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DESIGNING CROP ROTATIONS TO SUPPORT SUSTAINABLE AND HEALTHY DIETS

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Abstract

Balancing the social and environmental costs of food production with the nutritional needs of future populations under climate change is one of the greatest challenges facing twenty-first century agriculture. While dietary shifts toward environmentally sustainable and healthy diets are widely recognized as a key lever, there is limited guidance on how cropping systems can be designed to reliably supply such diets. Addressing this gap, our study aimed to link crop production planning directly with dietary recommendations, specifically the universal EAT-Lancet guideline diet proposed in 2019 to enable 9 billion people to eat healthily within planetary boundaries. We developed an innovative decision-support model to optimize cropping systems for supplying specific food systems according to EAT-Lancet recommendations. The model compares vegan, ovo-lacto vegetarian, and omnivorous diets while minimizing commodity imports and exports. It evaluates the composition and rotation of crops, the integration of grazing animals, and the balance of food and feed supplies, allowing for testing of alternative dietary scenarios and agroecological practices. Results indicate that longer and more diverse crop rotations, particularly those integrating temporary pastures and forage cover crops, are more likely to meet EAT-Lancet dietary requirements. Crop–livestock integration reduces excesses and deficits across commodities while providing sufficient calories and nutrients. Essential components include rapeseed for oil and oilseed meal, legumes for pulses, and multiple cereals. By explicitly linking crop system design to dietary guidelines, our model fills a critical knowledge gap, providing a practical tool to support multiobjective, sustainable food production. It offers actionable insights for aligning agricultural planning with healthy diets, advancing the environmental, economic, and social dimensions of future food systems.

1 Introduction

A variety of food systems has evolved through history in response to local socioenvironmental conditions. However, over the past decades, people with very different culinary traditions and cultural backgrounds stemming from their different food systems have started eating increasingly similar diets (Khoury et al. 2014). This has been encouraged by the increase in global incomes and wealth in many countries, which has economically strengthened a middle class and its demand for a more Westernized diet including more animal-based products and requiring more resources to produce (Popkin 1998; Godfray 2015).

This trend has been accompanied by the evolution of production systems toward what Colonna et al. (2013) classified as the "agroindustrial" model. While the agroindustrial model has been able to increase food production dramatically over the past century, it has also revealed strong environmental limitations (Gerber et al. 2013). The agricultural sector has reached the point where land expansion and technological innovations have allowed the highest food energy production in history. However, this achievement has been accompanied by an increasing specialization at the farm and landscape levels (Lemaire et al. 2014). The uniformity of these systems, and their reliance on large input-oriented chemical fertilizers, pesticides, and preventive use of antibiotics, has systematically led to negative outcomes and vulnerabilities (Meehan et al. 2011). Consequently, agriculture has become a cause of global environmental degradation (Ramankutty et al. 2018), leading to the current transgression of several planetary boundaries, within which humankind should remain in order to continue thriving for generations to come (Rockström et al. 2009). Over 48% of the food we consume today is grown under conditions that violate at least one of these planetary boundaries (Gerten et al. 2020). This highlights the need to redesign our food production systems and consumption patterns, inherently supported by the redesign of cropping systems.

The shift of eating habits toward more environmentally friendly and healthy diets is a key lever to build a sustainable future (Gerten et al. 2020). While the acceptable total amount of animal-based food in diets is still debated (Astrup et al. 2020), there is a large consensus that Westernized diets include excess meat and too little fiber-rich plant-based foods from both the health and the environmental perspective (e.g., (Wellesley et al. 2015; Aleksandrowicz et al. 2016; Chai et al. 2019)). Diets containing high amounts of refined sugar, refined fats, oil, and meat are known to greatly increase the incidence of type II diabetes, coronary heart diseases, and other diseases that lower global life expectancies (Feskens et al. 2013; Tilman and Clark 2014; Becerra-Tomás et al. 2020). Various expert- and modeling-based studies have been published in recent years to suggest how to redesign eating patterns. Stehfest et al. (2009), aiming to achieve important improvements in land use, greenhouse gas (GHG) emission, and human health, studied the possibility of a global transition toward a diet containing less meat or even a complete switch to plant-based protein foods. Analyzing Mediterranean, vegetarian, pescatarian diets—three diets that are usually considered interesting alternatives to the global-average diet—Tilman and Clark (2014) showed that all three alternative diets could reduce environmental impacts, particularly through lower GHG emissions. Alexander et al. (2016) defined an index for the human appropriation of land for food in order to specifically assess the effect of diets on agricultural land areas. They determined that the types of food commodities are more important than the quantity of food that is consumed in the determination of agricultural land use, largely because of the high land requirement for animal products. Following their findings, 55% less agricultural land would be needed if the world was to adopt the average Indian diet, with low meat intakes.

Willett and his collaborators of the EAT-Lancet Commission (Willett et al. 2019) took all these studies into consideration when proposing a universal guideline diet that would allow 9 billion people across the globe to eat healthily while respecting the planetary boundaries. This diet mostly consists of fruits, vegetables, and nuts that are usually supplied by horticulture and perennial agriculture, as well as a large amount of products that rely on annual crop agriculture, such as whole grains, legumes, starchy roots and tubers, unsaturated oils, and sugar. Their diet was designed to include no or low quantities of animal products (dairy products, meat, eggs, and seafood). According to Willett et al. (2019), to achieve its goals of sustainability, shifts in eating patterns toward the diet they suggest must be considered in a context of overall change in consumption patterns and in citizens' behavior and culture, such as a large reduction in food losses and waste, and major improvements in food production practices. The EAT-Lancet Commission also supports the Nexus approach (Kaddoura and Khatib 2017), by emphasizing sustainable food systems that align with environmental goals, including efficient water and land use and lower greenhouse gas emissions. This approach refers to the integrated management of water, energy, and food systems (often called the WEF Nexus) to promote sustainability, resource efficiency, and resilience. Integrating Nexus principles into dietary recommendations could encourage cross-sector collaboration and holistic policy design to address climate change, biodiversity loss, and resource scarcity.

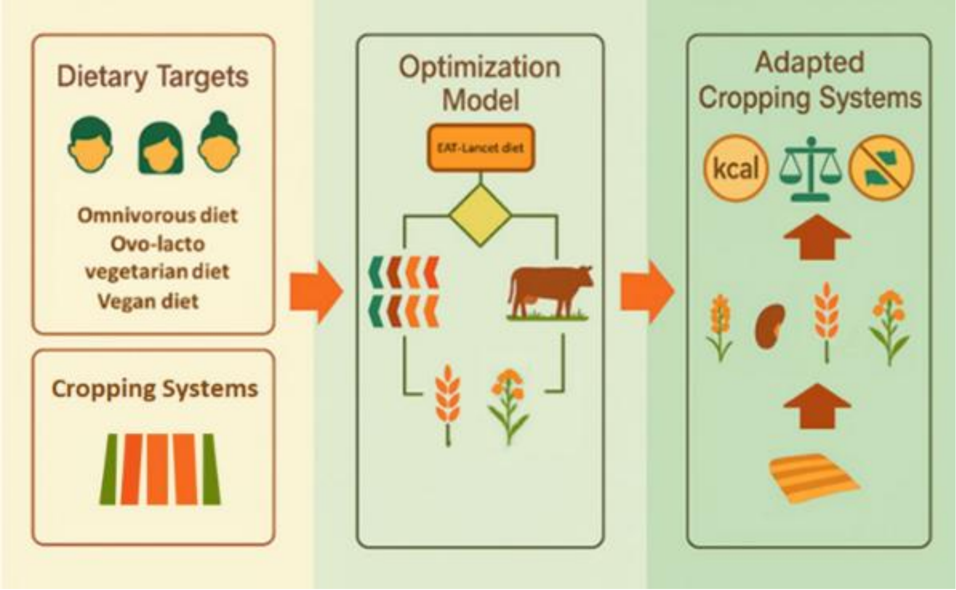
In order to provide locally such healthy and sustainable diets, it appears urgent to redesign food and agricultural systems and one of the crucial steps for this is to reconnect what sustainable crop rotation can offer to what people should ideally eat. One of the key reasons is the risks associated with supply chains in a globalized market. This has been evident in regions such as North Africa and the Middle East during the Ukraine war, where disruptions to food imports occurred (Abay et al. 2023), and in the European Union during the COVID-19 pandemic, which exposed vulnerabilities in the supply of essential goods like medical supplies (Bown 2022). These kinds of disruptions, particularly in the agricultural sector and food supply, are likely to intensify in the future due to climate change, threatening global food security (Gregory et al. 2005).

