

Limited net-export capacity undermines the Netherlands' 'feeding the world' narrative

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The Dutch agricultural sector's orientation towards exports attracts divergent views. Whereas some stakeholders advocate maintaining exports to help 'feed the world', others question the validity of this rationale and its environmental consequences. Here we assess the Netherlands' net-export potential using an agroecological food system model. We find that producing the food groups currently consumed domestically would require all available land in the country. Even with a shift towards more plant-based diets, the potential to export food remains limited if land is also required for strengthening natural ecosystems and fostering the biobased economy. These findings challenge the economic 'feeding the world' narrative and underscore the need for an ecological perspective. Our approach can be applied to other regions, helping to redefine their role in the global food supply.

The urgency to transform the way we produce, process, trade and consume food is becoming increasingly clear^{1,2}. Changing the structures, incentives and rules that currently drive unsustainable outcomes, however, is not easy, as food systems are complex, diverse and self-organizing entities in which stakeholders have different interests, views and perspectives. Realizing transformation, therefore, depends on the willingness and capacity of stakeholders to accommodate different views and interests and work towards a collective understanding of what needs to change in the future^{3,4}.

Recently, Wojtynia et al. (2019) found that stakeholders within the Dutch food system, characterized by highly intensive agriculture and a dense human population, are remarkably aligned in acknowledging its environmental and social challenges, such as biodiversity loss, climate change, farmer's livelihoods, animal welfare, human health and food waste⁵. This study also demonstrated that moving towards a more environmentally sound and socially just food system in the Netherlands is hampered by divergent views on the economic characteristics of the future food system, especially its orientation towards exports.

One group of stakeholders emphasizes the importance of food exports for the Netherlands and the globe; at present, the Netherlands is indeed one of the world's top trading countries and the second-largest exporter of agricultural goods (primary, unprocessed goods and secondary, processed goods). In 2023, total agricultural

exports were valued at 124 billion euros in the Netherlands and 179 billion US dollars in the USA⁶. Only about two-thirds of these exports, however, are of Dutch origin; the remaining third consists of imported products that are processed or traded. This first group of stakeholders argues that if the Netherlands does not produce these foods, they will be produced elsewhere with a higher environmental impact and/or a lower standard of animal-welfare⁷. In light of the pressing environmental challenges, these stakeholders advocate for maintaining food exports while reducing their national impacts with efficiency measures. Such measures are aimed at reducing the environmental footprint of food products by increasing yields per unit of resources used (for example, land) or emissions produced (for example, greenhouse gas emissions)⁸. Examples include precision fertilization and feeding, energy-neutral greenhouses, breeding for lifetime productivity of farm animals, utilization of technologies that reduce food losses and the use of low-emissions manure storage or spreading techniques⁹. This narrative is also observed in other food-trading countries, such as Ireland, and is further referred to as the 'feeding the world' narrative^{10,11}.

A second group of stakeholders, however, questions the position of the Netherlands as a food-exporting country, mainly based on environmental arguments. The first argument is that current exports, of especially animal-source food (ASF), largely depend on resources from abroad, especially feed. Literature indeed shows

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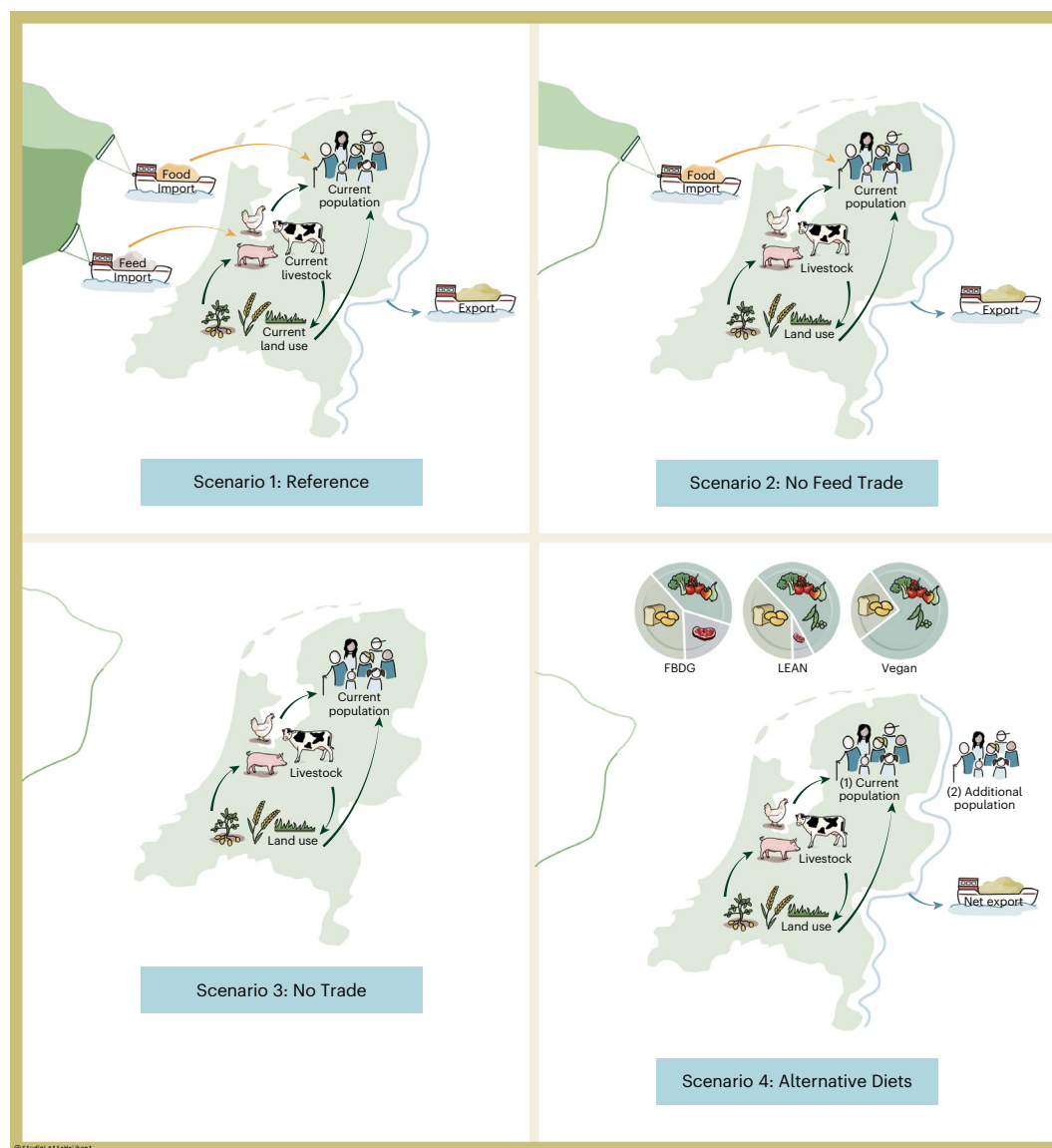


