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Leverage points for the uptake of organic food production and consumption in the United Kingdom

Tom Staton[1], Nicholas Davison[1], Sally Westaway[2], Lisa Arguile[1], Nina Adams[1], Victor Aguilera[3], Lillie Bellamy[4], Alysoun Bolger[4,5], Richard Gantlett[1,6], Steven Jacobs[7], Niamh Noone[8], Joanna T. Staley[9] & Laurence G. Smith[1,10]

Organic food systems are recognised as an important component in meeting United Nations' (UN) Sustainable Development Goals. A leverage points perspective can help to identify approaches which have the potential to facilitate transformative systemic change towards organic and sustainable farming. Using fuzzy cognitive maps developed from expert stakeholder opinions, we modelled a system of drivers of organic food production and consumption in the United Kingdom, according to the UN Sustainability Assessment of Food and Agriculture systems framework. The most influential concepts in the uptake of organic systems were related to system norms and values and social structures, such as short-term economic thinking, landowner engagement, and relationships with certification bodies. However, in a scenario analysis, organic stakeholders identified relatively shallower leverage points as more likely to change under a sustainable future, resulting in limited systemic change. This demonstrates the need for policies targeting system norms, values and social structures relating to food systems to facilitate the transition to organic and sustainable farming.

Transformation towards sustainable food production systems is urgently needed for agriculture to operate within planetary boundaries, defined as the environmental limits within which humanity can safely continue to thrive, and make progress on Sustainable Development Goals (SDGs)[1,2]. Organic agricultural systems have long been recognised for their potential contribution towards this transition because of their emphasis on sustainable principles such as reduction of synthetic inputs, crop and livestock diversification, soil health improvement, and natural methods for pest and disease control[3,4]. Given their inherent productivity limitations[5,6], organic systems are unlikely to be the sole answer to address the challenges of global food sustainability. However, they can play an important role in a sustainable future for food production and consumption by offering nature-based solutions to minimise adverse environmental impacts of production[7].

Organic systems also provide inspiration for a broader food system transformation[3,4]. The influence of organic systems extends beyond their immediate practices, contributing to the transition towards a globally sustainable food system. For example, organic systems can inspire the development, uptake, and regulation of other innovative sustainable agricultural systems such as agroforestry and conservation agriculture[3,4]. Organic systems can also contribute to a sustainable food system when accompanied by other measures, such as dietary changes and reductions in food waste, to overcome the productivity limitations of organic farming[8]. Furthermore, the adaptability of organic practices to local contexts highlights their relevance in addressing specific local environmental challenges, such as nutrient leaching[7,9].

The contribution of organic agriculture to sustainable food production is broadly recognised by both the scientific community[10] and European Union (EU) policies, for example, the Farm To Fork Strategy, which includes a target of at least 25% of agricultural land under organic farming by 2030[11]. In the United Kingdom (UK), although no such target has been set post-Brexit, conversion payments under the Countryside Stewardship scheme doubled for some organic systems in 2022[12]. The organic market in Europe more than doubled in size between 2011 and 2020, with the UK contributing to this, including a 12.6% increase in 2020 alone[13]. Despite this, the organic land share in the UK has decreased by approximately 25% over the past 10 years[14], representing one of the highest decreases amongst

[1]School of Agriculture, Policy & Development, University of Reading, Reading, RG6 6EU, UK. [2]Royal Agricultural University, Cirencester, GL7 6JS, UK. [3]UK Department for Environment, Food and Rural Affairs, London, SW1P 4DF, UK. [4]Biodynamic Association, Stroud, GL5 1QG, UK. [5]Biodynamic Federation Demeter International, 64295 Darmstadt, Germany. [6]Yatesbury House Farm, Calne, SN11 8YF, UK. [7]Organic Farmers & Growers, Shrewsbury, SY4 3AG, UK. [8]Soil Association Certification, Bristol, BS1 6AD, UK. [9]UK Centre for Ecology and Hydrology, Wallingford, OX10 8BB, UK. [10]Department of Biosystems and Technology, Swedish University of Agricultural Sciences, SE-234 22 Lomma, Sweden. e-mail: tom.staton@reading.ac.uk

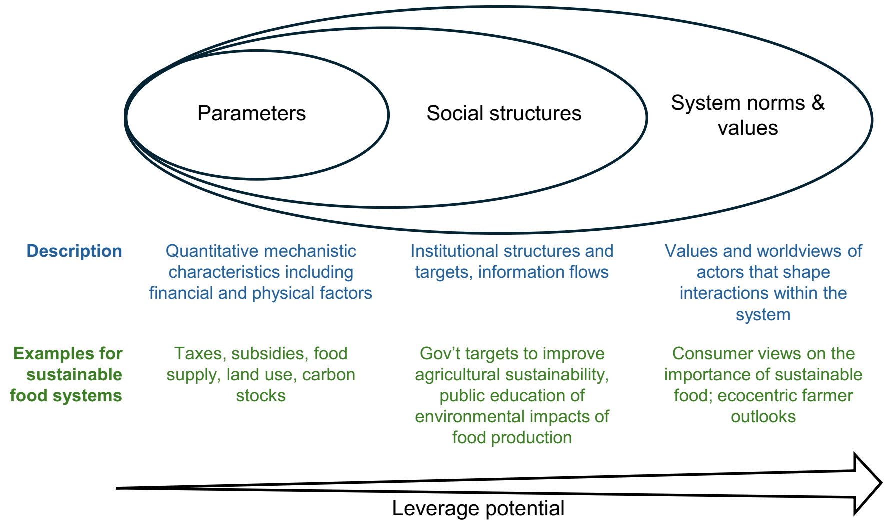

Fig. 1 | Adapted leverage points concept for sustainable food systems. The top nested categories represent realms of leverage (adapted from Abson et al.[20] and Davelaar[54]), where 'system norms & values' have the greatest potential for deep transformative change and constrain the interventions possible at shallower leverage realms (i.e., parameters).