Crop redistribution studies, investigating the allocation of crop species and activities to areas in agricultural landscapes (Memmah et al. 2015), involve complex decision-making processes that must balance multiple, often conflicting objectives to reduce trade-offs (Kaim et al. 2018). Several objectives can be prioritized in these strategies, including maximizing farmer profitability (Galán-Martín et al. 2015; Capitanescu et al. 2017), promoting circular agricultural systems (Van Zanten et al. 2023), enhancing water management practices (Singh 2012; Femeena et al. 2018; Rulli et al. 2024), ensuring food security (Femeena et al. 2018; Wang et al. 2022; Van Zanten et al. 2023), and increasing agricultural productivity for both food and biofuel production (Galán-Martín et al. 2017; Femeena et al. 2018). These objectives often coexist within a framework of complex constraints, such as climate change adaptation (Klein et al. 2013), reducing environmental impacts (Capitanescu et al. 2017; Femeena et al. 2018), adherence to agricultural policies (Galán-Martín et al. 2015), and respecting crop rotation requirements (Galán-Martín et al. 2015). The integration of these factors is essential for developing effective, sustainable agricultural strategies that balance profitability with ecological stewardship. In addition, addressing the issue of micronutrient availability (particularly for iron, calcium, vitamin B12, choline, iodine, and vitamin D) is important. Even if a diet meets the recommended intake for a nutrient, poor bioavailability can lead to functional deficiencies, particularly for iron, zinc, calcium, vitamin B12, and omega-3 fatty acids (Vesanto et al. 2016).

Despite the potential benefits, crop redistribution and land optimization strategies are still underutilized, especially in more developed regions. Current research and applied models primarily focus on optimizing food supply, often without fully addressing other essential aspects of agricultural sustainability, such as promoting food autonomy (Sali et al. 2016; Kuzmanovski et al. 2019; Van Zanten et al. 2023; Dai et al. 2023). Moreover, only a limited number of studies explore the competition for land between human food production and livestock or other animal uses (Van Kernebeek et al. 2016; Van Zanten et al. 2023; Wang et al. 2024). Additionally, few models incorporate guidelines for healthy, sustainable diets into their frameworks (Van Zanten et al. 2023; Wang et al. 2024; Rulli et al. 2024), even though such guidelines could play a significant role in shaping more sustainable and nutritionally balanced agricultural landscapes. Finally, to our knowledge, no other study has simultaneously designed and implemented realistic, nutritionally aligned crop rotations in the field as part of a spatially explicit land optimization model.

In this study, we propose an innovative approach to optimize the design of cropping systems (Figure 1).

Figure 1 Schematic representation of a decision-support model connecting dietary targets (EAT-Lancet) with optimized cropping systems under different dietary scenarios (omnivorous, ovo-lacto vegetarian, and vegan). The model integrates crop–livestock interactions, multiyear crop rotation planning, and food/feed balance constraints to align agricultural outputs with nutritional needs and environmental goals.



We propose a conceptual model, adapted to the Hesbaye region of Belgium. This region is characterized by (*i*) a current food system dominated by an agroindustrial model (UNDP 2020), (*ii*) a substantial level of environmental pressure on the planet (Batlle Aguilar et al. 2007; Hakoun et al. 2017), (*iii*) a densely populated situation, and (*iv*) a high human population density(human development index of 0.931 and 374 inhabitants per km^2). This situation reflects a type of food system commonly found in developed countries, characterized by limited long-term sustainability and a disconnection between local food production and consumption. However, it is important to recognize the diversity of agricultural systems even within developed regions and that such a model may not be directly comparable to those in resource-scarce or structurally different environments.

The objectives of our work were (*i*) to evaluate the capacity of our innovative decision-making model to assess how diversified crop rotations can fulfill specific nutritional requirements while minimizing imports and exports of food and feed commodities; (*ii*) to determine how these criteria are impacted by the duration and diversity of crop rotations, including crop–livestock integration; and (*iii*) to analyze the effects of contrasting human diets on the optimal utilization of crop (by-)products. To achieve these objectives, we applied the model on 40 contrasting crop rotations that were all consistent from an agronomic perspective but varied in length and crop diversity.

2 Material and methods

2.1 AGRONOMIC CONTEXT

The agronomic context of the silty region of Hesbaye (Belgium) was considered. The region is characterized by a temperate Cfb climate according to the Köppen–Geiger classification (Peel et al. 2007). Soils are Cutanic Luvisol (Schad et al. 2015), silty, with favorable natural drainage.

2.1.1 CO-DESIGN OF DIVERSE CROP ROTATIONS

Based on a participatory approach with experts from multiple disciplines (including agronomy, nutrition, and ecology and also including farmers), we co-designed 40 diverse crop rotations according to regional climatic constraints, contrasting by their duration and crop diversity. Then, given these rotations as inputs, our decisional model allows us to determine the use of crop (by-)products (*i*) to maximize the amount of dietary energy to satisfy human requirements, (*ii*) while minimizing the excesses and deficits in the different food and feed commodities, under the constraints (*iii*) of satisfying the eating patterns proposed by the EAT-Lancet commission which would allow the globe to eat healthily while respecting planet boundaries (Willett et al. 2019), (*iv*) in the contrasting contexts of an omnivorous, an ovo-lacto vegetarian, and a vegan diet.

We compared these 40 crop rotations (Table 1) varying in duration (3–8 years) and in major crop species and types (corn for silage or grain, hard or soft winter or spring wheat, winter or spring barley, sugar beet, potatoes, rapeseed, spring or winter peas, oats, hemp, temporary grasslands).

In order to maintain ecosystem services such as biodiversity, soil quality, nutrient management, water-holding capacity, control of weeds, diseases, and pests (Lin 2011; Kremen and Miles 2012), the following designing constraints were applied: (*i*) maximization of the inclusion of cover crops, (*ii*) a periodicity of legumes greater than 3 years, (*iii*) and the alternance of botanical families (i.e., Solanaceae, Brassicaceae, Amaranthaceae, and *Fabaceae*), except for *Poaceae*.

The objective was then to compare these contrasting crop rotations that were all consistent from an agronomic perspective. Some of these rotations were commonly practiced by farmers following a conventional model in the loamy region of Hesbaye, while others are more innovative, featuring longer durations and a greater diversity of crops, as often suggested in organic agriculture and agroecology.

