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An interactive model to assess pathways for agriculture and food sector contributions to country-level net-zero targets

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The Food and agriculture system plays a determining role in many countries ambitions to achieve net-zero by 2050. Sector pathways consistent with this objective most frequently describe sustainable intensification as the dominant response. This narrows the option space for the agricultural sector and restricts its ability to address multiple sustainability issues simultaneously. Here we present an interactive model ARISE (AgRIculture and food SystEm interactive model) which allows stakeholders to design complementary food and agriculture sector pathways and build consensus. As a first case study, we provided an environment-oriented NGO assessment of a UK agroecology pathway and evaluate the benefits in comparison with alternative pathways available in the literature and developed by the UK Government. This shows how the ARISE model can enable the exploration of critical trade-offs between the multiple sustainability objectives.

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Since the 1950s Green Revolution, the combination of mechanisation, new varieties of crops, and the intensive use of pesticides and synthetic fertilisers has allowed the continuous mitigation of global hunger and food insecurity[1]. For the United Kingdom (UK), the effect of the Green Revolution is illustrated by the increase in crop and animal-based production by 40% and 90% respectively over the last 60 years, while the population only grew by 30%[1]. Thanks to geographical and farm-level specialisation towards crops or livestock[2], and the simplification of the crop rotations around cereals and oil crops[3], the gains in efficiency enabled a 10% drop in land requirements over the same period. Nevertheless, the widespread adoption of these resource-intensive practices led to uneven benefits and critical sustainability impacts, both domestically and worldwide.

The simplification and decoupling of the crop and livestock systems corresponded with an increase in the use of synthetic fertilizers[1,3], formerly sourced from manure and symbiotic fixation from legume rotations. Cereal yields doubled between 1961 and 1990 but the use of synthetic fertilizers increased by about 300%[1]. The use of synthetic fertilizers has dropped by 30% since 1990, but cereal yields remain barely higher in 2020 than in 1990[1]. As a consequence of these intensive practices, the agriculture sector currently accounts for 77% of UK nitrous oxide (N_2O) emissions[4]. Around 75% of sediments, 60% of nitrates and 25% of phosphorous pollution in UK water bodies have farming origins[5]. These releases contribute substantially to the overshoot of multiple planet boundaries, including climate change, biodiversity loss, and the nitrogen and phosphorus cycles[6]. The simplification of crop rotations also increased the exposure to pests and thus the dependency to pesticides that contaminate UK ecosystems[5,7,8]. Indeed, the abundance of UK priority species has declined by 60% in the last 50 years, and 97% of wildflower meadows have been lost since 1930, with unsustainable agriculture identified a major driver[7] of this loss. Wild pollinator species as well as wild farmland birds also declined over the past 2 decades[8]. Empirical evidence associates pesticide use with the adverse health outcomes (e.g., leukaemia, Alzheimer's disease)[9] of agricultural workers while also being often detected in foodstuffs. Contamination has also been observed in 47% of consumer food samples tested in the UK in 2017[10].

The evolution of the British diet over recent decades has increasingly exposed the population to food-related diseases (from diabetes to psychological issues)[11] and leading to increased mortality. In 2018[12], around two third of the adult population were overweight (body mass index (BMI) ∈ [25;30[), i.e. 15% more than in 1993. Overall, the UK's National Health Service estimated the food-related diseases and deaths costs about £9.7bn per year (£49.9bn as societal cost)[13]. Also symptomatic to other high-income countries[14], it is estimated that 10Mt of food were wasted and lost in 2018, of which 70% can be attributed to households[15]. The BMI is an indicator that is used to categorize a person from underweight, to very severely obese. It is expressed in kg/m^2 and defined as the body mass divided by the square of the body height. The BMI is used by the World Health Organisation (WHO) as the standard for recording obesity[16] although its accuracy has been assessed as limited[17]. One obvious limitation is that the BMI does not distinguish between fat and muscle, meaning that muscular individuals like trained athletes can have BMIs up to 32 but not related to fat accumulation[18].

The UK agriculture sector was responsible for $42MtCO_2$eq.[19]of GHG (Greenhouse gas) emissions in the UK in 2018, about the tenth of total UK emissions. Despite increased production, however, emissions from the food and agriculture sector fell by 13%[19]since 1990. This was mostly driven by a decrease in the population of ruminant livestock that meant fewer total emissions from enteric fermentation[1,19]. However, the decoupling of livestock and crop production also led to a 15-fold increase in soybean cake fed to livestock between 1961 to 2020[1]. Two-thirds of which is imported from Latin America[1] where deforestation is occurring also as a consequence of expanded soybean cultivation[20]. Furthermore, the UK overall food self-sufficiency ratio has been decreasing over the years, from 75% in 1984 to 62% in 2018[21]. The external dependency on synthetic fertilizers and natural gas also places pressures upon the whole system through possible global shortages[22] which poses a systemic risk to the UK and requires continuous vigilance[23].

In 2019 the UK Government amended the 2008 Climate Change Act[24] to commit achieving net-zero by 2050, which requires that emission sources and sinks are in balance. About a dozen agri-food pathways have been developed to support the UK in achieving its 2050 net-zero target[25–28] in which dietary and behaviour shifts in combination with sustainable intensification is the dominant driver of reduced emissions[3,25–27]. Nevertheless, this techno-optimistic vision falls short in addressing some critical sustainability issues[3]. Such an approach describes an intention to do more with less, but this usually means continuing production with increased use of capital and increased farm expansion and specialization. This still falls short in terms of nitrogen cycle, biodiversity and landscape restoration[3]. It also risks mal-adaptation and mal-mitigation suppressing the calls for a real transformative change[29]. As an illustration, the 6th UK Carbon Budget[30] states that: "the ability of (…) agroecology farming measures to deliver deeper emissions reduction (…) and to deliver wider environmental benefits are not included in our scenarios due to the lack of robust evidence on the abatement potential", although some academic literature, for example, Poux et al. demonstrates otherwise[3,28]. Such literature also highlights that dietary changes are disproportionally critical to either a shift towards agroecology or towards sustainable intensification in Europe and the UK[31–33].

