



Dietary environmental impacts relative to planetary boundaries for six environmental indicators – A population-based study

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ABSTRACT

The environmental impact of Swedish diets was assessed for six indicators (greenhouse gas [GHG] emissions, cropland use, nitrogen application, phosphorus application, consumptive water use and extinction rate), using self-reported food intake within two population-based cohorts of men and women, 56–96 years of age. The dietary environmental impact was assessed in relation to *per capita* planetary boundaries, overall and by population subgroups, addressing the relative importance of specific foods and food groups. The total average dietary impact exceeded the planetary boundaries by 1.6 to 4-fold for five of the six environmental indicators; consumptive water use did not exceed the boundaries. Comparing the highest with lowest quintiles of the population impact showed >2.5-fold differences across all environmental indicators. Of the diet's total average environmental impact, animal-based, plant-based and discretionary foods accounted for 28–83%, 8–40% and 9–37%, respectively, across the six indicators. Animal-based foods dominated the impact on GHG emissions, cropland use and nitrogen and phosphorus application, while plant-based and discretionary foods contributed more to consumptive water use and extinction rate. Environmental impact was driven predominantly by consumption of red meat, dairy, fresh fruit and coffee. The findings show major challenges in affluent countries that have to be addressed to achieving sustainable food production systems and diets. They provide guidance on critical food groups, environmental indicators and population subgroups to prioritize in future efforts to reduce the environmental impact.

1. Introduction

Access to sufficient, safe and nutritious food is necessary for human health and well-being. At the same time, many challenges are linked to the current food system, which is responsible for major environmental impact and uses large amounts of natural resources (IPCC, 2019). The planetary boundaries framework indicates that several ecological and physical limits are at risk of being exceeded, including biodiversity loss, biochemical flows of nitrogen and phosphorus, land-system change and climate change (Steffen et al., 2015). Changes in food production and consumption are identified as one of the several essential measures required to limit further environmental impact and achieve environmental goals (Poore and Nemecek, 2018; Springmann et al., 2018).

Assessments of the environmental impact of specific foods and complete diets are dominated by climate impact analyses (Jones et al.,

2016). The lack of established methods to estimate some of the environmental effects (e.g., biodiversity loss) and the missing environmental data for specific foods partly explain the limited number of holistic environmental assessments performed on complete diets (Ridoutt et al., 2017). Climate impact has been shown to serve as an indicator for additional environmental effects in assessments of certain food groups, e.g., seafood (Ziegler et al., 2016), monogastric meat (Röös et al., 2013), and complete diets (Kalbar et al., 2017; Martin and Brandão, 2017). However, this is not the case for all food production systems, food items or environmental indicators. To avoid the risk of sub-optimized dietary recommendations, which may result in trade-offs between environmental effects, more knowledge is urgently needed on how complete diets and specific food groups affect different environmental indicators.

Research on the environmental impact of diets is primarily based on *per capita* dietary data or theoretical diets reflecting adherence to dietary

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recommendations (Perignon and Darmon, 2022). Therefore, knowledge is limited on how diet and its related environmental impact varies between population subgroups. This knowledge is valuable for identifying the subgroups in greatest need of dietary change.

To fill these knowledge gaps a comprehensive assessment of the environmental impact of Swedish self-reported diets was performed, including the variation by population subgroup, in relation to the planetary boundaries, using six environmental indicators. The results will add knowledge about the diet's environmental impact from a multidisciplinary perspective and indicate where potential trade-offs may exist between different environmental impacts. Findings will be useful for guidance on which changes in food consumption and production are most urgent to prioritize in policies and dietary recommendations to avoid exceeding the environmental planetary boundaries.

2. Method

2.1. Study population and assessment of dietary intake

The study population includes participants in the Swedish Mammography Cohort (25,540 women) and the Cohort of Swedish Men (26,578 men), aged 56–95 years, who filled in a food-frequency questionnaire (FFQ) in 2009 (Harris et al., 2013). Each of these two population-based cohorts was representative of the Swedish population in the age group of 56–95 years in terms of similar age distribution, attained education and prevalence of overweight compared to Statistics Sweden 2009.

Dietary information was derived from a self-reported 132-item FFQ (FAOSTAT, 2021; available at www.simpler4health.se). Participants with inadequately reported intake (energy intake outside 3 SD [standard deviation] of log-transformed mean) were excluded.

2.2. Assessment of environmental impact

The environmental impact of food items was calculated based on life cycle assessment (LCA) data for six environmental indicators: greenhouse gas (GHG) emissions (kg of CO₂e), cropland use (m²), nitrogen (N) application (kg of N), phosphorus (P) application (kg of P), consumptive water use (m³) and extinction rate (E/MSY = extinctions per million species-years).

The environmental impact was expressed per cooked edible weight of food at the consumer level. System boundaries include the most influential steps from farm to fork, including primary production, processing, packaging, international transportation and edible food loss and waste along the food chain (including consumer waste). Environmental impact from home transportation and cooking by the consumer was included in the assessment of GHG emissions but was considered negligible for other environmental indicators studied. Management of waste occurring along the food chain was not accounted for.

