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Towards sustainable diets and farming systems through land use optimisation

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The industrialised food system poses health and environmental challenges, raising concerns about its sustainability. Addressing these requires region-specific solutions that consider local agronomic and socio-economic conditions. This study examines how transforming the food system impacts land use and self-sufficiency in a defined region of a country. Using Wallonia as a case study, we modelled crop allocation across different pedoclimatic conditions and evaluated three diets—CURRENT, TYFA, and EAT-Lancet—under conventional and organic farming, with 30% or 10% food waste. Our results demonstrate that, regardless of farming practice, Wallonia cannot achieve self-sufficiency under the CURRENT diet. However, adopting the TYFA or EAT-Lancet diets would enable self-sufficiency and spare land for alternative uses, under conventional farming. Food waste reduction was pivotal for enhancing self-sufficiency under organic farming. This research offers a solid foundation for informing agri-food policies in Wallonia and can be extended to other regions seeking to improve local food security.

Over the past decades, there has been a dramatic global shift in the ways people eat, drink, and move. These changes have clashed with our physiology, leading to significant shifts in health outcomes[1]. The risk that poor diets pose to mortality and morbidity is now greater than the combined risks of unsafe sex, alcohol, drug, and tobacco use[2].

To support the food system and a growing population, agriculture has undergone a parallel transformation, adopting high-yield crop varieties, chemical fertilisers, pesticides, irrigation, and mechanisation[3]. However, this transformation has led to major environmental issues: food production (including transformation and distribution) accounts for nearly 30% of global greenhouse gas emissions[4] and 70% of freshwater use[5]. Converting natural ecosystems to farmland is a leading cause of biodiversity loss[6], while excessive nitrogen and phosphorus fertilisation causes eutrophication of lakes and coastal areas[7]. Pesticide use harms farmland biodiversity[8] and is linked to diseases such as cancer and hormone disruption[9]. Finally, under the current agri-food system, meeting food demands by 2050 may require an additional 0.2 to 1 billion hectares of agricultural land[10], often in forested or protected areas[11], challenging conservation efforts[12]. Future perspective for agriculture will be more than ever to meet both challenges of feeding a growing population, with rising demand for meat and high-calorie diets, while simultaneously minimising its global environmental impacts[13].

Several options have already been proposed to tackle these issues[14]. Among them, the change of eating habits towards more environmentally friendly and healthy diets is a key lever[15]. While the acceptable total amount of animal-based food in the diets is still debated[16], there is a consensus that westernised diets include too much protein from meat and too little fibre-rich plant-based foods from both a health and environmental perspective[17]. Reference diets, such as the one proposed by the EAT-Lancet[15] commission or the TYFA project[18], propose universal guidelines for a healthy food supply which respects planetary boundaries, emphasising reduced meat consumption and increased consumption of plant-based foods.

Another option proposed to address the previously mentioned issues is transitioning to a more environmentally sustainable form of agriculture, such as organic farming (OF) which is considered by the Food and Agriculture Organisation as a global set of farm scale agroecological levers[19]. Nevertheless, within Western European agricultural systems, OF exhibits lower yields[20–22] and would therefore need more land to produce the same amount of food as conventional farming (CF) (defined here as a farming system that employs all legally permitted agronomic tools to maximise production)[23].

Since large scale conversion to OF would provide environmental benefits only at the expense of reducing food production[24], the central question arising is to find ways to compensate for the reduction of yields that accompanies the implementation of organic practices, and more generally of agroecological levers. One solution lies in the optimisation of the arable land use allocation required to match the agricultural production of a territory and the food requirements of its inhabitants. Another solution is to reduce people's food waste[24].

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In this regard, the crop redistribution strategy —i.e., determining how best to distribute different crop types across available farmland—is one of the most important means to improve agricultural sustainability[25]. Agricultural land use optimisation specifically deals with the allocation of species and activities to areas in agricultural landscapes[26]. The current approaches can be broadly classified into two scales: at the farm and at the territory levels. Land use allocation problems have been widely formulated as mathematical optimisation problems considering multiple, mostly conflicting objectives and aim to minimise the trade-off between them[27]. Various objectives can be prioritised, such as maximising farmer profits[28] or circularity[29], but also improving water management[30] or biofuel production[25] for example. At the same time, different constraints must be considered, including climate change[31], environmental impacts[25,28], agricultural policies[32], etc. These factors all play a crucial role in shaping sustainable agricultural strategies and must be carefully balanced to achieve optimal outcomes.

Despite its significant potential, agricultural land optimisation remains underutilised, particularly in developed countries. Some research has addressed the issue of food self-sufficiency (FSS)[29,33,34]. However, with few exceptions[29,35,36], most studies overlook the competition between human and animal land use. Additionally, healthy and sustainable reference diets are rarely incorporated into land use optimisation models[29,36,37]. To our knowledge, no study has considered the comparison between CF and OF in an optimisation problem targeting a diet shift in parallel. Finally, based on the existing literature, no study has examined land optimisation with the goal of achieving FSS under different diets, while also accounting for food-feed competition and diverse production systems (CF and OF).

