



## **Diet changes in food futures improve Swedish environmental and health outcomes**

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# Diet changes in food futures improve Swedish environmental and health outcomes

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Aligning national food systems with global goals is required for sustainable transitions. We examine if realistic, context-specific dietary changes, mindful of Swedish food culture and in line with future scenarios, are sufficient to meet ambitious environmental goals. Here, we quantified diets based on the four Swedish Food Futures scenarios, which reflect prospects of technological development, behavioral change, import trends, and values. Scenario diet nutritional intakes and environmental impacts were quantified and related to health targets and nationally adapted climate, cropland, and biodiversity boundaries. Dietary changes in scenario diets reduced environmental impacts by 30% compared to current diets. No scenario stayed within the strictest climate boundary without removal of energy-related food chain emissions—resulting in 50–60% additional impact reduction. Food chain waste reduction by 50% resulted in an additional 8–10% reduction in impacts. Dietary changes can make substantial contributions to staying within global climate, cropland, and biodiversity boundaries and meet health targets, but improvements in production and waste reductions are also required.

Food systems are major drivers of climate and land-use change, freshwater use, and biodiversity loss, leading to the transgression of planetary boundaries at the global level<sup>1,2</sup> and locally downscaled boundaries in many places around the world<sup>3,4</sup>. At the same time, nearly 800 million people experience hunger, and close to three billion consume low-quality diets<sup>5</sup>. Food system pathways that reduce environmental impacts and food waste, increase resource use efficiency, and improve food access and diet quality are thus urgently needed.

Modeling studies have suggested that a combination of production-side improvements (e.g., better water, nutrient, and land management, emerging technologies, and phasing out fossil fuels<sup>6</sup>), dietary changes (especially reductions in animal products in high-consuming populations<sup>7,8</sup>), and reductions in food loss and waste<sup>9</sup> can reduce global food system impacts and possibly bring them within planetary boundaries<sup>1,10,11</sup>. Global-level studies are useful to illustrate overall potential, but more regionalized scenario studies can increase the salience, legitimacy, and relevance of these studies for local stakeholders and decision makers<sup>12,13</sup>. For example, global studies of dietary changes, commonly modeled using broad and general theoretical diets, have been critiqued for being unrealistic and not culturally acceptable<sup>14–17</sup>. There is a need to explore how—and to

what extent—more realistic and context-specific diets can contribute to food systems staying within climate and biodiversity boundaries, while at the same time being healthy and nutritious.

Anchoring modeling efforts in future scenarios that reflect different local discourses and perspectives on what a sustainable food system constitutes (refs., 16,17) can also help increase the usefulness of modeling studies by making them more actionable and relatable to different stakeholder groups<sup>17</sup>. By reflecting different food system narratives, scenarios can combine production-side improvements and dietary changes in various ways<sup>16,18,19</sup>. Typically, scenario narratives are based on different problem descriptions and reflect various beliefs, prospects of technological development, behavioral change, and values (e.g., regarding animal and environmental ethics)<sup>20–22</sup>. Narratives common in the representation of different futures of agriculture include: (i) agroecological approaches (which come in different flavors<sup>23</sup>) focusing on nature-based solutions and sociocultural transformation of food systems, (ii) sustainable intensification (producing more from less by increases in efficiency<sup>24</sup>), and (iii) emphasis on technological development in which, put simply, large parts of food production is moved from farms to labs (e.g., relying on emerging technologies<sup>25,26</sup>). Increasingly, other narratives of sustainable agriculture have emerged where

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## Box 1 | General strategy for developing quantified scenario diets

General strategy for developing quantified scenario diets with import trends imports by food group and diet can be found in SI Fig. 6 (import

pattern exceptions are noted in detail in the SM Table 3. Justifications in the Supplementary Material).

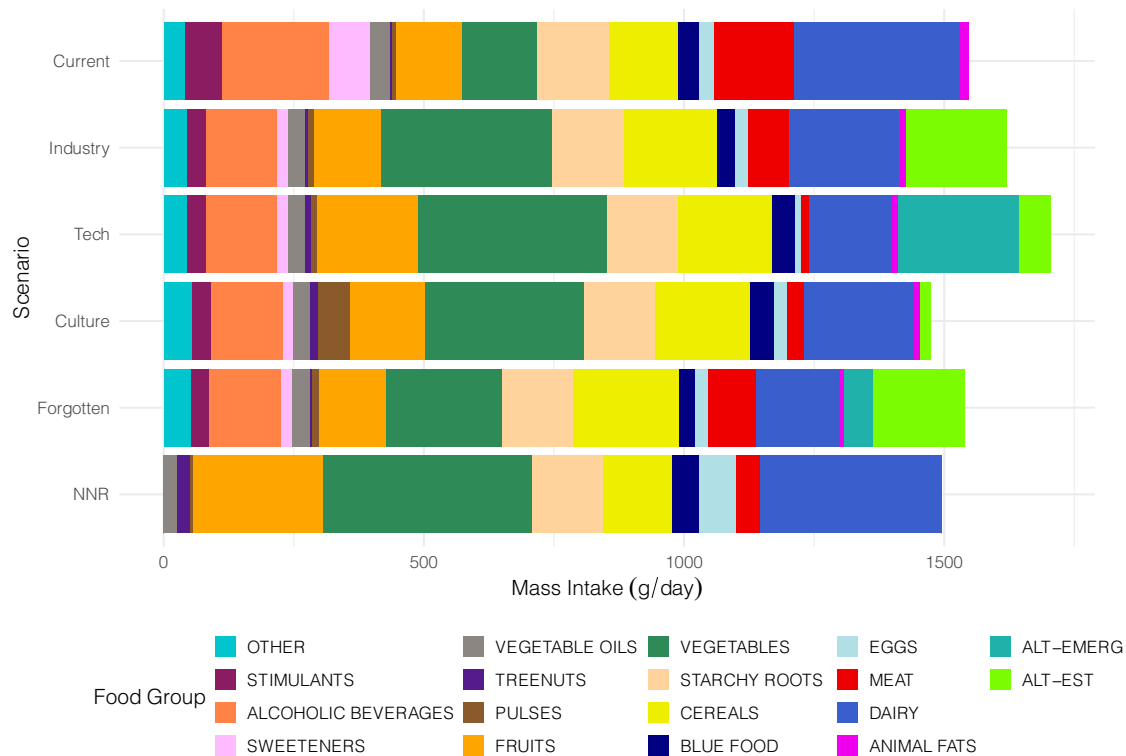
Food as Industry	Food as Food Tech	Food as Culture	Food Forgotten
<p>Representing sustainable intensification and the prevailing business-as-usual narrative, Food as Industry focuses on practices and policies that promote an increase in current Swedish agricultural production (primarily dairy, meat, and cereals), developing the food system towards becoming an important export-oriented industry sector.</p> <p>Diet: In Food as Industry, diets are similar to current diets, but with substantial reductions in animal products for climate reasons and major increases in fruit, vegetables, and legumes for health reasons. Hence, changes focused on those made to reach the health targets and reduce the main sources of environmental impact. Diets were based on foods from the Swedish food industry (e.g., dairy, peas, plant-based alternatives grown elsewhere and processed in Sweden).</p> <p>Market Share: In terms of food imports, food origins remained as in the current food system in this scenario, but with a change in import proportion; a general increase in Swedish share for most products (+10% points).</p>	<p>Food as Tech focuses on disruptive food technologies (such as emerging protein sources, including cell-cultured foods and microbial proteins) promoted by a small but growing set of start-ups in Sweden. The Food as Food Tech narrative was focused on a “more ambitious” climate impact reduction than Food as Industry and Food as Culture.</p> <p>Diet: The Food as Food Tech scenario diet more closely reflects the EAT-Lancet reference diet with reductions in dairy, meat, and fish, but animal source foods were replaced by higher-tech alternative foods (e.g., cultured meat, fish, and dairy, microbial fats and eggs).</p> <p>Market Share: Food origins remained as in the current food system, but there was a general decrease in Swedish share for most products (-10% points) for all Swedish produce.</p>	<p>The Food as Culture scenario uses an agroecological and down-sizing narrative, prioritizing local food systems and placing greater cultural and social value on food and agricultural landscapes, adopting nature-based and tech-cautious solutions.</p> <p>Diet: The Food as Culture scenario diet focused on locally produced and diverse foods, reclaiming food as central to life and culture. An increase in the diversity of food items consumed, in particular those with local origin, was assumed. For example, a substantial increase in pulses from Sweden (e.g., yellow and gray pea, fava bean-based tofu and tempeh, sunflower seeds, wild mushrooms, berries, freshwater and Baltic Sea fish species).</p> <p>Market Share: There was a large increase in Swedish market share (+20% points) for all Swedish products, with moderate to large changes to products where Sweden can potentially increase production and diversify the agricultural sector (e.g., potatoes, legumes/pulses). Food origins entail sourcing more regionally, shifting away from the tropics and North America, to the EU.</p>	<p>In the Food Forgotten scenario, food is not the focus of culture, industry, nor policy in Sweden. Rather, food production and consumption are constrained by EU climate policies. In contrast to the focused strategies seen in the other three scenarios, the Food Forgotten scenario suggests a passive (national food policy) approach to the Swedish food system where EU policies lead Swedish agriculture to prioritize climate mitigation and adaptation, entailing production of (bio-, solar-, wind-) energy and carbon credits, rather than food production, resulting in increased imports of food.</p> <p>Diet: The diet reflects the fact that people are eating the same types of food as in current diets, but with other ingredients that are generally from places with the most resource-efficient production systems, with the lowest climate impact. A climate tax on food is introduced implicating a much lower consumption of red meat and, in turn, an increased proportion of plant-based protein blended into meat products.</p> <p>Market Share: A general decrease in Swedish market share (-20% points) is assumed with a decrease in Swedish food production and an increase in imported food commodities. Increased food and feed imports from outside of the EU, as a key driver in this scenario, lends weaker support to farming in the EU.</p>

(iv) climate action, such as carbon farming to meet climate goals, is increasingly competing with agriculture<sup>27</sup>. Given the great heterogeneity of food systems and the contexts in which they operate, modeling of future food systems will need to be highly context-specific to be actionable.