LCA data were adapted from Moberg et al. (2020), representing the average environmental impact associated with food sold on the Swedish market between 2011 and 2015, capturing differences in environmental impact due to variation in region-specific production systems. These data were complemented by LCA data received via personal communication for specific fish species, vegetables, vegetable oils and fruits used to calculate data provided at an aggregated level in Moberg et al. (2020). The environmental impact of the 87 composite dishes was calculated according to the method and recipes described in Hallström et al. (2021). LCA data were adjusted to account for food loss and waste at the consumer level, non-edible parts and weight changes in cooking based on the methodology described in Hallström et al. (2021).

The most representative LCA data available for similar foods was used for foods where product-specific LCA data were missing. Product-specific LCA data were generally used for food items representing high consumption levels in Sweden. When necessary, the environmental impact was assessed on an aggregated level by matching single LCA data

to broader food groups (e.g., “other vegetables,” “nuts and seeds,” “liquor” and “chocolate and candy”). Sources of LCA data are further specified in Table S1.

2.3. Assessment of dietary environmental impact in relation to planetary boundaries

The individual's dietary environmental impact was estimated by matching dietary data (2.1) with product-specific food LCA data (2.2). The impact was assessed for total yearly consumption and per 1000 kcal of food consumed. The impact on each environmental indicator was presented as mean and standard deviation for the total study population and by gender. The study participants were also categorized into quintiles of their diet's impact on each of the six environmental indicators, where the first quintile (Q1) and the fifth quintile (Q5) represented subgroups with 20% lowest and 20% highest environmental impact, respectively.

The environmental impact was calculated for 12 food groups (Table S2). It was also reported for three broader food categories: (i) animal-based foods (red meat, poultry and eggs, dairy and seafood), (ii) plant-based foods (vegetables, fruits, berries, nuts, seeds, bread, grains, cereals, rice and pasta), and (iii) discretionary foods (non-alcoholic drinks except for milk, alcoholic drinks, sweets and snacks and other foods).

The mean environmental impact of the total diet in the total study population and in the subgroup with the lowest impact (Q1) and highest impact (Q5) were related to the absolute environmental boundaries proposed by the EAT-Lancet Commission, indicating a limit within which the global food system should operate to be categorized as environmentally sustainable (Willett et al., 2019). These boundaries and uncertainty levels are based on the concept of planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) and have been defined for all six environmental indicators assessed in this study. The global boundaries presented by the EAT-Lancet Commission were downscaled to *per capita* levels based on the method proposed by Moberg et al. (2020), by assuming an equal distribution across the global population in 2019 (7.7 billion) (United Nations, 2019).

3. Results

3.1. Dietary environmental impact in relation to planetary boundaries

The mean environmental impact of the diet per total yearly consumption and per 1000 kcal is presented in Tables 1 and 2. A considerable variation in environmental impact within the study population was observed across all environmental indicators (with a 2.6–3.6 times higher impact in Q5 than Q1 per total intake). The greatest variation was indicated for extinction rate and consumptive water use.

Table 1 and Fig. 1 illustrate how the diet's mean environmental impact in the total study population and in the groups with low (Q1) and high (Q5) impact perform in relation to *per capita* planetary boundaries for the global food system and their respective uncertainty intervals. The results show that mean consumptive water use in the total population (even in Q5) was within the planetary boundary and even below the lower range of the uncertainty interval. However, for all other environmental indicators studied, the mean dietary impact of the population exceeded the planetary boundaries. Most critical was the impact on N application and extinction rate, where the mean dietary impact of the population transgressed the boundaries by more than four-fold. In addition, the mean GHG emissions, P application and cropland use exceeded the boundaries by 1.6 times up to more than three-fold. Results for Q1 indicate that the use of cropland and consumptive water required to support the diet in the group with low impact were within the planetary boundaries, while the group with high impact (Q5) exceeded the boundaries of all environmental indicators by 2.5–7.5-fold, except for consumptive water use. In addition, P application and cropland use

Table 1

Dietary environmental impact in the total study population including men and women, and in the subgroups with the 20% lowest (quintile Q1) and the 20% highest (quintile Q5) impact, and in relation to *per capita* planetary boundaries for the global food system.

Environmental indicators	Mean environmental impact of diet per year (SD)			<i>Per capita</i> planetary boundary (uncertainty interval) ^a	Mean impact in relation to <i>per capita</i> planetary boundary (planetary boundary = 100%) ^b	
	Total study population	Q1	Q5		Total study population	Q1, Q5
GHG emissions (kg CO ₂ e)	2197 (827)	1247 (225)	3454 (711)	649 (610–701)	338%	192%, 532%
Cropland use (m ²)	2671 (1044)	1495 (269)	4262 (924)	1688 (1429–1948)	158%	89%, 252%
Nitrogen application (kg N)	52 (22)	28 (5.4)	86 (21)	12 (8.4–17)	444%	236%, 733%
Phosphorus application (kg P)	3.4 (1.2)	2.0 (0.3)	5.2 (1.0)	1.0 (0.8–2.1)	323%	188%, 499%
Consumptive water use (m ³)	48 (22)	24 (5.5)	81 (21)	325 (130–519)	15%	7.5%, 25%
Extinction rate (E/MSY)	5.7 E–09 (2.7 E–09)	2.7 E–09 (6.6 E–10)	9.8 E–09 (2.5 E–09)	1.3 E–09 (1.3 E–10–1.0 E–08)	441%	209%, 752%

^a Based on Willett et al., 2019 and Moberg et al. (2020).