To evaluate our conceptual model, we identified specific assessment criteria, including (i) a food system currently dominated by an agro-industrial production model; (ii) a high level of environmental pressure on the planet; (iii) a densely populated area; and (iv) a high human population index. We considered this scenario to be typical of food systems in developed countries that lack long-term sustainability and show a disconnection between local food production and consumption. The Walloon region of Belgium (in the southern part of the country) meets all these conditions.

Therefore, taking Wallonia as a case study, this research aims to determine whether it is possible to feed a region with the characteristics of a highly industrialised country with a healthy diet using sustainable practices. To do this, an optimisation model was designed to best allocate agricultural land by considering the pedoclimatic conditions of Wallonia's nine agricultural regions, officially defined zones characterised by similar soil and climate conditions. The goal is to align the food production of the territory with the consumption of its inhabitants. This objective will be examined under the current dominant conventional farming system, as well as under a fully organic scenario, with varying diets and levels of food waste, to contribute to the global shift toward a more sustainable society.

Results

Food self-sufficiency

Modelling indicated that, under the current food waste level (30%), achieving full FSS under the CURRENT diet was not feasible, whether using CF (84%) or OF (65%). However, feeding the entire regional population became possible if the average diet aligned with the nutritional recommendations of the EAT-Lancet and TYFA diets. For both diets, this level of FSS was only attainable through CF. In an OF system, FSS would reach 72% for the TYFA diet and 87% for the EAT-Lancet diet (Fig. 1).

When food waste was reduced from 30% to 10%, FSS improved, reaching 98% for the CURRENT diet in a CF system. Full FSS was still achievable for the EAT-Lancet and TYFA diets in a CF scenario. Additionally, in an OF scenario, FSS rose to 76% for the CURRENT diet, 88% for the TYFA diet, and 100% for the EAT-Lancet diet (Fig. 1).

For both levels of food waste, when FSS was not achieved, the capacity for self-supply varied between crops, with cereals, legumes, and oilseeds being the least supplied (Supplementary Figs. 1 to 6 and 9 to 14).

Land use

With 30% food waste, when FSS did not reach 100%, all available land was quite logically fully utilised. Only the scenarios involving a dietary transition allowed some land to be freed up, but only if CF was performed. Specifically, 3% of the available land remained unused under the TYFA diet, while 18% was left unused with the EAT-Lancet diet (Fig. 2).

When food waste was reduced to 10%, the CURRENT-organic and TYFA-organic scenarios still failed to achieve full FSS, requiring the full use of all available land. The CURRENT-conventional scenario also did not reach full FSS; however, 4% of the land remained unused, as the limiting factor was the excessive wheat demand needed to meet the dietary requirements of monogastric animals (Supplementary Fig. 14). The

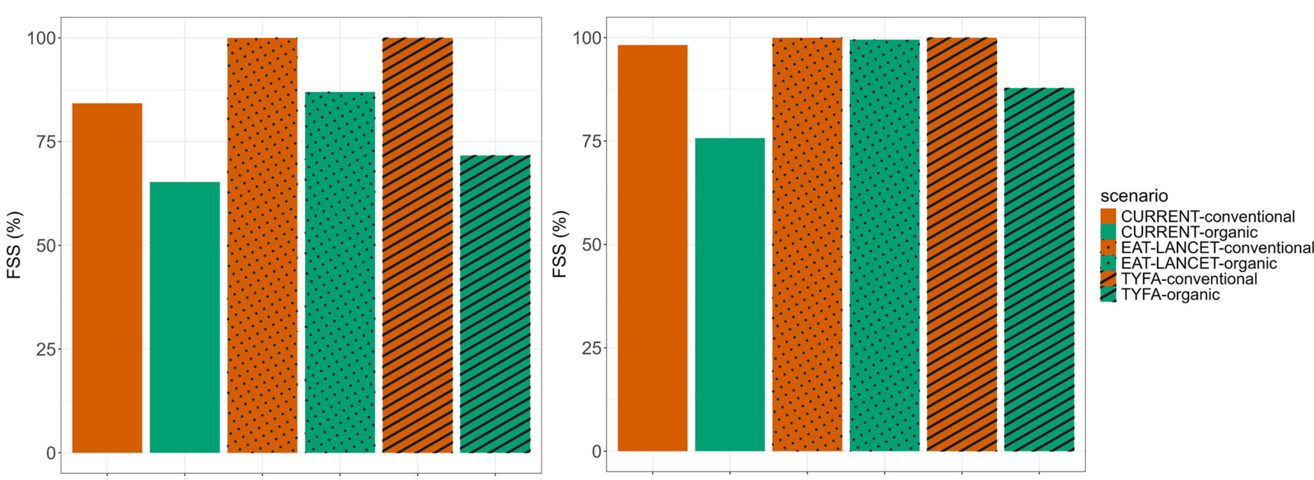

Fig. 1 | Food self-sufficiency (%) permitted by different diet–farming system combinations under 30% (left) and 10% (right) food waste scenarios. This figure shows the percentage of food self-sufficiency (FSS), meaning the average ratio between production and the territory's needs for each food category, achieved in Wallonia across six combined diet and farming system scenarios, modelled under two food waste assumptions: 30% (left panel) and 10% (right panel). The optimisation model allocates crops across agricultural regions to best align food production with local consumption needs for each scenario. The diets considered are CURRENT, EAT–LANCET, and TYFA, each evaluated under both conventional and organic farming systems. Scenario distinctions are indicated by colour and pattern: orange bars for conventional farming, green bars for organic; plain bars represent the CURRENT diet, dotted bars EAT–LANCET, and striped bars TYFA.