Fig. 1 | Scenario configurations explored. Model objectives: scenario 1 (Reference), reproduce the current state; scenario 2 (No Feed Trade), maximize animal-source food production from domestic land; scenario 3 (No Trade), reproduce the current diet from own agricultural land; scenario 4 (Alternative

Diets), (1) minimize land use or (2) maximize the number of people fed for three alternative diets. FBDG, a diet based on the Dutch Food-based dietary guidelines; LEAN, a diet that is land-use efficient and adequate in nutrients. Credit: Studio Lotte Heijkant.

that land use embodied in imported feed is about twice as large as domestic land use for feed production¹². The second argument is that especially the import of feed has led to the Netherlands having the highest livestock density in Europe¹³. This high livestock density leads to environmental issues in the Netherlands, such as acidification and eutrophication of local ecosystems. At the same time, the cycles of organic matter, nitrogen and other nutrients are disrupted in feed-producing regions such as Brazil and Ukraine, resulting in the demand for more artificial fertilizers in these countries^{12,14,15}. A third argument is that global food trade creates longer supply chains with more processing and handling steps, thereby raising the risk of increased food losses and waste, which negatively impacts food supply^{16,17}. A fourth, more recent, argument is the occurrence of feed-food competition in high-producing livestock systems. In many livestock-exporting countries, such as the Netherlands or USA, livestock are fed biomass that humans could also consume or that is grown on arable land that could have been used for food crop production directly^{18–20}. Hence many livestock systems in these countries, especially pig and poultry systems, are net consumers instead of net

producers of human-edible protein, and as such do not contribute to global protein supply^{21,22}.

Without sufficient alignment on the true value of the export orientation of the Dutch agricultural sector, including market, environmental and social impacts, transitioning to a more sustainable food future remains challenging, as export volumes shape the current food system⁵. Whereas recent studies explored the ecological and trade consequences of reducing feed imports^{23,24}, insights into the net food export potential of Netherlands are lacking. This net food export potential can be assessed by evaluating the number of people a country can feed, while accounting for the internalization of feed and food imports, and offers valuable insight into a country's contribution to global food supply.

Here we examine how many people could be fed in the Netherlands under different food system configurations, varying in feed and food imports and dietary choices. We applied an agroecological FOOD Systems Optimization Model (FOODSOM)^{23,25}. We assessed domestic and external land use associated with Dutch food production and consumption, and energy and protein export-to-import ratios, for a

Table 1 | Consumption constraints of diet scenarios

Food group	FBDG		LEAN		Vegan	
	Min	Max	Min	Max	Min	Max
Fruit	205	215	200	345	200	345
Vegetable	244	256	200	344	200	344
Grain	90	425	90	401	90	401
Legume	19	19	9	40	9	40
Nut	15	15	15	25	15	25
Oil	0	54	0	37	0	37
Tuber	154	162	0	240	0	240
Sugar	0	0	0	31	0	31
Fish	14	14	0	100	0	0
Other	0	0	0	50	0	50
Drink	0	0	0	500	0	500
Meat	70	74	0	72	0	0
Dairy	405	425	0	500	0	0
Alcohol	0	0	0	138	0	138
Spice	0	0	0	2	0	2

Maximum and minimum consumption constraints of the diet scenarios in grams per capita per day. Current diet is a result of the Reference scenario (Supplementary Fig. 1).

