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Using fuzzy cognitive mapping to assess the sustainability impacts of transitioning to pasture-fed production in the UK beef sector

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Abstract

One hundred percent pasture-fed beef production has been suggested as a promising approach for sustainable ruminant farming, due to the potential benefits that can accrue across a range of sustainability domains. This study aimed to investigate the impacts across the four domains of sustainability of a wholesale switch from conventional to 100% pasture-fed beef production in the UK. We used fuzzy cognitive mapping (FCM) as a method for extracting knowledge from multiple stakeholders to create representative systems models of both conventional and pasture-based beef production systems. We then conducted a scenario analysis to assess how a switch to a pasture-fed system could affect components of sustainability in the UK beef sector. The FCMs indicated that vegetation quality, grass use efficiency, and soil health were central components of the pasture-fed approach, while economic and regulatory aspects, and climate change targets were more central to mainstream production approaches. The most marked changes under the 100% conversion scenario were an increase in income from subsidies (27.3%) in line with 'public money for public goods', a decrease in ability to export beef (unless advice to reduce consumption of animal protein is followed) (23.5%), a decrease in land used for farming *vs* other uses (e.g., natural capital) (11.23%), and a decrease in the use of feed from agricultural co/byproducts (7.5%), freeing up these feed sources for more sustainable monogastric production. Therefore, the mapping and scenario analysis suggests that while upscaling the pasture-fed approach may reduce productivity, it would likely increase public goods provision and reduce feed–food competition in the UK.

Introduction

The world is facing an environmental crisis: the heating of the climate, caused by anthropogenic emissions of greenhouse gases (Pachauri and Meyer, 2014) is leading to extreme weather events and increased impacts on ecosystem functioning (Jentsch, Kreyling and Beierkuhnlein, 2007). These effects are exacerbated by mass species extinction also resulting from human activities (Ceballos, Ehrlich and Raven, 2020) and further threatening the functional ecosystems which provide the services on which humanity relies, including: clean water, clean air, a stable climate, and food production.

Livestock farming has its part to play in this crisis. The livestock sector has been reported to contribute to 14.5% of all anthropogenic greenhouse gas emissions (Rojas-Downing et al., 2017). Beef farming is responsible for 41% of these emissions, with methane caused by enteric fermentation of cellulose and nitrous oxide emissions from manure being particular issues (Poore and Nemecek, 2018; Wang et al., 2018). Expansion of agriculture also places pressure on biodiversity: agriculture is identified as a threat for 24,000 of the 28,000 species currently under threat of extinction worldwide (Ritchie and Roser, 2020).

The need to consider approaches for limiting the impact of livestock farming on functioning ecosystems is therefore urgent. One important approach is to reduce the amount of livestock products in human diets in certain parts of the world (Willet et al., 2019). At the same time, animal products, including beef, provide sources of high-quality protein and important micronutrients, and therefore some level of animal product consumption is considered important for preventing malnutrition (Adesogan et al., 2020; Kamilaris et al., 2020). Furthermore, grassland on which cattle are grazed can provide vital environmental, social, and cultural benefits (Bullock et al., 2011; Bengtsson et al., 2019), and livestock may be fundamental to maintaining these habitats and enhancing soil quality (Adesogan et al., 2020; Kamilaris et al., 2020).

Therefore, as well preventing overconsumption of livestock products, seeking systems of livestock production that minimize negative environmental impacts while benefiting ecosystem function and the delivery of ecosystem goods is also vital. Pasture-fed approaches in which ruminant livestock such as cattle exclusively consume grazed and conserved species-rich pasture and forage are promoted as such a system (Buller, 2008; Teague and Kreuter, 2020). Conventional beef production involves the feeding of concentrates to cattle which includes cereal grains and soybean (Horcada et al., 2016). In the UK, conventional beef farming consists of intensive, semi-intensive, and extensive systems. An intensive system involves housing and feeding of a concentrate diet immediately after the rearing phase, with no grazing on pastures (Meat Promotion Wales, 2014). A semi-intensive system involves periods of grass grazing, housing during the winter, and a housed finishing period (Meat Promotion Wales, 2014), when cattle are fed a nutrient-rich diet of concentrates for 3–4 months before slaughter to enhance beef yield (FAWC, 2019; see Fig. 1). An extensive system is similar to a semi-intensive system, with more of an emphasis on a grass-based diet and periods of extensive grazing, usually housed winter periods feeding mainly preserved grass, but still some feeding of concentrates, especially during the finishing period (AHDB, 2019, 2021; see Figs. 1 and 2). Intensive systems are not common in the UK; 87% of UK beef is produced using predominantly grass-based diets (i.e., semi-intensive and extensive systems; AHDB, 2019, 2021). Although about 70% of a typical British beef cattle herd's diet consists of grass, grains constitute 5% of the diet and silage from food crops 17%, the rest consisting of fodder beet and byproducts from other crops (AHDB, 2019, 2021).

This system of feeding human-edible crops is resource-inefficient, using up crops and land that could be used to feed humans directly, contributing to feed–food competition (Karlsson and Röös, 2019). In the UK, feed ingredients such as soybean are imported and often implicated with deforestation and habitat destruction elsewhere in the world; in 2019, 68% of soya imported into the UK was not covered by any standard guarantee against deforestation and land conversion (Efeca, 2020). Furthermore, the grass on which cattle are fed in conventional systems often consists of monocultures or simple mixtures (e.g., ryegrass/clover) (Rutter, 2006; French, 2017), requiring regular ploughing (every 3–5 years), sowing, fertilizing, and pesticide application (French, 2017; Toupet et al., 2020), resulting in reduced biodiversity (Dicks et al., 2020) and substantial loss of carbon from the soil (Reinsch et al., 2018).

Feeding cattle entirely on pasture avoids the environmental impacts of imported feed such as maize and soya and the issue of feed–food competition, instead turning human-inedible pasture into a valuable food source of high value protein and micronutrients (Place, 2018). Furthermore, with appropriate management, it can create and conserve species-rich grassland, provide an important habitat for a range of flora and fauna

Figure 1. Conventional beef production in the UK predominately consists of semi-intensive and extensive systems, where cattle are housed over winter (and during the finishing period for semi-intensive systems) where they are fed preserved forage and concentrates. Photo credit: SRUC.

Figure 2. Cattle in conventional beef systems (semi-intensive and intensive) usually graze on monocultures of grass. Photo credit: Martin Dawes, Wikimedia Commons.

(Bullock et al., 2011) and prevent loss of soil carbon and biodiversity through ploughing (Reinsch et al., 2018). For these (and other) reasons, pasture-fed livestock systems have been highlighted as a sustainable approach to beef production (Norton et al., 2022*a*, 2022*b*), especially on land in the UK well suited to grass growth (Broom, 2021).