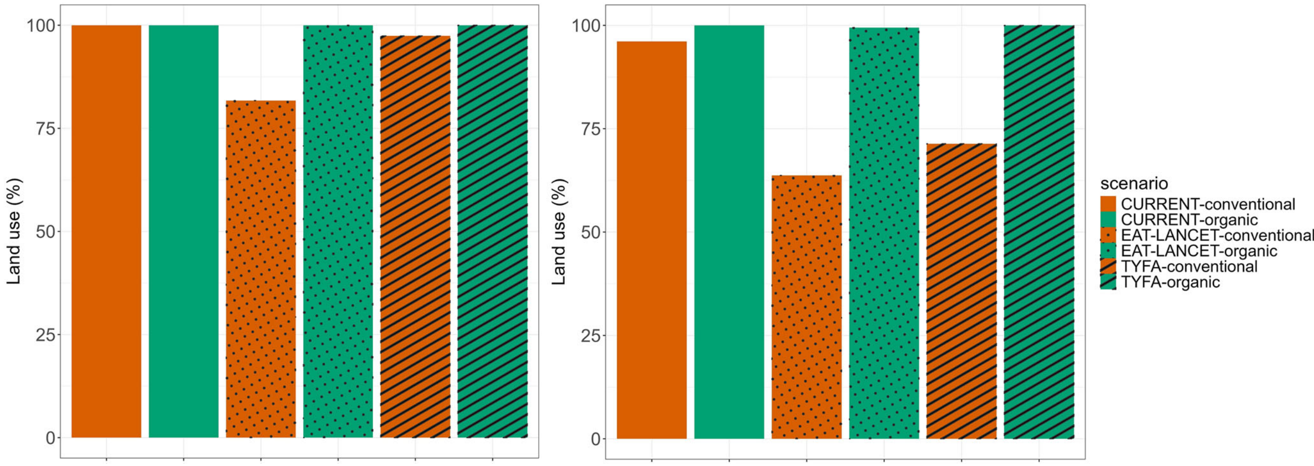

Fig. 2 | Land use (%) permitted by different diet–farming system combinations under 30% (left) and 10% (right) food waste scenarios. This figure illustrates the land use, meaning the area used by crops relative to the total available area in Wallonia according to the model, for six combined diet and farming system scenarios, under two food waste assumptions: 30% (left panel) and 10% (right panel). The model optimises land allocation across agricultural regions to meet food production requirements aligned with each diet scenario. The diets considered are CURRENT, EAT–LANCET, and TYFA, each paired with conventional and organic farming systems. Colours and patterns distinguish the scenarios: orange bars indicate conventional farming, green bars organic farming; plain bars correspond to the CURRENT diet, dotted bars to EAT–LANCET, and striped bars to TYFA.

EAT-Lancet-conventional scenario stood out as the least land-intensive, using only 64% of the available land. Its organic version achieved full FSS by utilising 99% of arable land. Regarding the TYFA-conventional scenario, 71% of the territory was required to reach full FSS (Fig. 2).

When looking at the optimised allocation of crops in each agricultural region, smaller regions tended to be the ones where the algorithm allocated greater diversity, whereas the large production areas were mainly dedicated to three crops: cereals, oilseeds, and protein crops (Supplementary Figs. 7 and 15).

Stocking rate

Under the initial scenario of 30% food waste, when targeting the EAT-Lancet diet, the current Walloon permanent grasslands area was sufficient to provide forage for cattle, resulting in stocking rates (LU/ha) ranging from 0.51 LU/ha in CF to 0.60 LU/ha in OF. The model results indicated that under the CURRENT diet, the stocking rate reached 2.11 LU/ha in CF and 2.05 LU/ha in OF. An additional 30687 ha of temporary grasslands were necessary to complement the forage production from permanent grasslands in order to meet forage requirements in the CF scenario, and 97474 ha in the OF scenario. In a TYFA diet, cattle density reached 1.97 LU/ha in OF and 2.03 LU/ha in CF. An additional 84951 ha of temporary pastures were required to fulfil the needs in the OF scenario, and 20151 in the CF scenario.

With a reduction in food waste to 10%, the stocking rate decreased to 0.40 LU/ha for the EAT-Lancet-CF scenario and to 0.46 LU/ha for its organic counterpart. For the CURRENT diet, stocking rates reached 1.80 LU/ha in CF and 1.90 LU/ha in OF. Finally, for the TYFA diet, the cattle density was 1.68 LU/ha in CF and 1.83 LU/ha in OF. Only in the CURRENT-organic and TYFA-organic scenarios, 32677 and 21886 ha of temporary grasslands, respectively, were necessary to complement forage production.

Considering all animals, the organic scenarios showed an overall increase of 12% in livestock numbers, regardless of diet or food waste. Switching from a CURRENT to a TYFA diet reduced herd size by 47%, and switching from a CURRENT to an EAT-Lancet diet reduced total livestock numbers by 73%. Regarding herd composition, in the EAT-Lancet and CURRENT scenarios, ruminants accounted for 23% and 28% of the total herd, respectively. In contrast, under the TYFA diet, this share increased to 48% (Supplementary Figs. 8 and 16).