Gordon et al.<sup>28</sup> developed four target-seeking scenarios for the Swedish food system, reflecting the overarching narratives presented above, but adapting each to the Swedish context and trends: Food as Industry (i.e., sustainable intensification), Food as Food Tech (i.e., tech-oriented futures), Food as Culture (i.e., agroecological transitions), and Food Forgotten (i.e., agriculture for climate mitigation rather than food production). The scenario narratives outline characteristics of four distinct food futures, suggesting dietary intakes, agricultural production systems, and dynamics of food imports and exports. In Box 1, the foci and the general implications of each scenario on Swedish diets are outlined.

Each scenario was designed to achieve ambitious targets for climate, biodiversity, and health, but in different ways and for different reasons. Food consumption targets for climate and biodiversity were constructed by downscaling the EAT-Lancet boundaries for the global food system to Sweden based on equal allocation of resources and emissions across all world citizens in 2045<sup>1,3</sup>. Health targets were set to reflect the dietary recommendations in the Nordic Nutrition Recommendations (NNR)<sup>29</sup>. The current Swedish diet is known to be far from these recommendations<sup>3,30,31</sup>, low in whole grains, blue foods, nuts/seeds, and pulses, and too high in meats, sugar, and salt, while also heavily exceeding per capita scaled planetary boundaries for greenhouse gas emissions, biodiversity, and cropland use<sup>3</sup>.

The aim of the present study was to assess the potential to remain within nationally-downscaled global climate, biodiversity, and cropland use



**Fig. 1 | Food intake by food group for current, scenario, and recommended diets.** Food intake in g per capita per day for the current diet, each scenario diet, and the recommended intakes by food group for the Nordic Nutrition Recommendations (NNR 2023); if no recommendation or the recommendation was to avoid intake was given for a group, those were set = 0; if a range was given, the average of the range was

set as the recommended intake amount for a group. ALT-EST alternatives to animal source foods produced with established technologies (e.g., tofu, tempeh, soy and non-soy meat, milks, cheese), ALT-EMERG alternatives to animal source foods produced with emerging technologies (e.g., cultured meat/milk, microbial protein/fats).

boundaries through dietary changes in line with the different scenarios narratives for the Swedish food system as described by Gordon et al.<sup>28</sup>. In addition to these scenario-specific dietary changes, we examined the additional effect of waste reductions and a phasing out of fossil fuels along the food chain. We quantified how far such dietary change, in combination with a reduction of food waste by 50% (reflecting the ambition in SDG 12.3<sup>32</sup>) and a transition to climate neutral energy use in primary production, transports, food processing, and packaging (reflecting the legally binding targets set by Sweden to be carbon neutral by year 2045), would go towards respecting the climate and biodiversity (in cropland use and relative species loss) boundaries while meeting health/nutrition targets.

This study presents a general approach for quantitatively assessing the potential of diet changes—alone or in combination with other food chain transformations—to reach nationally-downscaled global sustainability goals. The approach and methodology can be adopted for any country, accounting for local context. Additionally, while the results are specific to Sweden, they still provide insights that are relevant for discussions on food and agricultural policy in many other high-income, industrialized, trade-dependent countries with currently unsustainable (including unhealthy) diets<sup>3,31</sup>.

Across all scenarios, changing diets led to an average 30% reduction in environmental impacts, especially climate impacts. Yet, without removing energy-related emissions across the food supply chain, none of the scenarios remained within the most stringent climate boundary—removal of fossil fuels resulted in a further 50–60% climate impact reduction. Halving food waste added another 8–10% improvement in all impacts and scenarios. While changes in consumption are vital, reaching global environmental and health goals also demands transformations across the food system as well as policy and regulatory alignment.

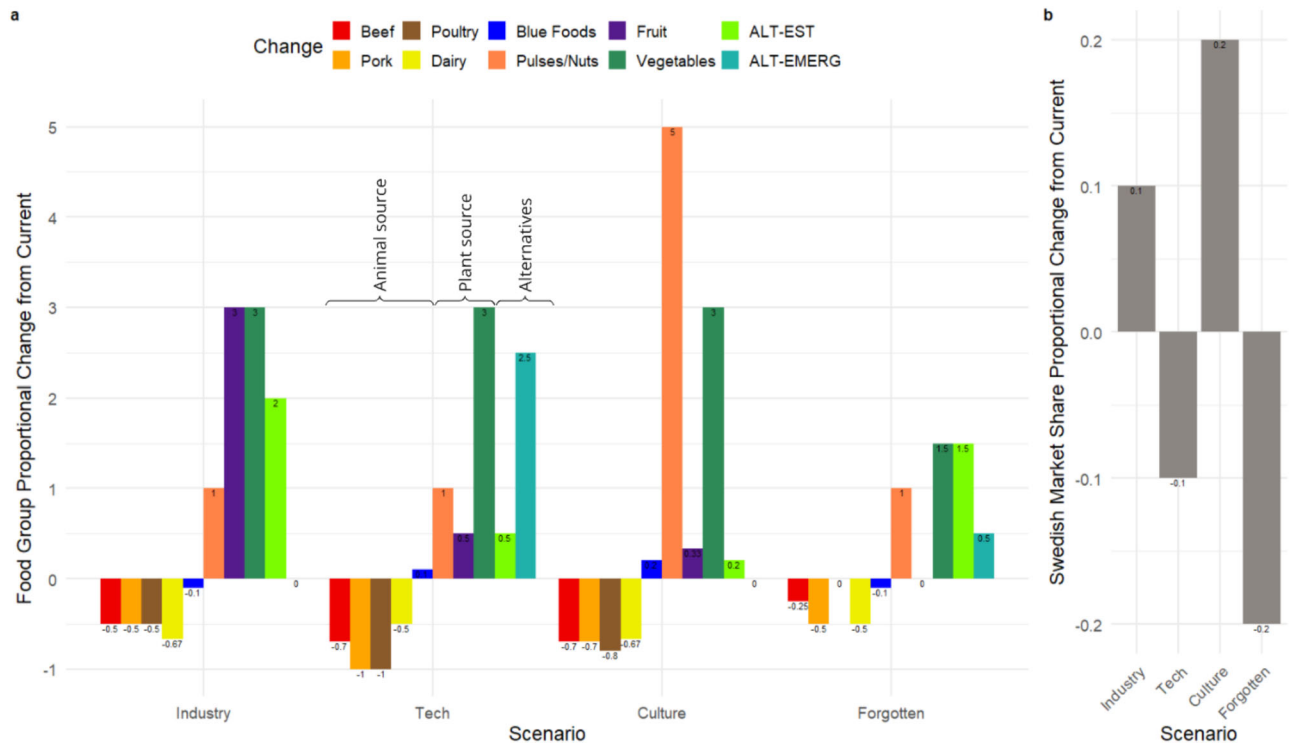
## Results

### Scenario diets

To reach health targets and respect environmental boundaries, two main changes to the current Swedish diet were necessary in all scenarios: a substantial increase in vegetable intake to reach health targets and a major reduction in animal foods to reduce climate and global biodiversity impact (see intakes compared to the NNR in Fig. 1, see also SM Table 11). For other food groups, which are not as critical for the health target, nor environmental boundaries, consumption was kept at fairly similar levels as current consumption to adhere to the local food culture.

In the Food as Industry and the Food Forgotten scenarios, meat consumption was reduced by 50 and 40% from current intake, respectively, and dairy by 30 and 70%, respectively. However, considering the importance of meat and dairy in current Swedish diets and food culture, we kept meat consumption relatively high in the Industry scenario, as the narrative emphasized Swedish food production in which meat and dairy currently play a dominating role. In the Forgotten scenarios, the emphasis was on status quo consumption, which also resulted in relatively high meat and dairy consumption, although more imported from the EU. Where animal products were replaced, this came mainly by cereals and (imported) soy meat and dairy product analogs in Food as Industry and Food Forgotten, reflecting a low investment in emerging product technologies or domestic legume production in these scenarios.

Consumption of meat was reduced by 80 to 90% from the current intake in the Food as Culture and the Food as Tech scenarios, and dairy by 30–50%, respectively. The substantial decrease in meat followed scenario pathways described, where there was substantially less demand for chicken and pork. Most ruminant products remained produced in Sweden to take advantage of several environmental benefits, including grazing biodiversity-



**Fig. 2 | Proportional changes by food group from the current to the scenario diets.** Proportional change from the current diet intake for (a) selected food groups and (b) the Swedish market share for all food groups in the scenario diets (Current = 0). ALT-EST alternatives to animal source foods produced using

established technologies (e.g., tofu, tempeh, soy and non-soy meat, milks, cheese), ALT-EMERG alternatives to animal source foods produced using emerging technologies (e.g., cultured meat/milk, microbial protein/fats).

rich semi-natural pastures. In Food as Culture, a large proportion of animal products was replaced by domestically produced, lightly processed legumes and cereals (e.g., cooked whole grain legumes or made into tofu and tempeh). The meat and dairy remaining in diets were produced in production systems including the use of semi-natural or permanent grasslands with high biodiversity values. In Food as Tech, animal products were replaced by alternatives produced using emerging technologies—foods not yet on the market but with the prospect for future scaling. These emerging alternatives include cultured meat and dairy, and microbial fats and eggs.