reference and three alternative scenarios (Fig. 1). The first scenario represents the current state of the food system in the Netherlands and provides a reference (Fig. 1, scenario 1). To reproduce the current state, we fixed current land use, livestock numbers, imports and exports of food and feed to 2020 levels and subsequently minimized the deviation between the current diet, based on food consumption surveys²⁶ and the modelled diet. We designed scenarios 2 to 4 to gradually explore the impact of avoiding feed and/or food imports on the potential to feed the Dutch population and to export surplus food, or in other words, to stepwise determine the net-export potential of the Dutch food system. The fourth scenario involved potential dietary changes, resulting in three different variants. The No Feed Trade scenario (Fig. 1, scenario 2) shows how avoiding feed imports, and therefore internalizing land use for feed production, will influence the export of animal-source food. The trade of plant-source food (PSF; excluding animal feed) and the human diet remained identical to the Reference scenario. The No Trade scenario (Fig. 1, scenario 3) examines whether the Netherlands can sustain its current diet from domestic land and whether any agricultural land remains available for other purposes, including exporting food. Scenario 4 also explores this No Trade scenario for three alternative diets (Fig. 1, scenario 4, and Table 1). The first alternative diet was based on the Dutch food-based dietary guidelines (FBDG), also known as the Wheel of Five²⁷. The second diet was designed to minimize land use while meeting the nutrient requirements of people fed (27 nutrients) and including upper and lower limits at food group level (more detail in Methods section), and is further referred to as the LEAN diet (Land-use Efficient and Adequate in Nutrients). Previous research has shown that such a LEAN diet is largely plant based and includes a moderate amount of animal-source food, derived from animals that are mainly fed with leftovers from arable land and grass resources²³. The third alternative diet was a vegan diet and included nutrient requirements derived from plant-source food only (25 nutrients), as EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid) and vitamin B₁₂ cannot be met without consuming animal-source food or supplementation. The vegan diet includes the same food group constraints as the LEAN diet. More details are given in Methods section. We assessed the land use required to feed the Dutch population under each alternative diet (objective 1: minimize land use). These results demonstrate how much agricultural land is freed up for food export or other purposes, such as

nature conservation or the production of clothing and biomaterials. To demonstrate the net-export potential of the Netherlands by changing human diets, we maximized the number of people we could feed from Dutch agricultural land under each alternative diet (objective 2: maximize the number of people fed).

Results

The Netherlands as a net importer of land and biomass

The reference results show that the current Dutch food system uses about 1.6 million of agricultural land in the Netherlands (Fig. 2a) and about 4.7 million ha abroad (Fig. 2b). This land outside the Netherlands is used to produce feed and food imported into the Netherlands. To enable its current agricultural exports, the Netherlands uses external agricultural land equivalent to three times its domestic area. The Dutch food system also imports more energy and protein than it exports (Fig. 3a), and, therefore, is a net importer of energy and protein instead of a net exporter. The reason why the Netherlands imports more energy and protein than it exports is because the majority of the external land use is associated with the production of feed (Fig. 2b), either directly or indirectly via the import of oil crops. These imported oil crops (that is, soybeans and oil seeds) are processed in the Netherlands, resulting in oil, being an energy-rich product and meal, being a protein-rich product. Subsequently, the oils are exported again, whereas the meals are utilized as livestock feed domestically. No matter how efficiently animal-source food is produced, using arable land to feed livestock is less efficient than using it directly for plant-source food production²⁸ and reduces protein and energy conversion ratios.

Whereas animal proteins are typically considered nutritionally superior to plant proteins, correcting for the differences in protein quality between plant and animal-source food will not affect the conclusion that the Netherlands is a net importer of protein. This is because a variety of different plant-source foods can supply all essential amino acids²⁹. On the basis of this, we can conclude that the Netherlands is currently not contributing to the 'feeding the world' narrative via net food exports.

The No Feed Trade scenario gives first insights into the potential of the Netherlands to export animal-source food by recoupling of livestock and feed production. Here the amount of feed produced domestically creates a natural ceiling to livestock numbers and hence determines the number of pigs, cattle and poultry that can be kept. This scenario, therefore, gives insight into the potential for exporting domestically produced animal-source food, while other constraints remained unchanged (that is, food import; current diet and population; Fig. 1, scenario 2). Results show that recoupling livestock and feed production in the No Feed Trade scenario decreased livestock numbers (beef cattle: 100%, sheep: 100%, dairy cattle: 19%, dairy goats: 100%, pigs: 56%, broiler chickens: 0%, laying hens: 0%; Supplementary Fig. 3) and animal-source food exports (44% in terms of protein), while still meeting the current human diet in the Netherlands. On the other hand, avoiding feed trade reduced our dependency on external land use by 3.3 million ha (Fig. 2b) and improved export-to-import ratios of energy (calories) from 0.33 to 0.7 and protein from 0.27 to 0.95. As both ratios are still below one, the country continues to import more energy and protein than it exports.

The No Trade scenario shows that we can produce our current diet by excluding items that cannot be produced in the Netherlands (for example, chocolate in the Other food group) or replacing them with locally available, functionally similar products (for example, substituting citrus fruit by other fruits from the Fruit food group) (Fig. 4). However, producing the current diet domestically requires all agricultural land (Fig. 5a), leaving no space to produce biomass for clothing, biomaterials or bioenergy or for food exports. To contribute to feeding the world or building a circular bioeconomy, therefore, the country may need to shift from the current diet to more plant-based ones.

