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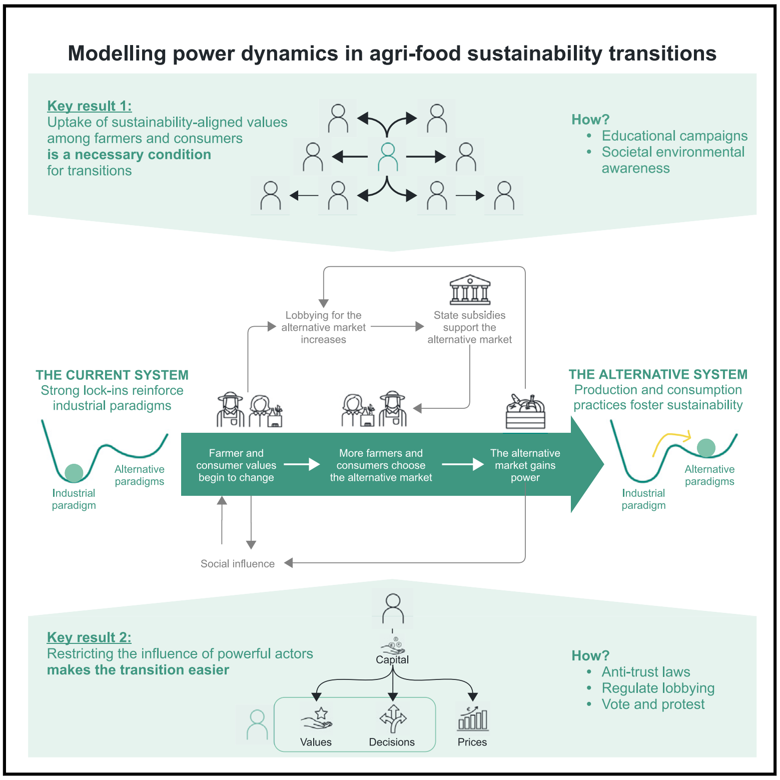
One Earth

Power dynamics shape sustainability transitions in a modeled food system

Graphical abstract



Highlights

- We use two variables—capital and values—to model power in sustainability transitions
- Transitions involve systemic shifts toward practices embodying "alternative" values
- Shifts in farmers' and consumers' values is a necessary condition for a transition
- Regulating power concentration lowers the barriers to sustainability transitions

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In brief

Consolidation of power contributes to undesirable lock-ins in global food systems. Efforts to transition to more sustainable alternatives should therefore consider how power is distributed between, and exercised by, food-system actors. We develop and apply a model of power dynamics in agri-food systems, focusing on interactions between farmers, consumers, markets, and the state. The results emphasize the need to regulate power concentration and reform the values underpinning the system to enable food systems that nourish people and nature.

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Power dynamics shape sustainability transitions in a modeled food system

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SCIENCE FOR SOCIETY Global food systems are dominated by industrial agriculture and concentrated supply chains. These systems are degrading human and environmental health, driving interest in transitions to more sustainable alternatives. Efforts to build sustainability typically target individual behavior (e.g., with subsidies and regulations), often proving ineffective or even sparking farmer protests. A more systemic approach is clearly needed; one that addresses the underlying power relations and values driving the system. However, studying "deep" interventions is hindered by difficulties in modeling these dynamics.
This study develops an approach for modeling power dynamics in agri-food systems and shows how this enables an exploration of deeper transformations. For sustainability advocates, the results stress the need to understand the values that underpin farmer and consumer decisions, as well as to support policies that "level the playing field" by limiting capital-rich actors' outsized influence.

SUMMARY

Transitions toward sustainable food systems are urgently needed to support planetary health. While farmer and consumer behavior are key drivers of sustainability, both are constrained by entrenched power structures that currently reinforce industrialized agriculture and supply chains. These structures are rarely represented in models of agri-food systems, limiting assessments of "deep" leverage points for transformation. Here, we utilize two variables—capital and values—to develop a stylized agent-based model of power dynamics between farmers, consumers, markets, and the state. Simulations show that a widespread shift toward sustainability-aligned values among both farmers and consumers is necessary for a system-wide transition. Moreover, interventions to limit power concentration can enable tipping points, with transitions occurring when only 20% of farmers' and consumers' values shift. Our model advances understanding of how power structures interact with individuals' behavior to produce lock-ins as well as how mobilizing sustainability-aligned values could enable more desirable futures.