To reach health recommendations, we increased the intake of vegetables, fruits, berries, and blue foods in all scenarios, compared to the current diet (Fig. 2a). In Food as Culture, most vegetables were domestically produced, while in Food as Tech, current high import shares remained, as investment in domestic production is lacking. Hence, fruit consumption in Food as Culture was mostly apples, while banana consumption (consumed at high levels currently but not produced in Sweden) was reduced to half. We increased consumption of nuts in all scenarios by more than double, but since current nut consumption is low in Sweden, nut intake was still low in all scenarios (5–14 g/day in comparison with the recommended level of 25 g/day<sup>1</sup>), as few nuts are currently produced in Sweden. Swedish market share of all foods increased on average in Food as Industry and Food as Culture and decreased in Food as Tech and Food as Forgotten, with differences by individual food group based on each narrative (Fig. 2b).

### Environmental impacts and boundaries

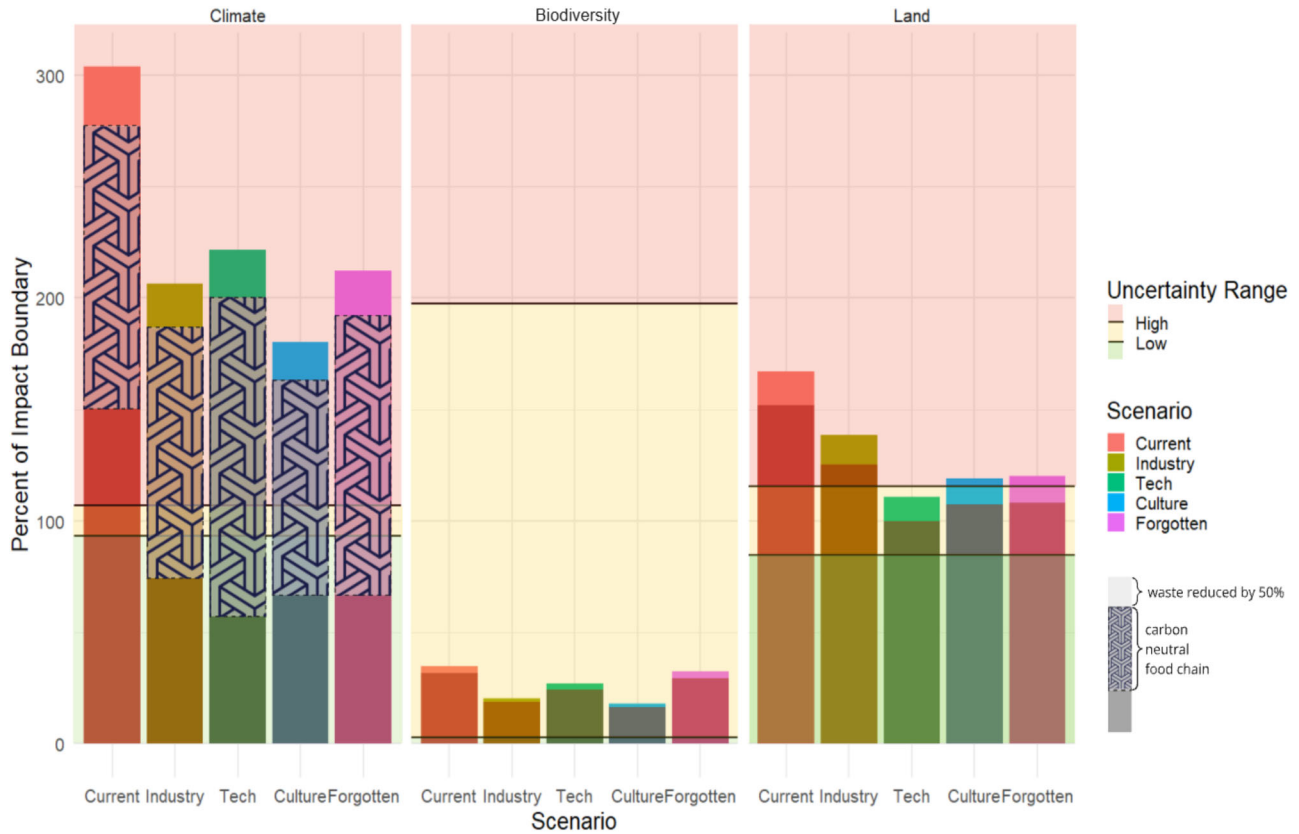
**Overall environmental impacts.** As expected, dietary changes in all scenarios reduced environmental impacts compared to the current diet. Climate impact reductions in the scenario diets ranged from 27 to 47% reductions from the current diet impact. However, diet changes alone did not allow any of the scenario impacts to move below the upper climate boundary. For global biodiversity impact, the reduction ranged from 7% in Food as Forgotten to 49% in Food as Culture; none of the scenario diets managed to remain below the uncertainty range of the biodiversity

boundary (which was, however, very large—see Supplementary Discussion). In all scenarios, cropland use was reduced 17–34% compared to current levels, but not enough to stay within the boundary. Impact shares apportioned to production in Sweden differed among scenario diets based on the amounts of foods imported vs. produced in Sweden in each scenario. The shares of impacts allocated to Sweden were highest in Food as Industry—33%, 29%, and 26% for climate, cropland, and biodiversity loss, respectively—and the lowest in Food as Tech—19%, 16%, and 9% for climate, cropland, and biodiversity loss, respectively (shares per food group and other impact categories can be found in SM Table 18).

When dietary changes were combined with a halving of food waste and the removal of energy-related emissions across the entire food value chain, all scenario diets stayed below the uncertainty range of the climate boundary (Fig. 3; more details in SM Tables 8–10). Fossil fuel phase out resulting in removal of energy-related emissions reduction lowered the climate impact by an additional 51–64% compared to the impacts of each scenario with fossil fuels. Halving of the food value chain waste reduced carbon footprint, biodiversity impact, and cropland use by an additional 8–10% compared to the impacts of each scenario excluding waste reductions (SI Table 1). The slight differences in impact reductions due to halving of food waste depended on the differing amounts of foods consumed in each scenario with the most waste—detailed results for all diet types by food, group, and whole diet can be found in SM Tables 13–15.

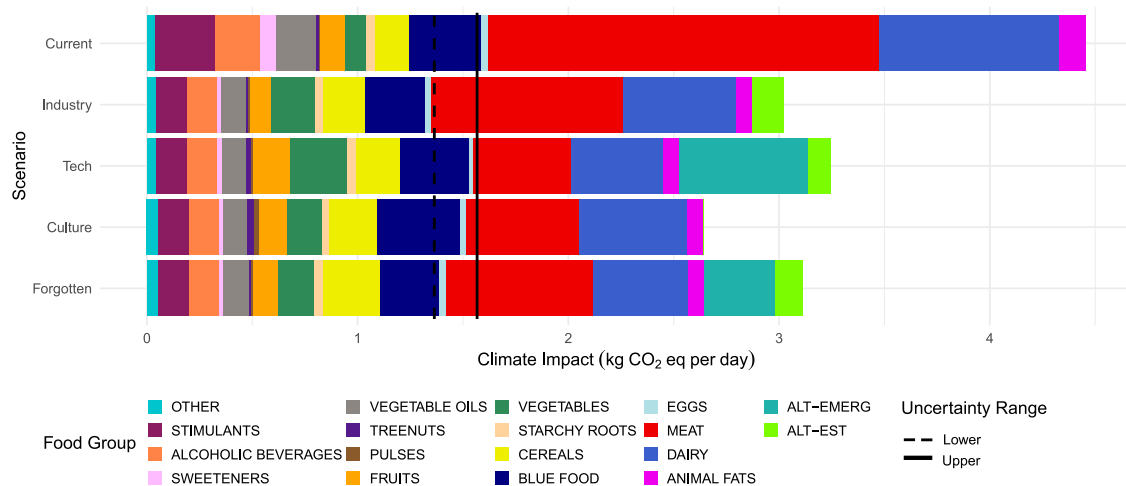
**Climate impact.** Despite substantial reductions of meat and dairy, animal foods were still among the greatest contributors to the climate impact (40–60%) of the scenario diets (compared to ~70% for the current diet) (Fig. 4; SI Fig. 1; SM Table 17.CF from ASF).

The impact of animal source food alternatives varied based on the type of alternative (emerging or established technologies) and the level of processing for established options. In Food as Tech and Food as Forgotten, the emerging animal source food alternatives caused a relatively large proportion (~15%) of the climate impact. The cell-based food items in the Tech and



**Fig. 3 | Climate, biodiversity, and cropland use impacts of current and scenario diets relative to boundaries.** The impacts of the current and four scenario diets, expressed as percentages relative to the average of each of the three environmental impact boundaries (Climate Impact, Biodiversity, and Cropland Use). The uncertainty ranges of the boundaries are shown between horizontal lines for high (green),

middle (yellow), and low (green). On each bar, the top segment in a lighter color shade shows the impact that could be reduced by a 50% reduction in waste across the food system production, retail, and consumer waste. On each climate impact bar, the middle, patterned segment shows the climate impact reduction due to the phase out of energy-related emissions.