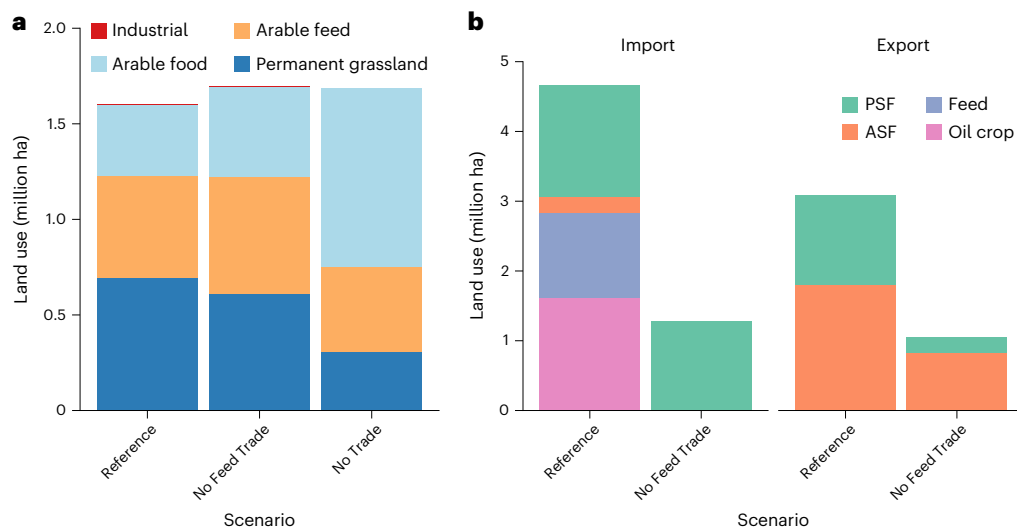


Fig. 2 | Agricultural land in use for scenarios with the current diet. a, Domestic land use (in million hectares, 1.69 million ha available). **b**, Import and export of land use of food and feed (in million hectares). For each traded product,

we first calculated the net trade flow and then multiplied these net values by product-specific land-use intensities. Industrial land refers to greenhouses and mushroom sheds.

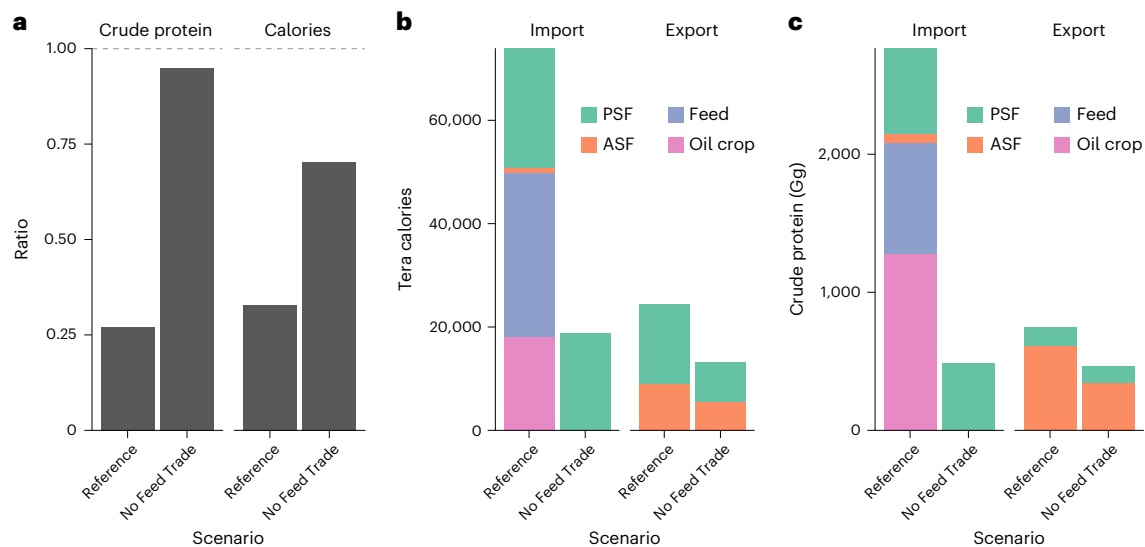


Fig. 3 | Nutrient export-to-import ratios and quantities in Reference and No Feed Trade scenarios. a, Nutrient export-to-import ratios. For each traded product, we first calculated the net trade flow. An export-to-import ratio >1 implies the country is a net exporter. **b**, Calories in imported and exported feed and food. **c**, Crude protein in imported and exported feed.

Effects of dietary shifts on domestic land use

To explore the potential of the Netherlands as a net food-exporting country, we assessed minimum land use of three alternative diets from domestic resources: FBDG, LEAN and vegan (Fig. 1, scenario 4: objective 1). Consistent with previous studies^{1,25,30}, we found that shifting from the current to any of these alternative diets substantially decreased land use, saving land for food exports, biomaterial production or nature. We also show that land use was lowest (0.64 million ha) and the number of people fed per ha highest, in the LEAN diet scenario (Fig. 5). This low land use has three causes. First, the LEAN diet is largely plant based, and the role of animal-source food is limited to dairy products and associated meat from culled cows and veal calves, and fish. Daily consumption of 194 grams of dairy products and 2.5 grams of associated meat per person provides 35% of the daily calcium requirements, and 32% of the daily vitamin B₁₂, whereas the consumption of fish and a small amount of eggs (3 grams) fulfils the remainder of vitamin B₁₂ and all

EPA/DHA requirements. Second, these dairy cows and veal calves were fed mainly with co-products from food processing, food losses and grass resources. This implies that the production of their feed was largely sourced from land unsuitable for the production of human food¹⁹ and, in part, utilized by-products, thereby reducing the need for additional land. Third, land use in the Vegan diet scenario was higher because the availability of certain nutrients, such as calcium, is lower in plant than in animal-source food. Moreover, the Vegan diet scenario cannot benefit from livestock fed on by-products that require no additional land but still provide valuable nutrients, such as calcium and vitamin B₁₂. It should be noted that EPA, DHA and vitamin B₁₂ were still met in the LEAN diet scenario. Supplementing these nutrients, which require land for production, in the Vegan diet scenario would further increase the difference in land use between the LEAN and Vegan diet scenarios (Fig. 5).