INTRODUCTION

Achieving sustainable agri-food systems will require more than incremental change.[1–3] Global development continues to follow industrial paradigms, which tend to value food primarily as a commodity,[4] intensify agriculture at the expense of the environment,[5,6] and concentrate power within a limited number of intermediaries between farmers and consumers.[7] In response, scientists, policymakers, and civil society organizations are increasingly advocating for transformative change toward more sustainable practices and a fairer distribution of power between food-system actors.[8,9] While there are many different visions of sustainable food systems,[10] it is clear that transitioning toward sustainability requires contending with the processes that currently reinforce industrial paradigms.[11–14] Identifying key social and political interactions in which to intervene is a necessary step toward breaking these lock-ins and catalyzing sustainability transitions in agri-food systems.

One central concern in sustainability transitions is how power is distributed and exercised. Power is unquestionably a central driver of both lock-ins and transitions, as actors exercise power to both reinforce the status quo and innovate with alternative practices and values.[15,16] Redistributing power from incumbent actors to (initially) niche actors is thus inherent in processes of sustainability transitions.[17,18] While there are many debates on how to best conceptualize power,[19] notions of power are increasingly present in narratives surrounding agri-food transitions.[20,21] Prominent examples include corporate concentration and political economy as key inhibitors of change,[1,4,12] inequalities in food access as a driver of food insecurity,[22] and grassroots organization of producers and citizens as a pathway toward sustainability.[23]

Process-based simulation models can contribute to understanding the dynamics of sustainability transitions.[24] Modeling can complement empirical knowledge by advancing understanding of interdependent mechanisms and assessing interventions that are difficult or costly to test in reality. Computational models have been widely used to explore future visions, scenarios, and interventions in agri-food systems,[25–28] as well as to build understanding of transition dynamics[29,30] and facilitate discussions among stakeholders.[31] Models can thus play many different roles in the policy cycle[32] and could complement the primarily qualitative analyses of power in transitions by assessing complex socio-political interactions under various assumptions and policy scenarios.

However, models rarely consider power dynamics between different kinds of actors. Most modeling studies instead focus on interventions that affect individual actors' values or goals as well as individual responses to policy incentives, such as subsidies for farmers.[26,27,33] Some work is beginning to explore more fundamental changes to system paradigms such as degrowth scenarios,[34] circularity,[35] and dynamic governance conditions.[36,37] Yet there remains a lack of formalization of the power relations between the actors in agri-food systems, such as farmers and value chains, which shape individuals' decisions and thereby the collective potential for systems change.[38]

By ignoring issues of power, model-based analyses have limited ability to simulate many dynamics that are central to narratives of agri-food transitions.[1,7,17,20] This risks ignoring the strong lock-ins caused by political economy factors,[1,12] such as well-capitalized and connected interest groups that actively shape (inter)national policy agendas to inhibit or redirect change.[4] Ignoring power also risks overlooking opportunities for catalyzing transitions, such as by fostering cooperation among actors to develop shared visions that can influence local policies.[39] Further, when based solely on historical data and dominant economic theories, models are constrained to reproduce previous patterns and worldviews,[40,41] which are often based on neoliberal principles such as economic growth or closing yield gaps.[42] These paradigms constrain the scope of solutions that can be modeled,[2] potentially creating a "meta" lock-in to current development trajectories. Modeling power relations is thus necessary to adequately assess systemic barriers and transition pathways.

Here, we aim to advance the representation of power dynamics in quantitative transition assessments in agri-food systems. We develop a stylized agent-based model of power dynamics between key agri-food actors and run experiments in the model to simulate lock-ins and sustainability transitions. We find that population-wide shifts toward sustainability-aligned values are a necessary condition for transitions to occur, and that regulating the ability for actors to consolidate power can lower the barriers to these transitions. Our results demonstrate the need for policies and interventions to target deep leverage points to foster food-system sustainability. By closing the gap between narratives of transitions and their representation in process-based simulation models, this study enables examination of these important but understudied leverage points for catalyzing agri-food transitions.