Table 1 List of the 40 rotations co-designed by the experts for this study

Code	Rotation	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
3.1	1	Silage corn	Winter wheat	Winter barley	–	–	–	–	–
3.2	2	Cereal corn	Winter wheat	Winter barley	–	–	–	–	–
3.3	3	Sugar beet	Silage corn	Winter wheat	–	–	–	–	–
3.4	4	Sugar beet	Cereal corn	Winter wheat	–	–	–	–	–
3.5	5	Sugar beet	Winter wheat	Winter barley	–	–	–	–	–
3.6	6	Potatoes	Winter wheat	Winter barley	–	–	–	–	–
3.7	7	Rapeseed	Winter wheat	Winter barley	–	–	–	–	–
4.1	8	Sugar beet	Winter wheat	Silage corn	Winter wheat	–	–	–	–
4.2	9	Sugar beet	Winter wheat	Cereal corn	Winter wheat	–	–	–	–
4.3	10	Potatoes	Winter wheat	Silage corn	Winter wheat	–	–	–	–
4.4	11	Potatoes	Winter wheat	Cereal corn	Winter wheat	–	–	–	–
4.5	12	Sugar beet	Winter wheat	Potatoes	Winter wheat	–	–	–	–
4.6	13	Sugar beet	Winter wheat	Rapeseed	Winter wheat	–	–	–	–
4.7	14	Potatoes	Winter wheat	Rapeseed	Winter wheat	–	–	–	–
5.1	15	Sugar beet	Winter wheat	Spring pea	Winter wheat	Winter barley	–	–	–
5.2	16	Potatoes	Winter wheat	Spring pea	Winter wheat	Winter barley	–	–	–
5.3	17	Rapeseed	Winter wheat	Spring pea	Winter wheat	Winter barley	–	–	–
6.1	18	Sugar beet	Winter wheat	Rapeseed	Winter wheat	Silage corn	Winter barley	–	–
6.2	19	Sugar beet	Winter wheat	Rapeseed	Winter wheat	Cereal corn	Winter barley	–	–
6.3	20	Potatoes	Winter wheat	Rapeseed	Winter wheat	Silage corn	Winter barley	–	–
6.4	21	Potatoes	Winter wheat	Rapeseed	Winter wheat	Cereal corn	Winter barley	–	–
6.5	22	Sugar beet	Winter wheat	Rapeseed	Spring potatoes	Winter wheat	Winter barley	–	–
6.6	23	Potatoes	Winter wheat	Rapeseed	Winter pea	Silage corn	Winter barley	–	–
6.7	24	Potatoes	Winter wheat	Rapeseed	Winter pea	Cereal corn	Winter barley	–	–
6.8	25	Potatoes	Winter wheat	Rapeseed	W.wheat + W.pea	Silage corn	Winter barley	–	–
6.9	26	Potatoes	Winter wheat	Rapeseed	W.wheat + W.pea	Cereal corn	Winter barley	–	–
6.10	27	Sugar beet	W.wheat + W.pea	Rapeseed	Spring potatoes	Winter wheat	Winter barley	–	–
7.1	28	Sugar beet	Winter wheat	Rapeseed	Winter wheat	Sugar beet	Winter wheat	Winter barley	–
7.2	29	Potatoes	Winter wheat	Rapeseed	Winter wheat	Potatoes	Winter wheat	Winter barley	–
7.3	30	Sugar beet	Winter wheat	Rapeseed	W.wheat + W.pea	Sugar beet	Winter wheat	Winter barley	–
7.4	31	Sugar beet	Winter wheat	Rapeseed	W.wheat + W.pea	Potatoes	Winter wheat	Winter barley	–
7.5	32	Sugar beet	Winter wheat	Rapeseed	Winter wheat	Spring peas	Winter wheat	Winter barley	–
8.1	33	Grassland temp.	Grassland temp.	Silage corn	Winter wheat	Sugar beet	Winter wheat	Rapeseed	Winter wheat
8.2	34	Grassland temp.	Grassland temp.	Cereal corn	Winter wheat	Sugar beet	Winter wheat	Rapeseed	Winter wheat
8.3	35	Grassland temp.	Grassland temp.	Silage corn	Winter wheat	Potatoes	Winter wheat	Rapeseed	Winter wheat
8.4	36	Grassland temp.	Grassland temp.	Cereal corn	Winter wheat	Potatoes	Winter wheat	Rapeseed	Winter wheat
8.5	37	Grassland temp.	Grassland temp.	Cereal corn	Winter wheat	Faba bean	Winter wheat	Rapeseed	W.wheat + W.pea
8.6	38	Camelina	Winter wheat	Faba beans	Winter wheat	Rapeseed	Winter wheat	Spring pea	Oats
8.7	39	Camelina	Winter barley	Faba beans	Winter wheat	Rapeseed	Winter wheat	Spring pea	Oats
8.8	40	Sugar beet	Winter wheat	Potatoes	Winter wheat	Rapeseed	W.wheat + W.pea	Silage corn	Winter wheat

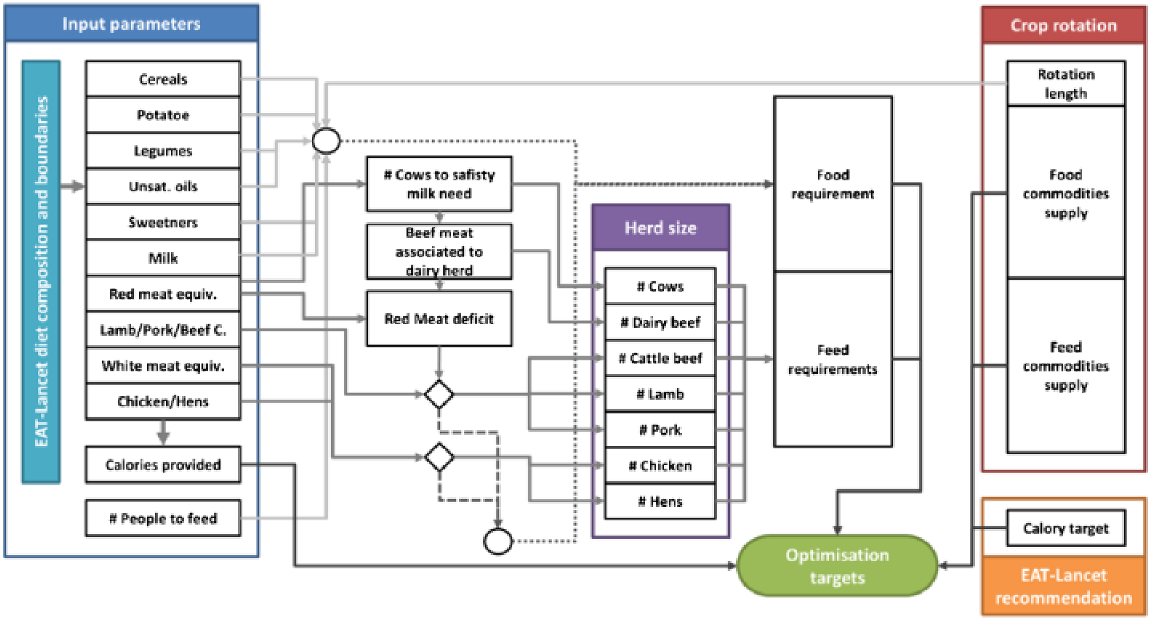
Interestingly, the last rotation assessed (rotation 8.8) is virtually the most representative of the soil occupation in Hesbaye—the percentage of each crop present in the rotation mimics the actual land use by major crops in Belgium—although this soil occupation is actually achieved with a combination of several types of 3, 4, or 5-year rotations.

No constraint was set either on fertility or soil management. The productivity of each crop species and type was computed from the yield statistics in Hesbaye between 2014 and 2018 (Statbel 2024). From the yield of each main commodity, by-products' production levels were also derived (e.g., straw from cereal grain or oilseed cake from rapeseed) to yield the total commodities produced per crop species and types, including cover crops and temporary grasslands.

2.1.2 OPTIMIZATION PROCESS TO MATCH TARGETED DIETS

An innovative approach was developed to optimize and assess the suitability of various crop rotations in meeting the nutritional requirements of specific diets (Figure 2). The optimization process has two objectives: (*i*) fulfilling a dietary energy target (kcal) to satisfy human requirements and (*ii*) simultaneously satisfying the eating patterns proposed by the EAT-Lancet commission (i.e., staying in the boundaries of each commodity). Furthermore, this optimization process was designed to answer two additional constraints: (*iii*) minimizing the excesses and deficits in the different food and feed commodities, including thus the one potentially required to meet the energy intake but not produced in the rotation, (*iv*) as well as achieving a solution in the contexts of an omnivorous, an ovo-lacto vegetarian, or a vegan diet. More details regarding the objectives and constraints are provided below.