Widespread multi-sector, multi-level, action is required to change what and how food is consumed, what and how it is produced, and to thereby lower its impacts on health, society, and the environment[34]. By whom and how such a transformation of the food and agriculture system is thought about and conceptualised leads to widely different but nevertheless insightful visions. For example, aligning multiple sustainability objectives can uncover critical trade-offs[35]; heterogeneous sustainability priorities among the stakeholders can lead them to support different if not opposite solutions. To fulfil this need to understand alternative pathways we have developed an exploratory and interactive model, named ARISE (AgRIculture and food SystEm interactive model) to provide the stakeholders with the means to investigate independently the relationships, synergies, trade-offs, and sensitivities between the key variables of the system. This enables multiple stakeholders to speak a common language, and to explore alternative pathways agnostically, backed up by an extended literature. As a first application, we provided the European Environmental Bureau (EEB)—a non-governmental organization (NGO) that brings together 170 civil society organisations in 35 European countries—with ARISE to give them the means to develop their own pathway for the UK food and agriculture system. The design and learning process enabled the NGO to think, explore, highlight, and consider the trade-offs between multiple and sometimes conflicting sustainability objectives. This paper aims at presenting this first experience, to demonstrate how the ARISE model can be used to enable stakeholders to develop new insights and pathways, and how to compare alternative pathways. Based on the work with the EEB, it also provides an agroecological pathway for the UK that offers alternative insights to a literature strongly dominated by discussion of sustainable intensification solutions.

Results

The following subsections presents the pathway designed in collaboration with the EEB using the ARISE model and describes how it has been designed.

Codesign process. Owing to travel restrictions and sanitary rules during the Covid pandemic lockdown, the codesign process was performed remotely. As a first step, the ARISE model was presented and discussed during a workshop organized by the EEB for their members. This included a two-ways knowledge transfer objective: (1) we presented the model, interface (pathway explorer), and how to use it, and described the set of levers and their ambition levels. Levers refer to a set of possible actions, technology deployment, practice shift, or behaviour changes that can affect the food and agriculture system, either positively or negatively (e.g., diet choices). Each lever can be set according to multiple ambition levels, i.e., the extent for which an action, technology, practice, or behaviour can be implemented (e.g., diet patterns based on historical trends, WHO recommendations, and so on). (2) We gathered feedback from the EEB members to identify possible flaws, missing features, and lack of user friendliness. Overall, we found the model to offer a strong basis for exploratory pathway analysis that covers most of their identified sustainability issues, except for their desire to better understand the cost of the system. The functionality to address this latter issue is currently under development using a true cost-of-food approach, i.e., including the externality costs[36]. However, it has not been implemented yet. It is worth mentioning that the nitrogen cycle and the agroforestry practices were refined in response to EEB Members' recommendations.

As a second step, we set up a series of interactive and bilateral remote meetings with the EEB to develop a pathway that accorded to their members' scenario narratives. The latter being expressed in terms of ambition levels used within the ARISE model as inputs (e.g., moving towards agroecological systems). Narratives referring to the model outcomes were checked once the model ran (about 5 min computation). Doing so, the model highlighted some trade-offs between the sustainability objectives. As an illustration, the combined set of narratives for self-sufficiency (increasing domestic indigenous production), diet shift (towards plant-based diets[34]), livestock density (grass-fed priority), and cropland and grassland management led to a substantial decrease in the required agriculture land area. This conflicted with one of the narratives that involved maintaining the current level of agriculture land area. Consequently, EEB explored several ways to prioritize their sustainability objectives. Finally, the pathway was refined for a reduced emphasis on dietary change while remaining in line with the WHO recommendations; this includes a lower reduction in livestock raising, mechanically driving up meat and feedstuff production and the use of agriculture lands to meet the grass-fed and self-sufficiency constraint. This illustrates the users' learning process and how the pathway was refined iteratively. Table 1 sums up the former and main EEB scenario narratives and how they were updated throughout the process.

Social behaviours. UK demography was assumed to follow UN projections to 2050 in terms of gender and age classes[37]. However, we considered a 25% decrease in the proportion of the population that was obese (i.e., BMI > 30) for each age and gender class. This ambition towards a more adequate physical activity and healthier diet led us to estimate the energy requirement according to each class[38], for an average of 2330 kcal/cap/day, which represents a 5.7% decrease compared to 2017, and to consider the widespread adoption of a healthier diet[38–40]: the meat intake is assumed to drop to 106 g/cap/day on average (i.e. about half compared with 2017), including 13 g of red meat, 73 g of poultry-meat, and 17 g of pig meat; consumption of dairy products is estimated to be almost halved (341 g/cap/day) while a 80% increase for eggs is considered (55 g/cap/day); the consumption of fruits and vegetables is estimated to increase up to 455 and 275 g/cap/day respectively (i.e., a 26 and 9% increase); the plant-based protein intake is estimated to increase, up to 40 g/cap/day for oil crops (mostly soyabeans), and up to 18 g/cap/day for pulses (i.e. about 3.5 and 5 times more than 2017 respectively) A 28% cut on starchy root consumption is assumed, leading to a 200 g/cap/day intake by 2050; The intake of alcoholic beverages and stimulants are estimated to drop by 28% and 40%, which represent a 16 and 186 g/cap/day intake by 2050. The households are assumed to reduce food wastes by 47% in volumes (51% in energy content) compared with 2015. Figure 1 presents the evolution of the UK food supply given these social behaviour trends.

The overall UK food supply expressed in metric tons is estimated to decrease by about 15% by 2050 compared with 2017 despite a 11% population growth (Fig. 1). The food supply for meat, and dairy and eggs are estimated to decrease by 50% and 36% respectively. Oil crops and pulses are estimated to increase by 186% and 87%, as protein-rich plants. Vegetable oil is estimated to drop by 12%, driven by the cut on fat intake. We assumed a moderate decrease of the stimulants and alcoholic beverages consumption (36 and 23% decrease by 2050).