^b Mean environmental impact relative *per capita* boundaries set at 100%, calculated according to the example for GHG emissions of the total study population (2197 kg CO₂e/629 kg CO₂e*100 = 338%), indicating that global boundaries were exceeded by 3.4-fold.

Table 2

Mean dietary environmental impact per 1000 kcal (SD) in the total study population including men and women, and in the subgroups with the 20% lowest (quintile Q1) and the 20% highest (quintile Q5) impact.

Environmental indicators	Total study population	Q1	Q5
GHG emissions (kg CO ₂ e)	2.66 (0.48)	2.08 (0.19)	3.36 (0.41)
Cropland use (m ²)	3.23 (0.63)	2.49 (0.24)	4.15 (0.59)
Nitrogen application (g N)	63 (15)	45 (5.6)	84 (14)
Phosphorus application (g P)	4.1 (0.7)	3.2 (0.3)	5.2 (0.6)
Consumptive water use (m ³)	0.06 (0.02)	0.04 (0.006)	0.09 (0.02)
Extinction rate (E/MSY)	7.1 E–12 (2.8 E–12)	3.9 E–12 (7.1 E–13)	1.1 E–11 (2.4 E–12)

related to the diet was within the uncertainty ranges of the boundaries in the group with low impact, as was the mean impact on extinction rate in both low- and high-impact groups of the population.

3.2. Environmental impact of different food groups

Fig. 2 illustrates how the consumption of different food groups contributed to the study population's mean total dietary environmental impact and dietary energy intake. More detailed results displaying environmental impact per sub-food group are provided in Table S2.

Animal-based foods, delivering on average 41% of total dietary energy, accounted for between 23 and 83% across different indicators of environmental impact in the study population, with the highest contribution to N application, GHG emissions and cropland use. Within animal-based foods, the largest impact was related to the consumption of red meat, accounting for 17–34% of the total impact across all environmental indicators studied. Consumption of lamb stands out by its high contribution to the extinction rate (17%), which dominated the total impact of red meat consumption, whereas beef and pork, including minced and processed meat, made a smaller contribution to this environmental indicator (5%). Dairy products accounted for a considerable share (23–46%) of the diet's total contribution to GHG emissions, cropland use and N and P application. However, their contribution to consumptive water use and extinction rate was more limited (5%), especially in relation to their large share of dietary energy (24%). The remaining animal-based food groups accounted for a smaller share of the

diet's total environmental impact, with the highest contribution to GHG emissions from seafood consumption (9%) and P application from “poultry and eggs” consumption (5%).

Plant-based foods, delivering on average 41% of total dietary energy, accounted for 8–40% across different indicators of environmental impact in the population, with the greatest contribution to consumptive water use and extinction rate. Plant-based foods accounted for more than a third (35–40%) of the impact on these two environmental indicators, largely driven by fresh fruit consumption accounting for 19% and 27% of the diet's total impact on consumptive water use and extinction rate, respectively. “Nuts and seeds” stands out as another food group contributing to a considerable share of total consumptive water use (8%) in relation to its limited share of dietary energy (1%). On the other hand, “bread, grains, cereals, rice and pasta” accounted for a relatively small share (3–7%) of the diet's total environmental impact in relation to their large contribution of dietary energy (25%).

Discretionary foods, delivering on average 18% of total dietary energy, accounted for 9–37% of the environmental impact in the population, with the greatest contribution to consumptive water use, extinction rate and P application. Consumption of non-alcoholic drinks accounted for a substantial share (20–27%) of the impact on these three indicators and accounted for more than 6% across all environmental indicators studied. Within this group, consumption of “coffee and tea” dominated, together representing 14–18% of the impact on consumptive water use, extinction rate and P application (mainly related to coffee intake). Other discretionary food groups responsible for ≥5% of the impact for selected environmental indicators were “soda and cordial” (8% of total consumptive water use), wine (6% of total consumptive water use, 5% of total extinction rate) and “chocolate and candy” (5% of total P application).

3.3. Difference in environmental impact between men and women

Results for men and women were greatly affected by whether the diet's environmental impact was assessed per total food intake or per amount of energy consumed (Table 3). Men had 13–36% higher environmental impact than women per total food intake across the environmental indicators studied. On the contrary, women had an as high or up to 21% higher environmental impact than men expressed per 1000 kcal.

Comparing men and women revealed differences in the diet's total environmental impact from different food groups (Table 4, Table S3). These differences were particularly prominent for consumptive water use and extinction rate. Animal-based foods contributed to a greater