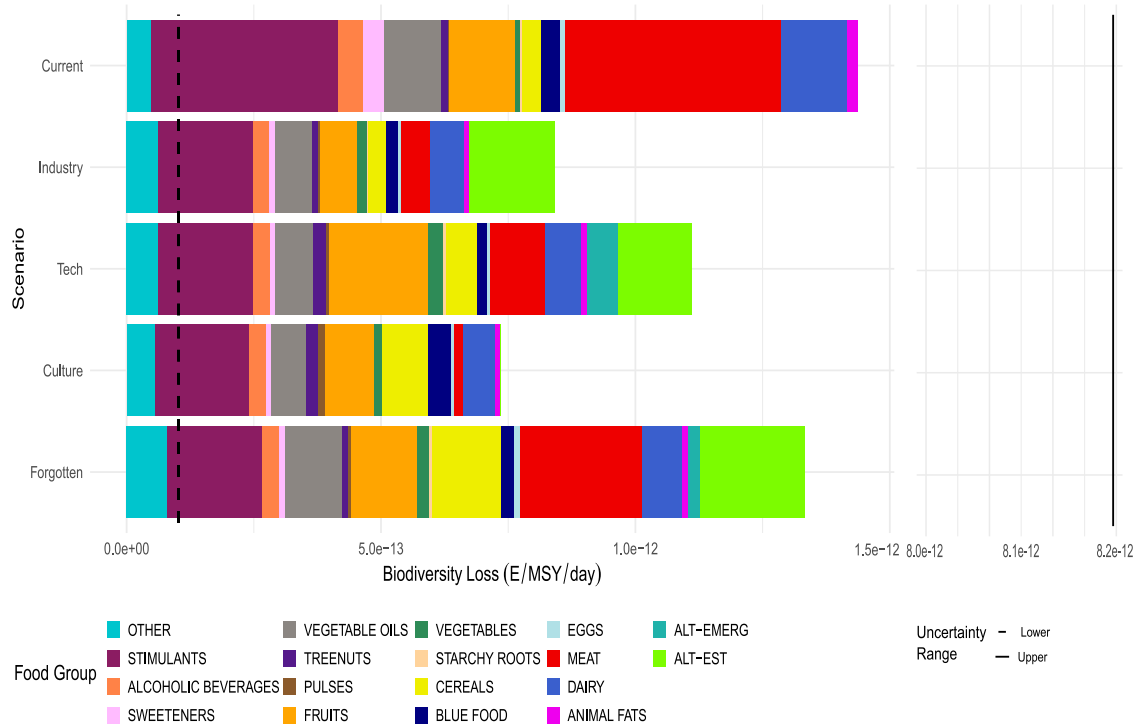


**Fig. 4 | Climate impact by food group for the current and scenario diets.** Climate impact by food group for the current and scenario diets in relation to the EAT-Lancet climate boundary—with the higher (solid line) and lower (dotted line) uncertainty range—scaled down to per capita based on the global population in 2045 (kg CO<sub>2</sub> eq. per day) by food group for the current and each scenario diet; OTHER = OIL CROPS, SPICES, MISCELLANEOUS, WILD FOOD; ALT-EST alternatives to

animal source foods produced using established technologies (e.g., tofu, tempeh, soy and non-soy meat, milks, cheese), ALT-EMERG alternatives to animal source foods produced using emerging technologies (e.g., cultured meat/milk, microbial protein/fats). Note that these emission estimates assume no reduction in supply-chain fossil energy use, food waste, nor agriculture-driven deforestation compared to current levels.

Forgotten scenarios caused large proportional impacts due to the high by-mass replacement of mainly beef and cheese. However, although reduced substantially, beef and milk from ruminants still had higher absolute impacts. In Food Forgotten and Food as Industry, the impacts from the

processed but established alternatives (e.g., legume-based meat, plant-based dairy, and soy-protein products) were estimated to have ~15–20% less climate impact per kg than the emerging technology foods in the Food as Tech scenario.



**Fig. 5 | Global biodiversity loss by food group for the current and scenario diets.** Global biodiversity loss (E/MSY per day) in total and by food group for the current and scenario diets in relation to the EAT-Lancet biodiversity boundary—with the higher (solid line) and lower (dotted line) uncertainty range—scaled down to per capita based on the global population in 2045; OTHER = OIL CROPS, SPICES,

MISCELLANEOUS, WILD FOOD; ALT-EST alternatives to animal source foods produced using established technologies (e.g., tofu, tempeh, soy and non-soy meat, milks, cheese), ALT-EMERG alternatives to animal source foods produced using emerging technologies (e.g., cultured meat/milk, microbial protein/fats). Note that these estimates assume no reduction in food waste compared to current levels.

In Food Forgotten, the consumption of poultry meat (kept at the same intake as current consumption and reliant on imported soy), palm oil, tomatoes, soy-protein products, and quinoa contributed substantially to the climate impact, mostly due to high intake but also due to relatively high impacts per kg of these food items, especially those associated with (current) deforestation. All scenario diets showed a notable climate impact from coffee—3–4% of the total climate impact, even though the intake of coffee was reduced by half in all scenario diets. Removal of all energy-related greenhouse gas emissions across the food chain reduced the total carbon footprint by an additional 40–60% across the scenarios (Fig. 3; SI Fig. 2). Halting agriculture-driven deforestation would have reduced carbon emissions by a further 5.2–8.5% across the scenarios.

**Global biodiversity loss.** We assessed global biodiversity impacts considering both land-use intensities and fragmentation effects given in Extinctions per Million Species Years (E/MSY) for five taxa—methods and data from the SAFAD database<sup>33</sup> ([www.safad.se](http://www.safad.se)). All scenario diets reduced the global biodiversity loss compared to the current diet, but to a widely different degree: from 7% reduction in Food Forgotten to a 49% reduction in Food as Culture (Fig. 5).

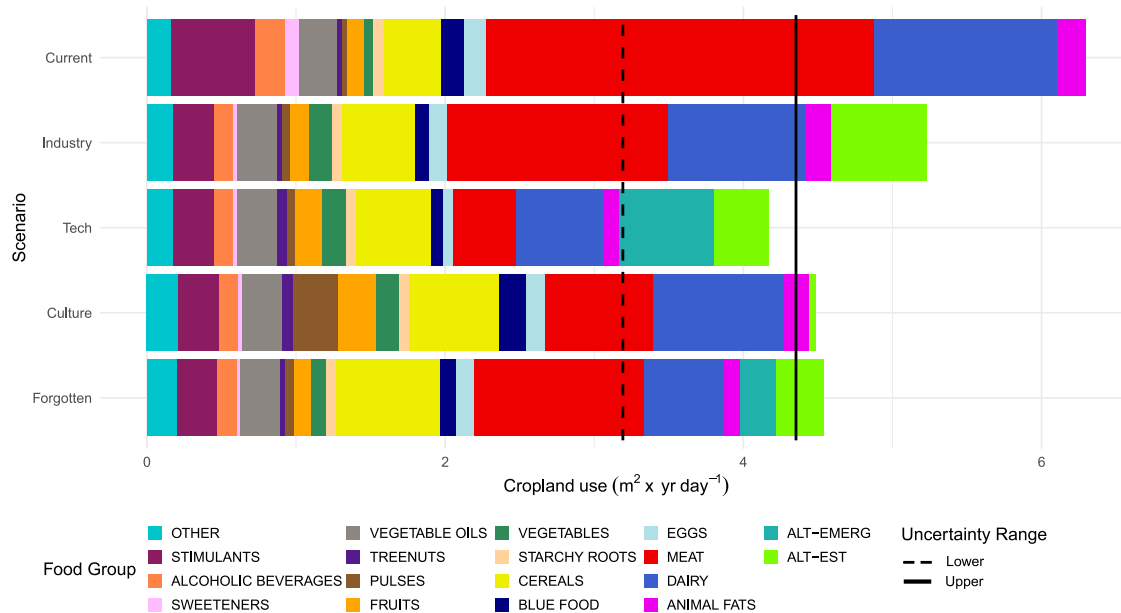
Production in Sweden causes lower biodiversity impacts compared to production in South America and Mediterranean areas, from which Sweden imports substantial amounts of food. Hence, Food as Culture has the highest biodiversity impact reductions compared to the current diet, mainly due to the decrease in consumption of imported foods and less animal source foods. Imported meat and dairy, stimulants (coffee, cocoa), vegetable oils, and fruits (especially bananas, which are consumed in high quantities) were the food groups mainly contributing to biodiversity loss in the current diet. Such imported foods also reflected a high biodiversity loss impact in the scenario diets (SI Fig. 1). A substantial share of the global biodiversity impact for animal products (20–77%) is associated with soy from Brazil and Argentina used for feed. All scenarios except Food as Culture have substantial biodiversity impact from soy-based meat and dairy alternatives, as

the soy is assumed to be grown in biodiversity-rich regions and imported to Sweden. In Food Forgotten, poultry (kept at current consumption levels) and pork (reduced by half from current levels), both of which have a substantial amount of soy feed in their diets, were also leading contributors to biodiversity impact. Coffee and cocoa intake accounted for a high proportion of biodiversity loss in the current diet; in all scenarios, coffee and cocoa intake were reduced by half, but were still proportionally highly impactful in all scenario diets. Coffee consumption in Sweden is among the highest in the world<sup>34</sup>, with very high waste levels; a reduction by half corresponds to consumption levels of many other European countries, which is still high from an international perspective.

Reducing meat in the diet substantially reduced the biodiversity impact, but the animal source food alternatives also contributed substantially to biodiversity impacts in Food as Industry, Food as Tech, and Food Forgotten due to the impact of imported soy (mostly from Argentina and Brazil) used in these products. The domestically produced alternatives of fava bean tofu, tempeh, and oat-based drinks in Food Forgotten and Food as Culture had a biodiversity impact that was an order of magnitude smaller than the emerging tech and imported foods from the alternatives group. Such differences are mainly due to the imported ingredients being grown in regions with high per-hectare biodiversity loss impacts from land use.

Vegetable oils also contribute to the biodiversity impact, with soybean, olive, and palm oils—all imported—in all scenarios, and soybean oil in the Food Forgotten scenario as the most impactful vegetable oils.

**Cropland use.** All scenario diets reduced the cropland use compared to the current diet by 17–34% (Fig. 6). Meat, dairy, and stimulants were the main contributors to cropland use in the current diet, collectively contributing over 75% of the cropland use (SI Fig. 1). Similar proportional contributors to cropland use—though with lower total cropland use—were reflected in the scenario diets. Beef, pork (except in Food as Tech, where it was removed), and cheese were the foods that contributed most to cropland use in all scenarios. Some animal source food



**Fig. 6 | Cropland use by food group for the current and scenario diets.** Cropland use ( $m^2 \times \text{year per day}$ ) by food group for the current and scenario diets in relation to the EAT-Lancet cropland boundary—with the higher (solid line) and lower (dotted line) uncertainty range—scaled down to per capita based on the global population in 2045; OTHER = OIL CROPS, SPICES, MISCELLANEOUS, WILD FOOD; ALT-

EST alternatives to animal source foods produced using established technologies (e.g., tofu, tempeh, soy and non-soy meat, milks, cheese), ALT-EMERG alternatives to animal source foods produced using emerging technologies (e.g., cultured meat/milk, microbial protein/fats). Note that these estimates assume no changes in production efficiencies or food waste rates compared to current levels.

alternatives also had high relative cropland use, in particular, the cell-based dairy in the Food Tech and soy-protein products in the Food Forgotten scenarios, because they rely on crops as raw materials, and due to their higher consumption than in the other scenarios compared to other alternatives.