Livestock raising. The widespread adoption of agroecological practices by 2050 is assumed. Consequently, livestock raising is assumed to shift towards a grass-fed system[28] in which the contribution of pastureland in the livestock feeding is increased by 23%, while the density for grazing livestock is assumed to decrease from 0.98 in 2017[1] to 0.9 lsu/ha in 2050[3] (lsu: livestock unit[41]). The phase out of imported soyabean and palm cakes by 2050 is assumed to prevent imported deforestation[20], for the benefits of rapeseed cakes produced in the UK. Meadows and pasturelands are assumed to adopt silvopasture practices, including the deployment of 50 m of hedgerow per hectare, thereby enabling the carbon sequestration of 0.05tC/ha[42]. As well as the plantation of trees for an additional 0.138 tC/ha, which remains conservative compared to Aertsens et al. (2013)[42] estimation. The livestock energy conversion efficiency (i.e., the ratio of energy converted from feed inputs to animal outputs in kcal) are considered constant[43]. Livestock yields are assumed to increase by 20% and 13% for the ruminants and broiler poultry compared with 2017[1,27], and to decrease by 16%, 9% and 3.5% for the dairy cattle, pigs and laying poultry respectively[1,27].

UK self-sufficiency for meat is assumed to be achieved by 2050, compared with 0.84, 0.76, and 0.56 ratios for UK self-sufficiency in poultry, bovine, and pigs in 2017[1]. Milk and eggs are assumed to reach up to their historical maximum self-sufficiency ratio, i.e., 1.33 and 1.13. Consequently, the UK domestic production for animal-based commodities is estimated to decrease by 24% compared with 2017 at the same time as the domestic supply drops by 40%. This is because the UK achieves self-sufficiency for meat.

The livestock population is estimated to decrease by 23% in 2050 compared with 2017 (Fig. 2). Livestock raising is estimated to move towards higher energy conversion efficiency animals, which is a continuation of the past trends[1]. Poultry broilers represented 30% of slaughtered livestock in 1990, 50% in 2017 and 60% by 2050; while the share of dairy cattle and laying poultry represent 25% of the total livestock population by 2050, compared to 21% in 1990, but only 16% in 2017. In contrast, non-dairy cattle which has a lower energy conversion efficiency (i.e.,

Table 1 EEB main narratives in a brief.

Issues	Former narratives	Updated narratives & lessons learnt
Social behaviours	The current UK diet, being unhealthy and resource intensive, moves towards a healthier and plant-based diet thereby lowering the prevalence of food related diseases and the consumption of land-intensive foods. Achieves the wastes and losses Sustainable Development Goal −12.3 target by 2050.	The diet shift objective was lowered to the WHO recommendation diet, thereby limiting the extent to which meat consumption was cut and allowing the maintenance of agriculture land close to current levels. Wastes and losses objectives remain unchanged although more ambitious levels were available in the model and in the literature.
Food security	The UK foreign balance deficit is high for both food and synthetic fertilizers. The target was to reach self-sufficiency for indigenous plant and animal-based commodities; and to reduce the use of synthetic fertilizers by at least-70%.	The model confirmed that the dynamics between self-sufficiency, diet shift, food supply, agriculture lands and the agroecological production system were aligned despite the lower agroecological yields. It even demonstrated that some commodities could be produced up to their historical maximum while maintaining the current agricultural areas. The model also confirmed the pathway to be compatible with reduced use of synthetic fertilizer (the synthetic fertilizer trade balance was not considered).
Imported protein cake	Complete phase-out of soybean and palm-based protein cakes used to feed livestock. Thereby eliminating imports from Latin America which contribute to deforestation.	The model confirmed that substituting imported protein cakes with a grass-fed system, and with local oil crop production were aligned with the other constraints (self-sufficiency, diet shift, food supply, agriculture lands and the agroecological system). Moreover, the model demonstrated the relocation of feedstuff production to allow the maintenance of the level of both cropland (feedstuff) and grassland (grass-fed system) despite the substantial diet shift (reduction in meat consumption).
Agricultural practices	Systematic deployment of agroecological and agroforestry practices., thereby limiting livestock density to 1 livestock-unit/ha for a better grassland management.	The model demonstrated that the agroecological system could be implemented by considering a lower level of effort in terms of shifting diets. Also, the livestock density level was lowered to maintain the grassland areas close to current levels. The model also confirmed the nitrogen cycle to be balanced by substituting leaving the residues in the field at a sustainable level, intercropping with legumes and using manure.
Carbon sequestration	Increasing carbon sequestration in the agricultural soil.	Given the combined narratives, the model enables the quantification of carbon dynamics within a scenario that includes no-tillage, intercrops, agroforestry (hedges and trees), spared land converted to forest as well as the land-use, land-use change and forestry dynamics.
Spared lands	Partly using spare lands for biodiversity conservation and land restoration.	The model allowed the EEB to balance land spared from agricultural production between forests (to foster carbon sequestration) and the restoration of natural ecosystems (limited to grassland with no-grazing in the model).
Non-food biomass	The lack of consensus amongst EEB members about the role of non-food biomass (i.e., biomaterials and bioenergy) led to the consideration of business-as-usual scenarios[27,61]	The model demonstrated that the current level of production of biofuels remain compatible with the other narratives/ constraints.