RESULTS

Methods summary and model description

This study uses two interdependent variables—capital and values—to model power dynamics in agri-food transitions. For this purpose, agri-food systems are defined as the web of actors and interactions involved in food production, distribution, consumption, and governance.[43] Capital describes the bundles of material and non-material resources that actors draw from in their social practices and interactions.[44,45] Values describe the relative importance that actors attach to different functions of agri-food systems and are modeled along a continuous spectrum ranging from "conventional" (v = 0) to "alternative" (v = 1). Conventional values correspond with the incumbent industrial paradigm that considers food primarily as a commodity and seeks to maximize productivity and/or efficiency through specialization and competitive markets. Alternative values, in contrast, represent the many narratives that recognize the social, ecological, and cultural qualities embedded in food and seek to promote agricultural diversity, ecological nutrient management, food sovereignty, and equity across supply chains.[17,23,38]

Within the frame of these variables, actors exercise power in order to build their capital and spread their values among other actors, ultimately impacting production and consumption practices in the wider system. Power may thus be exercised to either promote stability or change,[15] depending on the interests of the actors who exercise it. We conceptualize power as operating through three distinct forms of influence (Figure 1), whereby an actor can use their capital to directly influence another actor's behavior (instrumental power), affect another actor's values (discursive power), or modify the option space within which others act (structural power).[46]

The agent-based model formalizes the key interactions between different actors' capital and values in a stylized agri-food system. The purpose of the model and analysis is to investigate how interdependent power dynamics could enable or prevent the emergence of transitions. By focusing on these structural contexts, this study aims to go beyond many existing

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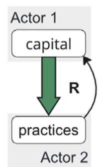
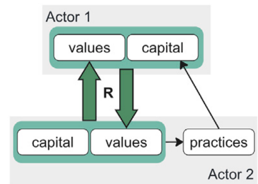
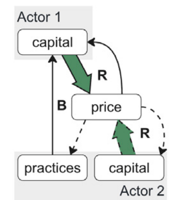
	Form of power [a]		
	Instrumental	Discursive	Structural
Interpretation in this study	Actors use their capital to directly influence others' practices	Actors use their capital to influence others' values	Actors use their capital to influence the option space of other actors [b]
Feedback diagram [c]			
Related empirical interaction dynamics	Commercial actors provide farmers with information and advice to inform their management practices[47] Retail sector develops private quality standards that prescribe specific farming or marketing practices[48] Development of infrastructure creates increasing returns to adoption across the value chain,[49] through factors such as convenience[50] and established logistics	Norms within farming communities around what constitutes a "good farmer"[47,51] Corporate actors engage in lobbying to impact the values embedded in government policy[7,52] Retailers impact public perception of food products[53] Societal pressure impacts the attention government gives to different issues (e.g., animal welfare[54])	Corporate actors exercise economic buying power[51,55,56] Governmental subsidies provide incentives for particular types of agricultural practices[57] Pooling capital (e.g., through cooperatives) increases bargaining power[58]

[a] These descriptions and the related empirical examples are pragmatically defined for the purpose of this study and could be categorised in many valid ways. For example, lobbying is often considered a form of instrumental influence, but in this study we consider lobbying to operate through the state's values, so it aligns most closely with discursive influence. Relatedly, the boundary between structural and instrumental power is ambiguous, as instrumental power typically acts through a secondary mechanism (e.g., price, information, regulations), so besides situations of extreme coercion it is rare for influence to be fully 'direct'.

[b] This is a restricted interpretation, as structural power relates more generally to an actor's capacity to impact the range of choices available to others.[46] We here use prices as an example of a key factor external to actors' decision-making processes that impacts their option space (i.e., impacting the payoffs of different practices).

[c] R = reinforcing feedback; B = balancing feedback; dashed lines indicate negative relationships; thick green arrows indicate power influences (i.e., using capital to influence another variable).

Figure 1. Representing different mechanisms of power through interactions between actors' capital, values, and practices

The feedback diagrams outline how the three forms of influence, depicted with bold arrows, can each conceptually instigate reinforcing feedbacks whereby power begets more power. These forms of influence are each codified in the agent-based model.[47–58]

simulation models that focus on system changes purely through individual behavior of a single actor group (e.g., farmers). The model is neither spatially explicit nor calibrated to represent a specific empirical context, but the modeled actors and processes reflect the prevailing power dynamics in European agri-food systems.[38] The model focuses on the relations between actors and to retain simplicity does not represent different commodities, agricultural yields, environmental processes and outcomes, or technology. As modelers, our framing presumes a normative directionality in which there is a need to transition food systems from the currently dominant "conventional" paradigm toward an "alternative" that we assume could better support sustainability and equity.