Discussion

The aim of this study was to align the food production of a given region with the consumption of its inhabitants to support sustainable diets and farming systems in the case study of Wallonia. Modelling reveals that achieving full FSS for the CURRENT diet habits is not feasible, whether using CF or OF. This highlights the vulnerability of the Walloon food system, with its supply chains deeply embedded in a globalised market. Some regions, such as North Africa and the Middle East, suffered from this vulnerability during the Ukraine war, when food import disruptions occurred[38]. The European Union faced similar issues during the COVID-19 pandemic, which exposed weaknesses in the supply of essential goods like medical supplies[39]. These types of disruptions, especially in the agricultural sector and food supply chains, are expected to intensify in the future due to climate change, further threatening global food security[40]. These findings underscore the importance of relocating food production[41].

The modelling results indicate that it would be possible to feed the entire population of the Walloon and Brussels regions with current levels of food waste if the average diet follows the nutritional recommendations proposed by the EAT-Lancet Commission. This transition to a healthy and sustainable diet would free up almost one-fifth of the land, creating opportunities for other agricultural uses, such as energy crops or the activation of additional agroecological practices to further enhance sustainability. Moreover, land use changes resulting from dietary transitions and improvements in FSS can support a diversification of crop rotations, even within CF. Such diversification has been shown to strengthen agroecosystem resilience by reducing vulnerability to pests, diseases, and climatic variability, while also improving water and nutrient use efficiency, and enhancing long-term soil fertility and health[42]. However, the EAT-Lancet diet lacks circularity, as it relies predominantly on monogastric animals for its meat supply[43]. In a context where more than half of the Walloon territory is covered by permanent grasslands, there is an opportunity to utilise this resource as fodder, as well as crop by-products, for ruminants. The TYFA commission took this into account in its proposed diet. Our model shows that it is also possible to achieve full FSS by following the recommendations of this diet while leaving a little land available for other uses.

In the context of the necessary agroecological transition[44], it is important to highlight that our study focused on OF, which represents one facet of this broader transition. Under the current parameters, a full transition to OF never achieved complete FSS for any of the three diets studied with a 30% food waste level. Only the more stringent EAT-Lancet diet, which significantly reduces meat consumption, allows almost full FSS. Therefore, other levers must be activated. In developed countries, food waste primarily occurs at the consumer level[45]. Cultural shifts in how consumers value food and understand the environmental impact of food waste could significantly reduce waste[46]. In a scenario where food waste is reduced from 30% to 10%, full FSS is almost reached for the CURRENT diet in a CF system, and full FSS is achieved for the EAT-Lancet and TYFA diets, using only 64% and 71% of arable land, respectively. Moreover, when transitioning to OF, food autonomy could be reached for the EAT-Lancet diet, though this would require almost all the available land, leaving little room for non-food production. In organic systems, the beneficial effects of diversified crop rotations, as discussed above, are further amplified. Reduced reliance on synthetic inputs leads to lower pollution of air, water, and soil, while simultaneously reducing toxicity risks to humans and wildlife. In addition, organic systems contribute to the preservation of natural resources and biodiversity, which are crucial for ensuring ecological balance and the long-term productivity of agricultural landscapes[47]. Altogether, these co-benefits, which must be considered when evaluating overall sustainability, underline that land use transitions can generate positive externalities beyond food production, contributing to a broader range of ecosystem services and delivering tangible societal gains. Moreover, when agroecological practices are deployed at the landscape scale, emergent properties and synergies arise that go beyond field-level effects. Large-scale transitions can reduce yield losses and enhance multiple ecosystem services simultaneously. These system-level benefits arise from complex interactions across spatial scales, emphasising the importance of integrated landscape management[48].

These findings also open a reflection on the land use strategies that underpin different agricultural systems. CF, particularly under the EAT-Lancet diet scenario, could be seen as leaning toward a land-sparing approach: intensifying production on limited areas to free up land for other uses or conservation. In contrast, OF systems, with their extensive practices and integration of biodiversity-friendly measures, align more closely with a land-sharing strategy, where production and ecosystem functions are interwoven across the landscape. While both strategies have merits and trade-offs, future research could benefit from explicitly assessing their implications for biodiversity, ecosystem services, and regional resilience. Adopting a landscape approach would allow for a more comprehensive evaluation of how to balance food production, conservation, and social needs in a multifunctional rural space.

Recent meta-analyses and long-term field experiments indicate that the yield gap between organic and conventional farming may decrease over time. Ponisio et al. (2015) found that the average yield deficit of organic systems is about 19%, smaller than earlier estimates, and that diversification practices such as multi-cropping and crop rotations can further reduce this gap[21]. Additionally, long-term trials have shown that organic yields can approach conventional yields after 10–13 years, associated with improvements in soil health and ecosystem stability[49]. These findings suggest that yield reductions are not fixed but can diminish as organic systems mature, which is an important consideration for future modelling efforts.