A 100% pasture-fed system of beef production is one where cattle are fed entirely on pasture, either preserved or grazed; no concentrates are fed at any stage (see Fig. 3). This system also differs from conventional production in that the forage cattle eat is more diverse, i.e., more species-rich than conventional grass monocultures. While most pasture in 100% pasture-fed system is extensively grazed, similar to conventional extensive systems, pasture-fed beef management in the UK is highly variable and changing, with more farmers experimenting with rotational grazing approaches, e.g., around one-third of the 56 farmers interviewed in the 'Sustainable economic and ecological grazing systems—learning from innovative practitioners' project (UK Centre for Ecology & Hydrology, 2018; Wagner, Waterton and Norton, 2023; Lisa Norton, personal communication, 2023). In the UK, a 100% pasture-fed approach to beef production is championed by the Pasture For Life, which certifies 100% pasture-fed products with their Pasture For Life marque (Pasture For Life, n.d.; Vetter, 2020).

UK pasture-fed beef has been shown to match dietary guidelines better than meat from conventional systems, qualifying as a source of long chain omega-3 fatty acids (Butler et al., 2021), containing a high nutrient density (Lee et al., 2021) and health-promoting phytonutrients (Van Vliet et al., 2021). Pasture For Life advocates that management of pasture through a pasture-fed livestock system can (i) improve soil structure which increases the soil's water-holding capacity, (ii) contribute to flood and drought mitigation, (iii) generate benefits to wild plant and animal biodiversity, (iv) recycle nutrients and reduce the need for fertilizers, and (v) capture carbon for climate change mitigation (Pasture For Life, 2018). Norton et al. (2022*a*) found that UK pasture-fed systems contain higher plant diversity and structure than UK grassland managed intensively for productivity (e.g., regularly reseeding as a ryegrass monoculture and applications of synthetic fertilizers and pesticides) and that farmers managing pasture-fed systems typically use very little synthetic fertilizer or pesticide (fossil fuel-based inputs). Seaton et al. (2022) found that maintenance of grassland on Pasture For Life farms, managed by grazing cattle, improved plant–soil interactions and microbial community structure, which leads to increased soil and general ecosystem health compared to land that is ploughed (e.g., for short-term conventional grassland management or for growing feed crops).

While there is evidence for the environmental and human health benefits of a pasture-fed approach, it is important to consider the wider impacts of a wholesale transition to this method of production. The impacts of transition to grass-fed livestock have been considered and reviewed in other studies (Tichenor et al., 2017; Provenza, Kronberg and Gregorini, 2019). Hayek and Garrett (2018) used a modeling approach based on current demographics of beef production in the USA to show that increases of around 30% in the national herd would be required to produce the quantity of beef currently produced if an entirely grass-fed approach was taken. While these studies provide insights into

Figure 3. Cattle in 100% pasture-fed systems only eat either fresh or conserved pasture, no concentrates are fed, and the pastures have more diversity of forage, i.e., are more species-rich than conventional grass monocultures. Photo credit: Andy Rummings and Pasture For Life.

potential impacts of types of grass-fed production, their assumptions and inputs remain largely based on conventional production models and thus fail to adequately consider the types of pasture-based systems adopted by Pasture For Lifein the UK, e.g., they fail to account for ecosystem services provided by pasture-based farming systems (Tichenor et al., 2017).

Therefore, this study aimed to investigate for the first time (to the authors' knowledge) the sustainability impacts of a wholesale transition to a 100% pasture-fed beef production system in the UK. A holistic view of sustainability was taken, using the four domains of sustainability defined by the Sustainability of Food and Agriculture Systems (SAFA) guidelines: Environmental, Economic, Social, and Governance (FAO, 2013). The methodology of fuzzy cognitive mapping (FCM) (described below) was chosen to extract knowledge from multiple stakeholders to create representative systems models of both conventional and pasture-based beef production systems and to assess the potential resulting sustainability impacts of a nationwide transition to grass fed systems in the UK.

Methodology

Fuzzy cognitive mapping

Cognitive mapping is the process of visually representing a mental model through individuals' knowledge of a system (Gibbons, 2019). A cognitive map features components of the system with causal relationships between those components, represented by directional arrows that may be positive (positive causality) or negative (negative causality). An FCM can be defined as an extension to cognitive maps where the relationships between components are no longer binary (only positive or negative) but instead include 'hazy degrees of causality'—fuzziness—(Kosko, 1986; Gray, Zanre and Gray, 2014), meaning variance in the degree of influence over one another. Components within an FCM must be able to increase or decrease, and relationships between components are given a weighting between −1 and +1, representing the valence of the relationship (positive or negative) and strength of the relationship (weak, moderate, or strong). In most applications, FCMs are developed by experts/stakeholders to produce mental models of a topic in which they have knowledge and experience. Experts first identify concepts/components within the system being studied, before defining relationships between components and the strength of these causal relationships (Gray, Zanre and Gray, 2014; Gray et al. 2015).

A semi-quantitative nature of FCM allows for scenario analysis, where the outcome of changes to the system can be predicted. The approach is also considered useful to facilitate discussions between stakeholders and extract knowledge to build an accurate representation of a system (Ziv et al., 2018), while also being a relatively easy model to build using software (Özesmi and Özesmi, 2004). For these reasons, the FCM approach was chosen to achieve the objectives of this study.

The methodology for the development of the FCMs produced in this study was adapted from Özesmi and Özesmi (2004) and Ziv et al. (2018), following a participatory, rule-based FCM approach, where complex, real-world qualitative socio-ecological system dynamics, and their relationships are represented to account for feedback and to allow for the simulation of scenarios (Gray, Zanre and Gray, 2014; Gray et al. 2015). To develop the FCMs and explore the implications of a 100% pasture-fed scenario in this study, two online workshops were held in 2020, to define contrasting approaches to beef production: pasture-fed and conventional.

Pasture-fed beef production

An online workshop (workshop 1) was held on October 23rd, 2020 via video conference with the research group of the Pasture-Fed Livestock Association (PFLA), which comprises a membership of farmers and members interested in how research can support and inform pasture-fed approaches. This workshop aimed to develop an FCM of this 100% pasture-fed system for beef production. Eight members of the PFLA research group (formed from members keen to engage with and learn from research) attended. These individuals were expert practitioners in 100% pasture-fed systems and therefore would be able to comprehensively map this system.

Conventional beef production

A second online workshop (workshop 2) was held on December 8th, 2020 with stakeholders from across the conventional beef production sector. Prior to that workshop, the research team mapped out the beef supply chain and drew up a list of relevant stakeholder organizations in beef cattle production (i.e., up to the point of slaughter). Representatives from these organizations were invited. A total of 15 individuals participated, representing government, industry associations, farmer associations, farm assurance scheme, and academia. As such, this selection of representatives is considered to be representative of the entire supply chain and the authors had confidence that they would be able to comprehensively map the conventional system. Details of the participants are not given here due to data protection.