Four main types of actors are modeled: farmers, consumers, the state, and markets (Figure 2). The modeled agents are heterogeneous and adaptive; agents are each characterized by dynamic levels of capital and values, and they exercise power in order to advance their capital and values within the system. The market agents are aggregate representations of the supply chains between farmers and consumers, thus each representing a collection of agri-businesses and retailers. In accordance with the one-dimensional values representation, we model two distinct market agents with fixed values: a conventional market (conv-Mkt, with v = 0) and an alternative market (alt-Mkt, with v = 1). The model includes populations of heterogeneous farmers and consumers, who exchange capital respectively by selling to and buying from the market agents. The farm-gate and retail prices in each market are updated at each time step, assuming that the alt-Mkt price is strictly higher than the conv-Mkt price and that agents use their capital to influence prices in their favor (i.e., *structural power*; see experimental procedures). There is a single state agent, which has dynamically evolving values and

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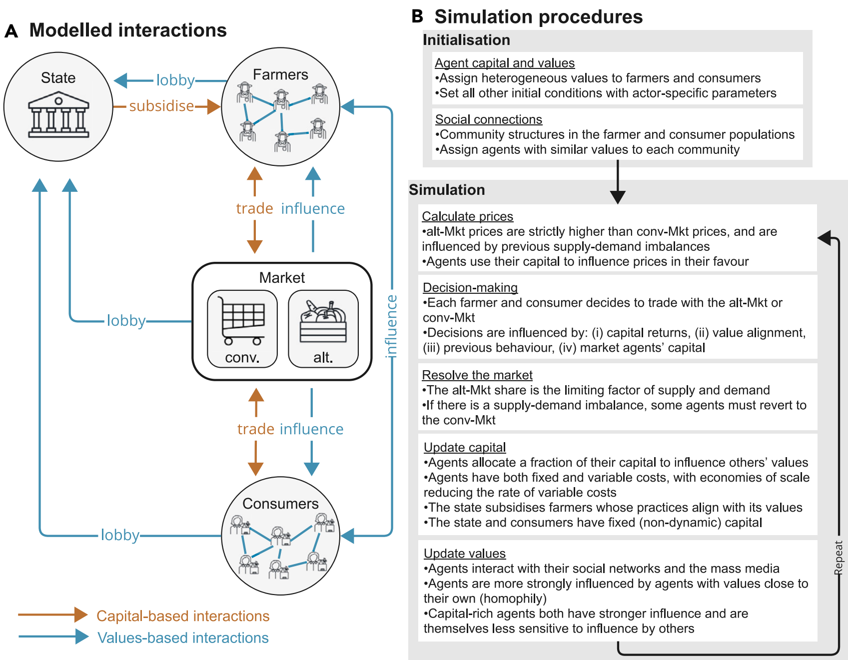

Figure 2. Overview of the actors, interactions, and processes in the agent-based model
Each farmer and consumer decides whether to trade in the conventional or alternative market, with a "transition" defined as a systemic shift in which the alternative market gains dominance. (A) shows the aggregate forms of interaction between actor types for visual clarity, but interactions occur in the model between individual agents within each actor type. Beyond the depicted values-based interactions (annotated blue lines), the model also represents opinion dynamics within static social networks in the farmer and consumer populations (see Figure S8). In (B), the bullet points describe key assumptions within each model component. The model processes are described in more detail in experimental procedures.

provides capital to farmers through subsidies, with higher subsidies given to farmers whose practices align with its values.

The core emergent outcome is the alternative market share, i.e., the fraction of trade flowing through the alt-Mkt agent. This arises through the distributed decisions of the farmers and consumers, who at each time step choose to trade in either the conventional or alternative market. Their decisions are modeled with multiobjective utility functions driven by: (1) value alignment—farmers and consumers prefer to trade in the market that aligns with their values; (2) capital returns—farmers seek to maximize income and consumers seek to minimize costs; (3) previous behavior—farmers and consumers exhibit a resistance to change; and (4) relative conventional/alternative market capital—the market agents can directly influence farmer and consumer decisions through mechanisms other than values and capital returns (*instrumental power*, e.g., representing coercion as well as convenience, knowledge, and access). However, it is possible that an agent's actual behavior may deviate from their utility-maximizing decision, as we assume that the alternative market is regional in scope and thus requires both willing farmers and consumers to function. This can create out-of-equilibrium market dynamics in which residual supply or demand for the alternative market impacts prices and, thereby, future decisions.