European countries[15]. Nevertheless, there is an interest in the UK and beyond in moving towards approaches that couple productivity with sustainable practices, such as crop diversification and reduced reliance on synthetic fertiliser inputs[16–18]. Such systems are often inspired by and built on organic approaches[4,19], but in order to be scaled up, require policymakers and other actors to create an enabling environment for innovation[3].

Enabling such a transformation requires a transdisciplinary understanding of the approaches that can enact change at a systemic level[20,21]. Sustainability science, which aims to find solutions to complex transdisciplinary problems[22], has been criticised for focusing on measures which are easy to implement but only have limited effects on the system and therefore have minor potential for transformational change[20,23]. The concept of 'leverage points' seeks to address this shortcoming by recognising the realms of a complex system which have the greatest potential to enable transformative change[21,23]. Abson et al.[20] propose that effective 'deep' leverage points lie in the intent and design of the system, rather than more tangible parameters and their feedbacks. This builds on Meadows'[23] theory that paradigm shifts, mindsets, and the goals of the system have the greatest potential in enacting transformational change. A recent systematic review of sustainability interventions in food and energy systems demonstrates the need for such a perspective, finding that most studies focus on more tangible system parameters which act as weak leverage points rather than deep leverage points related to system rules, values and paradigms[24]. In this study, we apply a leverage points framework adapted for sustainable food production and consumption systems, as illustrated in Fig. 1, and tested its applicability to organic food systems.

We aim to identify deep leverage points for the development of organic and sustainable farming systems through the following broad research questions; (1) what are the main factors that could affect the uptake of organic food production and consumption in the UK by 2050, and (2) how might these factors change under different future sustainability scenarios. Our methodological approach was based on fuzzy cognitive maps (FCM), which provide insight into how the components of a given system interact and influence each other, thus identifying the components that have the greatest influence, or leverage, on the system[25]. FCMs are of increasing interest in applied agricultural research[26–28]. Based on the results of a workshop attended by 18 expert stakeholders in organic agriculture, we used FCMs to conceptualise a model of organic food production and consumption in the UK, showing that factors relating to systems norms and values, and social structures, have the greatest influence on the system. We then test how the model would change under two contrasting sustainability scenarios. These comprised a highly sustainable versus a fossil fuel and high technology-driven future, based on the shared socioeconomic pathways (SSPs) for European agriculture and food systems[29]. We explored whether changes under these scenarios can be explained in terms of sustainability dimensions and leverage categories, and which scenario would lead to the greatest change to the baseline system. Stakeholders identified relatively shallow leverage points as most likely to change under a sustainable future, resulting in limited systemic change with implications for promoting the uptake of organic and sustainable farming systems.

Results

Fuzzy cognitive map structure (baseline scenario)

A total of 55 concepts that could affect the uptake of organic food production and consumption by 2050 within the UK were identified in a workshop attended by 18 expert stakeholders in organic agriculture and subsequently modelled in the FCM. A simplified structure of the FCM is presented in Fig. 2, while the 'top 30' concepts are ordered by centrality in Table 1. The concepts with the highest centrality, representing the sum of the extent to which they affect and are affected by other concepts, were 'short-term thinking in economics' and 'landowner engagement with organic farming'. These concepts had stronger effects on the system relative to being affected by other concepts (high 'outdegree'). 'Farmer-certification body relationships' also had a high outdegree, strongly affecting other concepts in the system. Other high-centrality concepts were 'consumer willingness to pay for organic' and 'food scares', which influenced the system to a similar degree as they were influenced by it. 'Greenhouse gas emissions' had the highest indegree, being most strongly affected by other concepts in the system, followed by 'consumer willingness to pay for organic' and 'soil health'.

All of the concepts influenced and were influenced by the system to some extent, with the exception of 'improved mental health', which was only affected by the system (receiver concept). Two other concepts had minimal influence on the system, namely, 'cultural value of food and farming methods' and 'community engagement with food production'.

Each of the concepts was categorised according to four dimensions of sustainability: governance, environmental, economic, and social[30], in addition to 'other' (see Table 1). Concepts associated with the 'other' dimension had the highest average centrality (Fig. 3a), which was driven by 'short-term economic thinking'. This was considered to be a broader concept than purely economics by the stakeholders, relating to holistic mindsets and planning, and was therefore placed into the 'Other' category rather than 'Economic'. These 'other' concepts had a much stronger influence on the system relative to being influenced by the system (outdegree vs indegree). Social concepts showed a similar pattern. Economic concepts had the lowest average centrality and were more influenced by the system than influencing the system (indegree relative to outdegree), as were environmental concepts.