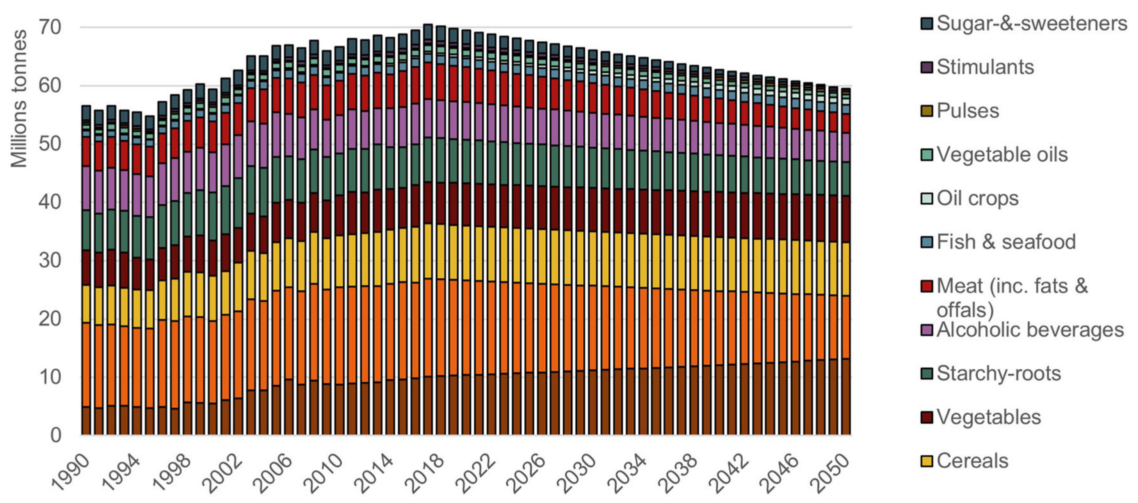

Fig. 1 Food Supply in the UK from 1990 to 2050 in the EEB pathway (tonnes)[1,37–40]. The 40 considered food groups have been aggregated for a better visibility. All figures and data can be found and can be explored through the pathway explorer provided as Supplementary Methods 2: ARISE guidelines.

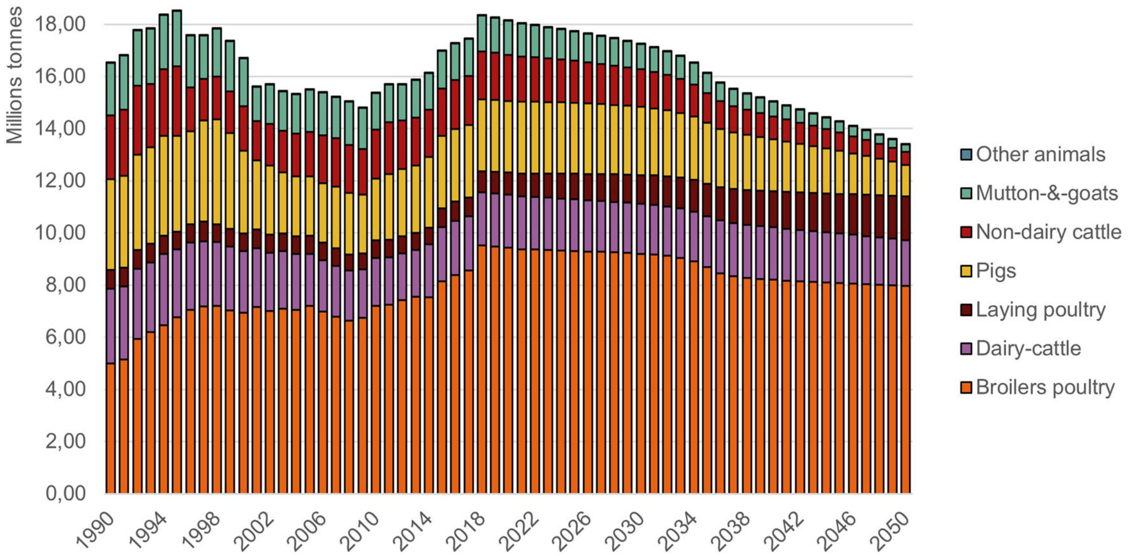

Fig. 2 Slaughtered/producing livestock in the UK from 1990 to 2050 in the EEB pathway (lsu)[1,27,43]. Slaughtered livestock refers to the animals slaughtered per year, while producing livestock refers to living animals (e.g. dairy cattle).

1.9% versus 13% for broiler poultry[43]), represented 15% of the livestock population in 1990, 10% in 2017, and 4% estimated by 2050. Slaughtered pigs are also estimated to be halved compared with 2017. The combined decrease of the livestock, the extensive use of pasturelands, and the shift towards higher energy conversion efficiency animals, allows the feed compounds supply to drop from 18 Mt in 2017 to 7Mt by 2050. The pasturelands are estimated to decrease by only 11% in 2050 compared to 2017, despite the large decrease of the grazing livestock population. That is to save and allocate meadows to biodiversity conservation (Aichi objective 11[44]).

Crops. Widespread adoption of agroecological practices is assumed by 2050. A progressive phase out of synthetic fertilizers and pesticides are assumed that contribute tackling multiple sustainability challenges: i.e., preventing biodiversity losses[7,8] and eutrophication for both soils and water bodies[5,28] (i.e., nutrient enrichment that causes structural changes to the ecosystem); lowering the health risks for both farmers and consumers[9,10]; decreasing the UK dependency to imported fertilizers and its related financial and shortage risk[22,23] (e.g. fertilizer imports costed the UK 130 M£ in November 2021[45]). While the UK is currently among the most intensive user of fertilizers in the EU-28[46], the nitrogen input-output ratio is assumed to reach 109%[28] by 2050, i.e. a nitrogen efficiency of 92%. The nitrogen is assumed to be sourced from manure and symbiotic fixation from legume crop rotations and intercropping practices[28]. Additionally, the no-tillage and cover crop practices are considered to increase the carbon storage in the soil by 0.1 and 0.16 tC/ha[42] respectively. We assumed the deployment of hedgerows on cropland, but we did not consider further tree plantation. That is because of the uncertainty about the impacts on crop yields although we considered conservative assumptions based on organic farming past experience[1,27,28]: about a 27% decrease for cereals by 2050 compared with 2017; from −25% to −45% for oil crops; and −42%, −38%, −35%, −10% for fruits, pulses, starchy-roots and vegetables accordingly.