It should be noted that experts from both workshops were subject to potential cognitive biases, i.e., errors in judgments and decisions related, for example, to social influences and misperceptions of probabilities and statistics (Bhandari and Hallowell, 2021). Although the consistency and reliability of decision-making by expert panels has been validated in many fields (see Bhandari and Hallowell, 2021), we aimed to mitigate the risk of cognitive biases by actively facilitating the workshops; for example, mitigating the dominance effect (individuals being subdued by dominant members of the group, Bhandari and Hallowell, 2021) by intervening to make sure everyone had a chance to speak and contribute.

Workshop structure

Both workshops followed the same structure, although an additional ‘scenario analysis’ item was added to the agenda of the conventional beef production system workshop (workshop 2). Both workshops were conducted online via video conference software. Prior to the workshops and during the workshop introductions, participants were sent material explaining what an FCM is and why this approach was being used. The workshops were facilitated by one member of the research team (ER), and three team members were present in both workshops to lend support to participants.

Workshop 1 began by asking participants to brainstorm the main components of the 100% pasture-fed beef production system (i.e., up to the farm gate) that fall into the four domains of sustainability defined by the SAFA guidelines: environmental, economic, social, and governance (FAO, 2013). An interactive whiteboard (‘Padlet’) was used for this purpose. Workshop 2 repeated this process but for the UK conventional beef production system. Once the components of each of the systems had been brainstormed by the participants, the research team amalgamated these into 10 main components for each sustainability domain, while participants took a comfort break. These were re-presented to the participants in the workshop for their final approval. The list of components was then translated into an adjacency matrix whereby each of the 10 components for each domain could be related to one another. An interactive spreadsheet (‘Google Sheets’) was used for this purpose.

The next stage of the workshop was for the participants to identify the key relationships between the components in the system, using the interactive spreadsheet. Key relationships were described as those where participants felt there was clear evidence for a relationship between the components, and a clear direction for that relationship (i.e., one component causing an increase or decrease in another). Participants also assessed the strength of the relationship, i.e., how strongly they believed one component increases or decreases the other, using symbols displayed in Table 1.

In workshop 1, time ran out for this stage to be completed, and it was therefore completed subsequently by participants collaborating on the interactive spreadsheet, which was circulated to the participants for their comments. To avoid running out of time for this stage of the process in workshop 2, the participants were split into three groups and randomly allocated one-third of the adjacency matrix to review and choose the components between which they believed a key relationship exists. Subsequently the research team suggested the direction (positive or negative) and strength (weak, moderate, or strong) for each of the key relationships, using the symbols displayed in Table 1, while the participants had a break. Participants then reviewed these relationships (as previously with three groups randomly assigned to review a third of the adjacency matrix each) and decided whether they agreed with or wanted to change the direction and/or strength.

Table 1. Symbols used in both workshops to represent the direction and strength of the relationships

Symbol	Relationship
+	Weak positive relationship (when one component increases, the other component increases a little)
++	Medium positive relationship (when one component increases, the other component increases moderately)
+++	Strong positive relationship (when one component increases, the other component increases a lot)
−	Weak negative relationship (when one component increases, the other component decreases a little)
−−	Medium negative relationship (when one component increases, the other component decreases moderately)
−−−	Strong negative relationship (when one component increases, the other component decreases a lot)

Defining relationships between the components (Table 1) was the final stage of workshop 1. In workshop 2 a further stage related to scenario analysis was carried out (see section 'Scenario analysis'). In this, participants were asked to identify one component in the conventional system from each of the four domains of sustainability that they thought would be most affected by a hypothetical switch to a 100% pasture-fed beef production system, and to assess whether they thought this component would increase or decrease following such a transition.

FCM construction

This section describes the process of constructing the fuzzy cognitive models for a 100% pasture-fed beef production system (workshop 1) and conventional beef production system (workshop 2), using the components and relationships defined by the stakeholders in the workshops. Free software FCMappers (FCMappers, n.d.) was used to construct the FCMs. A description of the mathematical model of the FCM used by FCMappers is described in Ziv et al. (2018).

After the workshops, the direction and strength of relationships were converted into numerical weights using the following rules, based on the approach used by Ziv et al. (2018):

- +0.7 If the link is strong and positive (+++)
- +0.5 If the link is medium and positive (++)
- +0.2 If the link is weak and positive (+)
- 0 If there is no interaction
- −0.2 If the link is weak and negative (−)
- −0.5 If the link is medium and negative (−−)
- −0.7 If the link is strong and negative (−−−)

FCMappers was applied to describe the role of each component in the system regarding its in-degree, out-degree, and centrality. In-degree and out-degree are calculated by the sum of the relationship weights between components. In-degree describes how influenced a component is by other components. Out-degree describes how much a component influences other components. Components with zero in-degree are classed as drivers, and with zero out-degree as receivers. Centrality is the sum of the in-degree and out-degree of the component and describes the importance of the variable whereby components with high centrality are highly connected to other components, and therefore control the dynamics of the system (Solana-Gutierrez et al., 2017). Through the computation of each component, regarding its in-degree, out-degree, and centrality, it is possible to reveal how people perceive the causal relationship(s) for a given system, and whether a single component is viewed as having a 'forcing function' affecting others, or little/no effect on other elements (Papageorgiou and Kontogianni, 2012).

FCMappers software was used to calculate a value for each component by setting the initial value to 1 and adding the sum of all incoming component values multiplied by the numerical weights of their relationships with each other (component weighting), in an iterative process until no further changes in component values occurred (for a full description of the mathematical model of FCM, see Ziv et al., 2018). The output from FCMappers was entered into network visualization software Pajek (Pajek, n.d.) to create a visual diagram of the FCMs.

Scenario analysis

The same software (FCMappers) was used to run the scenario analysis, to analyze the impact on the components of a switch to a pasture-fed system. Scenario analysis was based on the methodology used by Ziv et al. (2018). The components in the conventional system identified by the stakeholders as most likely to be affected by a transition to a pasture-fed system were fixed at a value of 1 if participants estimated that this component was likely to increase given a switch to a pasture-fed system, and 0 if they estimated that it would decrease. Running the iterative process described in section 'FCM construction' (component weighting) gave new values for each component in the conventional system, revealing the relative change in the value of each component under the new scenario of a pasture-based system as compared to the baseline state of the current conventional beef production system. This allowed for an assessment of the impact of a switch to an entirely pasture-fed system on the production of UK beef.