Cereal intake, with increased intakes of wheat and whole wheat flour from the current diet level, also had relatively high cropland use in all scenarios. The largest reductions of meat and dairy in Food as Culture resulted in lower total cropland use compared to Food as Industry and Food Forgotten. The replacement of animal source foods in Food as Culture was mostly with whole grain legumes and cereals, which therefore have a higher cropland use relative to the current diet. Slightly higher absolute cropland use for fruits in Food as Culture is due to the slightly lower yields of Swedish fruits compared to imported fruits. Coffee and cocoa intake again contributed a large proportion (~5%) of cropland use in all scenario diets, though reduced by half from the current intake.

**Nutrition outcomes**

All four scenario diets were healthier and more nutritious than the current Swedish diet, as they were all constructed to meet NNR recommendations. A closer examination of diet quality was done using the Nutrient Rich Diet (NRD)<sub>25,4</sub> index—an index of 25 positive nutrients to include and 4 negative nutrients to limit in the diet. Each of the scenario diets had a higher NRD<sub>25,4</sub> value than the current diet; the higher the value, the closer the diet is to the recommended intake for the 29 nutrients included in the index (Table 1).

All scenario diets had higher intakes of iron, fiber, folate, and vitamins C, E, and K, and lower polyunsaturated fatty acids than the current diet. Much of the improved intake of these nutrients was due to an increase in vegetable and whole grain intakes in each scenario—with Food as Tech having the largest proportional increases in vegetables and fruits, due to higher health ambition driven by EU regulation on nutrition for emerging alternatives in this scenario. The scenario diets had, due to the reductions in meat and dairy, lower vitamin B6 and B12 intake than the current diet (with the exception of B12 in Food as Tech having 50% more than currently due to high B vitamin content of cellular meat, dairy, and microbial fats). However, all scenario diets exceeded the recommendation for daily intake by more than 200% and 50% for vitamin B6 and B12, respectively. No scenario diet

**Table 1 | Nutrition and health outcomes for the current and scenario diets**

Diet	Nutrient richness (NR <sub>diet</sub> )	Nutrients to limit (LIM <sub>diet</sub> )	Nutrient Rich Diet Score (NRD <sub>25,4</sub> )	Diet diversity (HR × 10 <sup>7</sup> )	Protein quality (DIAAS)
Current	0.87	0.57	0.30	5.327	1.25
Industry	0.98	0.60	0.39	15.770	1.14
Tech	0.97	0.59	0.38	15.814	1.15
Culture	0.98	0.60	0.37	15.888	1.14
Forgotten	0.98	0.62	0.36	5.329	1.14

Nutrient Rich Diet<sub>25,4</sub> (NRD<sub>25,4</sub>) index measuring diet quality calculated with 25 positive nutrients with the Nutrient Rich score (NR<sub>diet</sub>) and 4 Nutrients to Limit (LIM<sub>diet</sub>). Rao's Quadratic Entropy (HR) calculated for the dietary diversity, and protein quality measured with Digestible Indispensable Amino Acid Score (DIAAS).

nor the current diet met the NNR recommendations for vitamin A and D, and only the Food Forgotten scenario met the selenium intake recommendation, known nutrients of concern for the Swedish population<sup>35</sup>. The scenario diets all had at least 50% lower intake of saturated fatty acids and were thus much closer to the recommended intake than the current diet, though none of the diets were below the recommended maximum amount of saturated fatty acids. All other nutrient intakes met recommended amounts in both the current and scenario diets (SI Figs. 3–5).

Dietary diversity was measured by the similarity-sensitive diversity metric, Rao's Quadratic Entropy (HR)<sup>36</sup> (Table 1). The highest scores in the relative dietary diversity metric were in Food as Culture, Food as Tech, and Food as Industry, diets which have a higher number of different types of food items in groups such as fruits, vegetables, cereals, and legumes and nuts, in particular, relative to the current and Food Forgotten diets.

Protein quality measured using Digestible Indispensable Amino Acid Score (DIAAS) was adequate (i.e., DIAAS ≥ 1) in all the scenario diets (Table 1). All the diets contain a mix of foods with complementary amino acid profiles that, in combination, lead to this high protein quality—any diet

with a DIAAS value  $\geq 1$  has adequate protein quality—DIAAS by food and diet in SM Table 16. Protein Quality.

## Discussion

Our results show that combining context-adapted dietary changes, reductions in waste, and the phasing out of fossil fuels can drastically decrease environmental impacts while nutrition outcomes are improved. However, despite major changes to all these factors, planetary boundaries were only safely met for climate. A range of food system scenario studies exists at the global and regional levels, some of which explore agroecological or organic transitions similar to Food as Culture<sup>37</sup> while others investigate food futures more generally<sup>38</sup>. However, few are tailored to the Swedish context, and those that do exist tend to focus on a single normative direction, typically aligned with agroecological or local food system futures, similar to our Food as Culture scenario<sup>13,39</sup>.

In contrast, the present study develops a set of four internally coherent yet contrasting food system futures to explore tradeoffs and synergies across environmental and nutritional dimensions. While these scenarios were not developed through direct stakeholder co-creation, they built on previous work that included participatory processes and stakeholder-informed elements. The scenarios reflect current narratives captured by, for example, a recent Q-methodology study on stakeholder perceptions of food system sustainability in Sweden<sup>17</sup>. Similarly, the Food as Industry scenario is informed by roadmaps and strategic documents produced by Swedish agri-food industry actors, representing their envisioned pathways, such as the 2025 Swedish Food Strategy. Our approach builds on previous scenario studies, combined with stakeholder and expert perceptions. The process for developing the original narratives is further outlined in section 2, “Current Trends, Drivers of Change, and Alternate Food Futures” in Gordon et al.<sup>28</sup>.

The Food as Tech diet had the largest climate impact of the four scenarios and a larger global biodiversity impact than both Food as Industry and Food as Culture (Fig. 3). Our analysis shows that emerging technologies, as alternatives to current food groups, may not be able to deliver substantial climate benefits without the phasing out of energy-related emissions and increases in energy efficiency of these technologies. In terms of biodiversity impact, the sourcing of raw materials for these emerging foods from less biodiversity sensitive areas is crucial.

Judging from our results, respecting the global biodiversity boundaries by keeping well below the uncertainty range is especially challenging. However, the uncertainty in the biodiversity boundary is exceptionally large (1–80 E/MSY<sup>1,40</sup>) as is the assessment of the biodiversity impact due to the need to account for differences in land use types, habitats, and intensities, as well as species and their respective ecosystem values<sup>41</sup>. Regardless of uncertainties in the biodiversity assessment, it is clear from our results that Sweden is currently externalizing substantial national impacts through food imports (i.e., exporting land use and environmental impacts of food consumption). The production of animal-sourced foods using imported soy as feed, luxury commodities (e.g., coffee, wine, chocolate), and oil crops in particular, are important drivers of global biodiversity impacts in diet assessments<sup>41–43</sup> all with impacts outside of Sweden. Further considerations are clarified in Supplementary Discussion: Trade in the Scenarios and Biodiversity in the Scenarios. As expected, the shares of impacts allocated to Sweden follow the trend that as imports to Sweden decrease, impacts allocated to Sweden increase, with the highest impacts in Food as Industry climate footprint and the lowest in Food as Food Tech biodiversity loss.

Our results show that lowering imports substantially reduces the global biodiversity impact for Swedish food consumption—mirrored in previous studies<sup>44</sup>. It should, however, be noted that the result of decreasing imports is not generalizable to countries in sensitive biodiverse areas, where the opposite would be true. Land use in Sweden causes low-biodiversity impacts in comparison with using land in many tropical regions or the Mediterranean, from where much of the food consumed in Sweden is imported. However, our focus on a global biodiversity indicator provides little information on how to fulfill local or national biodiversity goals, which may vary greatly between countries and regions. Indicators of local biodiversity and

ecosystem services are more elusive and difficult to quantify at the national scale, since they must be managed locally or landscape-wide, and benefits are often provided at small spatial scales. Although not modeled explicitly, the scenario narratives suggest that Food as Culture would have the largest positive effects on farmland biodiversity, while the other scenarios have variable effects on biodiversity depending on how national biodiversity policies play out<sup>45</sup>. Food as Culture is more biodiversity beneficial due to its focus on grass-based ruminant production, favoring the use and maintenance of biodiversity-rich semi-natural pastures relative to intensive meat and dairy production. Also, regenerative farming, rewilding, or restoration of wetlands and forests are practices that are more likely to occur under Food Forgotten or Food as Culture<sup>45</sup>. Globally, agricultural expansion is one of the main drivers of biodiversity loss<sup>46</sup>. A transition to a diet that uses less cropland (for example, in Food as Food Tech and Food as Culture) could therefore decrease the rate of agricultural expansion and/or free land for biodiversity-enhancing measures.

By halving food waste and abating energy-related emissions in the food value chain, all scenario diets could reduce the climate impact to below the lowest climate boundary uncertainty range. Though theoretically feasible, such elimination of energy-related emissions will require a diverse set of practices and emerging technologies that need to be rapid and supported by improvements in research, governance, financial, and policy mechanisms<sup>47</sup>. Our results show that a majority of the energy-related emissions in the diets were from livestock products, so reductions in animal source foods would entail reduced climate impact from energy use (SI Fig. 2).