Figure 2 Optimization model to best allocate the different food categories of the EAT-Lancet diet according to a given crop rotation, in order to minimize imports and exports.



The crop rotations previously designed were used as input of the algorithm. The algorithm aims at searching for the optimal solution in determining the best use of crops (by-)products, but the use of a given commodity as food or feed is not decided a priori; it will result from the optimization process itself and according to the defined constraints. For each crop across all assessed cropping systems, the ability to supply food, feed, and by-products was predefined in a database. Rotation length allows for normalizing the productions per year.

The first constraint in the optimization process was to respect the specifications of the EAT-Lancet diet (Willett et al. 2019) for each general food item category relevant in the context of field production (Table 2). As recommended in the study, a total amount of 2500 kcal day^{-1} has to be considered as a daily target. However, vegetables, fruits, and tree nuts were considered as food commodities that had to be produced from outside the modeled crop rotations and fixed to the average values suggested in Willett et al. (2019) of 300, 200, and 25 g.d^{-1}, providing 78, 126, and 149 kcal·d^{-1}, respectively. As made possible in the same study, dairy fats were included in milk. Lard or tallow, fish, peanuts, soy foods, and palm oil requirements were set to zero. Considering these adjustments, the final target for energy intake was set to 2054 kcal·day^{-1} for all the diets. This is the main criterion for the optimization process, and as such, it was given a greater weight than any other criterion.

Table 2 Boundaries for each commodities of the EAT-Lancet diet considered in this study. Food quantities are expressed as raw (uncooked, fresh) weights, except for wheat, rice, dry beans, and lentils, which are expressed as dry, raw weights.

	Quantities (g/day)		Calories	
	Minimum	Maximum	Minimum	Maximum
Rice, wheat, corn, and others	0	383	0	1339
Potatoes and cassava	0	100	0	78
Whole milk and derivative equivalents	0	500	0	306
Red meat (inc. beef, lamb and pork)	0	28	0	60
Beef and lamb	0	14	0	30
Pork	0	14	0	30
White meat	0	83	0	161
Dry beans, lentils, and peas	0	100	0	344
Unsaturated oils	20	80	177	708
All sweeteners	0	31	0	120

The ranges defined for each commodity in the EAT-Lancet diet (Table 2) were used as prior information of our optimization process (parameters a priori distribution). The number of people being fed per ha was also a parameter, with an a priori distribution ranging arbitrarily widely from 1 to 100 people and allowing for upscaling the needs. The optimization algorithm will automatically and randomly select values to be assessed within the a priori distributions. From there, a global achievable energy intake is computed for the objective function. Plant-based diet components (e.g., cereals and potatoes) will immediately drive a food demand, while animal-based diet components (i.e., meat, milk, and eggs) will drive the feed demand (Figure 2).

To compute the feed demand from the animal-based diet components, the algorithm works as follows. The number of dairy cows needed to supply milk was estimated using life cycles, herd dynamics, and annual production of milk. A resulting red meat production, coming from dairy beef cattle and culled dairy cows, was compared to the total red meat requirements. Where necessary, additional red meat was produced from pork, lamb, and beef cattle. Similarly, the number of chickens and hens required to produce the "white meat" category (i.e., chicken meat and/or eggs) was calculated. The annual production of milk, meat, and eggs per functional unit for each livestock species was computed from Wilkinson (2011). Outputs from animal by-products, such as meat from culled breeding females, were included for cattle, sheep, and pigs, but not for poultry. Annual requirements for grassland forage, human-edible crops, and crop by-products to feed the resulting herds were calculated based on forage and concentrate requirements and composition data (Wilkinson 2011), focusing on what could locally be produced. The human-edible crops used for animal feed were subtracted from the plant-based food commodities available for human consumption—priority is always given to food supply over feed.

A final constraint was to respect specific diets: an omnivorous, an ovo-lacto vegetarian, and a vegan diet. In each scenario, appropriate modifications were provided to the algorithms to consider livestock categories being fed or not and their respective products entering the balance of the diet. The feed requirements to sustain animal-based food production were calculated for the omnivorous and ovo-lacto vegetarian diets, while this step was skipped for the vegan diet. In the case of ovo-lacto vegetarian diets, we only focused on feeding milky cows and laying hens (including the underlying herd), but no valorization of associated meat was considered.

Finally, the objective function of the algorithm is computed from the difference between the energy provided and the energy target (2054 kcal day^{-1})—which is given a greater weight in the objective function—and from the balance in each category of food and feed supply/need. If a food or feed category is not produced in a sufficient quantity by the crop rotation (deficit), the algorithm will automatically consider it has to be imported from outside the rotation, just at the level required to meet the constraints. Contrarily, any commodity overproduced by the rotation will be considered as excess. This process was iteratively repeated during the optimization process, until an optimal solution was found, that is, identifying the optimal way in which each crop rotation can be used to sustain the diet and allow for the best food/feed ratio.

The algorithms were programmed in MATLAB (MATLAB *version 7.5.0 (R2007b)*, Natick, Massachusetts: The MathWorks Inc.). The optimization process was performed using the Differential Evolution Adaptive Metropolis (DREAM) algorithm (Vrugt et al. 2009). Detailed descriptions of the DREAM algorithm have been published in (Vrugt et al. 2009; Vrugt 2016). DREAM has been successfully used in a wide range of scientific disciplines (Vrugt 2016), among which are agronomy and crop modeling (Dumont et al. 2014; Duchene et al. 2021). The functions to compute the use of crop rotation to match a diet model can be obtained by contacting the authors. The DREAM source codes were obtained from the developer (Jasper A. Vrugt, personal communication).

2.1.3 ASSESSMENT OF OPTIMIZED CROP PRODUCTIONS AND DIET

The resulting diets matching the crop rotations best under the constraint of the omnivorous, ovo-lacto vegetarian, or vegan option of Willett et al. (2019) specifications were assessed using several criteria provided as outputs from the model: (*i*) the number of people supported per ha per year, (*ii*) the amount of calories produced by the crops used for feed or food purposes, (*iii*) the amount of calories required from outside the system, and (*iv*) the size of the animal herds supported by the rotation expressed in livestock units (Eurostat 2024). The nutritional value of the diet was assessed by means of the amount (g or mg·d^{-1}) and share (%) of animal-sourced protein, iron, and zinc in the diets. Animal-sourced protein is commonly considered to address the question of sustainability of eating habits owing to the higher environmental impact of livestock farming, even if this impact will strongly depend on the management (Qaim et al. 2024). It is also important because of the role of animal-based foods in providing an adequate balance of bioavailable essential amino acids. Animal-sourced iron and zinc allow addressing the bioavailability of various minerals in which plant-based foods are usually deficient from a nutritional perspective. Finally, the different components of the Nutri-Score and the Nutri-Score itself (ranging from A to E) of each resulting diet were calculated (Julia and Hercberg 2017): energy density (kJ/100 g), sugars (g/100 g), saturated fatty acids (g/100 g), Na (mg/100 g), fruits, vegetables, pulses, nuts, rapeseed, walnut, and olive oil (%), fiber (g/100 g), total protein (g/100 g). The latter were calculated using the USDA National Nutrient Database (USDA 2024). Food commodities that were not to be provided by the crop rotations under any crop rotation and optimization result (dark green, red orange, and other vegetables, tree nuts, and fruits) were set to similar levels for all crop rotations by systematically providing the required amounts suggested by Willett et al. (2019). Their nutrient content was also taken from the USDA National Nutrient Database. The architecture of the model can be found in Figure 2.