Results

Pasture-fed beef system

Figure 4 provides a visual representation of the FCM produced by the Pasture For Life participants, illustrating the 33 components considered as the main components of a 100% pasture-based system under each of the four domains of sustainability, and the links between components. The size of the component nodes (circles) indicates their centrality. The color of the component nodes indicates the sustainability pillar to which they belong (green for environmental, yellow for economic, blue for social, cyan for governance). The direction of arrows indicates the direction of the causal relationship between two components. Red arrows indicate negative relationships, blue arrows indicate positive relationships. The width of the arrow indicates the strength of the relationship. Table S1 in the Supplementary materials displays the metrics produced from FCMappers: centrality, out-degree, and in-degree.

The results indicate that five components were 'transmitters' in that their in-degree was zero: ratio of land owned to land rented, farm size, number of public footpaths, number of native breeds, and external monitoring e.g., of animal welfare. Five components were 'receivers' in that their out-degree was zero: connectivity of non-cropped habitat, preventive stock health, farm capital assets, number of farm products, and amount of government support payments.

Conventional beef system

Figure 5 provides a visual representation of the FCM produced by the conventional beef system stakeholders, illustrating the 38 components considered as the main components of the UK conventional beef system in each of the four domains of sustainability and the links between components. The size of the component nodes (circles) indicates their centrality. The color of the component nodes indicates the sustainability pillar to which they belong (green for environmental, yellow for economic, blue for social, cyan for governance). The direction of arrows indicates the direction of the causal relationship between two components. Red arrows indicate negative relationships, blue arrows indicate positive relationships. The width of the arrow indicates the strength of the relationship. Table S2 in the Supplementary materials displays the metrics produced from FCMappers: centrality, out-degree, and in-degree. The results indicate that three components were 'transmitters' in that their in-degree was zero: occurrences of extreme weather, price per kg, and import tariffs. There were no 'receiver' components.

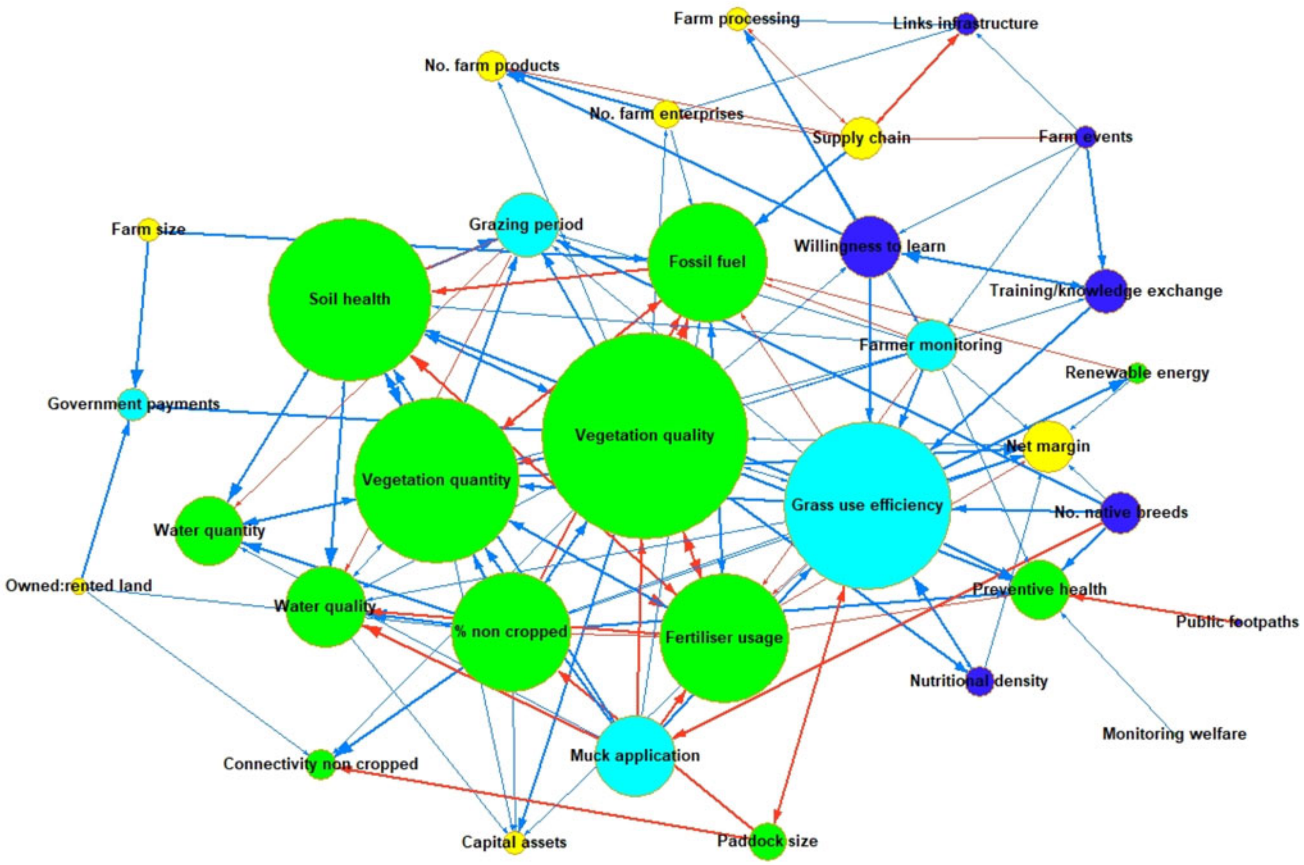

Figure 4. Visual representation of the FCM of the pasture-fed beef production system, as defined by Pasture for Life research group. Size of the component nodes indicate their centrality. Color of the component nodes indicate the sustainability pillar to which they belong: green = environmental, yellow = economic, blue = social, cyan = governance. Direction of arrows indicates the direction of the causal relationship between two components. Red arrows indicate negative relationships, blue arrows indicate positive relationships. The width of the arrow indicates the strength of the relationship.

Scenario analysis

Participants in workshop 2 reached the consensus that the following components in the conventional system from each of the four pillars of sustainability would be most affected by a hypothetical switch to a 100% pasture-fed beef production: price per kilo (economic), training/skill level (social), farm infrastructure/resources (governance), and production efficiency (environmental). Participants predicted that price per kilo would increase (due to a reduction in supply, according to the laws of supply and demand), training/skill level would increase (to enable farmers to switch to a different type of production method), and farm infrastructure/resources would increase (e.g., needing more resources such as seeds of different species to improve sward diversity, electric fencing for grazing management), and production efficiency (defined by the group as yield per unit time) would decrease. Yield of beef was predicted to decrease by the participants due to cattle taking longer to finish (reach desired slaughter liveweight) on a 100% pasture diet (Smith et al., 2019), as livestock growth rates are typically slower on 100% grass diets compared to cereal diets (Albanito et al., 2022). Cattle in 100% pasture-fed systems usually take over 20 months to finish, compared to 12–14 months in intensive conventional systems and 15–20 months in semi-intensive and extensive conventional systems (Meat Promotion Wales, 2014).