In addition to phasing out of fossil fuels, there are other production-side mitigation options, not explored here, that could be implemented. An additional 7%–18% reduction in total greenhouse gas emissions from agriculture globally could come from, for example, reductions in enteric fermentation and increased nitrogen use efficiency<sup>48</sup>. The potential of production-side measures to lower the environmental impacts of food systems depends on the degree of implementation, but also on technological development and efficiency improvements. Negative emissions, such as the removal of carbon dioxide from the atmosphere using agroforestry or adding biochar made of crop residues to soils, may further decrease the climate impact<sup>49</sup>, essential for a net-zero agricultural sector<sup>47</sup>. However, such net-zero strategies have many uncertainties related to potentials for storage, including saturation and the stability of carbon stored in, for example, soils and biomass<sup>50,51</sup>. Dietary change may further enable carbon sequestration by freeing land that can be used for carbon sequestration using afforestation<sup>18,52</sup>. Yet, the theoretical freeing of land that follows from dietary change does not automatically translate into land being afforested; policies to ensure such developments would be needed for such potential to be realized.

Increased crop yields can lower cropland use. The potential to increase crop yields in Sweden through improved management and higher nutrient inputs may be about 10–20% with current crop genetics and in climate conditions of today<sup>53</sup>. Additional yield increases may be possible in the future through improved crop genetics, but such quantification is complicated by uncertainties about future climate change and adaptation<sup>54</sup>. However, increasing yield does not in itself reduce cropland expansion, as it may also result in a “Jevon’s paradox” (i.e., increased productivity can lead to increased land expansion, potentially driven by increased profitability)<sup>55</sup>.

Global biodiversity impacts of Swedish food systems can be reduced substantially by lowering imports more than in the modeled scenario diets, leading to more production and consumption of domestic foods and lowering consumption of high-impact imports. Although we can conclude that solutions to substantially lower impacts from the Swedish food system are available, our results confirm the need for “unprecedented ambition and coordination” of efforts for food systems transformation<sup>56</sup>, or put differently, a “technological-cultural U-turn,” to keep the global food system within planetary boundaries<sup>10</sup>.

The scenario diets were constructed to reflect *realistic* food futures with particular attention to the national food culture through current and historical trends in average food intake. Still, the changes in the consumption of certain food products were quite drastic. In the scenario diets, meat intake

was reduced by more than 50%, dairy by 30–50%, and vegetable intake more than doubled. At the same time, the changes from current diets were less extreme than a move to, for example, the EAT-Lancet reference diet<sup>1</sup>. So, while our ambition was to keep the scenario diets realistic and culturally appropriate, the substantial impact reductions aimed for will require substantial changes to diets. However, using current diets as the baseline for comparison is not necessarily consistent nor fair for setting dietary norms, as consumption of meat, for example, has increased by some 50% in Sweden during the last 30 years<sup>57,58</sup>. Implementing dietary change presents complex challenges due to varying practical and social pathways among the futures<sup>59–61</sup>. For example, to promote increased intake of plant-based alternatives, companies may focus on the “foodie” or cultural reorganization around the valuation of food, as in the Food as Culture scenario, or shift the focus to the convenience of less impactful, processed plant-based choices, as in Food as Industry<sup>62</sup>.

There are further nuances inherent in increasing healthfulness of diets and staying within boundaries for environmental impacts. For example, the large proportional climate impact of blue foods is at odds with increasing such foods in diets following health recommendations, also seen in diets in similar countries such as Finland<sup>48</sup>. Another tradeoff related to blue food not considered here is the biodiversity impacts of capture fisheries on aquatic ecosystems<sup>63</sup>. Thus, more attention should be paid to such tradeoffs in making dietary recommendations for health and lower environmental impacts. Such tradeoffs also imply that the greatest environmental and health benefits of meat and dairy reductions do not rely on increases in emerging tech or processed plant-based foods, but instead on eating more whole grain cereals, legumes, seeds, and pulses (produced domestically or in similar low-biodiversity-impact regions). Such diet changes provide a more efficient pathway to climate and biodiversity impact reduction, as seen in other Swedish studies<sup>31</sup>. However, large increases in consumption of only lightly processed legumes (e.g., beans and peas soaked and cooked) or meat alternatives produced with established technologies (e.g., tofu and tempeh) are hampered by the taste, familiarity, and attractiveness of such foods still being substantially lower than meat in Sweden<sup>64</sup>. Further considerations clarified in Supplementary Discussion: Health and Nutrition Indices in the Scenarios.

The scenarios assessed here intentionally examine pathways where enabling conditions may not yet be present, thereby highlighting potential risks, limitations, or areas where additional support will be needed for proposed strategies to succeed. Food as Food Tech, for example, explores a future where technological innovation is heavily relied upon, but where its feasibility remains uncertain. The emerging alternatives group contributed more than expected to the Food as Food Tech climate and cropland impacts and was second only to meat in the Food Forgotten scenario. Our results indicate that the alternatives which have a lower technology readiness level, or emerging food technologies (e.g., cellular meat, fish, and milk) and the more processed, imported soy- and plant-based foods, might not provide as large a climate impact reduction potential as some studies indicate<sup>31,65–67</sup>. Although we developed informed best estimates of energy use for future emerging technologies here, such technologies are currently energy- and infrastructure-intensive. Energy-related impacts from primary production may be reduced in such emerging technologies if they are developed at efficient scales<sup>68–70</sup>. Renewable energy sources can lessen climate impacts further, which is also true for the established technologies. It is also worth noting that Sweden already has a (near) carbon-neutral electricity system, largely dependent on a base of hydropower, and there is a large potential for expanding carbon-neutral electricity generation.

Lastly, it should also be pointed out that the future Swedish food system will likely be a combination of these four scenarios and other pathways beyond the values and worldviews they represent. Future work could look into combinations of certain aspects of each scenario to explore how the sum of each might remain within the boundaries. There is also a need for further research modeling enabling conditions such as policy measures, barriers to implementation, and distributional effects across different segments of the

population for each scenario. Further work should assess how to make just, equitable, and diverse food futures<sup>71,72</sup> (e.g., how such future diets contribute to or detract from food systems literacy and vice versa<sup>73</sup>), what roles the approach to sufficiency and degrowth dietary shifts can play<sup>74–76</sup>, and the unintended effects of dietary change causing so-called social, economic, and environmental spillovers<sup>77</sup>.

Dietary changes are a critical step toward sustainable food systems, but true transformation demands bold action across the value chain, including production and consumption, the cutting of food loss and waste, and transitions to clean energy. The scenarios explored here underscore the complexity of balancing health, culture, and environmental boundaries, revealing both opportunities and tradeoffs. Developing narratives and quantitative models that are target seeking—here, nationally-scaled food system boundaries—addresses calls for integrative methods to operationalize and visualize pathways to global goals at regional scales<sup>78</sup>. The method presented here allowed for a unique exploration of differing futures and their outcomes for environmental boundaries and health targets, developed in a way that takes stakeholder views and perceptions into consideration<sup>12,79,80</sup>. The futures explored here aim to reflect possible, tangible pathways to staying within planetary boundaries, which can be just and inclusive, informing policy, practice, and aesthetics of sustainable food futures<sup>81</sup>. The methods used here provide an approach for articulating a national to regional set of future pathways to meeting imperative global goals with coherence across scales and food systems sectors, actors, and challenges.

## Methods

### Methods overview

We quantified diets based on the four Swedish Food Futures narrative scenarios, Food as Industry, Food as Food Tech, Food as Culture, and Food Forgotten, described in detail in Gordon et al.<sup>28</sup>. All four scenarios focused on the Swedish Food system and aimed at simultaneously improving the three goals of healthy diets, climate mitigation, and halting biodiversity loss, while at the same time reflecting the specificities of six key aspects of the Swedish food system: trade, governance/institutions, supply chains, production of crops, livestock, and blue foods, cultural values around food, and consumption. For each scenario, we used current intake trends and dietary recommendations for food group intakes to develop four different scenario diets (see Box 1). Reduction in animal source foods needed to reach especially climate targets was imperative in all four scenarios. Using indicators for health, climate impact, cropland use, and biodiversity impacts, we assess how far these consumption changes go in contributing to consumption-based goals for each indicator: climate, healthy/nutrition, and global biodiversity loss.

### Strategy for scenario diet development

The goal was to develop future diets that follow the scenario narratives and contribute to fulfilling the multiple goals of health, climate mitigation, and biodiversity conservation. We wanted, to the extent possible, to reach targets with diets that adhere to the current local (national) food culture and food production. The reference diet (current food intake) was used as the point of departure and represents the current national food culture. Further, future diets should be healthy (i.e., follow nutritional guidelines) but at the same time allow for some unhealthy/luxury food items such as coffee and alcoholic beverages. As a last step, we also checked that the food intake in the respective food groups fell within the ranges of those in the EAT-Lancet diet for the diets to get closer to staying within environmental boundaries. However, for the diets to be culturally appropriate in terms of degree of change from the reference (current) diet, we did allow for the diets to diverge from the suggested ranges for some food groups (e.g., dairy, nuts/seeds, and starchy roots) in some of the scenario diets.

The scenario diets were developed in three steps:

1. Develop diets that are consistent with the scenario descriptions and follow national food consumption patterns. This was done by:

- a. creating a reference diet based on current food intake
  - b. changing the reference diet in line with the scenario narratives
2. Check that the diets are healthy, following the NNR in terms of food group level consumption
  3. Check consumption at the food group level in relation to the ranges in the EAT-Lancet diet to increase the likelihood of the diets staying within environmental boundaries.