It is assumed that the UK becomes self-sufficient for (indigenous) crop-based commodities, leading the domestic production to decrease by a third in 2050 compared to 2017 (Fig. 3). That is mostly driven by the cut to feed supply (−11Mt) implied by the dynamics of social behaviours, livestock raising, and self-sufficiency. The self-sufficiency for wheat and starchy roots is assumed to be achieved, compared to a 0.94 and 0.91 ratio in 2017, while pulses reach a historical maximum (1.76). The harvested area is estimated to increase by 10% compared with 2017 (about its 1990 level). That is because of the lower yields implied by the agroecological practices. It is worth noting that a decrease of sugar-crop production is assumed due to the social behaviours' changes but also as a conservative assumption regarding the uncertainty about the yields of chemical free sugar beet.

GHG emissions. The food and agriculture related emissions are estimated to be halved in 2050 compared with 2017. That is mostly driven by social behaviour change[32]. The move towards agroecological practices enables the carbon sequestration of agricultural soils to be widely enhanced (Fig. 4, trees, hedges, cover-crops, no-tillage)[28,42]. Also, the remaining spared lands are partly used for reforestation that also contributes to enlarge the carbon sequestration potential of the UK. As a result, the pathway allows the food and agriculture system to reach net-zero by about 2040. This is because we assumed an s-curve shape as a policy-driven deployment of the agroecological practices that is typical from new technology/policy deployment (e.g., biofuels deployment in the EU-28).

In 2050, a net emission sink of −14 $MtCO_2eq$ is estimated. The decrease of the livestock population mechanically reduces the manure related emissions over the years (about 50%). While the transition towards monogastric livestock at the expanse of the ruminants enables enteric fermentation emissions to be cut by 60%. The conservation of most meadows and pasturelands coupled with the planting of trees and hedgerows enables carbon sequestration to be widely increased, up to 3.1 MtC from trees (i.e., about 12.6 $MtCO_2$), and 0.56 MtC from hedgerows (2.3 $MtCO_2$). The phase-out of synthetic fertilizers combined with better nitrogen efficiency allows fertilizer-related emissions to be cut by 90%. The increase of the cropland combined with agroecological practices enables carbon sequestration to be increased up to 1.1 MtC through cover crops (4.3 $MtCO_2$), 0.6MtC from no-tillage (2.7 $MtCO_2$) and 0.3 MtC from hedgerows (1.3 $MtCO_2$) by 2050. It is worth noting that the drained organic soils-related emissions issues were not addressed.

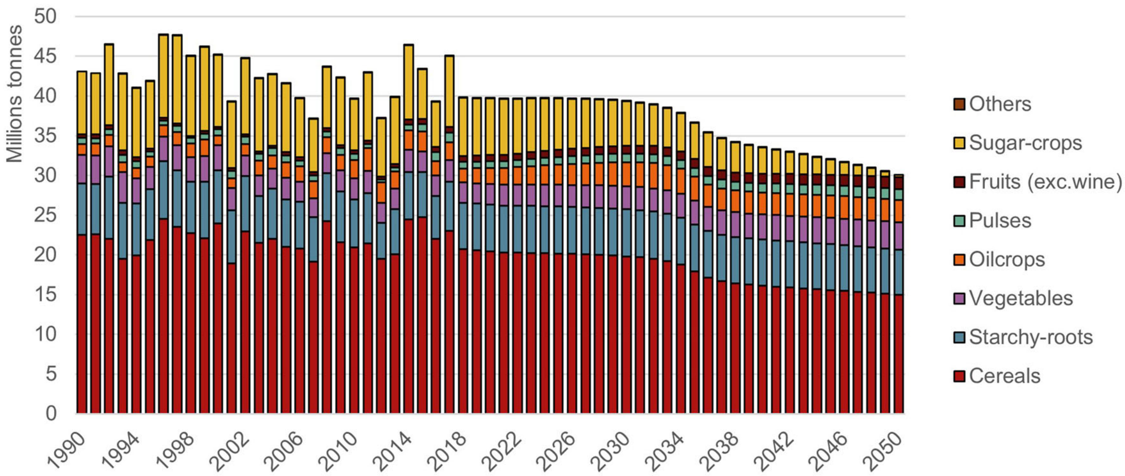

Fig. 3 Evolution of the crop production in the UK from 1990 to 2050 in the EEB pathway (tonnes)[1,27,43]. The food groups have been aggregated for a better visibility.

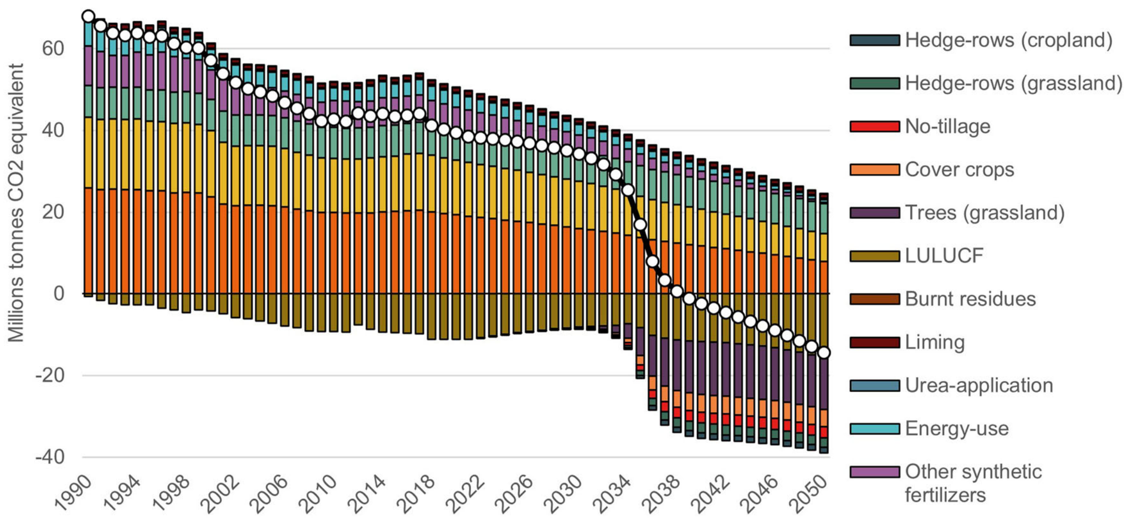

Fig. 4 Evolution of the food and agriculture system related GHG emissions in the UK from 1990 to 2050 in the EEB pathway(MtCO2eq). The GHG sources have been aggregated for a better visibility, and to match the common reporting format[19].