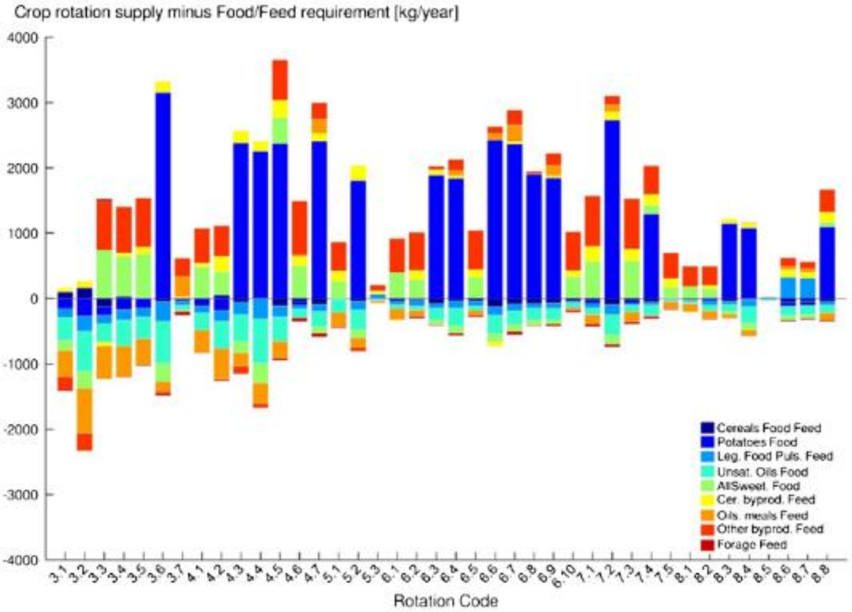
A principal component analysis (PCA) was conducted using the singular value decomposition approach. It was implemented under the R language (R Core Team 2023). The *prcomp* function from the "*factoextra*" library was used. Data were centered and standardized as recommended. Optimized diet composition (including elements composing red and white meat), excess/deficit in commodities, the nutritional value of food (iron, protein, zinc, etc.), the different components of the Nutri-Score, and the number of people fed constituted the analyzed data, to understand the variability in the data set. Diet type, share of crops in each rotation, and herd compositions (expressed in LSU) were used to structure the dataset, as parsing arguments, to further understand how the different variables were related.

3 Results and discussion

3.1 LAND USE

Results show that short-term rotations are less self-sufficient and lead to higher commodity excesses or deficits (Figure 3, S1, S2). Three-year rotations display particularly large deficits in different food and feed commodities in all the diets considered (depending on the crops that were cultivated). Long-term rotations very importantly reduce the deficits, even if results strongly differ between rotations of the same duration with different crop species (Figure 2, S1, S2).

Figure 3 Excesses and deficits in food and feed commodities compared to the EAT Lancet requirements, for all rotations considering an omnivorous diet. In rotation's labels, first numbers indicate duration in years.



Following our model results, the ideal rotation must contain rapeseed to supply oil for humans and oilseed meals for livestock (for the omnivorous and ovo-lacto vegetarian diets), one legume crop for pulses, and several cereals as the main energy source in the diets designed according to Willett et al. (2019) (Figure 3, S1, S2).

For all diets and in all tested crop rotations, cereals are almost at equilibrium (Figure 3, S1, S2). Our model was built to ensure that when there are no potatoes in the rotation, it minimizes the amount of tubers required in the diet so that deficits are as low as possible. Yet potatoes are always an issue when they are included in the rotations as they always lead to overproduction (on average 1989 ± 585 kg/ha/year). Unsaturated oils are always in deficit. Concerning sweeteners, they are in excess when sugar beet is cropped, but in deficit when this crop is absent from the rotation (Figure 3, S1, S2). In the omnivorous and ovo-lacto vegetarian diets, oilseed meals are in deficit when no rapeseed is included in the rotations or when rapeseed is present but legume crops are absent because the frequency of rapeseed is too low in these crop rotations (Figure 3, S1).

Vegan diets can feed more people on average (32.7 ± 9.7 vs 25.7 ± 6.2 for omnivorous and 29.6 ± 6.5 for ovo-lacto vegetarian diets) (Fig. S3, S4, and S5), and deficits are globally lower than for the two diets allowing the inclusion of animal-based foods (Fig. S2). Yet some commodities are in large excess, while many others have to be supplied from outside (Fig. S2). Excesses are generally higher for all rotations with vegan diets than with diets including animal-based foods, and increasing rotation duration does not permit decreasing these excesses. They are particularly important for crop by-products that are usually used as feeds: forage (2441.9 ± 1774.3 kg/ha/year for vegan, 4.2 ± 99.7 kg/ha/year for ovo-lacto vegetarian, and −18.5 ± 20.7 kg/ha/year for omnivorous), oilseed meals (322.6 ± 252.4 kg/ha/year for vegan, −150.7 ± 301.2 kg/ha/year for ovo-lacto vegetarian, and −111.5 ± 212.6 kg/ha/year for omnivorous), brans (301.6 ± 53.2 kg/ha/year for vegan, 138.7 ± 111.8 kg/ha/year for ovo-lacto vegetarian, and 99.2 ± 77.8 kg/ha/year for omnivorous), etc. (Fig. S2). Those are strong clues indicating that vegan diets may not represent the most efficient use of land, particularly when assessed through the lens of agricultural land productivity and resource allocation. Although vegan diets eliminate the need for land-intensive livestock farming (Poore and Nemecek 2018), they may result in a mismatch between crop production and actual human nutritional needs, especially in terms of by-products and biomass that are not directly consumed. Nevertheless, from a farming system perspective, the share of biomass produced in excess under the constraint of vegan diets could be used as green manure or as input for agrosourced fuel production. In this way, while vegan diets might initially appear suboptimal in terms of direct land-use efficiency, they could still support a circular agricultural system. The redirection of unused biomass toward environmentally beneficial applications reinforces the potential for integrated, multifunctional farming models that align food production with sustainability and energy resilience (Schader et al. 2015).

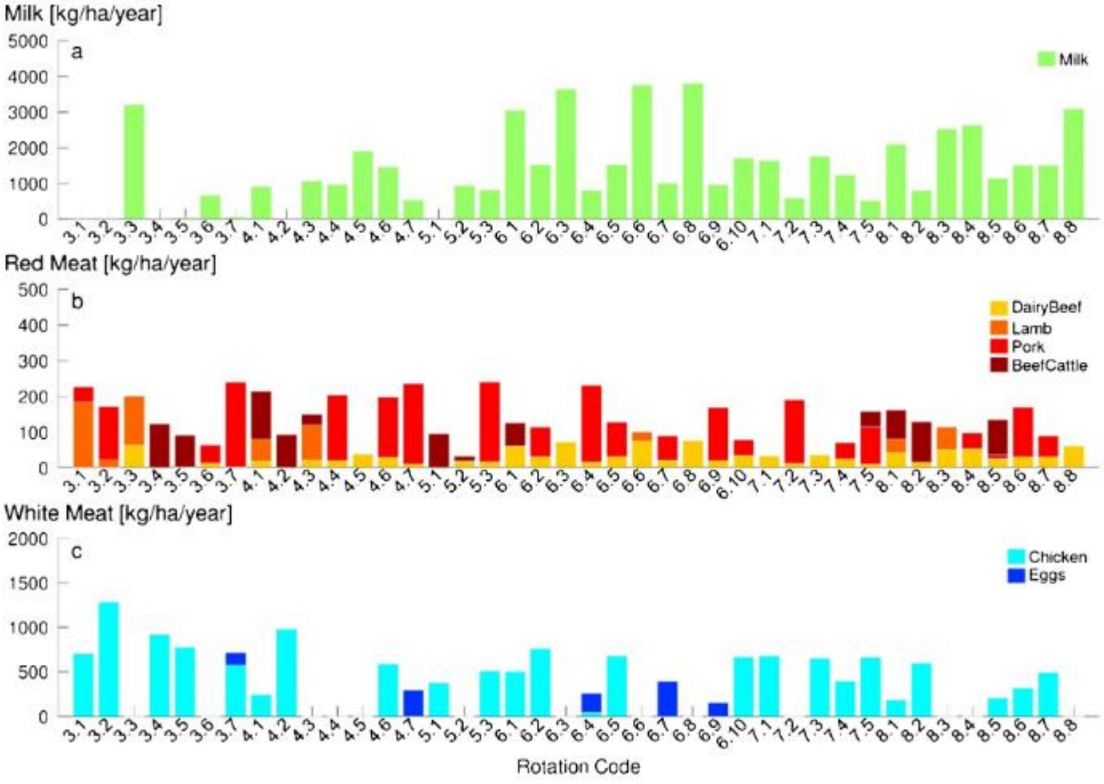
Observations, showing that diets with small amounts of animal proteins are more efficient in terms of land use, are consistent with the results of other studies (Peters et al. 2016; Van Kernebeek et al. 2016; Van Zanten et al. 2018). However, for ovo-lacto vegetarian diets, the question of the fate of animals used for eggs and milk production fully remains (e.g., 46.5 ± 32.3 kg/ha/year of dairy meat). In the omnivorous diets, their terminal destination as meat at the end of their productive life allows for a higher efficiency in the use of dairy cattle, raising questions about vegetarian diets in terms of food system efficiency and circularity (Van Zanten et al. 2019).