In short, more plant-based diets free substantial agricultural land for potential export. We therefore assessed how many people

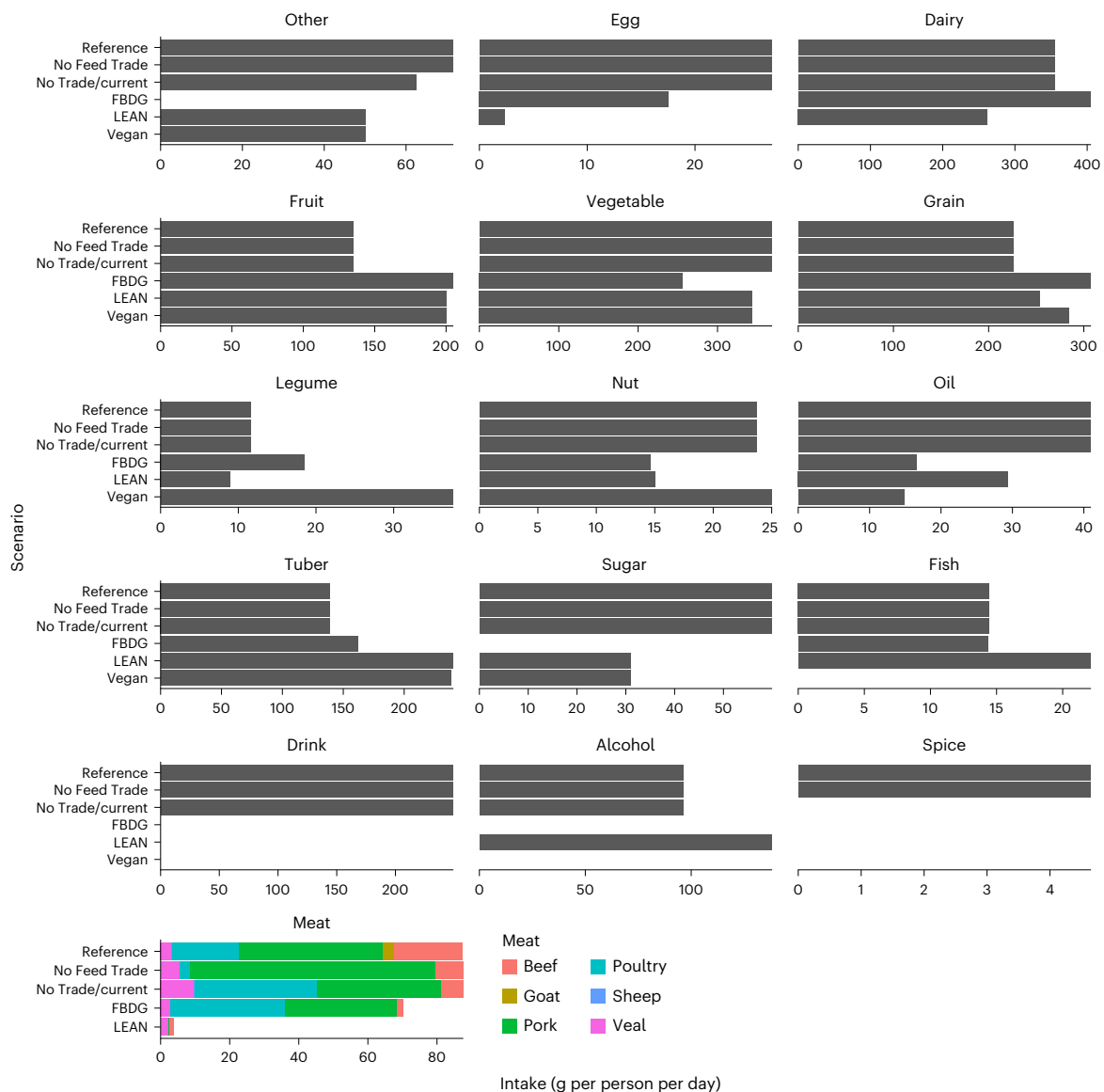


Fig. 4 | Human dietary intake across scenarios. Human dietary intake of food groups and individual food items under the different scenarios, expressed as grams per person per day.

the Netherlands could feed if all agricultural land were allocated to food production under different dietary scenarios (Fig. 1, scenario 4: objective 2). Results are presented below.

Effects of dietary shifts on the potential to export food

The Netherlands can feed its population of 17.4 million people (2021) with the current diet, without relying on food or feed imports. Shifting towards an FBDG or vegan diet would allow the country to nourish an additional 9.9 to 13.9 million people, whereas adopting a LEAN diet could support up to 18.1 million more people (Fig. 6). The nourishing potential of the FBDG diet was not constrained by land availability but rather by the limited availability of marine fish required to meet the recommended intake of 14 grams per person per day. Given a projected population of approximately 20 million people by 2050³¹, these findings suggest that the Netherlands has some room for food exports. However, to become a net food-exporting country and contribute to feeding the world, a transition to a more plant-based diet is needed, both in the Netherlands and in its main export countries. To enhance net food supply, future food exports have to be largely plant based.