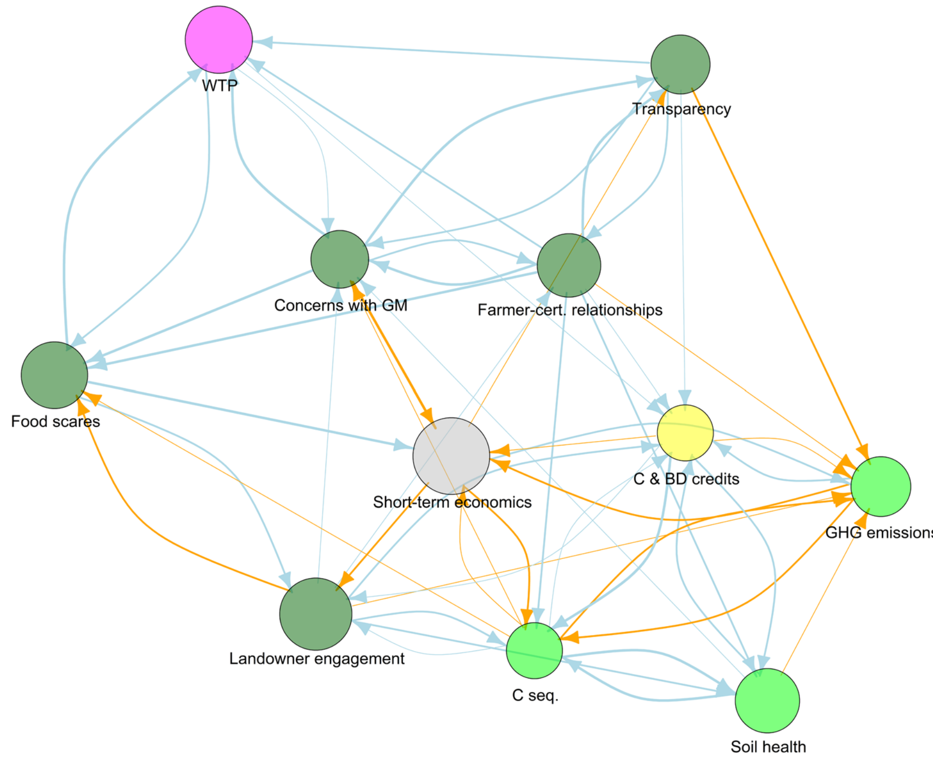

Fig. 2 | Simplified fuzzy cognitive map network showing the main factors that could influence the uptake of organic food production and consumption by 2050. This network shows the top 11 concepts with the highest centrality. Concepts are coloured according to their dimension under the Sustainability Assessment of Food and Agriculture systems (dark green = 'social', light green = 'environmental', magenta = 'economic', yellow = 'governance', grey = 'other') (see Table 1). Light blue arrows represent positive interactions, whereby one concept increases another concept in the direction of the arrow, while orange arrows represent negative interactions. Line width represents the strength of the relationship. Concept names are abbreviated, see Table 1 for full names. BD biodiversity, C carbon, GHG greenhouse gas, GM genetically modified, WTP willingness to pay.

In terms of leverage categories (see Fig. 1), concepts relating to system norms and values had the highest mean centrality, followed by social structures, with parameters having the lowest centrality (Fig. 3b). A subtle shift in the indegree vs outdegree was also apparent, with concepts relating to norms and values having a slightly higher outdegree relative to indegree, indicating they influence the system more than being influenced by it.

Scenario analysis

Two scenarios were tested to explore how the FCM system could respond to contrasting future sustainability pathways, namely SSP1 'agriculture on sustainable paths' and SSP5 'agriculture on high-tech paths'[29]. One concept from each of the four Sustainability Assessment of Food and Agriculture systems (SAFA)[30] dimensions plus a fifth 'other' dimension was clamped at a high or a low value based on stakeholder votes, while a sensitivity analysis was undertaken to test the second-highest voted concept in each of the five dimensions. Under the SSP1 sustainable scenario, according to our FCM, strong decreases were observed for 'short-term thinking in economics', 'extent and effectiveness of green washing', and 'resistance from vested interests', which was supported by the sensitivity analysis (Fig. 4a). The effect on 'reliance on imported feed' was less clear, with the sensitivity analysis finding an opposite trend to the main analysis. Other changes were a decrease in food waste and losses, an increase in fossil fuel prices, and higher subsidies/payments under agri-environment schemes.

Modelled changes were less clear under the SSP5 fossil fuel, technology-driven scenario, where the sensitivity analysis was less supportive of the main analysis (Fig. 4b). The strongest change was for a decrease in fossil fuel price. However, in the sensitivity analysis, this was clamped at a high level in accordance with stakeholder responses. Furthermore, under the main analysis, 'land availability for food production' and 'cost of living' both decreased, with increased 'processing capacity', but the sensitivity analysis found the opposite effect. A consensus was however found for increases in 'reliance on imported feed', 'food waste and losses', 'availability of labour', and 'carbon and biodiversity taxes', while 'extent and effectiveness of green washing' increased and was clamped at a high level in the sensitivity analysis. As illustrated by the x-axis scale in Fig. 4a versus Fig. 4b, changes to unclamped concepts were significantly higher under SSP5 than SSP1 ($t = -3.267$, df = 49, p-value = 0.002; mean absolute change in equilibrium values = 0.0180 in SSP5 vs 0.000753 in SSP1).

Discussion

In this study, we use fuzzy cognitive maps (FCM) to construct a model, based on expert stakeholder opinions, of the factors that could influence the uptake of organic food production and consumption by 2050 within the UK. We then explore the impacts of future scenarios under contrasting sustainability pathways (SSP1 and SSP5). The resulting modelled system was complex, with 55 distinct concepts and 720 interactions identified. Our results reveal the importance of more qualitative and behavioural aspects, such as short- vs long-term economic thinking, landowner engagement with organic farming, and farmer-certification body relationships, in influencing the uptake of organic food production and consumption (concepts with high outdegrees and centrality). By contrast, more quantitative environmental and economic aspects tended to have less influence on the system (lower outdegree), instead being more influenced by the system (higher indegree).