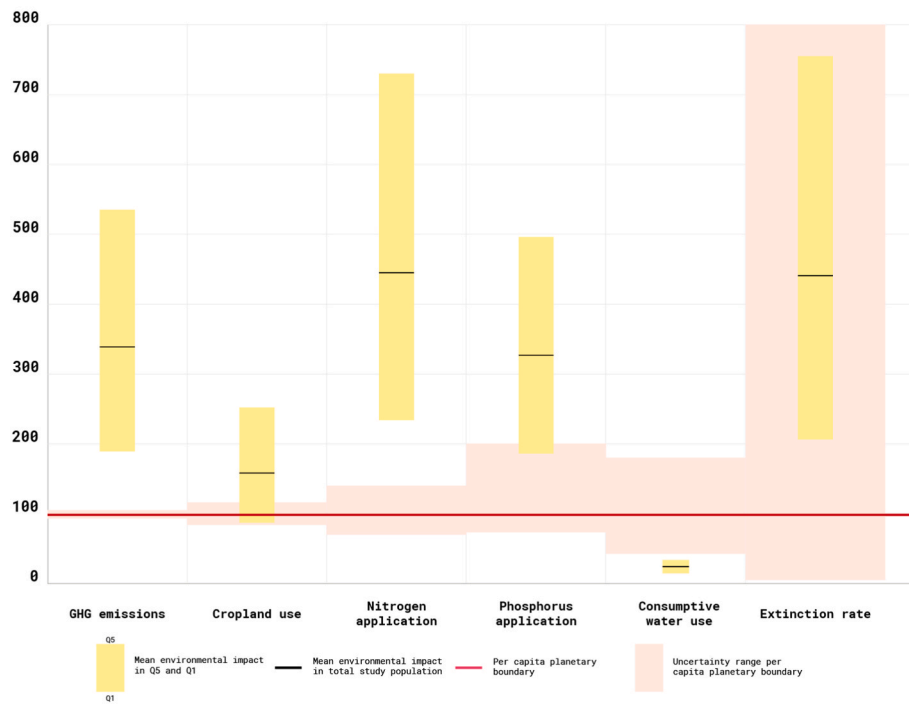


Fig. 1. Mean dietary environmental impact in the total study population and in the subgroups with the 20% lowest (quintile Q1) and the 20% highest (quintile Q5) impact in relation to *per capita* planetary boundaries for the global food system.

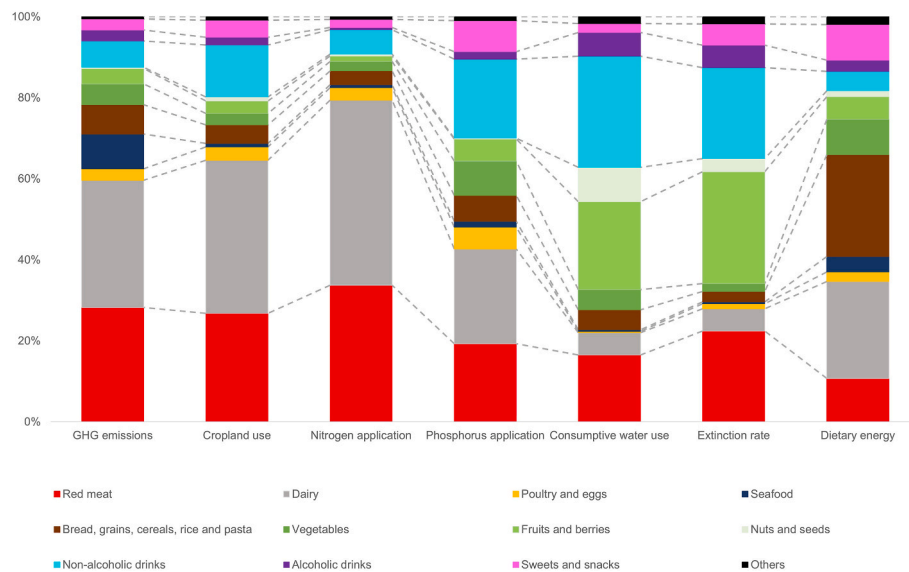


Fig. 2. Contribution to mean environmental impact and dietary energy intake per food group for the total population.

Table 3

Mean environmental impact of the diet, for men and women separately, per total yearly intake and per 1000 kcal.

Environmental indicators	Total intake per year		Per 1000 kcal	
	Men	Women	Men	Women
GHG emissions (kg CO ₂ e)	2515	1868	2.6	2.7
Cropland use (m ²)	3059	2270	3.2	3.3
Nitrogen application (kg N)	60	44	0.06	0.06
Phosphorus application (kg P)	3.8	2.9	0.004	0.004
Consumptive water use (m ³)	51	45	0.05	0.07
Extinction rate (E/MSY)	6.2 E–09	5.3 E–09	6.5 E–12	7.7 E–12

share of the impact on consumptive water use and extinction rate in men compared to women, while no or small gender differences were found for other environmental indicators. Within the group of animal-based foods, red meat contributed to a larger share of total impact across all studied environmental indicators in men compared to women. In women, dairy products were instead responsible for a greater share of the diet's GHG emissions, cropland use and N application. Plant-based foods contributed to a larger share of total impact across all studied environmental indicators in women compared to men. Within this group, women's higher intake of fruit explained the main difference between genders, but higher intake of nuts and seeds also had an impact especially on consumptive water use and extinction rate. Discretionary foods contributed to a larger share of total impact across all

Table 4

Percentage contribution of animal-based, plant-based, and discretionary foods to the environmental impact and energy intake in the diet of men and women in the study population.