The results highlight the importance of livestock and principally ruminants, to convert inedible byproducts of the human food industry and forage into edible milk, eggs, and meat (Eisler et al. 2014; Van Kernebeek et al. 2016).

3.2 HERD COMPOSITION

In the 40 tested rotations, the share of milk and beef in omnivorous and milk in ovo-lacto vegetarian diets is correlated to the presence of temporary grasslands but also to corn silage, forage cover crops, and crops providing fiber-rich byproducts (Figure 6, S6 and S7). However, it is important to acknowledge that these results are influenced by the model's input parameters (such as assumptions related to livestock feed) and may vary if these inputs are modified. Under the omnivorous scenario, ruminants are not always the most adapted species to be integrated with crops in a perspective of feed vs food competition (Figure 4). Pork and chicken are proposed by the optimization process when cereal crops and co-products for feed are abundant in the rotation. Regarding the chicken-to-egg ratio for poultry, the model is often falling for chicken, as it seems to be more efficient to use the feed energy captured by the system than eggs. This is probably due to the short life cycle of chicken considered here (42 days) and the use of males and females alike, while for laying hens, only newly hatched females are kept and it takes almost 5 months for pullets to start laying their first egg (Fig. S8-S9).

Figure 4 Quantities of animal products (milk[a], red meat[b] , white meat, or eggs[c]) in kg/ha/year produced for each crop rotation in the case of an omnivorous diet complying with the recommendations of the EAT-Lancet commission (namely: red meat 28g/day (dairy beef, lamb, pork and beef cattle); white meat (chicken meat and eggs) 83g/ day; milk (whole milk and derivative equivalent 500 g/day). See also Table 2



Interestingly, we observe that not all crop rotations in the omnivorous diet are to produce milk. Even if meat is produced and consumed in all rotations, the sources of red and white meat differ (Figure 4). In the case of the ovo-lacto vegetarian diet, milk is produced in all rotations, but eggs are not. When no eggs are produced, the production of milk is usually more important (Fig. S10).

It is commonly accepted that land use for the production of a unit of protein is generally lower with plants than animal sources (De Vries and De Boer 2010; Nijdam et al. 2012; Bai et al. 2021) but it is strongly linked to the considered livestock species and livestock production system. Dairy foods have the most efficient feed to food protein conversion ratio, followed by eggs and chicken and then pork and lamb. Beef production is the least efficient way of supplying animal proteins through animal feeding in current farming systems (Smil 2002). However, ruminants can take advantage of forage, grazing lands, and food processing residues that are not digestible for nonruminant species, converting these so-called low opportunity-cost feeds, farm animals recycle biomass and nutrients into the food system that would otherwise be lost to food production (Van Zanten et al. 2019), expressing better feed efficiency than nonruminants when food/feed competition is eliminated (Van Zanten et al. 2016). The integration of temporary grasslands and forage cover crops in rotation will thus allow a higher production of beef at a lower expense.

In addition, these temporary grasslands will add some biodiversity in the rotation and the agricultural landscape. They can also have fertilizing and weed control effects, through the presence of legumes and animal manure and through competition for light and grazing, respectively (Schuster et al. 2019). They are also highly effective in restoring soil health, reducing soil erosion and, under appropriate management, result in more C sequestration than emissions (Crème et al. 2020). Incorporating forages and ruminants into agroecosystems can also improve soil ecological function through the minimization of tillage, inorganic fertilizers, and biocides and enhance wildlife habitat (Teague et al. 2016).

3.3 ENERGY INTAKE

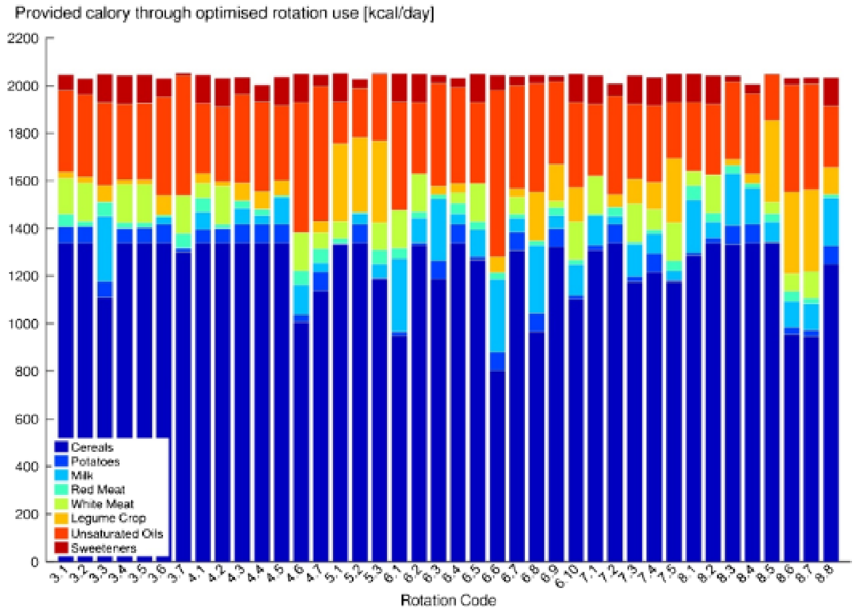
Excesses in dietary energy were never encountered in the optimized diets for all rotations, but the model minimizes the deficits (Figure 5, S11 and S12). In all rotations, the commodities produced were indeed able to provide at least 97.5%, 97.2%, and 95.7% of the recommended energy intake set to 2054 kcal per day for the omnivorous, ovo-lacto vegetarian, and vegan diets, respectively. 30/40 rotations were able to supply 100% of the energy intake in the omnivorous diet, while this was the case for 24/40 and 12/40 rotations for the ovo-lacto vegetarian and vegan diets, respectively.

As a reminder, the total supply in energy in the EAT-Lancet diet is 2500 kcal day^{-1} with, in our model, tree nuts, vegetables, and fruits providing the additional energy from outside the cropping system.

Yet, all these results are to be nuanced as there are many debates about the relevancy of some nutritional recommendations proposed by the EAT-Lancet Commission diet and the fact that it is very severe in terms of energy intakes and animal-based foods leading to a potential decline in the supply of micronutrients such as iron, zinc, and vitamins B_6 and B_{12} (Beal et al. 2023).