The three steps for developing the scenario diets are further explained below:

The first step was to build a reference diet from the scenario narratives and current dietary data in Sweden. Scenario narratives and their key differences for diets are described in Gordon et al.<sup>28</sup>. The narratives were developed in accordance with expert stakeholder input and reflection on future food systems pathways for the Nordic context<sup>13,28</sup>. Current intake data for foods at the ingredient level ( $n = 168$  foods) were harmonized by intake in g/day and classified into 21 larger food groups. Source data for different food groups varied<sup>82,83</sup>. We first used the data and food categories from FAO Food Balance Sheets (food products that are not consumed were removed). The FAO data were used when it was in line with national statistics and for the food categories where no national statistics were available. For some food categories, such as meat, we use national statistics of raw meat supply<sup>82</sup>. Food waste at the household level was also taken into consideration, and waste was removed from the final consumption data, raw weight<sup>84</sup>. This means that, for the nutritional indicators, we only account for what is eaten (but not what is wasted), whereas for the environmental indicators, we account for total demand for food (i.e., both what is eaten and what is wasted). Full explication of the data source for each food item in terms of current consumption and waste adjustments can be found in SM Table 2. Product Database.

We also collected data on the current import share of each food item as consumed in the Swedish diet from Schwarzmüller & Kasnter and for dairy products SBA<sup>82,85</sup>—see SM Table 5. Diets and Import Proportions. Once data on the current intake by food ingredient and group were collected, the current diet in Sweden (2020) served as the foundation for the development of intake and import share quantities for each scenario—see SM Table 6. Export Trends. Intakes and import shares were set for individual food ingredients by checking each scenario narrative for descriptive information on intakes to ensure each diet was consistent with the scenario descriptions and intentions<sup>28</sup>. Full details of the dietary intakes and imports by food, group, and diet can be found in SI Fig. 6, SM Table 1. Scenario Diets, and key changes made across the scenarios can be found in SM Table 4. Key Swaps.

The second step was to develop the diets to be healthy and follow the recommended food group intakes. We iteratively developed the individual food intakes by comparing scenario diets and their estimated macronutrient intakes, and the food group level consumption with recommendations made for the Nordic context. NNR are developed as the scientific advisory documents for developing national dietary guidelines<sup>29</sup>. The NNR gives both nutrient and food group guidance for healthy, and according to the latest version, environmentally friendly, intakes for Nordic populations<sup>29</sup>. We followed their recommended intakes for dietary energy and proportions of energy from fat, protein, and carbohydrates for healthy adults when developing the scenario diets. It is recommended to consume between 2055 and 2811 kcal/day for both female and male adults between 18 and 65 years old, from low to highly active lifestyles. For total fat, daily recommended intakes range from 25 to 40 percent of total energy intake (E%) of the full diet, corresponding to 76–103 g/day of fat intake. Protein intake recommendations are for 10–20 E% of the current diet, totaling between 76–104 g/day of protein. Recommended carbohydrate intake is 45–60 E%, corresponding to between 266 and 363 g/day of carbohydrates. Fiber is recommended to be  $\geq 30$  g/day. We also used NNR guidelines for food group intakes for food group totals (Fig. 1). For example, in the Blue Foods group, the NNR gives the overall advice, “It is recommended to consume 300–450 g/week (cooked or ready-to-eat weight), of which at least 200 g/

week should be fatty fish. It is recommended to consume fish from sustainably managed fish stocks<sup>29</sup>.”

The third step was to compare and adjust food group intakes following the general guidelines of the EAT-Lancet diet<sup>1</sup>. In addition to being designed for favorable health outcomes, it has been shown that in combination with food waste reductions and technical improvements, the EAT-Lancet Diet can meet global environmental targets for the food system<sup>1,86</sup>. Therefore, adjusting the diets so that food intake of different food groups falls within the suggested range in the EAT-Lancet Diet should increase the probability of the diets remaining within the environmental boundaries. However, for the diets to reflect current dietary patterns in Sweden, many of the scenario diets diverged from the suggested EAT-Lancet ranges for several food categories. This includes, for example, dairy and starchy roots. Sweden has a high consumption of dairy products (also a historically high consumption) and high domestic dairy production, which is largely based on the cultivation of grass-clover leys that can be grown in large parts of the country (also in the northern parts where crop cultivation is more challenging). Starchy roots (potatoes) are historically a staple food in Sweden, and therefore, consumption was kept constant throughout all of the scenarios.

A more detailed elucidation of food group level changes from the current diet baseline and justifications for each scenario diet can be found in SM Table 3. Justifications. The final intake amounts and import share on the Swedish market for each food item in each scenario diet can be found in SM Table 1. Scenario Diets.

### Food-item-specific data collection

To quantify the nutritional and environmental impact outcomes for the scenario diets, we needed to collect data on nutrient contents and environmental impacts at the individual food item level.

**Nutrient content.** Nutrient composition data were collected at the individual food ingredient level (e.g., wheat flour in breads, or sugar in all cooked or composite dishes) from the National Food Agency in Sweden (Livsmedelsverket). We use the Livsmedelsverket data as it provides the most up-to-date and comprehensive dietary intake data for Sweden<sup>87</sup> and as it matches the dietary consumption data for the Swedish adult population<sup>82,83</sup>. The Livsmedelsverket data contains validated and unified data for 57 nutrients in units per 100 g of food. We collected data on raw food items to match the intake in g/day of foods at the ingredient level—see SM Table 2. Product Database. Following previous methods for diet modeling, we did not account for any potential differences in nutrient content from cooking and preparation for any food groups and across all scenarios<sup>31,65</sup>.

**Environmental impacts.** Environmental footprints were collected from the SAFAD database<sup>33</sup> at the individual food ingredient level, harmonized with the dietary consumption data. Briefly, the SAFAD database contains data on environmental indicators of food items as consumed in several European countries, reflecting domestic production and imports from main import countries. SAFAD has a selection of products harmonized with the list of European Food Safety Authority FoodEx2 coded food items<sup>88</sup>. Impacts of the whole food item, regardless of if they were produced in Sweden or imported, are accounted for in the SAFAD tool. It was thus also possible to calculate the proportion of impact for each food, food group, and scenario diet allocated from Sweden. To calculate the share of each impact attributed to Sweden in each food item, the inverse of import shares per food ingredient (i.e., amount not imported, or produced in Sweden) was multiplied by the impact of each respective food item per kg, and that value was then divided by the final impact amount per food ingredient. The totals of impact proportions were then summed per food group and scenario diet, respectively.

SAFAD expresses the environmental impact per kg or liter of food product (in edible bone-free weight for meat and fish). SAFAD includes data both for raw unprocessed commodities (e.g., apples, milk), processed basic foods like wheat flour and rapeseed oil, and ready-to-eat meals like pizza and

**Table 2 | Impact boundary ranges**

Target	Lower limit (unit/cap/day)	Boundary average (unit/cap/day)	Upper limit (unit/cap/day)	References
Climate Change	1.36 kg CO <sub>2</sub> eq	1.47 kg CO <sub>2</sub> eq	1.57 kg CO <sub>2</sub> eq	1,92
Cropland Use	3.19 m <sup>2</sup>	3.77 m <sup>2</sup>	4.35 m <sup>2</sup>	1,92
Biodiversity	1.02 × 10 <sup>-13</sup> E/MSY	4.14 × 10 <sup>-12</sup> E/MSY	8.18 × 10 <sup>-12</sup> E/MSY	1,92

Impact boundary ranges, lower, average, and upper limits for environmental impacts, and the source of the boundaries.

lasagna. We used data for raw unprocessed commodities and processed basic foods in our calculation, and system boundaries include primary production (agricultural processes or fishing), food processing (e.g., milling of flour or pressing of oil), transport, packaging, and any food loss and waste during processing, at the retail, and at the consumer. Cooking impacts were hence not included; however, we assumed that the ingredients would generally require a similar amount (in terms of energy) for cooking across all scenarios. SAFAD uses economic allocation to divide emissions and resource use across products that come out of the same commodity (e.g., oil and cake from rapeseed). Meat and offal were treated as a single product, and emissions from livestock production were allocated based on the total quantity of meat and offal produced. We assume current cropland yields and animal production efficiencies in the Swedish food system and for import countries. Import share proportions per food ingredient were adjusted with the SAFAD tool based on the current Swedish food system, and then modifications were made to reflect the customized import share proportions for each scenario. For the carbon footprint, the SAFAD database contains the impacts disaggregated for the different greenhouse gas generating steps, e.g., energy use in primary production, manure management, and transport. To estimate the carbon footprint assuming a phase out of fossil fuels in the energy system, we only included emissions from energy-related processes.

To align with the targets from Gordon et al.<sup>28</sup>, three environmental indicators were used in the assessment: carbon footprint (kg CO<sub>2</sub>e per kg of food), biodiversity impacts from land use (E/MSY per kg of food), and cropland use (m<sup>2</sup>\*year per kg of food). The carbon footprint measures the climate impact of dietary choices by calculating greenhouse gas emissions in carbon dioxide equivalents (CO<sub>2</sub>e) using the Global Warming Potential (GWP) metric. GWP aggregates the effects of gases like carbon dioxide, methane, and nitrous oxide based on their impact over 100 years (GWP100), following international standards. The model uses recent IPCC values: CO<sub>2</sub> (1), biogenic methane (27.0), fossil methane (29.8), and nitrous oxide (273)<sup>89</sup>. Biodiversity impacts from land use are evaluated using the method established by Scherer et al.<sup>41</sup>. This approach estimates how land management practices and land use intensities, like cropping or pasture, affect different species compared to natural habitats. Notably, biodiversity loss assessment is challenging and comes with major uncertainties. The cropland use metric calculates the land required (in m<sup>2</sup>\*years) to produce diet components, important for understanding land resource demands. Cropland use is estimated by 1/yield, while livestock products include cropland for feed, reflecting the land intensity of dietary choices.

**Scenario diet impacts and boundary quantification**

We then calculated climate, cropland use, and biodiversity impacts for the current diet and each scenario diet using the above collated food-item-specific data and intake amounts. We used consumption-based environmental boundaries for the Swedish food system following the targets set in the scenario narratives report<sup>28</sup> and scaled for an equal per capita sharing of the global EAT-Lancet planetary boundaries, and their sensitivity interval, for the medium population growth scenario of world population by 2045<sup>1,90</sup>—see SM Table 7. Boundaries and Benchmarking for the boundaries and calculations. For the biodiversity boundary, we also scaled the boundary to the number of taxa included in the source data of Chaudhary and Brooks<sup>91</sup>. We then calculated the difference between the scenario diet totals and the boundaries (Table 2).