Under future sustainability scenarios, a relatively strong consensus was reached as to how the system would change under the most sustainable scenario (SSP1), including strong decreases in short-term economic thinking, green washing, and resistance from vested interests. However, modelled changes under the fossil-fuelled, technology-driven scenario (SSP5) were very uncertain, perhaps reflecting the experience and knowledge gaps of the participants, with model outputs conflicting with stakeholder opinions and a sensitivity analysis.

Our findings are consistent with the theory that characteristics associated with system norms and values and social structures have the greatest potential to enact change across the system, i.e., deep leverage points[20,23]. For example, the three concepts with the highest centrality were all categorised under 'system norms and values' (short-term thinking in economics, landowner engagement with organic, and consumer willingness to pay for organic). Furthermore, concepts associated with system norms and values tended to have relatively higher outdegree vs indegree, i.e., they influenced the system to a greater extent than being influenced by it (Fig. 3b). This implies that concepts associated with system norms and values are the main

Table 1 | List of concepts according to their dimension under the Sustainability Assessment of Food and Agriculture systems (SAFA)[30] and leverage category (see Fig. 1), ordered by measure of centrality in the FCM model

Concept	SAFA dimension	Leverage category	Centrality	Indegree	Outdegree
Short-term thinking in economics	Other	System norms & values	18.6	6.7	11.9
Landowner engagement with organic farming	Social	System norms & values	17.5	4.4	13.1
Consumer willingness to pay for organic	Economic	System norms & values	16.3	8.2	8.1
Food scares	Social	Parameter	16.1	7.1	9.0
Soil health	Environmental	Parameter	15.6	7.8	7.8
Farmer-certification body relationships	Social	Social structures	15.4	2.6	12.8
Greenhouse gas emissions	Environmental	Parameter	14.5	9.2	5.3
Transparency: consumer awareness of labels and organic standards	Social	Social structures	14.3	3.7	10.6
Concerns with genetically modified crops	Social	System norms & values	14.0	3.5	10.5
Carbon sequestration	Environmental	Parameter	13.6	7.5	6.1
Carbon and biodiversity credits	Governance	Parameter	13.6	5.6	8.0
Consensus on sustainability metrics	Other	Social structures	13.2	3.2	10
Water quality	Environmental	Parameter	13.0	7.1	5.9
Dietary shift to more seasonal, local and organic	Social	System norms & values	12.8	7.2	5.6
Evidence and awareness of biodiversity benefits	Environmental	Social structures	12.8	7.4	5.4
Environmental targets	Governance	Social structures	12.5	5.1	7.4
Subsidies/payments under agri-environment schemes	Governance	Parameter	12.0	6.8	5.2
Sudden supply chain shocks	Economic	Parameter	11.5	4.3	7.2
Understanding of the link between soil, plant, animal and human health	Governance	Social structures	11.5	5.2	6.3
Land availability for food production	Environmental	Parameter	10.9	4.0	6.9
Training and education of new farmers	Social	Social structures	10.7	4.0	6.7
Land use change—converting arable to grassland/woodland	Environmental	Parameter	9.9	5.9	4.0
Consumer awareness of the benefits of organic production methods	Social	Social structures	9.8	7.6	2.2
Media messaging	Social	Social structures	9.5	4.2	5.3
Price of organic food	Economic	Parameter	9.3	6.6	2.7
Pasture condition	Environmental	Parameter	9.2	7.3	1.9
Pests and diseases	Environmental	Parameter	8.9	3.5	5.4
Animal welfare	Environmental	Other	8.7	6.9	1.8
Media support and coverage	Social	Social structures	8.7	6.6	2.1
Innovation opportunities	Governance	Social structures	8.6	5.8	2.8

Indegree and outdegree represent, respectively, the extent to which the concept is affected by and affects other concepts in the FCM. Only the top 30 concepts are shown (according to centrality); see Supplementary Table 1 for the list of all 55 concepts.

factors identified by the workshop participants that influence the uptake of organic food production and consumption, albeit it is important to note that the role of parameters in influencing the system was nevertheless substantial.

When an agreed target and knowledge of the system begin to be understood, the final stage in transformation is to bring about change. This concept is often termed 'transformative knowledge'[31–33], which includes policy interventions, education and communication, participatory processes, and a reconsideration of values and assumptions[31,32]. To explore ideas for transformative knowledge, the findings of this study were presented back to the same stakeholder group in November 2023. Feedback included further clarification on the meaning of short-term economic thinking, including looking after short-term financial profit, particularly in terms of purchasing, rather than long-term sustainable thinking. For example, one participant stated, "with a short-term economic profit-driven scenario, we are robbing the future". To address this, long-term economic policies towards the food system were suggested, including building public goods into agricultural payment schemes. Adjustment of market systems was also suggested so that food prices represent the true cost of production. Transformative knowledge requires a combination of promoting leverage points around 'uptake' or 'scaling-up', along with overcoming barriers associated with non-adoption. Although our research question focussed on the former, the stakeholder group did interpret this question to include barriers, as reflected in the high importance of non-adoption factors such as short-term thinking in economics.