Discussion

Sustainability challenges usually involves multiple stakeholders with heterogenous and conflicting values at stake[47]. Not all stakeholders have the means to address the complexity of these challenges through science-based approaches, but this does not make their perspectives less insightful. EEB could not find a good match for their food and agriculture system perspective in the literature. First, the food and agriculture system literature is not as rich and not as detailed as the literature describing energy system transitions when it comes to GHG mitigation pathways. Second, the literature is lacking descriptions of agroecological-focused pathways compared to sustainable intensification pathways[3,25–27]. Finally, addressing the complexity of the food and agriculture system is challenging and modelling is an invaluable support to both understanding and decision-making. For these reasons, the EEB was looking for support to design an agroecological pathway to contribute to the Common Agricultural Policy debate. Following the co-design process enabled by the ARISE model, the EEB could evaluate better the impacts and necessary trade-offs of agroecological solutions. Importantly, the same approach is accessible via the ARISE model to other stakeholder groups that seek to build consensual pathways that are internally consistent.

The EEB pathway leads to a decrease of −60 $MtCO_2$eq. of UK agriculture sector GHG emissions compared to 2017, against −50 and −80 $MtCO_2$eq for the Climate Change Committee pathways (excluding the extra BECCS), and −72 $MtCO_2$eq for the Centre for Alternative Technology respectively. All these pathways require a high level of ambition, but the effort, and the benefits, are shared differently (Table 2).

All pathways rely on strong social behaviour efforts. That is because they are disproportionally influential for the food and agriculture sector regardless to the production system specifications[31,32]. The EEB's assumptions require a moderately higher effort in terms of diet shift, but a moderately lower effort in terms of waste reduction and losses cut compared to the 'balanced net zero' pathway. Both these pathways are conservative compared to the tailwinds and zero carbon pathways which assume up to a 50 and 58% cut for meat and dairy products consumption (up to 92% for red meat)[25]. Such a cut in red meat would call into question the sustainable management of grassland as highlighted as desirable in the initial EEB narratives (Table 1).

Contrary to social behaviours, the shift towards a different production system is heterogeneous. Both zero carbon Britain and EEB pathways assume lower yields driven by low-input practices by

Table 2 Comparison of key determinants of the UK pathways.

Drivers	EEB-Pathway (ARISE model)	Balanced-net-zero	Tailwinds	Zero carbon Britain
Social behaviours	50% cut in meat & 45% cut in dairy products; 50% cut in food wastes;	35% cut in meat & dairy products; 60% cut in food wastes;	50% cut on meat & dairy products; 30% of lab-grown meat; 70% cut in food wastes;	58% cut on meat and dairy products, (92% for beef); 50% cut in food wastes;
Agricultural production system	Agroecological practices: decrease of livestock density (−8%), phasing out imported cakes; livestock yields range between +20 and −16%; Cover-crops, no-tillage, intercropping; crop yields decrease by 45% to 10%; Phasing out synthetic fertilizers and pesticides.	Sustainable intensification practices (50-75% deployment): genomics, GMO, precision feeding and monitoring, chemical intake; increased livestock density (+10%); Doubling grassland yields; grass and legumes (n-fixing), cover crops, perennial non-woody crops; Expected yields (cereals): +65% compared to 2017.	Same as balanced net-zero (up to 80% deployment). Expected yields (cereals): +95% compared to 2017	Conservative yields have been considered based on 2011-2012 data.
Bioenergy & BECCS	Biomass: 2017 status quo, no BECCS (160TWh);	Biomass: 250 TWh/year; BECCS deployment: 52MtCO_2eq/year Mobile & stationary machinery run on electricity and hydrogen;	Biomass: 500 TWh/year; BECCS deployment: 97MtCO_2eq/year Mobile & stationary machinery run on electricity, biofuels, and hydrogen;	Biomass: 230 TWh/year; no BECCS
Land management	Afforestation: 1.3 Mha; Restauration of peatlands is not considered; Agroforestry measures: +50% hedgerows, tree plantation on 10% of grasslands;	Afforestation: 1.2 Mha, 50 kha per year; Restauration of peatlands; Agroforestry measures: +40% hedgerows, tree plantation on 10% of farmlands;	Afforestation: 1.5 Mha, 70 kha per year; Restauration of peatlands; Agroforestry measures: +40% hedgerows, tree plantation on 10% of farmlands;	Afforestation: 3.6 Mha, 115 kha per year; 50% of peatlands are restored;

It includes the 6th Carbon Budget main and most optimistic scenarios (balanced-net-zero & tailwinds), the Centre for Alternative Technology's Zero Carbon Britain. Other previously identified pathways were not included due insufficient details for the food and agriculture system. Table's data refer to 2050 targets.

2050 compared to 2017. In contrast, the other pathways consider very ambitious yield gains while at the same time assuming a lower use of inputs. For example, cereal yields are assumed to increase from +65 to +95% compared to 2017[1,30], i.e., about 25-45% higher than the FAO most optimistic scenario for 2050[27]. Sustainable intensification narratives and pathways are highly reliant on technology (Table 2): the widespread adoption of breeding technology (genomics, genetic modification), precision feeding (monitoring and adjusting feed intake), enteric fermentation inhibitors (chemical intake), electrification of mobile and stationary machinery, and bioenergy associated with BECCS. The latter is assumed to remove from 52 to 97 $MtCO_2$eq. per year by 2050 (i.e., 20% of the UK current emissions). Nevertheless, whether BECCS can actually deliver actual negative emissions in the UK still remain to be demonstrated[48,49].