Discussion

Our analysis reveals that the Netherlands has just enough agricultural land to produce the current diet for its 17.4 million people in 2020. Only with a shift towards more plant-based diets would agricultural land become available, equivalent to feeding an additional 9.9 to 18.1 million people. Agricultural land is not just needed for food production; it is also required for producing seed material, making clothing or biobased materials. Nijdam et al.³² found that we need about 0.5 ha of land per capita for the Dutch consumption of mainly wood, paper, clothes and bio-energy³². This equates to 8.7 million ha for a population of 17.4 million people—far exceeding the available agricultural land, even with a transition to a LEAN diet. At the same time, agricultural land is under pressure from housing, infrastructure, nature and recreational use. The Kunming–Montreal agreement, for example, mandates the restoration of at least 30% of our land and water ecosystems by 2030 to safeguard biodiversity³³. Currently, nature reserves account for part of the 2.4 million ha of non-agricultural land in the country, but strengthening these reserves in line with the agreement may require converting agricultural land. Finally, the Dutch government’s ambition for a fully circular economy by 2050 also requires a portion of

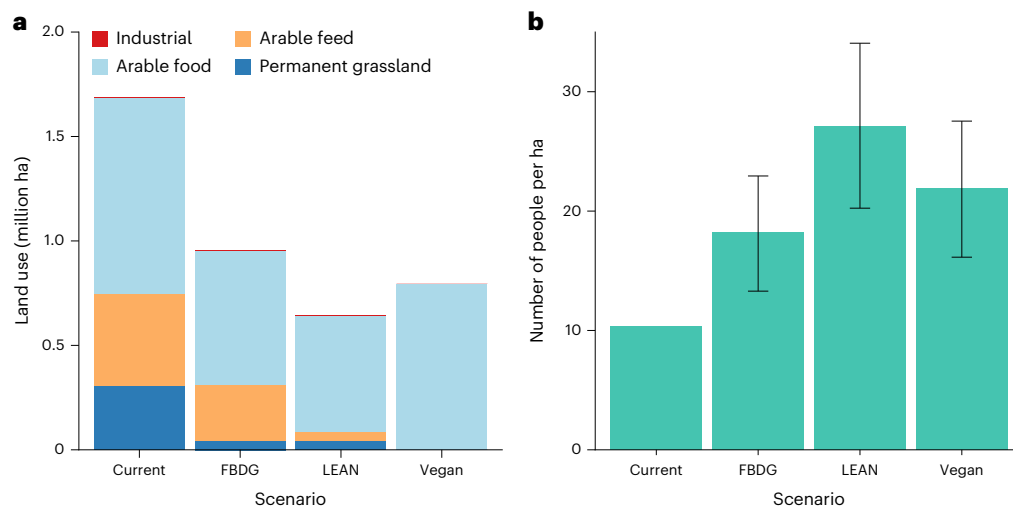


Fig. 5 | Agricultural land-use indicators for scenarios with alternative diets aimed at minimizing land use. a, Domestic land use (in million hectares) based on default crop yields. **b**, Number of people fed per hectare; bars are based on

default crop yields, and whiskers are based on optimistic and pessimistic crop yields (Methods). Industrial land refers to greenhouses and mushroom sheds. Current, current diet in the No Trade scenario.

the agricultural land for biomass production to support, for example, sustainable housing (Ministry of Agriculture Nature and Food Quality, 2018). These factors highlight that the Netherlands is, and will likely remain, a net importer instead of a net exporter of biomass. This is not a completely unexpected outcome, given the high population density of the Netherlands. With a density of 518 persons per km², it is the second most populated member of the European Union, after Malta³⁴.

Our analysis challenges the ‘feeding the world’ narrative from a biophysical perspective. We show that, when accounting for other land demands such as those for a circular economy and nature restoration, the Netherlands—given its high population density—has little to no potential to be a net exporter of food. Nonetheless, the Netherlands does contribute to feeding the world in two alternative ways. First, the Netherlands remains a major exporter of seeds and seed potatoes. Second, it plays an active role in developing and disseminating knowledge and technologies for sustainable production and consumption worldwide. Both contributions could be further strengthened in the future. Additionally, enabling net food exports while strengthening natural ecosystems and fostering a circular economy requires a shift towards predominantly plant-based diets. Our findings substantiate the need to move away from the ‘feeding the world’ narrative, which frames food as a tradable economic product and instead build a more holistic alternative³⁵. This alternative narrative envisions a future where socio-economic systems operate within a safe-and-just operating space, ensuring the well-being of the planet, humans and animals³⁶. However, such dietary and export shifts would have far-reaching consequences for the entire Dutch food system, particularly given that meat consumption in the Netherlands has shown little change over the past decade³⁷.

This study is relevant to other food-exporting regions and countries. Our approach can be applied elsewhere to assess their biophysical potential for food exports. Such net-export potential is highly context specific and influenced by variations in agroecological conditions, and human populations and livestock densities. For example, Ireland, with fewer people and animals, and more land unsuitable for food cropping, may have a biophysical advantage for exporting animal-source food compared to the Netherlands³⁸. Moreover, this study is explorative in nature³⁹, aiming not to make predictions but to contextualize and provide strategic guidance on potential pathways for a sustainable Dutch food system. We focussed on the carrying capacity of the Netherlands for net export; we did not assess the economic comparative advantage of the country nor the impacts on social welfare,

as these would require a different or additional modelling approach. The optimistic outcomes of optimization models such as FOODSOM are difficult to achieve in practice but show the theoretical potential of food system changes. Additionally, while our data—where available—are based on 2020, key factors such as production, imports and exports do fluctuate annually depending on regional climatic conditions and international developments⁴⁰.