Our scenario analysis provided further insight into transformative knowledge and supported the contention that leverage points associated with system norms and values are important in the transition to a sustainable future for food production (SSP1 scenario). There was a reasonably strong consensus on the modelled changes under a sustainable future, which were also intuitive and broadly in line with the SSP1 scenario for European agriculture[29]. Specifically, short-term thinking, green washing, and vested interests all strongly decreased in this sustainable scenario, highlighting the importance of institutional structure[20]. This could include building long-term public goods into economic systems and policies[10,34,35], and regulating against green washing and vested interests[4]. Food waste also strongly decreased under a sustainable future, which would be required to meet food demands if agriculture shifted towards more sustainable but less intensive

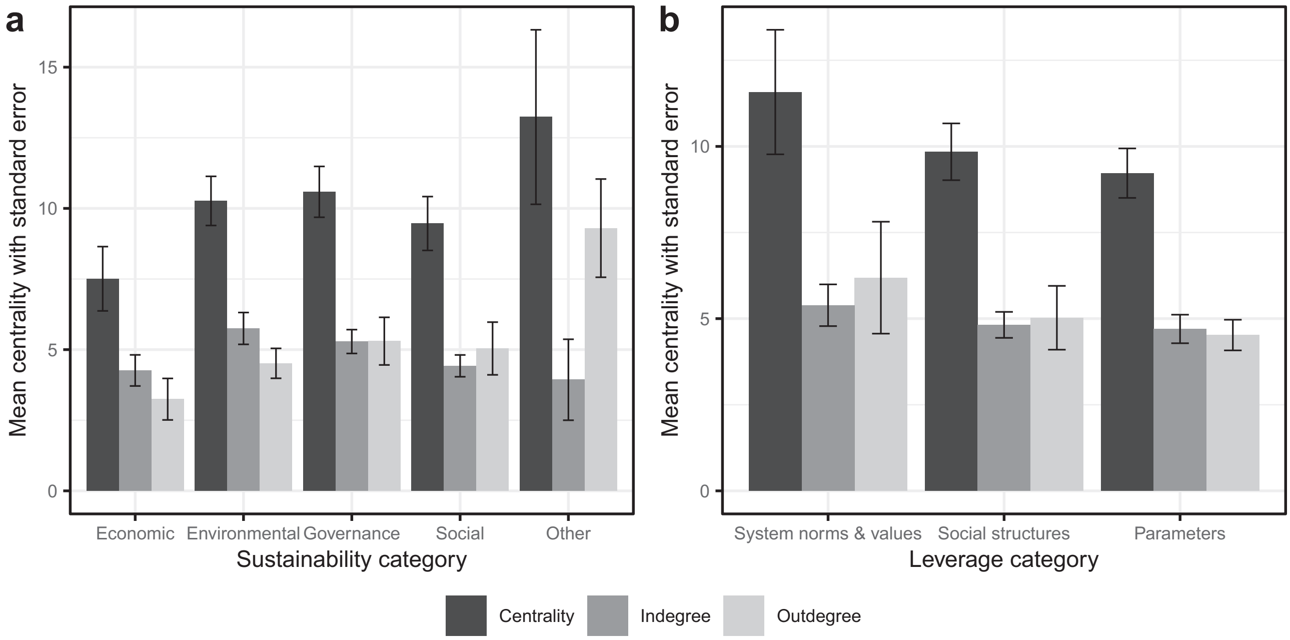

Fig. 3 | Mean centrality, indegree and outdegree of categories of factors that could influence the uptake of organic food production and consumption by 2050. Factors are grouped according to **a** sustainability categories (SAFA dimension) and **b** leverage categories (see Fig. 1).

methods[8]. Increases in fossil fuel prices and subsidies/payments under agri-environmental schemes were also indicated by the model under a sustainable future, suggesting a role of institutions to design systems to incentivise sustainable farming practices and disincentive fossil fuel consumption[10]. This was accompanied by decreases in the conversion of grassland and woodland to arable uses, and in animal antibiotic use, consistent with a lessened focus on agricultural intensification. Access to green spaces increased under this scenario, indicating a role of connectedness to nature, which is associated with environmentally sustainable consumption and food choices[36,37]. The change in reliance on imported feed was the only inconsistent effect in the top-ten concepts (sensitivity analysis conflicted with the main analysis). In this case, dietary shifts to more seasonal, local, and organic were clamped in the main analysis, which might reduce reliance on imports, whereas in the sensitivity analysis, the price of organic food was clamped at a low level, increasing the reliance on imports given the reduced productivity of organic systems[5].

Model predictions under the fossil-fuelled, high technology-driven scenario (SSP5) were less clear, although there was consensus on an increased reliance on imported feed, food waste, labour availability, taxes for carbon and biodiversity, and green washing. These changes are consistent with a food system geared towards maximising the efficiency of production in a global context, resulting in reliance on imports and limited action to address food waste or green washing[29]. However, the effects on fossil fuel prices, land availability for food production, cost of living, processing capacity, and conversion of grassland and woodland to arable were inconsistent, indicating the uncertainty of the system under a scenario where sustainability is not prioritised, at least according to our stakeholder perceptions.

Perhaps surprisingly, overall modelled change under the fossil fuel driven scenario (SSP5) was significantly higher than the sustainable scenario (SSP1), indicated by the significantly higher absolute change in equilibrium values of unclamped concepts. This is because concepts identified by the stakeholders as more likely to change under SSP5 influenced the system to a greater degree than the concepts identified under SSP1 (mean outdegree in SSP1 6.02 vs 7.48 under SSP5, main analyses). In other words, the factors that stakeholders identified would change the most under the SSP1 sustainable scenario would have relatively limited leverage potential, according to the model. This implies that in order to achieve systemic transformative change, a shift in focus is required to address deeper leverage points such as short-term economic thinking, landowner engagement with organic and sustainable farming systems, and relationships with certification bodies.

