If diet shifts toward less resource-intensive eating patterns are pursued politically, then further research should focus on comprehensive health impact assessments to ensure that alterations in diets do not lead to disadvantageous side effects. If not well balanced, the dietary styles which tend to be most beneficial in environmental terms (i.e., a vegan and vegetarian diet) could lead to an insufficient supply of essential nutrients (vitamin B<sub>12</sub>, iron, calcium, zinc, long-chain *n*-3 fatty acids, creatine etc.). Relevant literature, which expands this debate of possible health implications of an undersupply, but also of an oversupply is as follows.<sup>62–67</sup> Particular attention and further research should therefore focus on potentially undernourished subgroups (such as toddlers, children, pregnant women, sick people, the elderly, etc.).

## ■ ASSOCIATED CONTENT

### ● Supporting Information

Detailed supply, consumption, intake data and conversion factors for the years 1985–89 and 2006 as well as the energy contents of the food products analyzed and further, detailed tables of life cycle inventory (LCI) and impact assessment (LCIA) of the food groups analyzed are provided. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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### Notes

The authors declare no competing financial interest.

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#### ■ NOTE ADDED AFTER ASAP PUBLICATION

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