	Animal-based foods		Plant-based foods		Discretionary foods	
	Men	Women	Men	Women	Men	Women
GHG emissions	71%	71%	15%	18%	13%	11%
Cropland use	69%	68%	10%	13%	21%	19%
Nitrogen application	83%	83%	7%	8%	10%	9%
Phosphorus application	50%	49%	19%	23%	31%	29%
Consumptive water use	26%	19%	33%	48%	41%	33%
Extinction rate	34%	24%	29%	43%	37%	33%
Dietary energy	40%	41%	40%	42%	19%	17%

environmental indicators in men than women, mainly attributed to differences in non-alcoholic drink consumption.

4. Discussion

4.1. Dietary environmental impact in relation to planetary boundaries

The study shows major challenges and needs for measures to achieve sustainable food production systems and diets based on these in affluent countries like Sweden. An indication of which environmental indicators are most critical to prioritize can be obtained from the dietary impact and distance to the planetary boundaries. The mean dietary environmental impact exceeded *per capita* planetary boundaries of all indicators analyzed in the studied population, except for consumptive water use. For several of the indicators (N application, extinction rate, GHG emissions and P application) the boundaries were transgressed more than three-fold, and for these indicators, even the impact in the subgroup with the lowest impact (Q1) exceeded the boundaries. The results were also assessed in relation to their estimated uncertainty ranges to consider the uncertainties of proposed environmental planetary boundaries and underlying methods on which they are based. Uncertainty ranges vary greatly between environmental indicators, with the largest uncertainty indicated for extinction rate. For two environmental indicators, N application and GHG emissions, the upper limit of the uncertainty ranges was exceeded, even in the low-impact group (Q1), which further underlines the severity of the diet's impact on these environmental indicators.

4.2. Variation in environmental impact between subgroups of the population

In contrast to many previous studies, this analysis highlights variations in environmental impact between subgroups of the study population. The results indicate large variations in environmental impact within the study population, with more than 2.5 times the difference in impact between low and high-impact groups across all environmental indicators. This suggests a large potential for reduced environmental impact through dietary changes accepted and consumed by parts of the Swedish population. The largest variation between subgroups in the population was noted for extinction rate and consumptive water use, indicating a particularly large potential for reduced impact via diet change for these environmental indicators. The difference in impact between subgroups is due to differences in dietary patterns and the large variation in environmental impact per kg of product existing between food items (Moberg et al., 2020; Poore and Nemecek, 2018). An overall higher consumption of all food groups was observed in Q5 as compared to Q1, especially pronounced for alcoholic drinks, fruit and "snacks and sweets". Animal-based food consumption differed by more than 6-fold between low and high-impact groups and thus also contributed to the difference in environmental impact.

This study further shows that the environmental impact of individual

diets was primarily affected by whether differences in energy intake were accounted for in the method used. Men have previously been identified as a group with higher dietary environmental impact than women, e.g., in Germany (Meier and Christen, 2012) and Australia (Ridoutt et al., 2021), which was also shown in this study when results were presented per total food intake. However, when the impact was expressed per 1000 kcal, women had an as high or higher environmental impact. Depending on the purpose of the analysis, both methods may be useful. Expressing the dietary environmental impact per total food intake is required when relating results to absolute environmental boundaries or comparing the diet's environmental impact to other consumption-based activities. Estimating the environmental impact per 1000 kcal removes the impact due to differences in energy intake and is thereby suitable to demonstrate environmental impact by focusing on differences in dietary composition. The results will also be more standardized by reporting environmental impact per energy intake, allowing for comparisons between subgroups, populations, and different studies. While the impact reported per energy intake may be considered more accurate for some purposes it fails to capture the effects of over-consumption of food, indicated to be an important driver of dietary environmental impact (Sundin et al., 2021).

4.3. High-impact food groups to prioritize in future policies

This study shows that both animal-based, plant-based and discretionary foods contributed substantially to the diet's total environmental impact (23–83%, 8–40%, and 9–37%, respectively, across all environmental indicators). However, the food groups differed in their impact across environmental indicators. While animal-based foods dominated the dietary impact on principally GHG emissions, cropland use, and N and P application (49–84% of total dietary impact), plant-based and discretionary foods had more significant contribution to the diet's impact on consumptive water use and extinction rate (together responsible for 70–77% of the total dietary impact on these indicators). Discretionary foods also contributed substantially (30%) to the total dietary impact on P application. Moreover, the results indicated that a large proportion of the total dietary environmental impact was related to the consumption of some specific food groups. This is interesting as it highlights food groups in which changes in production and consumption will have the greatest potential for reduced environmental impact. When focusing on food groups with the highest contribution to the diet's total environmental impact (Fig. 2, Table S2), cheese, "milk and yoghurt," processed red meat and minced red meat appear as important drivers of dietary impact on GHG emissions, cropland and N and P application. Fresh fruit and "tea and coffee" are examples of food groups that especially contributed to dietary impact on consumptive water use and extinction rate. Environmental impact from specific food groups was related to both the amount consumed and the environmental impact per produced amount. When interpreting these findings, the contribution of dietary energy and nutrition from different food groups is therefore essential to keep in mind.