In all crop rotations and for all diets, the production of cereals provides the largest share of energy, followed by unsaturated oils. When potatoes are included in the rotation, their dietary use is maximized with still overproduction as discussed above (Figure 3, S1 and S2). In some rotations, legume crops are also important sources of energy. These contribute obviously to a greater part of the calories intake for the vegan diet (Fig S12). Under a vegan scenario, the model always maximizes the share of cereals in the diets, up to the upper threshold defined by the EAT-Lancet diet, to compensate for the absence of energy-dense animal-source foods. The inclusion of sweeteners was variable but consistently limited, in accordance with the EAT-Lancet recommendation of no more than 31 grams per day, which corresponds to approximately 5% of total energy intake in a 2,500 kcal/day diet (Figure 5).

Figure 5 Share of the different food commodities in the provision of energy by all the rotations in the case of an omnivorous diet.



3.4 NUTRITIONAL PROFILE

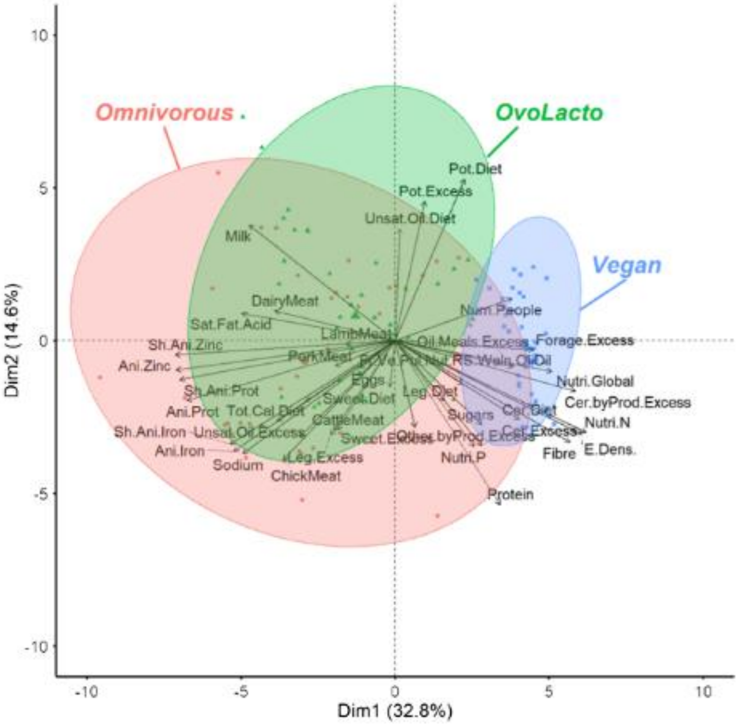
From the optimized use of farming system production as feed and food, nutritional profiles were derived (see supplementary material), allowing for an integrating analysis from an agricultural and nutritive perspective (Figure 6, S6 and S7).

Figure 6 presents a principal component analysis (PCA) of the nutritional profiles derived from the optimized crop rotations applied to three dietary patterns: omnivorous, ovo-lacto vegetarian, and vegan. This analysis highlights the nutritional differences and similarities between diets, based on two principal axes (Dim1 and Dim2), which together explain 47.4% of the total variance (32.8% and 14.6%, respectively).

Omnivorous diets (red circles) are mostly located on the left side of the PCA plot and are associated with terms such as "protein," "sodium," "zinc," "iron," and "unsaturated fat," reflecting the higher presence of animal-based products rich in high-quality proteins and bioavailable micronutrients. Ovo-lacto vegetarian diets (green triangles) are more centrally located and are characterized by terms such as "milk" and "dairy meat," suggesting a balance between plant and animal sources. Vegan diets (blue dots), clustered on the right, are associated with terms like "fiber" and "sugars," indicating a higher intake of dietary fiber and naturally occurring sugars from plant-based sources.

Interestingly, variables such as "number of people nourished," "forage excess," and "Nutri-Score" are also projected on the right-hand side of the PCA space, suggesting that vegan diets are associated with a higher potential to nourish more people and generate surplus forage, while maintaining high nutritional quality as indicated by Nutri-Score.

Figure 6 PCA analysis of crop rotations according to the matching with the requirements of the EAT-Lancet commission for omnivorous, ovo-lacto vegetarian, and vegan diets. Clusters highlight the type of diet. Abbreviations used in the figure are as follows : byProd = by products, Cer. = cereals, E.Dens = energy density, ExcDef = excess or deficit, Fr.Ve.Pul.Nut. RS.Waln.OliOil = fruits, vegetables, pulses, nuts, rapeseed, walnut, and olive oil, Leg. = legumes, Nutri. = nutriscore, Num. = number, Pot. = potatoes, Prot. = protein, Sat.Fat. = saturated fat, Sh.Ani = share of animal, Sweet. = sweeteners, Tot.Cal. = total calories, Unsat. Oil = unsaturated oils.



All crop rotations scored A for their Nutri-Score whatever the optimized diet (omnivorous, ovo-lacto vegetarian, vegan), indicating high nutritional quality and lower risk of developing health issues linked to nutrition (Deschasaux et al. 2020; Mozaffarian et al. 2021). As a reminder, the algorithm underpinning the Nutri-Score label is derived from the UK Food Standards Agency (FSA)/Office of Communication (Ofcom) nutrient profile model, also known as "model WXYfm." It assigns negative points (ranging from 0 to 10) for less desirable elements (namely energy, sugars, saturated fats, and sodium) and positive points (ranging from 0 to 5) for favorable components such as fiber, protein, and the proportion of fruits and vegetables. Nutri-Score A is the highest nutritional quality within the framework of this system. This rating is typically assigned to foods that are low in energy (calories), saturated fats, total sugars, and sodium, while being high in beneficial components such as fiber, protein, and the percentage of fruits, vegetables, legumes, nuts, and selected healthy oils like rapeseed, walnut, or olive oil (van der Bend et al. 2022).

These results are in accordance with the objective of the EAT-Lancet commission, aiming to reduce the risk of diet-related obesity and other noncommunicable diseases, including coronary heart disease, stroke, and diabetes.

The share of animal proteins in diets was also correlated with herd sizes. Contents in animal protein were almost always higher in omnivorous diets, except when more pork and lamb than beef are produced as sources of red meat (Fig. S14).

However, some rotations applied to the ovo-lacto vegetarian diets, but also to the omnivorous diets, had values that were really low in terms of total protein supply (with minima of 54.5 g/day for omnivorous and 54.2 g/day for ovo-lacto vegetarian). These values are borderline according to the WHO recommendations (WHO et al. 2007) of 58 g of total protein per day for 70-kg individuals, especially if less than ⅓ is supplied as animal-based protein for its higher biological value. This is unfortunately the case of most low protein scoring diets and the case of all vegan diets, obviously (with a minimum of 40.6 g of proteins/day). Interestingly, eight rotations supply over ⅓ of animal-based protein in the omnivorous diets while still complying with the EAT-Lancet recommendations. Van Zanten et al. (2018) have shown that the best land use in terms of number of people supported is reached when people eat 20–25 g animal protein/day. In our study, some farming systems are a bit higher (e.g., crop rotations 3.7 is providing 28.7 g/day of animal proteins in the omnivorous diet and 29.8 g/day of animal proteins in the ovo-lacto vegetarian diet). The least efficient at this level (crop rotation 8.5) provided 13.9 and 10.5 g animal proteins per day for the omnivorous and ovo-lacto vegetarian diets, respectively. Several studies have shown that higher plant protein intake was associated with lower mortality (Song et al. 2016; Budhathoki et al. 2019). However, attention must be paid to the provision of minerals, micronutrients, and vitamins. In addition to protein, iron (Fe) is one of the most critical nutritional requirements to be met in most diets in humans. Content in Fe was similar in all diets, with the exceptions of ovo-lacto vegetarian diets favoring high consumption levels of eggs (Fig. S13), which are among the richest in Fe of the animal-based foods (USDA 2024). It is interesting to consider as it could be an indicator of the level of mineral elements of animal origin. Its deficiency is more often the result of low bioavailability than low total supply (Hambræus 1999). Iron and some other minerals are more bioavailable in animal products. Plant-based foods can be rich in Fe but are usually deficient in bioavailable forms of iron from a nutrition perspective, especially for adult women. As shown by Päivärinta et al. (2020), flexitarian diets containing a small proportion of animal products would provide healthy and more sustainable alternatives for current, mostly animal-based diets.