The low stocking rate in the EAT-Lancet scenarios stems from the fact that meat production from the dairy farming system alone is nearly sufficient to meet the population's needs. Therefore, forage produced on permanent grasslands is sufficient to fulfil the needs of cattle. A major advantage of permanent grasslands lies in their extensive management: in natural grasslands where the symbiosis between legumes and nitrogen-fixing bacteria is optimal, nitrogen fixation can range from 150−250 kg/ha/year[50]. Ruminant farming on these grasslands thus allows for the transfer of fertility from grasslands to other cultivated plots, leading to a net nitrogen input into the system. Moreover, this manure input helps increase organic matter levels in the soil[51]. In addition to agricultural production, grasslands provide numerous ecosystem services such as carbon storage through photosynthesis and grazing[52], soil stabilisation, regulation of water and pollutant flows, as well as the preservation of biodiversity[53,54].

Under the TYFA and CURRENT diets, stocking rates on grasslands are higher because of the increase in beef meat consumption. In some scenarios, the establishment of temporary grasslands in the agricultural landscape is necessary to complement forage production for ruminants. A major benefit of temporary grasslands that include legumes is the provision of nitrogen to subsequent crops through symbiotic fixation[55]. They also help increase the organic matter content in agricultural soils[56]. The implementation of temporary grasslands in a crop rotation significantly reduces the prevalence of weeds[57] due to the crop diversification effect[58], the increased competitiveness of grasslands against weeds compared to crops[59], and the management of the pasture (grazing and/or mowing) which depletes weed stocks. This effect is further enhanced by the integration of livestock, which reduces weed pressure even more compared to systems without grazing[60]. Our modelling results regarding herd proportions under the TYFA diet are consistent with those obtained by Poux and Aubert, who highlighted similar trends in the composition of herds in their assumptions for the TYFA diet compared to current practices in Europe. This agreement strengthens the validity of our approach and confirms that the recommendations of the TYFA diet, in terms of herd management, are realistic and applicable in the current context of the studied region.

Smaller agricultural regions tended to be those where the algorithm allocated greater crop diversity, while larger agricultural regions were generally less diversified. This pattern can be explained by the generally lower yields in smaller regions, due to more constraining pedo-climatic conditions specific to these areas of Wallonia. Consequently, the algorithm found it easier to fine-tune total production by assigning a greater diversity of crops to these smaller regions rather than to larger ones, where increasing diversity would significantly raise overall production. Developing a tool capable of generating crop rotation plans tailored to the specific allocation of surfaces in each agricultural region would be a valuable innovation. By linking land allocation to practical, rotation-ready planting strategies, such a tool could help farmers better optimise their practices, making the model's recommendations more tangible and actionable. This approach would support the dual goals of enhancing resilience and strengthening local FSS.

The findings of this study provide a solid foundation to inform policymakers on issues related to food and agricultural policies in Wallonia. They reveal that, under the CURRENT diet, whether based on CF or OF, the region cannot achieve full FSS. However, shifting towards diets based on the EAT-Lancet or TYFA recommendations would not only enable its food autonomy but also free up land for other non-food uses, exports, or a transition towards more diversified and sustainable farming systems. Reducing food waste emerges as a key lever to improve FSS, particularly within OF. This work confirms the conclusions of previous studies that have already shown the great potential of waste reductions and/or transitions towards healthier diets[14,24].

One limitation of the present study lies in the use of single representative crops for each food group, which simplifies the modelling process but may overlook intra-group variation in nutritional content and agronomic performance. For instance, differences between winter wheat and oat in terms of nutrient density and land use requirements are not captured. This simplification was necessary to maintain coherence with available yield data and the aggregated nature of the dietary models used (CURRENT, TYFA and EAT-Lancet), but future studies could address this by disaggregating food groups, provided consistent data are available across production systems.

It would be relevant to explore complementary indicators, such as the socio-economic impact of the relocation of food production with dietary changes and a transition to more sustainable agricultural practices. Analysing greenhouse gas emissions associated with these transformations, and the resulting cropping systems, would also provide valuable insights, as would the study of biodiversity impacts, which play a crucial role in ecosystem resilience. Beyond these factors, it is crucial to consider the implications of climate change on the future resilience of food systems. Recent global analyses show that rising temperatures will significantly impact crop yields, including in regions traditionally considered productive and climatically stable[61]. Considerable variability in yield changes is expected across different regions, making the future uncertain and difficult to predict. This highlights the need to shift towards cropping systems that are both productive and resilient under climate stress. Moreover, climate change is expected to exacerbate pest pressures in both managed and unmanaged ecosystems, posing additional risks to crop productivity and plant health that must be factored into future food system resilience strategies[62]. To improve the accuracy and relevance of modelling exercises, it is essential to explicitly incorporate changes in crop yields driven by climate change, as failing to do so risks underestimating future vulnerabilities and adaptation needs. Our results support this direction by identifying pathways to food autonomy that also reduce pressure on land, opening opportunities to implement more diversified, agroecological practices adapted to future conditions.

It would also be relevant to consider other regions, such as Flanders, when addressing food security and the transition to sustainable food systems. While local production is encouraged, aiming for complete self-sufficiency is unrealistic. We recognise that trade with other regions will always be essential, fostering mutual benefits through imports and exports. These exchanges will remain necessary to compensate for fluctuations in local production, meet the population's nutritional needs, and ensure dietary diversity. This interconnectedness is vital for mitigating economic uncertainties while enhancing the resilience of food systems globally.