Full results of the scenario analysis, i.e., the relative change in the values of components in the conventional beef production system based on artificially fixing production efficiency to zero, and price per kilo, training/skill level, and farm infrastructure/resources to 1 are shown in Figure S1 in the Supplementary materials. Figure 6 illustrates the main effects of switching to an entirely pasture-fed system on the main components of UK beef production, as predicted by conventional stakeholders, by displaying the components with a relative change value >1% or <−1%.

Discussion

Central components and key relationships

FCM was used to extract a mental model of both UK conventional beef production (a system that is largely forage-based but with a significant proportion of the diet consisting of concentrates), and an entirely pasture-fed system, as exemplified by the Pasture For Life certification scheme. This proved to be an effective technique for extracting knowledge from multiple stakeholders to create representative systems models, which allowed for a ‘thought experiment’ (via scenario analysis) of wholesale transition from conventional to pasture-fed production, based on stakeholders’ predictions of the main components affected by this transition. Running an experiment where all beef production in the UK is switched to a 100% pasture-fed approach is understandably not possible, making this type of modeling approach both practical, but also valid due to participation of stakeholder experts in both systems.

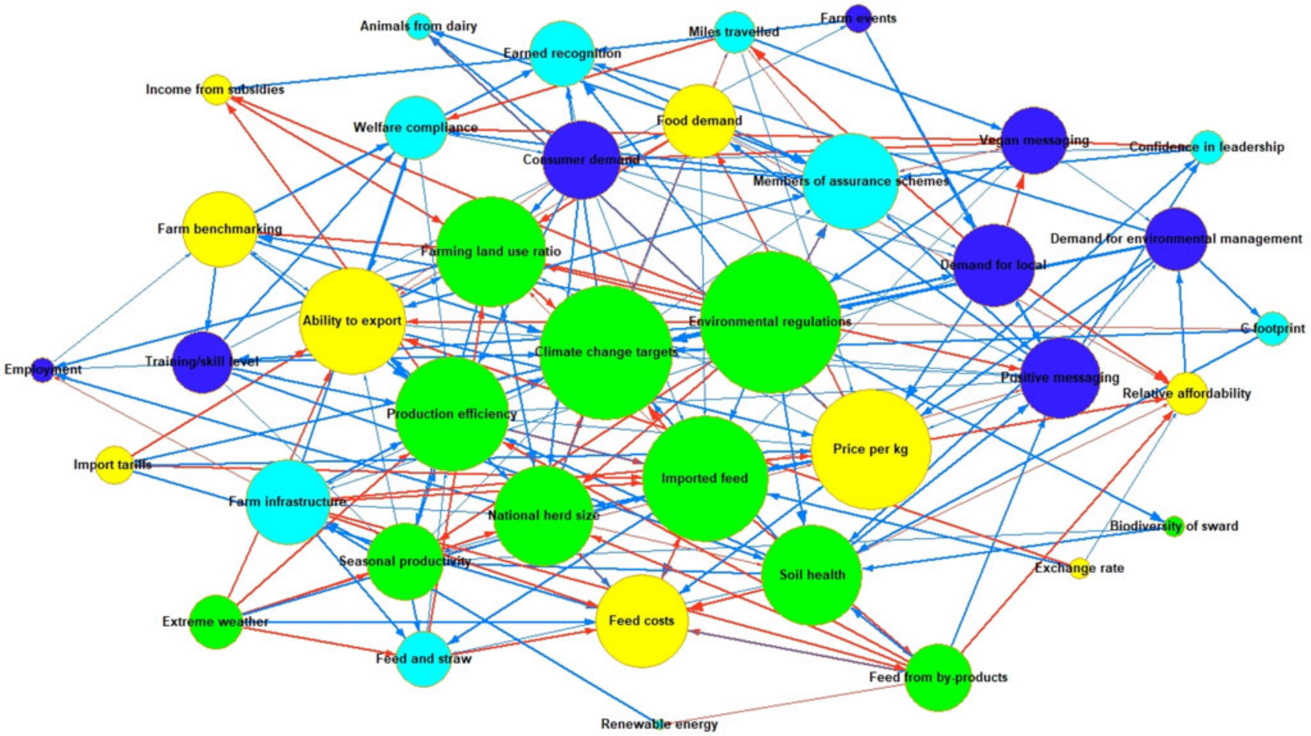

Figure 5. Visual representation of the FCM of the conventional beef production system, as defined by 15 stakeholders from across the beef sector. Size of the component nodes indicates their centrality. Color of the component nodes indicates the sustainability pillar to which they belong: green = environmental, yellow = economic, blue = social, cyan = governance. Direction of the arrow indicates the direction of the causal relationship between two components. Red arrows indicate negative relationships, blue arrows indicate positive relationships. The width of the arrow indicates the strength of the relationship.

The FCM of the UK conventional beef production system (Fig. 5) was larger and more complex than that of the pasture-fed beef production FCM (Fig. 4), in that it had five more components, and more key relationships between the components. This could be due to more inputs and a greater market reach, including export, of the conventional system compared to