With respect to the production of bioenergy, the EEB pathway is the most conservative pathway with no change in biomass production o compared with 2017. The 3 other pathways assume an increase in biomass production from +45% to 310% compared with 2017. This difference arises because land spared from food production is balanced differently between bioenergy, reforestation, and biodiversity conservation. The EEB pathway emphases carbon sequestration through the large deployment of hedges rows (close to balanced net zero assumption) and tree plantation in meadows and pasturelands (conservative compared to the estimated potential[42]). It also assumed spared land is allocated for biodiversity conservation to meet the Aichi objective 11[44]. Sustainable intensification pathways allow the area of spared land to be larger because of the increased yield gains assumptions. Thus, they assume a concurrent increase of reforested lands and bioenergy production. However, assuming the large deployment of technology-optimistic solutions in the modelling exercise can increase the risk of adverse impacts as society moves towards net-zero paths[29].

Overall, the EEB pathway does not require greater behaviour effort than the other pathways in order to contribute to the achievement of the net-zero objective. In many respects it is based on more conservative assumptions than the alternative sustainable intensification pathways.

Limits. There is no such thing as a best pathway given the multiple and conflicting values at stake. Coordination, consultation, and good policy facilitation is required to address the sustainability of the complex food and agriculture sector[34]. Thus, it is critical that each stakeholder group can express themselves and share their perspective. Although substantial work remains to be done to achieve this objective, we aim to make a step forward in easing the access to food and agriculture science-based models by the nonmodeller community and thereby facilitate the dialogue between stakeholders. The ARISE model still requires limited but critical information technology skills (e.g., software installation, prompt usage). Thus, important steps remain to be made in that direction. To this end, we are currently developing a webtool that will allow any user to explore the sustainability of the food and agriculture system. This ongoing work builds on the Transition Pathway Explorer[50] webtool which provides a user-friendly interface to the EU-Calculator family of models[31].

Engineering changes across the food and agriculture system are very complex even when the economics of supply chain management is narrowly conceived[34]. Further work is required to provide economics and cost inputs. Our future research will be to develop a tailor-made methodology to compute the true cost of food[36] of each pathway, i.e., an accounting approach to assess the externality and dependency for economic, environmental, social and health effects. The later methodology will also enable us to cover a broader range of impacts that are currently not implemented such as health-diet dynamics and impacts and biodiversity benefits.

As highlighted by the LANCET report[34], the scale of change that is required to mitigate climate change and transform food systems is unlikely to be successful if left to the individuals alone. Furthermore, evidence that improved infrastructure and regulations could increase healthy food and sustainable consumption is scarce because of poor policy and insufficient data. Further research is urgently needed to define the adequate set of policy interventions that would enable the feasibility of any ambitious pathway for a sustainable agri-food system.

Methods

Model. The AgRIculture and food SystEm interactive model (ARISE) is an original interactive quantitative model that systemically links the key mechanics of the food and agriculture system in the UK (see Supplementary Methods 2: ARISE guidelines). It was initially made available as part of the European Calculator's pathway explorer[51,52], but it has been further developed to provide the users with a more detailed approach of the food and agriculture system in the context of the European Common Agricultural Policy design and debates[53].

From fork to farm, ARISE accounts for and is calibrated against: (1) country demography through the population growth per age, gender, and BMI[37]. That enables to assess the theoretical food energy requirement[38]; (2) the food supply through the FAOSTAT commodity balance[1], that enables us to compute an average diet; (3) food wastes and losses[14], which allow us to estimate the actual food intake and its gap compared to the theoretical requirement; (4) food self-sufficiency ratios[1] enable us to compute the primary production and derived by-products for processed and livestock-based food, as well as the supply for the livestock feed given their energy conversion efficiency[1,43]; (5) supply of land based commodities for other-uses (e.g. biofuels, fibres)[1,54] and the systemic by-products mechanics[52,55,56] are considered (e.g., cakes and oils produced from oil crops); (6) domestic self-sufficiency ratios[1] enable us to compute the domestic production for crop-based commodity given the supply for food, feed, energy and other-uses; (7) harvested lands are computed given the yields and expected climate impacts[1,27]; (8) the nitrogen balance is computed given the agricultural practices[27,28]: nitrogen exports from crops and residues, and the nitrogen inputs through manure, food industry by-products, etc.; (10) the inputs requirement[1,19,54] (e.g. synthetic fertilizers, lime, energy, etc.) are computed given the lever setting constraints (e.g. agroecology, sustainable intensification); (9) dynamics of land use are computed using the United Nations Framework Convention on Climate Change land transition matrix data[19], enabling us to compute the converted land area (e.g. forest to grassland); (10) the carbon dynamics for each land and transition types are computed considering the biomass, deadwood, litter and soil carbon pools; (11) The GHG emissions are computed using partly endogenous emission factors (e.g. based on the land dynamics), or exogeneous factors (e.g. enteric fermentation[1]); (12) Other sustainability impacts are computed using Sustainable Development Goal indicators provided by FAOSTAT[1];

Similar to the 2050-Calculator family of models, ARISE enables its users to set ambition levels for multiple levers, expressing possible changes by 2050 for the social behaviours, policy, and technology, etc. against which sustainability impacts can be assessed. Up to 200 levers can be set individually, but aggregated levers allow the users to set several sub-levers at once to avoid the information overload. In a brief, the user can explore how the following drivers will shape the food and agriculture landscape by 2050: (1) the climate scenario that will affect the yields and irrigation (from Representative Concentration Pathway 2.6–4.5 to 8.5)[27]; (2) the international production system and trade matrix[1,27], that will affect the extent of GHG and land leakages (based on FAO-2050 scenarios)[27]; (3) the social behaviours that compute the energy requirement, wastes and losses, and dietary patterns (from past trends to flexitarian diets[27,31,57]); (4) the desired level of within-country self-sufficiency for each commodity (including: historical high/low, past trend continuation, and other literature scenarios[27,58]); (5) the supply of biomass for bioenergy per technology (e.g. Hydrotreated Vegetable Oil) and type (liquid, solid, gaseous) and biosourced materials (from phasing-out/no-deployment, to the most optimistic literature-based estimations)[52,59]; (6) The crop production system: from agroecology to intensive agriculture[27,28], affecting the yields, input-use, etc.; (7) Same for the livestock production system; (8) land management (e.g. agroforestry practices)[19,42]. Once computed, the users can save and explore their pathways in the transition pathway explorer (Fig. 5).