While it isn't necessary or desirable for a region to exist in complete self-sufficiency, it is important to demonstrate that it has the ability to produce enough food to feed its population, thereby strengthening its food sovereignty. Food systems research can play a crucial role by exploring redesigns and assessing the impacts and trade-offs of various alternatives[29]. In this context, developing local solutions rooted in agroecological principles is crucial in addressing the challenges of modern food systems[63]. Agroecological practices can enhance ecosystem services contributing to the resilience of agricultural systems. However, their full potential can only be realised when combined with complementary measures like dietary shifts, food waste reduction, and supportive policies. Furthermore, agroecology encompasses a wider societal dimension, including reconnecting producers and consumers through shorter supply chains and fostering local food sovereignty. Together, these agronomic, ecological and social dimensions of agroecology form an integrated approach necessary for sustainable food system transformation[44]. In this study, we designed a generic procedure, along with its underlying model, to contribute to these broader objectives. This model can be applied to any region—whether local or supra-national—aiming to enhance its food security by relocating its food production.

Methods

Diets

Three diets were evaluated for this study (Table 1). The reference diet was retrieved from Poux et Aubert (2018)[18] and represented the current dietary pattern in Europe. Based upon an existing study on Belgian consumption[64], targeting this diet as the current Walloon diet is a reasonable assumption. The second was the diet proposed by the TYFA (Ten Years For Agroecology) commission : a European initiative that aimed to envision and propose a scenario for agroecological transition in European agriculture by 2050[18]. The third was the diet proposed by Willet et al. in 2019, as part of the EAT-Lancet commission, a global initiative that sought to define a diet capable of feeding healthily a growing global population while respecting the planet's ecological boundaries[15].

The food requirements for each food category were considered for 4950000 people (Wallonia and Brussels region) for an entire year. Finally, a current food waste percentage of 30% was taken into account[45] at first. This estimate includes both food waste and food loss occurring during harvest and post-harvest stages. An alternative scenario assuming a reduced food waste and loss rate of 10% was then considered.

For the Eat-Lancet diet, all categories of added fats were aggregated into a single large category, as were vegetables. Legumes and tree nuts were aggregated into a single large category.

Table 1 | Daily consumption of each food category (g/day) according to the CURRENT[18], TYFA[18] and EAT-Lancet[15] diets

Food category	CURRENT	TYFA	EAT-Lancet
Cereals	278	300	232
Oilseeds	34	34	51
Potatoes	116	80	50
Sugar	36	23	31
Legumes	5	30	125
Vegetables	134	300	300
Beef	37	36	7
Pork	88	36	7
Poultry	58	20	29
Dairy	505	300	250
Eggs	20	10	13

Fish was excluded not only because Wallonia lacks access to the sea—limiting local fish production—but also because the study focuses on optimising the use of land resources, which is independent of marine production. Fruits were left out because, in Wallonia, they are mainly produced through perennial tree crops, which do not fit into a land allocation strategy based on arable land and crop rotations. Beverages were also excluded to stay aligned with the EAT-Lancet diet framework, which does not include them. To be consistent among the TYFA and EAT-Lancet diets, a requirement of 300 g of vegetables per person per day was considered.

Since fruit production was not taken into account, the current arable land allocated to orchards was not considered in the model.

For each diet, lamb meat requirements were aggregated with beef meat requirements because cattle represent the vast majority of ruminant production in Belgium[65].

Animal production

Four categories of animals were modelled: cattle, pigs, laying hens, and broiler chickens. The parameters regarding the production levels and the diets considered are available in Table 2. In the algorithm, total requirements and production were given in fresh matter for all categories except forage, which was expressed in dry matter.

Human and animal nutritional needs were combined to calculate total crop requirements. When the FSS rate was below 100%, this meant that only a proportional share of the combined human and animal demand could be satisfied. The deficit was distributed proportionally according to the relative consumption ratios between humans and the different animal categories.

Crop production

For each food category in the diet scenarios, the yield levels of the most representative open-field crop species in Wallonia were selected for modelling. Thus, winter wheat represented the cereal category, rapeseed stood for oilseeds, peas for legumes, sugar was produced from sugar beet, and vegetables were represented by carrots. The following crop conversion factors were applied in the model: sugar beet to sugar (0.18) and pulp (0.22), rapeseed to oil (0.44) and meal (0.56), and winter wheat to flour (0.75) and bran (0.25)[66].

This approach was aligned with the aggregated nature of the dietary frameworks used (CURRENT, TYFA and EAT-Lancet), which do not specify individual crop species within food groups. Representative crops were therefore chosen to reflect regional production patterns and to ensure consistency in yield data, especially across CF and OF.