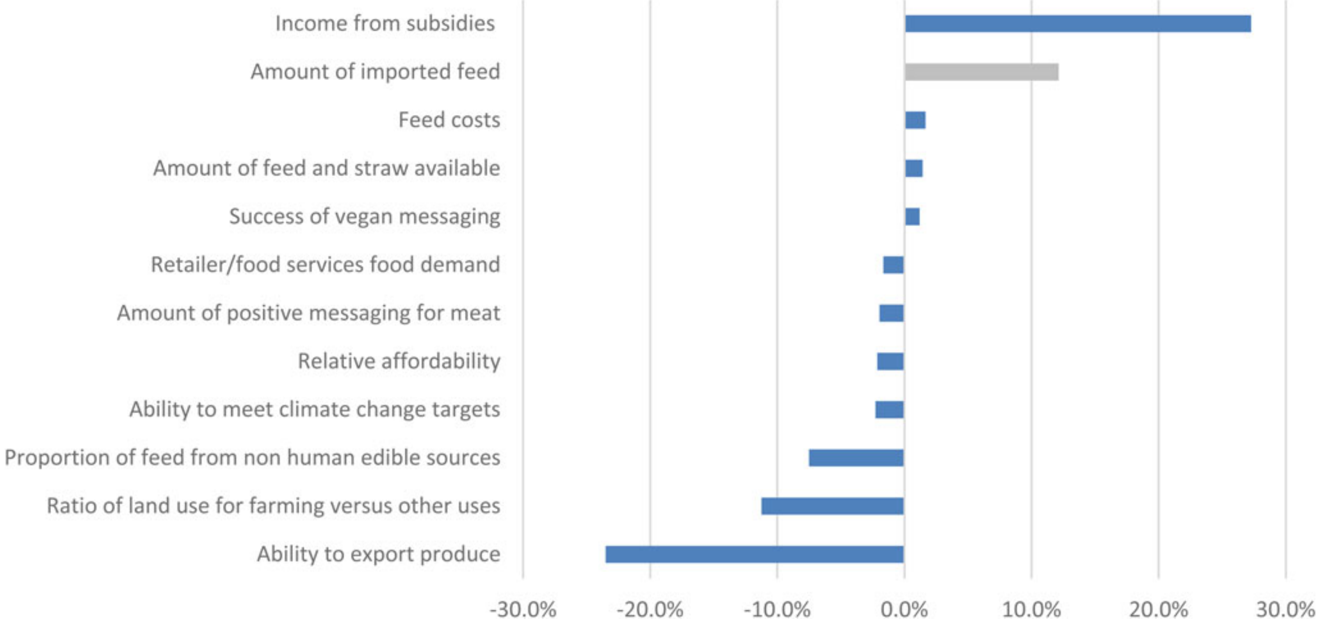

Figure 6. Main results of the FCM scenario analysis. Relative change (%) in the values of components in the conventional beef production system based on a decrease in production efficiency, and an increase in price per kilo, training/skill level, and farm infrastructure/resources. This illustrates the effect predicted by participants on the main components of UK beef production if it were switched to an entirely pasture-fed system. Percent change is relative to the value of components in the conventional beef production system FCM. Changes to 'Amount of imported feed' (shaded gray) is an artifact of the modeling approach (see 'Discussion' section). Components with a relative change value >1% or <−1% are displayed here; for full results, see Figure S1 in Supplementary materials.

the pasture-fed system. The relatively simple structure of the pasture-fed approach illustrated in Figure 4 is indicative of a system less reliant on external inputs and thus more resilient to external pressures (El Chami, Daccache and El Moujabber, 2020; van der Werf, Knudsen and Cederberg, 2020). There were many relationships between components identified by stakeholders as key (i.e., clear evidence for a relationship and a clear direction for that relationship) for both the pasture-fed and conventional systems. This illustrates the complexity and interconnectedness of both systems as defined by knowledgeable stakeholders.

The environmental component 'vegetation quality', defined by the group as species richness of the sward, was the most central component in the pasture-fed beef production system, as indicated by the relative size of this component in Figure 4. This was followed by the governance component 'grass use efficiency', defined as the use of sustainable grazing practices such as rotational grazing, and the environmental components 'vegetation quantity', and 'soil health'; all three of these components had a similar centrality score, as indicated by their relative size in Figure 4 (and centrality metrics in Table S1 and Fig. S1). Centrality demonstrates the importance of the component in the system, with high centrality components controlling the dynamics of the system (Solana-Gutierrez et al., 2017). Hence, the most important factors in a pasture-fed beef system relate directly to the environmental resource at the heart of the pasture-fed system: pasture (Vetter, 2020). Despite a recent focus on the global warming abatement potential of grass-fed beef systems (e.g., Bellarby et al., 2013; Garnett et al., 2017; Mottet et al., 2017) the FCM produced in workshop 1 did not reveal 'greenhouse gas mitigation' as a central component, although this aspect could be implicitly represented through the components 'vegetation quality', 'fossil fuel use', and 'soil quality' given their influence on greenhouse gas mitigation (e.g., through avoided manufactured fertilizer as a result of biological nitrogen fixation by clover and other legumes in pasture, and/or through carbon sequestration under grassland; Smith et al., 2019).

Environmental components were also very central to the conventional beef production system, according to stakeholders from government, industry, farming groups, veterinary groups, research consultancy, and certification bodies. However, economic components were more central in the conventional beef system than in the pasture-fed system. The most central, and therefore important components in the conventional system were 'the extent of environmental regulations', 'ability to meet climate change targets', 'amount of imported feed', 'price per kilo', and 'production efficiency', as indicated by their relative size in Figure 5 (and centrality metrics in Table S2 and Fig. S1).

These results indicate that 'environmental regulations' and 'ability to meet climate change targets' currently have the most influence over the dynamics of conventional beef production, as shown by a large out-degree and a large in-degree respectively (Table S2, Fig. S1). This is understandable during a time when environmental concerns such as the climate and ecological crises have such great prominence in society, and beef production is under particular scrutiny due to its environmental impacts (Garnett et al., 2017). Similarly, imported feed is an environmental concern in terms of the risk that production of this feed is associated with land clearance and deforestation and increased transport (Flysjö et al., 2012). If beef producers are to meet environmental regulations and climate change targets, it follows that the amount of imported feed used is also very influential within the system. Price per kilo and production efficiency are key economic and production factors affecting how much beef is produced, and what price the farmers receive for it (Greenwood, 2021). Interestingly, as with the pasture-fed system, soil health was also central to the conventional system (but not as central), whereas 'biodiversity of the sward' had very low centrality. This component is akin to the component 'vegetation quality' in the pasture-fed system, which had the highest centrality.

The potential impacts of a 100% transition to pasture-fed beef production

Participants predicted that this transition would lead to: (1) a reduction in production efficiency (defined as yield per unit time), due to a less concentrated source of energy in the form of grass compared to concentrate feed used in the conventional system and therefore a longer time to reach slaughter weight; (2) an increase in the price of beef, due to a drop in domestic supply; (3) an increase in training/skill levels, due to the need for farmers to learn the necessary skills to manage an entirely pasture-based system; and (4) an increase in certain farm infrastructure due to a need for resources required to support a pasture-based system, e.g., fencing for paddocks, seeds for enriching pastures, etc.

Following implementation of these predictions within the conventional system FCM, using the methods described in section 'Scenario analysis', there was a decrease in 17 components, no change in three components, and an increase in 14 components, although for nine of these the increase was less than 1% (0.01–0.99%)—see Figures 6 and S1. The most marked changes were a predicted increase in income from subsidies (27.3%), an increase in imported feed (12.1%), a decrease in the ability to export produce (23.5%), a decrease in the ratio of land use for farming *vs* other uses (11.23%), and a decrease in the proportion of feed from non-human-edible sources (7.5%) (Fig. 6). Each of these is discussed in the subsections below.

Increase in the imported feed: methodology artifact

An increase in the imported feed component in the scenario analysis (Fig. 6) was caused by a negative relationship between production efficiency and imported feed (i.e., a more efficient feed conversion ratio meant less feed needed). The predicted reduction in production efficiency would therefore result in an increase in imported feed. However, this is an artifact of an FCM modeled on a conventional production system that utilizes feed other than pasture, and does not follow in a 100% pasture-fed system where imported feed is not used. For this reason, an increase in imported feed can be removed from the conclusions.

Increase in income from subsidies

An increase in income from subsidies was the greatest predicted effect of a transition from conventional to pasture-fed. This is largely due to the negative relationship between production efficiency and income from subsidies within the FCM for conventional beef, and the prediction of a lower production efficiency in a 100% pasture-fed scenario. The negative relationship between level of subsidy and production efficiency, found in this study, is in line with previous research and may be linked to a dependence on subsidies discouraging innovation on-farm (Kumbhakar and Lien, 2010; Bojnec and Latruffe, 2013; Sargison, 2020).