The FCM methodology provided unique insights into a complex system, allowing us to quantify the leverage potential of under-studied, fuzzy concepts, such as short-term economic thinking, in the uptake of organic and sustainable farming systems. As such, FCM was a useful method for identifying deep leverage points in a complex, transdisciplinary system and has potential for further applications, including leverage points perspectives for sustainable transformation.

Our findings should be understood in the context that the FCM methodology does not intend to model reality, but rather the participants' perceptions and interpretations of the functioning of a complex system at a certain time[38,39]. Although providing valuable insight into the views of expert stakeholders on organic food systems, the findings and, indeed, the phrasing of the language are a product of the stakeholder's perceptions. This could explain some of the uncertainty under the SSP5 scenario, given that the stakeholder group was likely less familiar with this pathway compared with the SSP1 scenario. A broader stakeholder engagement, including those from conventional backgrounds, would likely provide further insight into reasons for the non-adoption of organic and sustainable agricultural systems. For example, more 'conventional' stakeholders could provide additional clarity regarding some of the broad concepts of 'vested interests' and 'landowner engagement with organic'. Additionally, conventional stakeholders would likely raise different factors relating to non-adoption, such as impacts on productivity and profitability, which were largely overlooked by our organic stakeholders who had a more ecocentric mindset[40,41]. Such an exercise would potentially be impactful because, thus far, the organic sector is a somewhat niche market, especially in the UK and Europe[13]. Extending this niche towards a mainstream future would require engagement by farmers and other stakeholders from different backgrounds and with different values and mindsets. However, such a broad exercise could be hindered by the inherent resistance of conventional stakeholders to engage with the focal concepts.

Although our study was carried out in a UK context, global relevance is highlighted by the potential value of embracing social-ecological complexity in sustainability science[42]. Nevertheless, additional insights could be gained by applying a similar FCM analysis to developing countries, where organic

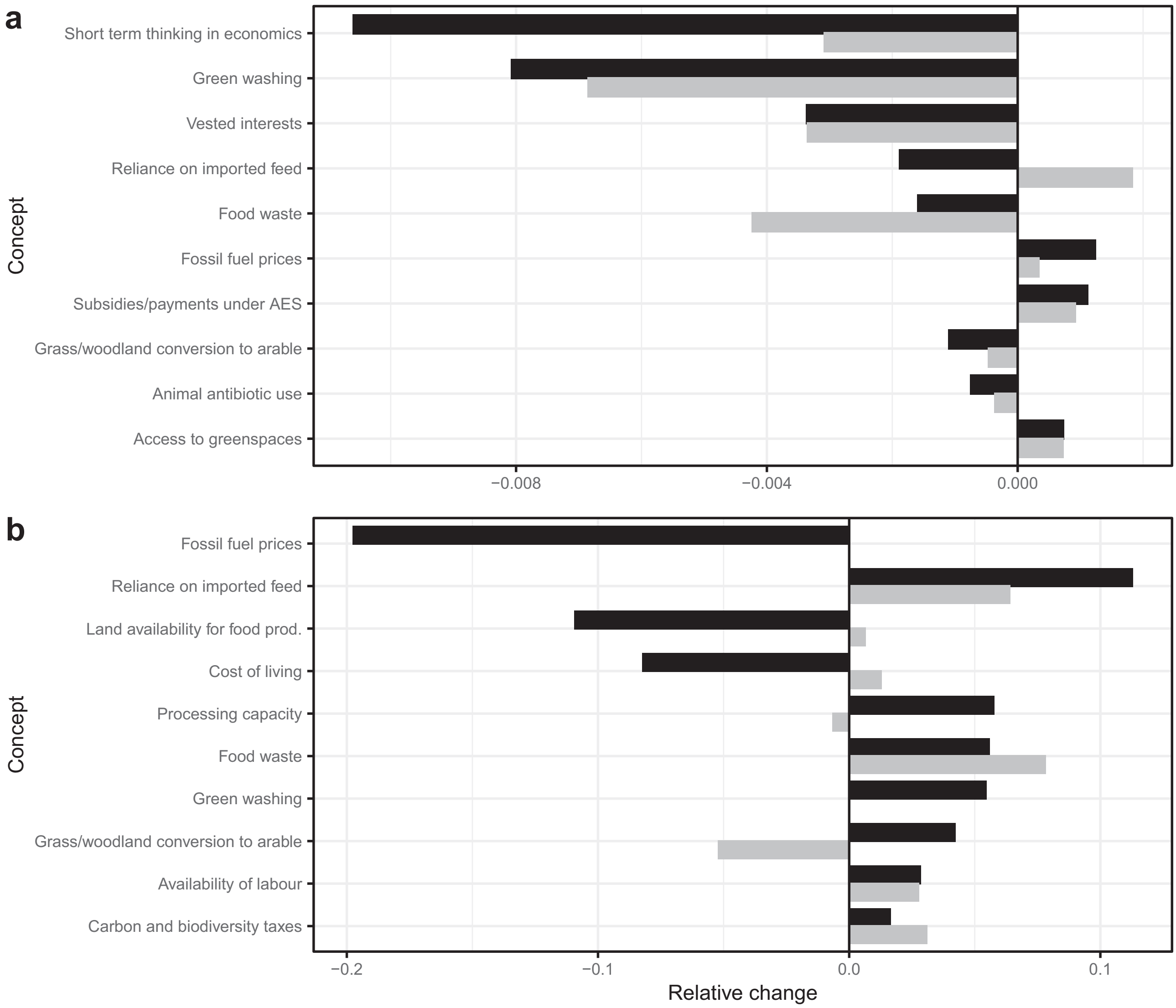

Fig. 4 | Main changes under contrasting future sustainability scenarios. Results of the SSP1 sustainable (**a**) and SSP5 fossil fuel, technology-driven (**b**) scenario models, where relative change is the difference between the SSP scenario and the baseline. Black bars represent the main analysis where one concept with the highest consensus in each of the five groups was clamped, while grey bars represent a sensitivity analysis whereby other concepts with a high consensus were clamped (see Table 2 for clamped concepts). Only 10 concepts with the highest relative change under the primary model are shown (excluding concepts clamped in the main analysis). Clamped concepts under the sensitivity analysis are not shown (fossil fuel price and green washing in (**b**)). AES agri-environment schemes. Concept names are shortened, see Table 1 for full names.

and sustainable food systems have distinct challenges, such as food security, limited consumer demand for organic products, and farmer training and support[7,43].