Within this context, we explored the potential to feed additional people under a No Trade scenario using three alternative diets. Nonetheless, we acknowledge that food trade can have ecological and social benefits, while enhancing resilience^{41,42}. Importing products into the Netherlands, such as citrus fruit, coffee or tea—items that can be produced much more efficiently elsewhere—can contribute to sustainable utilization of global resources⁴³. If traded fairly, such exchanges can also support agricultural economies in the countries of origin. Additionally, food imports free up domestic land for export-oriented food production. To prevent nutrient accumulation or depletion and the associated environmental problems, however, nutrient imports and exports must remain largely in balance²⁵. Recycling human excreta to reduce dependence on finite resources such as phosphate rock may also help maintain nutrient balances in this context. Currently, however, large quantities of animal feed are imported to sustain high livestock numbers and support the export of animal products²³. This practice has resulted in a substantial surplus of animal manure, leading to groundwater pollution and the degradation of natural ecosystems⁴⁴. Adding human excreta to this system could further exacerbate existing nutrient surpluses. Combined with our land-use findings, therefore, we suggest that if the Netherlands allocates part of its land-to-food exports, these exports should be primarily plant-based processed food products, with any co-products generated from processing raw materials into food remaining in the Netherlands. Exports of animal products should originate from animals that are fed with regionally produced biomass, preferably biomass that is inedible for humans and not produced on land suitable for food crop cultivation. This strategy supports regional cycling of nutrients from both animal and human excreta and optimizes land use. Whereas the Netherlands is not likely to be a net exporter of much food, it can still contribute seeds, technology and knowledge to support more sustainable global food systems.

Our findings, combined with prevailing consensus among Dutch stakeholders on environmental and social themes⁵, provide a basis for co-creating a new, holistic narrative. As recently recognized by the

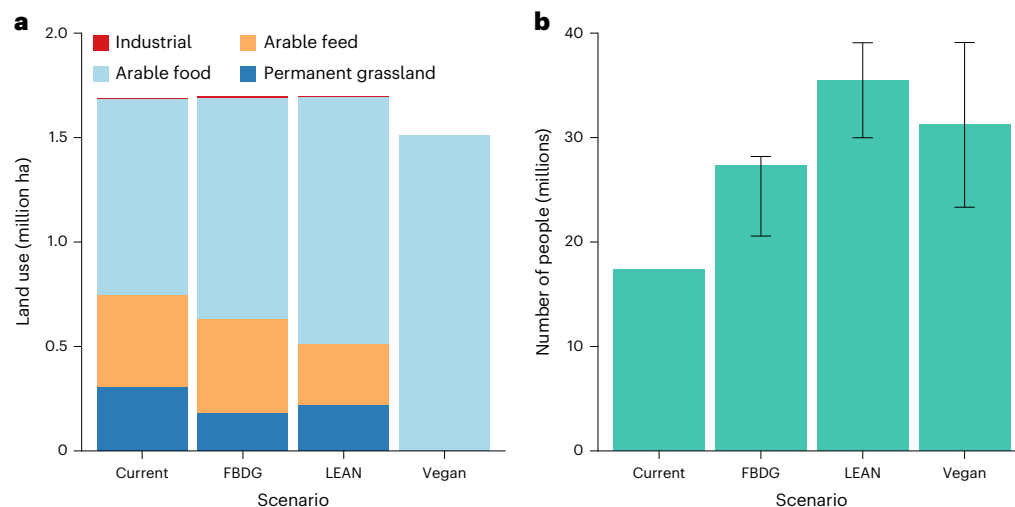


Fig. 6 | Agricultural land-use parameters for scenarios with alternative diets aimed at maximizing the number of people fed. a, Domestic land use (in million hectares) based on default crop yields. **b,** Number of people fed (million);

bars are based on default crop yields, and whiskers are based on optimistic and pessimistic crop yields (Methods). Industrial land refers to greenhouses and mushroom sheds.

European Union, joint efforts in shaping this narrative are crucial for advancing a more just and sustainable food future⁴⁵. Beyond building a new common narrative, achieving a sustainable food future requires concerted action and unprecedented levels of transformative change⁴⁶. While local conditions will vary, our approach has value in other regions with high human and animal densities, helping to redefine their role in creating a sustainable food future.

Methods

We deployed the agroecological FOOD Systems Optimization Model (FOODSOM) to grasp the complex interactions between food production, consumption, trade, diet and land use for a set of food system scenarios within the Netherlands^{23,25}. The model and data for the Dutch case are available in a public GitLab repository, which includes extensive model documentation. In this analysis we updated the reference year to 2020 and updated the cropping systems in line with ref. 47. Results of the model evaluation are available in Supplementary Figs. 1 and 2. We consider FOODSOM the most appropriate agroecological food systems model for this study as it incorporates context-specific local production data and can be parameterized for different geographical regions and scales^{23,25}. In this analysis, the Netherlands is modelled as a single spatial unit, but FOODSOM can also be run with 12 provincial or 355 municipal spatial units⁴⁷. FOODSOM input data are pre-processed in R, the linear model is written in GAMS and solved using the CPLEX solver, and the results are post-processed in R and visualized with Shiny.

FOODSOM consists of several components, that is, the cropping system, the livestock system, fisheries, processing, trade and the human diet. In this analysis we updated the reference year to 2020, and results of the model evaluation are available in Supplementary Information.

Cropping systems

On 1.6 million ha of arable land and grassland, and on 5,742 ha of greenhouses and mushroom sheds, 68 crops can be grown to produce food for humans or feed for animals. In this study, we incorporated crop yield and balanced fertilization approach improvements developed by Tamsma et al.⁴⁷. Crop yields were calculated for different combinations of soil texture, groundwater level and groundwater salinity (44 in total). Groundwater salinity affected only irrigated crops, as saline irrigation water reduces yield. The yield for each soil texture–groundwater level–salinity combination was calculated by multiplying the attainable yields (derived from well-managed experiments) by the

maximum loss fraction associated with these factors⁴⁷. Additionally, the resulting yields were multiplied by 0.8 to account for potential losses from weeds, pests and current management inefficiencies⁴⁷. To assess the sensitivity of this management factor, two alternative variants were tested: an optimistic case with a multiplier of 1.0 and a pessimistic case with a multiplier of 0.6 (Figs. 5b and 6b).