Data source

Historical data. the model is calibrated over the 1990-2017 time period. The domestic supply (food, feed, nonfood), production, yields, input-use, and emission factors are calibrated against the FAOSTAT database over the 1961-2017 period[1]. The energy-use is calibrated against the Eurostat and FAOSTAT, and accounts for fourteen energy carriers[1,54]. The bioenergy supply includes gaseous, liquid, and solid biofuels, which are calibrated against Eurostat and UK official statistics[54]. Solid biofuels consist of power, heat and combined power and heat generation.

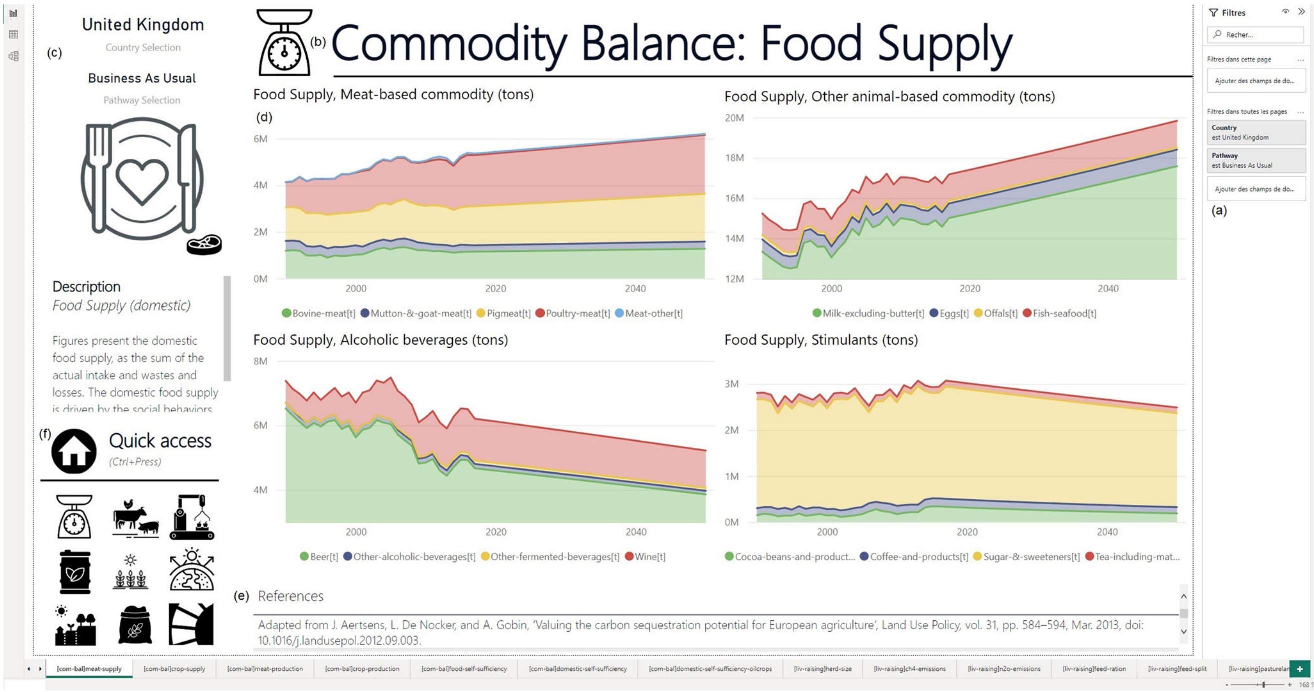

Fig. 5 ARISE pathway explorer. The pathway explorer includes 71 tabs to explore. (**a**) Interactive selection of country and pathways; (**b**) Tab name; (**c**) description of the tab being displayed; (**d**) Figures; (**e**) References associated to the figures, country, and pathway; (**f**) interactive quick access menu.

Gaseous bioenergy also consider biogas uses. Liquid biofuels consist of Fatty Acid Methyl Esters, Hydrotreated Vegetable Oil, and Biomass to Liquid biodiesels, and cereal sugar-crops, cellulosic-based ethanol. The land-use, land-use change, and associated carbon dynamics are calibrated against the official United Nations Framework Convention on Climate Change inventories (1990-2017)[19]: it includes cropland, grassland, forest land, artificial land, wetland, and other-lands dynamics.

Future time series. the ambition levels express the extent for which the users can explore various assumptions (e.g., dietary changes). These ambition levels are calibrated against the scientific literature[52,60]. As a rule of thumb, ambition levels are set to range from the least to the most ambitious scenario that we found in the literature. For example, the production system can be set from intensive to agroecological systems, which systematically constraint a set of dynamics, such as the yields, input-uses, etc. The set of levers and their related ambition levels have been designed based on the literature and the former 2050-Calculators; And then reviewed, refined and validated through multiple stakeholders' consultations and workshops[52,60].

Pre-saved scenarios. Additionally, we developed alternatives to enable the users to compare multiple pathways to their own: the Look-Up scenario assumes the widespread deployment of a flexitarian diet, a 75% cut on wastes and losses, and a larger deployment of agroforestry practices: The Business as Usual scenario was designed to match the insights from the FAO-2050 ref. [27].

Data availability

Scenarios' data is available in the ARISE pathway explorer in Supplementary Methods 2: ARISE Transition Pathway Explorer (Power BI file) & ARISE Data (XLS file). The ARISE complete database is in open access: https://github.com/dr-gbaudry/arise-knime.

Code availability

ARISE code is in open access (https://github.com/dr-gbaudry/arise-knime), and guidelines are provided as Supplementary Methods 2: ARISE guidelines.

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Author contributions
G.B. has developed the ARISE model and transition pathway explorer, and he led the co-design process; L.C. has developed the lifestyles related features; G.B., L.D.L., and R.S. contributed to the scoping of the model features. All authors contributed to the discussion, analysis, interpretation of the results; All authors contributed to the writing of the manuscript.

Competing interests
The authors declare no competing interests

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