**Diet quality and health assessments**

**Diet quality.** Here, we use the targets for Swedish food consumption identified by Jonell<sup>92</sup>. They outline diet quality metrics such as food intake level (e.g., adherence to food-based dietary guidelines, NNR, EAT-Lancet), diet quality scores, and diet diversity. Nutrient adequacy was assessed through balanced energy intake as well as intake levels of individual nutrients in relation to recommended values and nutrient quality scores. Dietary health effects such as deaths and DALYs caused by nutritional deficiencies, overweight and obesity prevalence, and metrics focusing on undernutrition were beyond the scope of this study<sup>92</sup>.

To ensure meeting health and diet quality targets (e.g., adherence to food-based dietary guidelines), we first incorporated food group guidance from the NNR and EAT-Lancet diets into the scenario development—see Methods Strategy for scenario diet development—and iteratively assessed by comparison with recommended food group intake levels. We compare the current diet and each scenario diet with recommended intake levels by food group from the NNR<sup>29</sup> and the EAT Diet<sup>1</sup> intakes (SM Table 11. Group Intake).

Diet quality was measured through a comparison of the NRD score<sup>93</sup>. NRD or Food scores are the most common metric used in analyses of foods, nutrient density, and in subsequent nutritional Life Cycle Assessment, when environmental impacts of foods/diets are compared by their relative nutrient contribution<sup>93</sup>. The NRD score (Diet specifically here, as we assess whole diets) assesses the nutritional content of diets in relation to the recommended dietary allowances (RDAs). In this study, the NRD<sub>25,4</sub> is composed of 25 qualifying Nutrient Rich (NR) nutrients and 4 nutrients to limit (LIM)<sup>93</sup>. The NRD<sub>25,4</sub> was calculated by modifying Green et al.’s<sup>93</sup> formulas for NR<sub>diet</sub> and LIM<sub>diet</sub>; follows First, a total of 25 positive nutrients were included in the NR<sub>diet</sub> as the data availability allowed for comparison with given recommendations from the NNR, given in Eq. (1):

$$NR_{diet} = \frac{1}{n} \times \sum_{i=1}^n \left( \frac{\frac{i_j}{calories_j} \times kcal}{RDA_i \text{ or } AI_i} \right) \tag{1}$$

Where *n* = the total number of nutrients with positive health association, *i* = value of individual nutrients with positive health association—normalized by comparison with the total energy in each diet (calories)<sub>*j*</sub>, *j* = scenario diet, kcal = total energy intake per day (kcal), RDA = Recommended Daily Allowance, and AI = Adequate Intake. Capping was used to prevent the disproportionate impact of overconsumption of any one positive nutrient on the NR<sub>diet</sub> total; so, if NR<sub>diet</sub> was >1, the value was capped at 1. NR<sub>diet</sub> was calculated over 25 positive nutrients in the meals (see SM Table 12.NNR\_RDAs\_db for the list of daily recommended values of each nutrient).

Secondly, 4 nutrients to limit were included in the LIM<sub>diet</sub> as the data availability allowed for comparison with given recommendations from the NNR, given in Eq. (2):

$$LIM_{diet} = \frac{1}{n} \times \sum_{i=1}^n \left( \frac{\frac{i_j}{calories_j} \times kcal}{MRV_i} - 1 \right) \tag{2}$$

Where *n* = the total number of nutrients with negative health association, *i* = nutrients with negative health association, *j* = scenario diet, MRV =

Maximal Reference Values. This was calculated over 4 nutrients to limit in the meals—sodium, and total polyunsaturated, monounsaturated, and saturated fatty acids, selected as they have set upper limit of recommendations in the NNR.

Lastly, the difference of  $NR_{diet}$  and  $LIM_{diet}$  for each scenario diet was calculated, given in Eq. (3):

$$NRD_{25.4,diet} = NR_{diet} - LIM_{diet} \quad (3)$$

Several food-based dietary guidelines include recommendations for dietary diversity, due to both health and environmental reasons<sup>94</sup>. The NNR encourage consumption of a variety of different types of legumes, fruits, vegetables, and fibrous foods, among others<sup>39</sup>. To assess the relative dietary diversity of the scenario diets we used the similarity-sensitive diversity metric Rao's Quadratic Entropy (HR)<sup>36</sup>. Originally, HR is a measure of biodiversity and accounts for the following key aspects of biodiversity: abundance, richness, and similarity of functional role<sup>95</sup>. Here, we assessed only *relative* dietary diversity across the diets, not absolute dietary diversity, since maximizing HR would theoretically be equal richness across all dietary items, with high intakes of all foods, and such intake would not necessarily equate to a healthy dietary composition. In the case of dietary diversity, HR is a measure of functional similarity when two food items are selected at random, here taking into consideration the (dis)similarity of nutritional content of all of the foods in the diets, their abundance and richness following Eq. (4):

$$HR(p) = \sum_{ij=1}^S d_{ij} p_i p_j \quad (4)$$

Where  $S$  is the total number of food items,  $p_i$  and  $p_j$  are the relative abundances of food items  $i$  and  $j$ , respectively, and  $d_{ij}$  the dissimilarity between foods  $i$  and  $j$  measured by differences in nutritional composition—calculated from the 57 nutrients included in the nutrient content data per food item—via the Euclidean distance measure<sup>95</sup>.

**Nutrient adequacy.** Intake of micro- and macronutrients was assessed in relation to their respective recommendations in the NNR (2023)<sup>29</sup>. We assessed the percent of intake for each of the 25 positive (NR) and 4 nutrients to limit (LIM) as in the  $NRD_{25.4}$  against their recommendation in the NNR for each of the current and scenario diets separately—see the full list of daily recommended values of each nutrient in SM Table 12.NNR\_RDAs\_db.

Protein adequacy does not only depend on sufficient intake of total protein, but also on the composition of amino acids and their digestibility in the human digestive system. To assess these protein quality factors, we used the method recommended by the FAO (2013)<sup>96</sup>, namely calculating the DIAAS. Briefly, DIAAS measures a food's content of the most limiting indispensable amino acid, adjusted for digestibility in the small intestine, relative to nutritional needs (see FAO, 2013 for details<sup>96</sup>). A DIAAS score above 1 indicates sufficient supply of all indispensable amino acids for a person consuming the minimum safe intake of total protein as recommended by WHO<sup>97</sup>. Conversely, a DIAAS score below 1 indicates a risk of insufficient supply of at least one indispensable amino acid, at the minimum safe protein intake. Note that a DIAAS score below 1 (i.e., low protein quality) can be compensated by consuming more total protein than the minimum safe intake, which for adults is estimated at 0.83 g protein per kg body weight per day (WHO)<sup>97</sup>, or about 58 g protein per capita per day for a 70 kg adult.

To calculate DIAAS for the diets, we first collated data on the content of digestible indispensable amino acids (DIAA) from the sources referenced by Adhikari et al.<sup>98</sup>. We calculated the average DIAA content per unit total protein (expressed as grams of digestible amino acid per kg protein) for each of the food categories listed by Adhikari et al.<sup>98</sup>: beef, cereals, dairy products, eggs, legumes, nuts, and pork. Data on DIAA content of eggs was complemented using the results reported by Woyengo et al.<sup>99</sup>. We then

calculated the total DIAA intake by multiplying the protein intake from each component of the diets (wheat, peas, beans, milk, cheese, etc.) by the DIAA content of the corresponding food category. Due to a lack of DIAA content data for fish, poultry meat, and game meat, we assumed the average DIAA content of beef and pork. For protein concentrates, protein isolates, and novel foods, we used the DIAA content of the most similar corresponding whole food. The whole-diet DIAA intake was then normalized by the amino acid pattern for adults<sup>96</sup>, and DIAAS was calculated as the lowest of the individual amino acids (see DIAAS by food and diet in SM Table 16.Protein Quality).

## Waste reduction

As an additional “what-if” analysis, we examined how the outcomes of the scenario diets would differ if, across the entire food system, waste and loss were reduced by 50% from current levels. In addition to the main analysis of dietary changes, which differ in each scenario, we adjusted each food item in each scenario diet to have 50% less waste and loss from each of the production, retail, and consumer food life cycle stages using the SAFAD data, as outlined above. These methods follow previous food systems models for respecting planetary boundaries with a halving of food waste<sup>10</sup> as well as the United Nations Sustainable Development Goal (SDG) 12.5 to “substantially reduce waste generation”<sup>100</sup>. The import share proportions and all food amounts in this sensitivity analysis of waste reduction remained the same as in the main analysis. See Supplementary Discussion for more details on waste reduction in the scenarios.

## Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

## Data availability

All nutritional (Livsmedelsverket Sweden<sup>87</sup>), import (Schwarzmueller & Kasnter (2022), SBA (2023)<sup>82,85</sup>), and environmental impact (SAFAD database<sup>33</sup>; [www.safad.se](http://www.safad.se)) data in this study is sourced from previously published or openly available data. Additional supplementary materials are available in the following repository: <https://github.com/cazamazac/foodfutures-scenariodiets>. Code for the analysis and visuals is available upon request from the corresponding author.

## Code availability

Code for the analysis and visuals done in R v.4 is available upon request from the corresponding author.

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## Author contributions

R.M. led the analysis, visualization, and writing. R.M., H.K.P. and E.R. led planning and data collection. R.M., H.K.P., E.R., R.E. and U.M.P. worked on data collection and data validation. H.K.P., U.M.P., H.R.C., G.P., R.E., J.B., J.K., L.J.G. and E.R. assisted in creation and validation of scenarios. All authors have approved the final manuscript.

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## Competing interests

The authors declare no competing interests.

## Additional information

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