In addition to these overall patterns, other food groups accounted for a large proportion of the diet's total impact on individual environmental indicators, e.g., the impact on extinction rate related to the consumption of lamb and, at a more aggregated food group level, GHG emissions related to seafood and consumptive freshwater use related to "nuts and seeds". It is also noteworthy that total consumption of beverages (including milk and alcoholic drinks) accounted for 14–34% of the diet's total impact across all environmental indicators. Many environmental assessments and guidelines for sustainable diets currently exclude beverages (e.g., Willett et al., 2019), and the results from this and previous work (Hallström et al., 2018) suggest that this is an important food group to include in future work. The same conclusion applies to discretionary foods, which also deserve a greater focus as they may contribute largely to dietary environmental impact and include foods that should be limited in the diet from a health perspective (Ridoutt

et al., 2021).

The results also indicated several food groups with limited contributions to the diet's total environmental impact despite being important dietary energy sources. These food groups included bread, "grains and cereals," "roots and tubers" and seafood (which has a minor impact on all environmental indicators except for GHG emissions), as well as "cookies and cakes." With the exception of "cookies and cakes," these food groups are also recommended from a health perspective and can therefore be interpreted as important elements of sustainable diets. Within these food groups, environmental and health effects can be further optimized by favoring products and production systems with the lowest environmental impact (e.g., in the selection of seafood, where large variations in environmental impact exist between species and production systems [Hallström et al., 2019]), and the greatest health benefits (e.g., by choosing whole grains over refined).

4.4. Methodological considerations for the environmental assessments of diets

The results of this and similar research studies are greatly affected by the underlying methods and data used. Uncertainties exist both in dietary and environmental data, and data availability and methods vary between environmental indicators. Methods to assess water use and impact on biodiversity are examples of indicators in which there is a lack of scientific consensus regarding the best method, and large variations may result from using different methods (Bunsen et al., 2021; Crenna et al., 2020). Compared to more established methods, e.g., GHG emissions assessments, LCA data availability is also more limited for these two environmental indicators. The results of this study indicate a large potential for reduced impact on these environmental indicators through relatively small and targeted changes in diet. However, based on the underlying uncertainties described, it is important to evaluate the reliability of the results.

In this study, the use of freshwater was accounted for by calculating the consumptive blue water use, i.e., the use of groundwater and surface water, which reduces the flows in watersheds by disallowing the return flow to the river or aquifer of origin. The primary focus on the water use inventory has been on irrigation in cultivation and as a water source for animals, as these practices account for a major part of global freshwater use. Water used as a food ingredient was included, but not water used in cleaning. However, this probably does not greatly affect the results since the most critical water use in the food supply chain was still accounted for, i.e., the agricultural use. Water scarcity varies greatly in different parts of the world, and it is more disruptive to use a quantity of water in an area with high water scarcity than in an area where water is abundant, as in Sweden. This is not accounted for in the consumptive blue water use indicator.

The impact on biodiversity in the study was based on the methodology by Chaudhary and Brooks (2018). The method is practical and easy to use for LCA purposes but has flaws. The method allows for three different intensity levels of land use: intensive, low and minimal. However, the difference in characterization factors between the levels is very small, making it challenging to distinguish impacts from, e.g., conventional and organic agriculture. Another limitation is that the method only shows negative biodiversity impacts, which means improvements or positive contributions to biodiversity, e.g., a varied crop rotation or grazing high value natural grasslands, were not considered. Furthermore, the method does not include insects as one of the taxonomy groups assessed, and only covers land use, so the impact on wild-caught seafood was not included. In this study, the biodiversity impact was recalculated to extinctions per million species-years (E/MSY), following the methodology in Moberg et al. (2020). Here, the biodiversity loss was first allocated over 100 years, then divided by one-millionth of the total number of recognized species globally. Although the choice of 100 years as a time horizon can be argued to be in line with the choice of the period for the chosen climate metric GWP100

and the fact that most agricultural land expansion has occurred during this period, it is an arbitrary choice that greatly affects the outcome.

In this study, a few food items constituted a large part of the dietary environmental impact (Fig. 2, Table S2). When interpreting these results, it is essential to consider underlying uncertainties in the methods used, as exemplified by the following two examples. For lamb, environmental data used showed a 58-times-higher impact on extinction rate than beef per kg of bone-free meat consumed in Sweden. The very high impact for lamb is due to a high characterization factor in Chaudhary and Brooks (2018) for the loss of plant species in New Zealand and the rest of the world (approximately half of the lamb meat consumed in Sweden is imported). Whether or not this high impact on plant species is realistic, is difficult to assess based on the data provided in the methodology. "Nuts and seeds" is another food group that stands out by its high fresh water use per kg, exceeding by at least fourfold that of other plant-based foods such as fruit and berries. However, due to a lack of data, differences in environmental impact within this food group were not accounted for. Almonds and peanuts were instead used to represent all nuts, which might overestimate the water use in this study due to the high water use of almonds grown in the USA.

4.5. Possibilities for reducing the diet's environmental impact

Reducing the dietary environmental impact to the extent that its impact will be within planetary boundaries will require large changes in both production and consumption of food, including measures to reduce food loss and wastage along the food supply chain. The measures with the greatest potential to contribute to reduced environmental impact depend on the food group and environmental impact in question. The results presented constitute a basis for effective and tailor-made measures to reduce the environmental impact of our diets. It is possible to prioritize measures depending on the environmental indicators that are the most important and balance them with other indicators and consumption levels. At the same time, it facilitates accurate guidance on the dietary shifts that will be most influential in reducing specific environmental impacts while avoiding burden-shifting and increasing other impacts. However, as described above, the uncertainties are large, and data is often lacking, so it is not possible at this stage to fully utilize this potential and define detailed improvement measures on e.g., specific products.