This relationship of course depends on there being a subsidy structure in place as well as on what that structure is based (Kumbhakar and Lien, 2010). This relationship and its influence could be affected by the proposed environmental land management scheme in England and new schemes in other UK devolved administrations which seek to pay public money for delivery of environmental benefits such as increased animal welfare, increased biodiversity, and carbon capture (Department for Environment, Farming and Rural Affairs, 2023), which pasture-based systems seek to deliver (Pasture For Life, 2018). As such, an increase in income from subsidies can be said to be in line with UK sustainability objectives, according to the proposed new, post-Brexit subsidy structures.

Decrease in the ability to export produce

The second largest change was a decrease in the ability to export produce (Fig. 6), due to a decrease in production efficiency, an outcome that is in line with previous studies highlighting the relationship between production efficiency and amount of product exported in the livestock sector (Michalk et al., 2019). If overall production efficiency decreases, it therefore follows that ability to export will diminish. The UK exported approximately 9% of beef produced in 2019 (National Beef Association, 2019). However, if consumption levels decrease to the proposed level to meet human and planetary health, then it is possible that a surplus of beef production may remain for export. In support of this, the Food Farming and Countryside Commission (FFCC) modeled a transition to agroecological farming in the UK (Food Farming & Countryside Commission, 2021). It models a UK diet based on dietary recommendations from the European Food Safety Authority and the changes needed to address the climate and ecological crises, resulting in a 25% reduction in beef consumption. Production was modeled as a pasture-based system, an approach that has the potential to be less damaging, regarding global warming potential, than the conventional alternatives, in particular through the replacement of manufactured nitrogen fertilizer with biological fixation through legumes in grassland (Smith et al., 2019). The results revealed a predicted surplus of beef of 24% for export (Food Farming & Countryside Commission, 2021). Moves toward such pasture-fed systems could therefore support progress toward 'less and better' animal protein consumption (although improved scientific characterization of the term 'less and better' is crucial for a meaningful assessment of livestock systems against this value-laden term; Sahlin, Röös and Gordon 2020).

However, it should be noted that if UK and worldwide beef demand were to remain at current levels, then the predicted drop in beef production and ability to export due to a shift to 100% pasture-fed system could result in this demand being met by production elsewhere in the world, with potential environmental trade-offs. Currently, major importers of UK beef are Ireland, the Netherlands, France, Hong Kong, Italy, Belgium, the Philippines, Germany, Spain, and China (AHDB, 2023). Demand from these countries could instead be met by the largest beef exporter in the world: Brazil (zu Ermgassen et al., 2020). However, beef production in Brazil has a large negative environmental impact as it is a major driver of deforestation and as such a major driver of biodiversity decline and greenhouse gas emissions (zu Ermgassen et al., 2020). Therefore, it is imperative that any move to 100% pasture-fed production including policy levers must be accompanied by levers to reduce beef production and demand, in order to prevent such environmentally negative trade-offs.

Decrease was the ratio of land use for farming *vs* other uses

The next largest predicted decrease was the ratio of land use for farming *vs* other uses (11.23%, Fig. 6), i.e., the amount of land used for farming would decrease and land for other uses would increase. This outcome resulted from the relationship between this element and the components 'ability to export' and 'income from subsidies'. The more positive attitude toward nature conservation observed within grassland farmers following agroecological practices is likely to be an important explanatory factor—farmers following an agroecological approach often see the inclusion of agri-environment schemes and their management as an essential part of managing the farm system, rather than an external interference, and are therefore more likely to devote land to conservation (Hammes et al., 2016). Increased uptake of diversification measures within agroecological farming systems may also contribute, as farmers adopting measures such as agri-tourism, rewilding and care-farming are likely to take areas out of production to provide the space and/or facilities required (Lobley, Butler and Reed, 2009). Although such systems are likely to supply less food per hectare than their conventional counterparts, evidence suggests that net ecosystem service delivery is likely to be greater when considering a raft of impacts on society (e.g., encompassing social wellbeing and biodiversity impacts; Reganold and Wachter, 2019). Such benefits align with current UK policy objectives such as Defra's 25 Year Environment Plan, and support for public goods provision through UK agriculture (de Boon, Sandström and Rose, 2022).

Evidence also suggests that food system adjustments could support a transition to such 'multifunctional' systems, for example the FFCC study highlights that agroecological systems such as pasture fed could support growing populations while still freeing up approximately 7.5% of current agricultural land, if accompanied by reductions in food waste and meat consumption (Food Farming & Countryside Commission, 2021). In addition, approximately 5 million tons of human-edible food is wasted at the household level in the UK (WRAP, 2018); therefore any potential decrease in productivity from agroecological farming system could be counteracted if we reduce our profuse waste of food (Muller et al., 2017).

Decrease in proportion of feed from non-human-edible sources

Finally, the scenario analysis predicted a decrease of 7.5% in the proportion of feed from non-human-edible sources (Fig. 3). By this the participants meant farming co- and by-products which could be classed as 'waste', e.g., arable and horticultural produce not meeting human consumption standards, spent grain, oil cakes from oil production, etc. These food sources would not be consumed directly by humans, therefore can only be used for human nutrition by feeding to livestock. However, the use of these non-human-edible feed sources in ruminant livestock production competes with monogastric livestock production. Monogastric animals rely on arable and horticultural co- and by-products as they cannot efficiently digest pasture the way that ruminants can (Schothorst Feed Research, 2020). Currently conventional pig and poultry production systems use grain-based animal feed containing human-edible grain and resulting in land being used for growing animal feed instead of human food, competing directly with human food needs ('feed–food competition'; Breewood and Garnett 2020; Molossi et al., 2020; Wyngaarden, Lightburn and Martin, 2020). Consumption of human-edible food by monogastric (and ruminant) livestock results in a lower human edible feed conversion efficiency, i.e., a net loss in energy and protein supply available to humans (Molossi et al., 2020; Wyngaarden, Lightburn and Martin, 2020). Instead, using co- and by-products in monogastric livestock production represents a circular economy where human-inedible waste is recycled into human-edible food, and food–feed competition and the associated inefficient use of resources is reduced or eliminated. Indeed, Wyngaarden, Lightburn and Martin (2020) modeled that maximizing forages as feed for ruminant and using by- and co-product feeds and wasted foods in monogastric production, as well as integrating crop and livestock systems, could reduce arable land use for feed production by 41% while still maintaining sufficient animal protein for a healthy diet. Thus, switching to 100% pasture-fed beef cattle system would be beneficial in creating a pork, poultry, and egg production system that is more sustainable (and potentially more profitable) than the current conventional systems for these livestock. Furthermore, such by- and co-products can also provide a valuable feedstock for anaerobic digestion (AD) plants, helping to support renewable heat and electricity generation while providing a valuable fertilizer product in the form of digestate (the material remaining after the AD process; Vaneeckhaute et al., 2018).