Conclusion

Our findings are consistent with the leverage points perspective for a transformation towards a more sustainable food system in that concepts associated with system norms and values and social structures had the greatest potential for systemic transformative change in the uptake of organic and sustainable food systems in the UK. In particular, qualitative behavioural aspects had the greatest role in influencing the uptake of organic food production and consumption, whilst more quantitative environmental and economic aspects tended to be more influenced by the system. Our scenario analysis provided a strong consensus on modelled changes under a sustainable future, in contrast to a fossil fuel, high technology-driven scenario. However, the factors which stakeholders believed would change the most under a sustainable scenario had limited leverage potential compared with the fossil fuel scenario. These findings indicate a need to shift focus to target deeper leverage points, such as long-term economic thinking, landowner engagement with organic and sustainable farming systems, and relationships with certification bodies, to deliver systemic transformative change.

Methods

Fuzzy cognitive maps (FCM)

Knowledge of a system can be broadly represented in terms of concepts, their interdependencies and causes, all of which can be uncertain and imprecise. FCMs were developed to visually represent causal relationships between concepts in 'fuzzy' contexts, i.e., where knowledge is non-binary[25]. This means FCMs are especially applicable to knowledge domains that are not wholly quantitative, such as social and behavioural patterns.

FCMs are broadly built around two components; concepts (sometimes referred to as nodes, vertices, components or factors), and interactions between concepts (also known as edges, arcs or links)[38]. Concepts are the features or classifications of a system and can influence each other through positive or negative interactions of a certain weight. For example, Concept A might have a weak positive influence on Concept B, which could have a strong negative influence on Concept C, which positively influences Concept A, and so on. FCMs allow the researcher to determine the significance of each concept in terms of the extent to which they influence, and are influenced by, other concepts in a given system. It is also possible to examine individual interactions between any two concepts, and the impact of changing one or more concepts on other concepts in the system. Therefore, FCMs are well suited to examining semi-quantitative system dynamics as well as exploring changes to a system under future scenarios.

FCMs have been used in a wide range of research topics. Recent applications in agricultural research include farmer perceptions of sustainability[26], public goods governance[27], and constraints and opportunities for sustainable intensification[28]. The application of FCM in this study was broadly based on Ziv et al.[38], which contains more details regarding the mathematical model of FCM.

Stakeholder workshop

Input data for the FCM was derived from an online workshop hosted by the University of Reading in March 2023. A total of 38 stakeholders from 23 organisations were invited to participate in the workshop. These were selected based on membership in professional organisations and societies related to organic food systems, taking account of their technical knowledge, reputation, and involvement in the organic sector in the UK, and including a range of organisations from the private sector, government, and research[44]. A total of 18 participants from 10 organisations attended the workshop, including representatives of academic institutions (7 participants), charities and certification bodies (6 participants), a government department (3 participants), and agricultural businesses that advocate organic food and farming (2 participants).

Following an introduction to the project, aims of the workshop and the concept of FCM, the workshop was split into three main parts. In the first part, participants were asked to respond to the following question: '*What are the main factors* ['concepts' in FCM terminology] *that could affect the uptake of organic food production and consumption in 2050 within the UK?*' This question was set in the context of the workshop aim, which was to '*identify the most important / influential elements for a scaling-up of organic agriculture and food systems in the UK*'. Participants were asked to categorise each of the factors/concepts they contributed according to four dimensions of sustainability under the United Nations' Sustainability Assessment of Food and Agriculture systems (SAFA): governance, environmental, economic, and social[30], with 'other' also allowed. At the end of this first part, a matrix spreadsheet was developed with all concepts represented in both rows and columns. During the second part, participants were split into three groups to define which concepts interact and to what extent. Firstly, each participant was asked to highlight cells in the matrix to define interactions between concepts. Next, each group (led by a facilitator) collaboratively agreed on the direction (positive or negative) and strength (weak, medium or strong) of each interaction.

The third part of the workshop was a scenario analysis. We selected two contrasting shared socioeconomic pathways (SSPs)[45,46], which have been adapted specifically for European agriculture and food systems[29]. These comprised the most sustainable scenario (SSP1) and the most fossil-fuelled, technology-driven scenario (SSP5) (see Table 2). These opposing scenarios were selected with the aim of providing clarity and contrast between the two scenarios and the baseline 2050 scenario. Participants were briefed on the two scenarios, including a reading of the relevant parts of the 'Eur-Agri-SSPs' in Mitter et al.[29], and then split into three groups to answer the following question: '*How would the factors under each pillar of sustainability (governance, environmental, economic, social) change under each SSP scenario?*' To answer this, participants were asked to vote on one concept from each of the four sustainability pillars plus the 'other' group, which they expected would change most strongly under each SSP scenario. Each group then decided, as a collaborative exercise, whether the voted concepts would increase or decrease, and the strength of effect (change slightly, to a moderate extent, or a lot), for each SSP scenario.