What can be said is that there are differences in which measures to prioritize within the large cluster of products since the results are more robust on a higher level. For red meat and dairy, the results indicate that measures to reduce GHG emissions, cropland use and application of N and P are critical to prioritizing. Improved production efficiency, better use of manure and improved feed management are examples of measures suggested to limit the impact of these indicators in the production system (Grossi et al., 2018). On the consumption side, reduced intake of these high-impact products, as well as favoring foods and production systems with better environmental performance within the broader food groups, has major potential for reduced environmental impact in countries like Sweden, where consumption levels are high. For plant-based and discretionary foods, the results highlight the importance of limiting adverse effects on biodiversity and consumptive water use. From a production perspective, this includes efforts towards biodiversity conservation and promoting agricultural practices that enhance biodiversity and allow for improved water management (Willett et al., 2019). Consumers can also make a substantial contribution by generally limiting the excessive intake of food, especially those foods with low nutritional values. Environmental certifications and eco-labeling could further be helpful to guide consumers and implement targeted measures within specific food groups.

4.6. Findings in relation to previous research

Environmental impact of Swedish diets has previously been assessed

in several studies summarized in Hallström et al. (2021), of which four studies included additional environmental indicators (Table S4) besides climate impact (Cederberg et al., 2019; Martin and Brandão, 2017; Moberg et al., 2020; Rööfs et al., 2015). Those four studies were all based on dietary data from national statistics representing *per capita* consumption. The findings of this study are especially relevant to compare with the study by Moberg et al. (2020) in which the environmental impact of the Swedish average diet was assessed in relation to the planetary boundaries. The average environmental impact of Swedish diets in this study was 2–33% lower than reported by Moberg et al. (2020), across all indicators assessed. The greatest difference was noted for P application and extinction rate, while good consistency between the studies was found for GHG emissions. The environmental data used in this study was essentially the same as those used by Moberg et al. (2020), with the difference being that this study's system boundaries go beyond the retail stage. Differences in results between the studies are likely also due to variations in consumption patterns of the studied populations, where this study represents an older study population with different dietary preferences compared to the average consumption statistics.

Previous assessments of Swedish diets estimated that animal-based foods account for more than half (about 60–90%) of Swedish diets' total impact on multiple environmental indicators (climate impact, cropland use, total agriculture land use, nitrogen use, acidification, eutrophication and biodiversity damage [Table S4]) (Martin and Brandão, 2017; Moberg et al., 2020; Rööfs et al., 2015). In those studies, plant-based and discretionary foods are indicated to have a more outstanding contribution to consumptive water use, P application, human and ecosystem toxicity, and extinction rate. In addition, consumption of mainly imported vegetables, fruit, nuts, coffee, tea and cacao has been highlighted as food groups contributing substantially to the pesticide footprint associated with the Swedish diet (Cederberg et al., 2019).

Dietary patterns and their environmental impact differ widely between countries. Swedish diets share general characteristics with many affluent countries, including higher *per capita* consumption of total energy, animal-based foods and alcoholic beverages and lower consumption of cereals, fruit and vegetables than the world average (FAOSTAT, 2021). Half of the current global food production is estimated to depend on planetary boundary transgressions, but the impact varies between regions and environmental indicators (Gerten et al., 2020). Country-specific differences were also highlighted by Chaudhary and Krishna (2019) in an assessment of diet sustainability, including 152 countries of which a majority, exceptionally high-income countries, had high environmental impact exceeding multiple planetary boundaries.

4.7. Strengths, limitations, and future research needs

A strength of this study is that dietary environmental impact was assessed based on self-reported diets, which, unlike theoretical diets, account for food acceptability aspects. The dietary data were moreover based on a large number of individuals that allowed distinction between subgroups of the population. The study population represents middle-aged and older individuals that should be kept in mind when interpreting the results and comparing them with other studies. Due to differences in dietary habits and underlying food production systems, the results of this study may not be representative of other regions. Dietary data were reported in 2009 and thus do not capture any potential changes in dietary consumption that may have occurred over the past decade. National consumption statistics, however, indicate relatively minor changes (<10%) in consumption of most food categories during this period (Swedish Board of Agriculture, 2022). Charcuteries, milk, cream and beer are examples of foods and beverages of which Swedish *per capita* consumption was decreased, whereas consumption of vegetables increased. Uncertainties related to self-reported diets, such as the underreporting of unhealthy foods, may also have influenced the results.

Future studies focusing on populations of different age groups based on updated dietary data will provide improved knowledge of variations in the dietary environmental impact among population subgroups.

The assessment included six environmental indicators that allowed for evaluating the potential trade-offs between indicators. Environmental impact from the most influencing parameters in food production, from farm to fork, were covered, including edible food loss and waste throughout the food chain. Differences in environmental impact due to variation in region-specific production systems were accounted for by mainly using LCA data representing the average environmental impact of foods on the Swedish market. A limitation of this study was that consumption of vegetable oils and spreads was only included in the analysis as part of composite dishes as the food questionnaire did not allow for an estimation of quantities consumed. Consumption of vegetable oils and margarines has previously been estimated to account for 1–5% of the average Swedish dietary impact across the studied environmental indicators, with the highest contribution to the extinction rate (Moberg et al., 2020). In addition, the lack of product-specific LCA data for some foods (e.g., “nuts and seeds,” liquor, and “chocolate and candy”) implied that aggregation of food products into broader groups was necessary and may hide variations in the impact of specific products and production systems.