Omissions

There are potential negative impacts of the scenario analysis not captured by the FCM exercise. For example, a reduction in production efficiency (defined by the group as yield per unit time) due to cattle taking longer to finish may have a negative economic impact (i.e., less money per unit time for the farmer), especially if 100% pasture-fed beef becomes the norm rather than a premium product for which farmers can charge a premium price. However, PFL farmers tend to have lower costs compared to conventional benchmarks (Norton et al., 2022*b*), a positive economic impact of a 100% pasture-fed system which could mitigate the negative economic impact above. Furthermore, there is a potential negative environmental impact of longer finishing times in the form of higher greenhouse gas emissions due to methane from enteric fermentation (i.e., longer time to slaughter meaning a longer time spent producing methane; Hammar, Hansson and Röös, 2022). These increased emissions may be able to be offset by improved carbon sequestration by soils and diverse grassland in pasture-fed systems, and especially where trees are incorporated in a silvopasture system (O'Brien, Markiewicz-Keszycka and Herron, 2023); however, there is an inconsistent evidence base on the extent to which pasture systems can sequester and store more carbon to partially or completely mitigate other greenhouse gas emissions in the system, likely due to complexity and context-specificity of the issue (Jordon et al., 2024). Furthermore, time to reach slaughter weight also has a genetic (breed) component, as well as a dietary component. Entirely pasture-fed systems normally use traditional native breeds that, although are slower growing, are more suited to pasture and consequently less reliant on grains for finishing (AHDB, 2019), which results in an increased human edible feed conversion efficiency (Molossi et al., 2020). Therefore, this trade-off is more nuanced than simply saying pasture-fed systems take longer and therefore are less productive or efficient.

There are also potential environmental benefits of pasture-fed livestock systems that were not an output of this FCM exercise. For example, positive biodiversity effects: pasture-fed livestock production has been associated with increased plant species richness and soil invertebrate abundance, as well as improved soil health, compared to conventional livestock production (Norton et al., 2022*a*). It may also be associated with reduced eutrophication (excessive richness of nutrients in waterbodies leading to harmful algal blooms and killing other wildlife; NOAA, n.d.). Unlike 100% pasture-fed systems using few or no inputs in their species-rich swards, negative impacts of conventional practices include increasing eutrophication of terrestrial, freshwater, and ultimately marine habitats (Benton et al., 2021). The focus of conventional systems on monocultures of nutrient demanding ryegrass and concentrates results in excess nutrients (Withers et al., 2019) which impact well beyond the farm gate. Omission of these and other potential environmental benefits represents a limitation of the study, as discussed below.

Limitations of the study

The use of an FCM technique in the current study was limited in terms of the complexity it could capture. Beef production is very complex whether conventional or pasture-based, with many more components than the 38 and 33 respectively that were identified by participants. In addition, many relationships in the system are not straightforward in their causal direction or strength and may be condition dependent. Therefore, both the maps produced, and the conclusions drawn from the scenario analysis represent a simplified version of the real-life situation, and may not capture all of the potential benefits and drawbacks of a wholesale transition to 100% pasture-fed beef production. Some of the aspects of the pasture-fed approach to production that are exemplified in production standards, and within recent literature (e.g., promotion of biodiversity, animal welfare) are not explicitly represented in the FCM, suggesting that the mapping approach, or its implementation may have missed fundamental elements of the system being studied (although such aspects could be 'implicitly represented' in other components, such as pasture quality). This limitation is reflected by Levy, Lubell and McRoberts (2018), who reviewed the cognitive maps of 148 leaders in sustainable agriculture and found more complex forms of causal structure were under-represented in the experts' maps.

Group dynamics may have differed between workshops 1 and 2. However, a facilitator was present to ensure engagement from all participants and to work through any differences in opinion so that the results reflected group consensus. Workshop 2 also differed from workshop 1 in that the direction and strength of relationships between components were suggested, due to brevity of time, which could have introduced bias into the study. However, the workshop participants adjusted any relationships they did not agree with; therefore, the authors believe that the results truly reflect stakeholder opinion.

The study was also limited in its geographic focus. Limitations on time and resources prevented an extension of the stakeholder pool beyond the UK, potentially limiting the relevance and scope of this study (e.g., regarding land use change impacts associated with the production of imported feed). Nevertheless, the focus on a UK case study could have relevance for other countries facing similar socio-ecological/socio-economic conditions and limitations. Combining the FCM approach with environmental modeling approaches, such life cycle assessment, could help to provide a more complete picture of the impacts associated with transition scenarios related to or including 100% pasture-fed livestock farming.

Conclusions

Pasture-fed approaches to livestock management have the potential to improve ecosystem function and the delivery of ecosystem goods (Buller, 2008; Teague and Kreuter, 2020); however, the impacts of scaling-up the pasture-fed approach are still uncertain. This study set out to assess the sustainability impacts that could result from the wholesale adoption of 100% pasture-fed beef production in the UK through FCMs. The following key findings were identified through this process:

1. A switch from conventional to pasture-fed beef production in the UK could result in a large increase in income from subsidies, and a marked decrease in (i) the UK's ability to export beef, (ii) the ratio of land used for agriculture relative to other uses such as conservation, and (iii) the amount of food by-product feed used in the beef industry.
2. Moving to pasture-fed systems could support the availability of co- and by-products from the production of food for human consumption for other purposes such as feeding monogastric livestock or AD.
3. The amount of land used for farming could decrease and land for other uses such as conservation could increase by moving to a pasture-fed approach through inclusion of agri-environment schemes and their management as an essential part of managing the farm system, resulting in net ecosystem service delivery.
4. Vegetation quality, grass use efficiency, and soil health are considered by selected actors to be the most important/influential elements within pasture-fed beef production.
5. Production efficiency elements, environmental regulations, and climate change targets are considered the most important elements affecting the UK conventional beef industry.
6. FCMs could provide a useful tool for the identification of effective leverage points within future agricultural systems research.
7. The outcomes of a shift to 100% grass-fed beef production could align with current/future policies in the UK for increased public good provision through agriculture.

Participatory mapping of the pasture-fed and conventional approaches to beef production revealed that a widespread shift toward pasture-fed livestock farming could support the balanced and effective delivery of public goods and sustainability, although challenges could remain regarding levels of production, product prices, and the UK's ability to export. More support for the integration of pasture-fed approaches within the conventional industry could enhance sustainability and resilience in the UK beef sector, while further research on the impacts of scaling-up this approach could help to reveal trade-offs and synergies across sustainability domains.

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