Fuzzy cognitive maps analysis

The first two parts of the workshop yielded a total of 55 concepts (factors that could affect the uptake of organic food production and consumption by 2050 within the UK) and 720 interactions between the concepts. Following the workshop, the matrix of interacting concepts was converted to a numeric scale between -1 and $+1$, to conform with the required input for FCM. This conversion was based on the methods of Ziv et al.[38], whereby weak relationships were scored 0.2, medium relationships 0.5, and strong relationships 0.7. Positive and negative relationships were coded by corresponding signs, e.g., a strong negative relationship was -0.7.

Consideration was given to the application of qualitative aggregation, whereby similar or related concepts are combined, to reduce the number of concepts[38,47]. However, it was considered that the concepts were sufficiently distinct that qualitative aggregation would lead to a substantial loss of information within the FCM. Therefore, two FCMs were built, using the 'nochanges.scenario' function with 25 iterations (which reached equilibrium in both models) in the FCMapper R package[48]. Firstly, a full FCM which contained all concepts and interactions. The role of each concept in the full FCM was calculated using three indices, namely centrality, indegree and outdegree. The centrality of the concept represents the strength of its weighted interactions with other concepts in the FCM and comprises the total of the indegree and outdegree. Indegree is the extent to which a concept is influenced by other concepts in the system, while outdegree represents the influence that a concept has on other concepts.

The second FCM comprised a simplified model containing only 11 concepts with the highest centrality scores. This was built solely for visualisation purposes because the full FCM was difficult to interpret visually. The top 11 concepts were selected because the graph became difficult to interpret with more concepts, while there was a relatively high difference between the 11th- and 12th-ranked concepts (see Table 1).

To explore whether a concept's interaction with the system differed according to SAFA dimensions, the mean and standard deviation of centrality, indegree and outdegree were calculated for each dimension. To test the leverage points concept (Fig. 1), each of the 55 concepts was categorised as representing 'system norms and values', 'social structures', 'parameter', or 'other' (see Table 1). This categorisation was undertaken by the lead author and presented back to the stakeholder group in November 2023. For each leverage category, the mean and standard error of the centrality, outdegree and indegree metrics was calculated.

Scenario analysis

Scenario analysis was undertaken by 'clamping' concepts to a high (1) or low (0) value so that the effect of their change under future scenarios on other 'unclamped' concepts could be evaluated by comparing their equilibrium values against the baseline scenario[38,49]. To avoid overly constraining the scenario analysis, the top-voted concept from the stakeholder workshop in each of the five sustainability groups (governance, economic, social, environmental, other) was clamped, for each of the two scenarios (see Table 2). The clamped value for each concept was set as '1' or '0', depending on whether the stakeholders identified an increase or decrease under the scenario. Each scenario was tested using the 'changes.scenario' function in FCMapper, with 25 iterations which reached equilibrium values.

To examine the robustness of the scenario analysis, a sensitivity analysis was undertaken whereby the second top-voted concept was clamped in each sustainability group if it received at least three votes, instead of the top-voted concept (see Table 2). If the second top-voted concept received less than three votes, the top-voted concept was again clamped. Where two concepts were tied in second place (with at least three votes), both concepts were clamped (thus a total of six concepts were clamped in the sensitivity analyses for both the SSP1 and SSP5 scenarios). The clamped values were set as 1 or 0, as for the main scenario analysis.

Finally, to test whether the modelled overall change in the system differed under the SSP1 versus SSP5 scenarios, we calculated the mean change in equilibrium values of unclamped concepts in the main analyses, after converting all values to positive. A t-test was then run to determine

Table 2 | Overview of the contrasting future sustainability scenarios, and the top factors that are predicted to change according to stakeholder votes, with the direction of change

Scenario	SSP1	SSP5
SSP name[45]	Taking the green road	Fossil-fuelled development—taking the highway
Eur-Agri-SSP name[29]	Agriculture on sustainable paths	Agriculture on high-tech paths
Change in governance factors	↑ Environmental targets	↓ Environmental targets (↑ Resistance from vested interests, ↓ innovation opportunities)
Change in environmental factors	↑ Evidence and awareness of biodiversity benefits	↑ Extreme weather events (↑ Greenhouse gas emissions)
Change in economic factors	↑ Uptake of organic by major retailers (↓ Public perception of organic food as a luxury item, ↓ price of organic food)	↑ Sudden supply chain shocks (↑ Fossil fuel prices)
Change in social factors	↑ Dietary shift to more seasonal, local and organic (↑ Cultural value of food and farming methods)	↑ Food scares (↑ Extent and effectiveness of green washing)
Change in other factors	↑ Consensus on sustainability metrics	↑ Short-term thinking in economics

These factors were clamped in the sensitivity analysis. Factors in brackets represent the second-most voted concepts (where these received at least three votes) and were clamped in the sensitivity analysis instead of the main concept in the same cell.

whether there was a significant difference between the change in unclamped equilibrium values under SSP1 versus SSP5.

All analysis was undertaken using R version 4.3.1[50], using the packages FCMapper[48], and igraph and ggplot2 for visualisations[51,52]. The preliminary results of the analysis were presented to the stakeholder group in November 2023, and the main points of feedback are included in the "Discussion".

Reporting summary

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

Data availability

Data collected from the first part of the workshop are openly available via FigShare with the identifier https://doi.org/10.6084/m9.figshare.25664250[53]. Data from the second part of the workshop are available in Table 2 in the main text.

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Author contributions
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The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Tom Staton.

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