Crops can be fertilized with artificial fertilizer, animal manure and compost, to meet their nitrogen (N) and phosphorus requirements. Additional N sources include atmospheric deposition, net mineralization in peat soils and biological N fixation by legume crops. In the Reference scenario, N fertilization follows national legislation⁴⁸. All other scenarios apply a balanced N fertilization approach. Nitrogen requirements, defined as the sum of N offtake in crops and residues plus unavoidable losses, were calculated by dividing N offtake by the fraction of available N taken up by the crop. Uptake fractions for arable crops and grassland in each soil–groundwater–salinity zone were obtained from ref. 49. These fractions were multiplied by 1.25 to reflect the higher nitrogen uptake efficiency expected under balanced fertilization relative to current application limits^{49,50}. Phosphorus requirements are based on a balanced fertilization approach including an unavoidable loss fraction in all scenarios⁵¹. The cropping system also includes a maximum crop share per crop and botanical family to simulate crop rotations (that is, the minimum frequency sugar beets can be grown is 4 years, which results in a maximum share of 25%). In the Reference scenario crop areas were fixed to current crop areas³¹.

Livestock systems

Seven livestock systems (beef cattle, broiler chickens, dairy cattle, dairy goats, pigs, laying hens and sheep) can consume crops, food losses and co-products to satisfy their protein and energy requirements within their feed intake capacity. Beef cattle, broiler chickens, dairy cattle, pigs and laying hens include three different productivity levels. High represents current Dutch livestock production, whereas mid and low represent less-intensive systems found in Europe. Dairy goats and sheep only include high productivity. Livestock systems include parent stocks (for example, sows in a pig system) and reproductive stocks (for example, replacement calves in a dairy system). Livestock numbers are fixed to current animal numbers in the Reference scenario and cannot exceed current animal numbers. Additionally, ruminant diets must contain at least 50% grass-based feeds to ensure sufficient fibre intake and allow natural grazing behaviour.

Capture fisheries

Besides livestock products, humans can also consume fish from marine capture fisheries. Current fisheries landings are assumed (2020)³¹.

Processing

Crops, livestock and fisheries products are processed into food products, by-products and animal feed^{52,53}. By-products can be fed to livestock or composted. When raw materials (that is, unprocessed crop, livestock (products) and marine fish) and food move through the supply chain, food losses and waste occurs. Food losses are composted (with the compost returned to the soil) or fed to livestock, while food waste is composted to adhere to current legislation. The quantity of food losses and waste is estimated using food loss and waste fractions⁵⁴.

Trade

Raw materials and food can be imported or exported to contribute to the global food system (depending on the scenario). However, due to the limited geographical coverage of national models, FOODSOM does not account for the origin of imports or the destination of exports. Current import and export data in the Reference scenario were based on food balances from national statistics (Agrimatie, where available: livestock products, grains and oil seeds) or FAOSTAT (all other products)^{55,56}. The current trade of live animals was accounted for in the Reference scenario⁵⁵ but was excluded in all other scenarios. Trade of animal feed including products where the production of animal feed is the primary driver (for example, processing soybeans and rapeseed into oil and meal) was excluded from the No Feed Trade scenario. The export of animal-source food is an outcome of the No Feed Trade scenario. The land use related to the import and export of raw materials and food items (Fig. 2b) was based on current life-cycle assessment data post optimization solve^{52,57}.

Human system

In the No Feed Trade and current diet scenarios, consumption is equal (where possible) to the modelled reference diet on a food item level (dairy, vegetable, sugar, grain, tuber, egg and other) or food group level (drink, alcohol, fish, meat, oil, spice, fruit, nut and legume). Meeting current consumption at a food group level allows food items that cannot be produced in the Netherlands to be replaced with ones that can (for example, oranges can be replaced with apples).

In the diet scenarios, diets are optimized to meet nutrient requirements, which includes 27 nutrients and an upper and lower limit on consumption at a food group level to prevent over consumption of certain food groups (Table 1). The requirements for all nutrients, except calcium, was based on Dutch Health Council recommendations²⁷. We used a lower requirement for calcium based on UK nutrition council recommendations to ensure the Vegan diet scenario remained feasible without animal-source foods and calcium requirements were consistent across scenarios⁵⁸. Calcium recommendation in The Netherlands are higher than comparable countries. The upper limit of food groups in the LEAN and vegan diets that do not increase the risk of non-communicable diseases was based on the 95th percentile of current consumption in the Netherlands²⁶, whereas the upper limit of food groups that do increase the risks of non-communicable diseases was based on the EAT–Lancet diet¹. In case minimum consumption recommendations were available, we also included a lower limit on a food group (grain, legume, fruit vegetable and nuts)⁵⁹.

Reporting summary

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

Data availability

The data to run FOODSOM for this study are available at <https://git.wur.nl/aps/foodsom-public>. Source data are provided with this paper.

Code availability

The FOODSOM code associated with this study is available at <https://git.wur.nl/aps/foodsom-public>.

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Author contributions

B.v.S. and I.J.M.d.B. designed and conceptualized the study. B.v.S. further developed the agroecological model, performed the analyses and created the visualizations. B.v.S. and I.J.M.d.B. wrote the first draft, and C.E.v.M., O.v.H., S.J.O., R.H. and M.K.v.I. provided expert input on specific topics. All authors reviewed and approved the final paper.

Competing interests

The authors declare no competing interests.

Additional information

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