For a better understanding of environmental impacts from the food system, more research is needed to provide environmental data on additional products as well as region-specific data, especially within food groups identified as important drivers of dietary environmental impact. More transparency is also needed in future studies on the geographical origin of the food products consumed. For environmental indicators with a lack of scientific consensus regarding the best method (e.g., water use and impact on biodiversity), further method development is particularly important in future research. This study suggests that both animal-based, plant-based and discretionary foods contribute largely to dietary environmental impact. Therefore, future studies should aim to include a complete diet, including beverages and discretionary foods, which have often been left out of environmental assessments.

No standardized method exists to operationalize the planetary boundary frameworks to a given sector level, such as the food system. Therefore, different methods are proposed to define environmental boundaries as well as how emissions and resource space should be allocated over time, between different activities and the global population (Björn et al., 2020). Depending on the underlying assumptions the environmental boundaries used in this study could be set both lower (e.g., by accounting for future global population growth) and higher (e.g., by allocating a greater share to adults than children). The uncertainty in *per capita* planetary boundaries, notably high for extinction rate, was partly accounted for by describing estimated uncertainty ranges but needs to be considered and refined over time.

Due to the limited scope of this paper, results should be interpreted in a broader context covering both additional ecological indicators and other sustainability aspects including health, ethical and economic considerations. Environmental indicators not captured in this study include, e.g., local and regional impacts such as chemical pollution, site-dependent eutrophication, acidification and water availability, as well as marine extinction rate (Moberg et al., 2020). Environmental indicators specified in national environmental goals and international frameworks, e.g., the UN Sustainable Development Goals (United Nations, 2015) and the Product Environmental Footprint Protocol (European Commission, 2018), indicate essential aspects to consider in future studies.

5. Conclusion

This study assessed the environmental impact of self-reported Swedish diets in relation to *per capita* planetary boundaries. The results show major challenges to achieving sustainable food production

systems and diets in affluent countries like Sweden. Large changes in both production and consumption of food will be required to reduce the dietary environmental impact to the extent that its impact will be within planetary boundaries. The potential for reduced dietary environmental impact varies depending on the food group and environmental indicator in question, and large differences may exist between population subgroups. Achieving the greatest impact reduction while avoiding trade-offs between environmental indicators may therefore require policy measures targeted at specific food groups, environmental indicators and population subgroups. The main conclusions of this study can be summarized as follows.

Dietary environmental impact in relation to planetary boundaries

- The study population's mean dietary environmental impact exceeded *per capita* planetary boundaries of all indicators analyzed by 1.6 to 4-fold, except for consumptive water use.
- Dietary impact on nitrogen application, extinction rate, GHG emissions and phosphorus application were the environmental indicators that most exceeded planetary boundaries, indicating that these are critical to prioritizing in future policies.

Variation in the environmental impact between population subgroups

- Dietary environmental impact varied 2.6–3.6-fold between low and high-impact population subgroups, suggesting a large potential for reduced environmental impact through dietary changes accepted by parts of the Swedish population.
- Men's higher dietary environmental impact compared to women for all indicators studied was eliminated or reversed when energy intake was accounted for. This emphasizes the importance of correct comparisons in subgroup evaluations and highlights the impact of considering both food choices and total intake.

Contribution of environmental impact from different food groups

- Both animal-based, plant-based and discretionary foods contributed largely to dietary environmental impact. Therefore, future studies need to better capture the environmental impact of complete diets, that include beverages and discretionary foods, rather than assessing only the impact of major food groups.
- Food groups differed in their impact across environmental indicators, which emphasizes the importance of considering more indicators than climate impact only. Animal-based foods dominated the dietary impact on GHG emissions, cropland use, and nitrogen and phosphorus application, while plant-based and discretionary foods had a more considerable contribution to diets' impact on consumptive water use and extinction rate.
- Dietary environmental impact was predominantly driven by a few specific food groups, including red meat, dairy, fresh fruit and coffee, which should be prioritized in future policies.

Future research needs

- Improved knowledge on variation in sustainability performance among population subgroups could better inform targeted policy interventions.
- Additional good-quality environmental data on specific food products and production systems in different regions is needed to reduce uncertainty in future dietary environmental assessments.
- Method development is required to allow dietary assessments, including both ecological, social and economic sustainability perspectives. More holistic food sustainability studies are needed to avoid trade-offs between sustainability perspectives.

CRedit authorship contribution statement

E. Hallström: Conceptualization, Methodology, Environmental data, Investigation, Writing – original draft, preparation, Writing – review & editing, Visualization. **J. Davis:** Methodology, Environmental data, Writing – review & editing. **N. Håkansson:** Formal analysis. **S. Ahlgren:** Writing – review & editing. **A. Åkesson:** Conceptualization, Methodology, Writing – review & editing. **A. Wolk:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **U. Sonesson:** Conceptualization, Writing – review & editing, Funding acquisition, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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