3.5 CONSEQUENCES TO CURRENT SPECIALIZED PRODUCTION SYSTEMS IN BELGIUM

Presented results clearly show that the present-day land use in Belgium has to be improved in order to support a more sustainable diet. In particular, there is a large excess in the production of potatoes, which is exported, when the country presents a deficit of animal feeds, which are compensated through imports.

Improvements should also concern livestock production. The herd sizes proposed by the optimized model are far from the herd sizes that are usually encountered in the Hesbaye (Riera et al. 2019). For rotation 8.8, the optimized herd size would be 0.48 cows and 0.32 dairy beefs and would allow feeding 25.7 people per hectare. This would correspond to an average of 61.8 g of red meat intake per day. Herd sizes proposed in our optimally used rotation would follow the same trend as the suggestion made by Riera et al. (2019), showing that herd size in Belgium could be reduced to provide the animal protein needed. However, it is important to note that these values represent averages calculated over the total agricultural area. At the regional scale, the total number of animals implied by the model would likely be higher, reflecting the cumulative livestock needed to meet dietary requirements. This suggests that cooperation between farms could help optimize the distribution of livestock and feed resources, improve nutrient cycling, and support overall production efficiency, while recognizing that individual herd sizes may vary due to local conditions and management practices. At the same time, exporting red meat to other territories could be considered a supplementary strategy to balance surpluses and deficits, though the feasibility and desirability of such exports would depend on broader economic and environmental factors.

Under the vegan diet constraint, conclusions are more difficult to draw for the Hesbaye case study, due to the large excesses in feed crops or nonedible crop parts that cannot be exploited through animal production. A rotation producing no forage (e.g., rotation 3.7) seems to be well adapted to vegan dietary patterns. However, as stated before, some of the commodities produced in excess could be used to supply agrosourced fuel production (Hoogwijk et al. 2003). In this case, rotations 5.3 and 8.5 are also good options to consider for the vegan diet.

Considering all these exposed results, one rotation (rotation 8.5) seemed to be highly adapted to the specific Hesbaye context, minimizing deficits and excesses (food waste or exports) for all commodities, under the omnivorous and ovo-lacto vegetarian diets. Such a rotation is long (8 years), containing 2 years of temporary grasslands, cereal corn, 3 years of winter wheat in which one is associated with winter peas, faba beans, and rapeseed. Typically, this rotation fits under the definition of integrated crop–livestock system (Lemaire et al. 2014).

However, it is important to acknowledge that our results are inherently dependent on the set of crop rotations considered, which served as the starting point for the optimization of the dietary scenarios. These rotations, while diverse in structure and representative of Belgian agricultural conditions, inevitably constrain the nutritional and agronomic outcomes explored in the study. The botanical diversity within and across crop rotations plays a key role in shaping both the nutrient supply and the environmental performance of food systems. Increased species diversity (particularly within botanical families) can enhance resilience, improve nutrient cycling, and expand the range of available food products, especially plant-based protein sources. Future work should therefore explore a broader set of rotations, including those integrating a wider variety of legumes, oilseeds, vegetables, and underutilized crops. This would allow for a more comprehensive assessment of the nutritional and agroecological potential of diversified cropping systems and might open up new possibilities for designing diets that are both nutritionally adequate and environmentally sustainable.

In this study, permanent grasslands were not considered, as the aim was to remain consistent with the agricultural practices of the Hesbaye region, which is dominated by arable farming and where permanent grasslands represent a relatively small proportion of land use. However, their inclusion could be relevant in other contexts. Also, in our approach, we chose to work with single, longer rotations to simplify the model and ensure that all required commodities could be produced each year. This is made possible by assuming that the same rotation could be implemented across different fields, each starting at different points in the cycle. In this way, the full set of crops is present at the landscape level every year, even if not all crops are present in each individual field annually. Another possibility would have been to model a mosaic of shorter, complementary rotations. However, we hypothesize that longer and more diverse rotations are likely to have more beneficial effects overall, particularly in terms of enhancing soil health, disrupting pest and disease cycles, and improving system resilience.

Finally, the energy required for food production (which will vary depending on cropping systems, agronomic practices, and subsequent food processing (e.g., for sweeteners)), as well as waste generated along the supply chain will also be important to take into account.

4 Conclusions

This study introduced a conceptual decision-making model designed to evaluate how crop rotations can meet specific dietary targets, providing a practical tool to anticipate and guide necessary changes in agricultural systems. By applying the model to 40 contrasting crop rotations and the EAT-Lancet dietary guidelines, we demonstrated that it is theoretically possible to design local crop rotations capable of supplying the Belgian population with staple foods, although fruits, vegetables, and tree nuts remain outside the scope.

In relation to our initial objectives, we can explicitly state that (i) the model successfully assessed how diversified crop rotations can fulfill specific nutritional requirements while minimizing the import and export of food and feed commodities, confirming its capacity as a decision-support tool; (ii) the analysis revealed that the duration and diversity of crop rotations, particularly when integrating grazing animals and temporary pastures, strongly influence the balance of food and feed supplies, improve nutrient cycling, and help meet the daily caloric and nutrient requirements defined by dietary guidelines; and (iii) the comparison of contrasting human diets (including vegan, ovo-lacto vegetarian, and omnivorous diets) demonstrated that diet type affects the optimal utilization of crop by-products, surplus biomass, and the efficiency of the cropping system. Collectively, these results show that all three objectives have been met, providing a robust framework for aligning crop system design with dietary goals.

The novelty of this work lies in its explicit linkage between crop production planning and human dietary requirements. The model allows for multiobjective optimization of crop rotations while simultaneously considering environmental, nutritional, and economic factors. It also provides a flexible tool to explore alternative dietary scenarios or agroecological practices, supporting context-specific, sustainable food system design. Moreover, the study highlights the value of integrated crop–livestock systems for completing nutrient cycles, recycling co-products, and supplying micronutrients essential for human health, while also demonstrating how surplus biomass from cover crops can enhance soil fertility, reduce erosion, and support multifunctional farming systems.

While the EAT-Lancet diet has limitations (such as strict constraints on energy and animal-source foods that could lead to micronutrient deficiencies), our findings underscore that dietary and agricultural transitions must consider local environmental, agronomic, and socioeconomic conditions. Ultimately, this modeling approach offers a powerful tool for designing sustainable, context-specific crop rotations, yet long-term field trials, potentially coupled with soil–crop models, remain necessary to assess the agronomic resilience and resistance of the systems over time.

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Authors' contributions BJ and DB conceptualized the study and designed the conceptual framework of the model; BJ and DC per- formed the data collection; DB implemented the model and conducted

the statistical analysis; BJ, DB, DC, DM, DT, and CPCF analyzed the data; BJ, DB, DC, DM, DT, and CPCF produced the manuscript. BD and JB have equally contributed to the study.

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Data availability The raw data and code used in this study are available upon request. Interested researchers can contact the corresponding author via email to access these resources, which include data sets, calculation files, experimental protocols, and any other relevant materials.

Declarations

Competing interests The authors declare no competing interests

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