Agricultural regions

The yields of the different crops for each agricultural region were calculated based on the average of the 2019–2023 period available on StatBel[65], and the

Table 2 | Parameters of the model regarding pig, cattle, chicken meat and egg production

Animal	Parameter	Hypothesis	References
Pig	FCR (including feed for parent animals)	3	69
	Pig feed composition	90% cereals – 7% legumes – 3% rapeseed meal	
	Pig weight at slaughter	115 kg	
	Pig muscle content (in relation to live weight)	0.6	70,71
	Livestock unit (LU) pig	0.3	72
Cattle	Milk / cow / year	8492 l	69
	Cow fecundity	0.98	
	Replacement rate dairy cows	0.19	
	Replacement rate suckler cows	0.10	
	Mortality rate offspring	0.01	
	Carcass weight at slaughter dairy cow	280 kg	
	Carcass weight at slaughter dairy heifer	270 kg	
	Carcass weight at slaughter dairy bull	325 kg	
	Carcass weight at slaughter suckler cow	340 kg	
	Carcass weight at slaughter suckler heifer	300 kg	
	Carcass weight at slaughter suckler bull	340 kg	
	Slaughter age dairy cow	87 months	
	Slaughter age dairy heifer	24 months	
	Slaughter age dairy bull	18 months	
	Slaughter age suckler cow	144 months	
	Slaughter age suckler heifer	18 months	
	Slaughter age suckler bull	18 months	
	Ingestion/year dairy cow	4700 kg d.m. forage, 1600 kg cereals and coproducts, 400 kg oilseeds meals, 1200 kg legumes, 600 kg sugar beet pulp	
	Ingestion/year dairy heifer	1800 kg d.m. forage, 200 kg cereals and coproducts, 20 kg oilseeds meals, 300 kg sugar beet pulp	
	Ingestion/year dairy bull	966.67 kg d.m. forage, 700 kg cereals and coproducts, 133.33 kg oilseeds meals, 466.67 kg sugar beet pulp	
	Ingestion/year suckler cow	3300 kg d.m. forage	
	Ingestion/year suckler heifer	2133.33 kg d.m. forage, 400 kg cereals and coproducts, 400 kg legumes	
	Ingestion/year suckler bull	2133.33 kg d.m. forage, 400 kg cereals and coproducts, 400 kg legumes	
	Meat yield	0.73	73
	LU Milking Cow	1	72
	LU Suckler Cow	0.8	
	LU Female < 1 year	0.4	
	LU Male < 1 year	0.4	
	LU Female < 2 years	0.7	
	LU Male < 2 years	0.7	
Broiler	FCR (including feed for parent animals)	1.8	69
	Broiler feed composition	70% cereals – 15% legumes – 15% rapeseed cake	
	Weight at slaughter	1.9 kg	
	Bones in the carcass	17%	74
	Carcass yield	75%	75,76
	LU broiler	0.007	72
Laying Hen	FCR (kg feed per kg egg)	2	69
	Layer feed composition	70% cereals – 20% legumes – 10% rapeseed meal	
	Eggs per hen	20 kg	
	LU laying hen	0.014	72

Table 3 | Average crop yields (tons of fresh matter / ha for all categories except forage, which is expressed in tons of dry matter / ha) along with the area (ha) for each agricultural region in Wallonia[65]

	Cereals	Forage	Legumes	Maize	Oilseeds	Potatoes	Sugar beet	Vegetables	Area
Ardenne	6.76	10.50	2.95	43.09	3.39	28.40	79.47	43.07	31838.48
Condroz	8.33	11.25	3.67	40.35	3.73	38.35	76.13	58.15	89978.16
Fagne	7.47	8.25	3.41	38.42	3.03	35.10	71.17	53.23	5158.44
Famenne	7.21	9.00	3.32	39.37	3.47	40.95	72.88	62.10	24752.76
Haute Ardenne	4.50	9.75	2.35	37.01	3.03	16.48	87.63	24.98	2949.51
Herbagere	8.95	11.25	3.50	44.69	3.47	46.14	89.25	69.96	8975.23
Jurassique	6.53	11.25	2.06	38.28	3.61	21.89	86.80	33.19	9031.15
Limoneuse	9.29	12.00	3.87	43.91	3.91	41.85	89.86	63.46	213830.14
Sablo-Limoneuse	9.00	12.00	3.94	43.21	4.04	42.86	84.29	65.00	37006.08

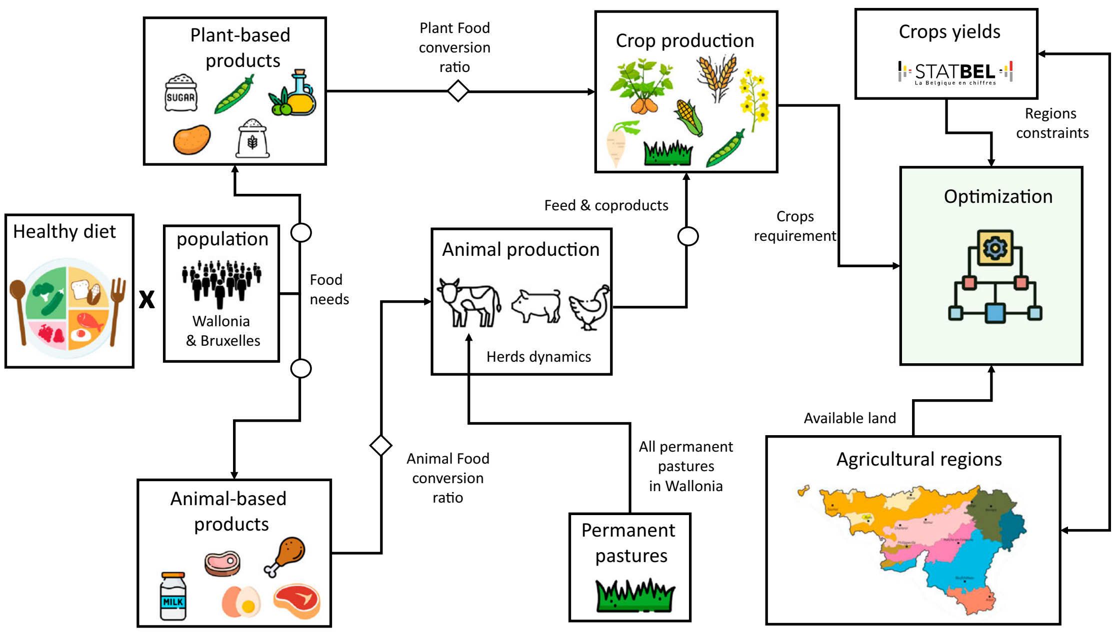

Fig. 3 | Visualisation of the Walloon food system optimisation model. For each diet–farming system–food waste scenario, the model optimises crop allocation across Wallonia's agricultural regions to meet total food demand for the Wallonia and Brussels population (~4.95 million) over 1 year. Food requirements are converted into crop and land needs using representative crops and region-specific yields for conventional and organic systems. Land use constraints include fixed permanent pasture areas and a maximum of 50% land allocation per crop per region. The optimisation minimises the difference between total production and consumption across all food categories and regions.

available area in each agricultural region corresponded to that of 2023 (Table 3). The mean yield of vegetables for Wallonia was obtained through the regional centre for horticultural advice (CIM, *personal communication*) and was benchmarked based on potato yield in each agricultural region. The current area of permanent pastures in each agricultural region was considered unchangeable in the model. Their production was included in the calculations for forage needs. If this was insufficient, temporary pastures could be allocated to complement forage production. The yields of temporary and permanent grasslands were obtained by the regional advisory centre specialised in this area[67]. The surface area of the agricultural region "Campine Hennuyère" was considered negligible (38 km^2) and was therefore not taken into account individually, as it was aggregated with the "Sablo-Limoneuse" region.

Organic practices

To model OF, yield reduction factors were applied on each plant and animal category (Table 4). Animal diets did not need to be changed, as they already complied with organic specifications. These yield reduction ratios were based on average long-term estimates from published literature[18,21,22], aiming to reflect steady-state conditions after conversion to OF. Our modelling assumes a conservative scenario consistent with current average performance levels in Wallonia and Western Europe. This choice allows comparability with other food system modelling studies using similar assumptions.

Optimisation

The model was designed using R software 2023.12.0 version[68]. The optimisation algorithm used was the "NLOPT_LN_COBYLA" from the *nloptr* package. It is a derivative-free, nonlinear optimisation method that constructs linear approximations of the objective and constraint functions. The *maxeval* parameter was set to 250 000 and *xtol_rel* to 1.0e-6. A visualisation of the food system model is available in Fig. 3.

The R model was developed based on the food demand of the population. This demand was determined by multiplying the daily food requirement per person for each food category by the number of days in a year and by the total population in Wallonia and Brussels.

Table 4 | Crop yields reduction ratio when switching from conventional to organic farming for crops[18,21] and animals[22]

Category	Yield reduction
Cereals	0.75
Rapeseed	0.55
Pea	0.65
Potatoes	0.65
Sugar beet	0.80
Maize	0.85
Vegetables	0.80
Temporary pastures	0.89
Cattle (meat and milk)	0.86
Pigs	0.90
Poultry layers	0.90
Poultry broilers	0.91

The demand for animal-based products was converted into crop production needs by considering the annual dietary requirements of each type of animal (for cattle) or production cycle (for monogastric animals). When co-products were available as a result of the food requirements, these were subtracted from the feed demand for the associated feed categories. The food and feed demands were then aggregated to determine the total needs for cereals, legumes, forage, maize, oilseeds, potatoes, sugar beets, and vegetables.

In each agricultural region, the maximum area allocated to any crop was limited to 50% of the total land area. The last constraint applied in the optimisation algorithm was not to exceed the available land in each region. The objective of the algorithm was to minimise the sum of the squared differences between total production across the territory and the total population demand for all food categories (see Eq. (1)).

$$\sum_{category=cereals}^{category=vegetables} \left(Need_{category} - Offer_{category} \right)^2 \qquad (1)$$

Evaluation criteria

For each of the six diet-system combinations, three parameters were evaluated: (i) land use, meaning the area used by crops relative to the total available area, (ii) food self-sufficiency expressed as % FSS, meaning the average ratio between production and the territory's needs for each food category, and (iii) the livestock density in LU per hectare of grasslands (only for grazing animals) along with the total livestock number (in LU).

Data availability

All data generated or analysed during this study are included in this published article.

Code availability

The underlying code for this study is not publicly available but may be made available to qualified researchers on reasonable request from the corresponding author.

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Author contributions
B.D., J.B. and T.D. designed the conceptual framework of the model. T.D. implemented the model and performed the runs of the model. B.D., J.B. and T.D. analysed the data. T.D. wrote the first draft of the manuscript. B.D., J.B. and T.D. edited and reviewed the manuscript.

Competing interests
The authors declare no competing interests.

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