Agents' capital and values are updated at each time step. Agents first gain and/or lose capital through trade, then incur expenses that increase with their capital but exhibit economies of scale. Any remaining capital is divided between building their own capacity (i.e., saving) and spreading their values by lobbying or influencing other actors in their networks (i.e., spending). For simplicity, consumer and state capital are held constant throughout each simulation.

Agents' values are updated based on the social interactions depicted in Figure 1A as well as diffuse societal narratives. The social networks within the farmer and consumer populations have community structures (i.e., clusters of more densely connected individuals), and the model is initialized with each community having similar values among its members (see Figure S8). At each time step, each agent interacts with all others in its network as well as with the diffuse societal narrative (e.g., representing mass media, with a values orientation given by the mean of all farmer and consumer values, weighted by their capital). The magnitude and direction of influence resulting from a modeled social interaction depends on: (1) the degree of value alignment between the two agents (homophily), i.e., individuals tend to more strongly connect with others who have similar values; and (2) the relative capitals of the two agents, such that high-capital agents both have more influence and are themselves less easily influenced (*discursive power*; see experimental procedures).

Although the complexity introduced by the interactions makes it difficult to anticipate the system's behavior, the binary distinction between the conventional and alternative markets implies that the model may converge to at least two distinct states. These configurations will each exhibit a degree of resilience, due to the self-reinforcing nature of the power feedbacks. Yet the model may also describe transitions between power configurations, as external drivers (e.g., shifting consumer values) may activate internal feedbacks that shift agents' practices and the system-wide balance of capital.

Simulation experiments

We begin by illustrating the model dynamics under two representative simulation runs. The first depicts the "baseline" initialization that indicatively reflects the current state of many global agri-food systems, i.e., conventional-leaning values and weak alternative markets. The second simulation generates a transition by including an external discursive influence that pushes a subset of farmers' and consumers' values toward the alternative paradigm. This external influence represents the impacts of trends outside the modeled agri-food system, such as the increasing salience of crises that give rise to pro-environmental attitudes.

We then experiment with the model to examine how different kinds of interventions may generate transitions. We design four interventions—increase capital, decrease path dependencies, regulate power concentration, and change values—that involve adjusting model parameters relating to progressively deeper leverage points (Table 1). We examine the impacts of the interventions relative to the baseline scenario, first in isolation and then bundled together.

Multiple simulations are run for each experimental condition to account for both the effects of stochasticity (e.g., randomness in the social network generation) and uncertainty in the model parameterization. Specifically, we used pattern-oriented modeling to identify multiple plausible parameterizations, each of which generates model outputs that match a set of stylized macro patterns (see supplemental information). The results describe the distribution of model behavior across the entire set of plausible parameterizations, thereby incorporating the impacts of parameter uncertainty and mitigating risks of equifinality in the model parameterization.[68]

Modeling a lock-in and a transition

Under the baseline initial conditions, the conv-Mkt has the most capital of any agent (Figure 3A) and uses its capital to influence others' values, increase its profit margins, and directly impact farmer and consumer decisions. Due to the state's conventional values (Figure 3C), farmers trading in the conventional market receive more subsidies and so have higher capital (Figure 3A). By the end of the simulation, most actors have conventionally leaning values (Figure 3C) and almost all trade flows through the conventional market (Figure 3E). Additional experimentation with the initial conditions (Figure S11) demonstrates the strong lock-in associated with this model setup, as agents' capital and values must change substantially to disrupt the conv-Mkt's dominance. Yet a small minority of farmers and consumers continue to trade in the alternative market (Figure 3E). These agents' values differ strongly enough from the conventional paradigm that they are insulated from its discursive influence, due both to the homophily condition and the community structure within the agent populations (i.e., these agents may exist within distinct communities).

With an external discursive influence pushing 50% of farmer and consumer values toward the alternative paradigm (the "change values" intervention in Table 1), the system progressively transitions toward a dominant alternative market (Figure 3B). By the end of the simulation, farmers producing for the alternative market have higher capital (Figure 3B), due both to supportive state subsidies and the higher price offered by the alternative market (Figure S3). However, the conv-Mkt is never eroded completely, as some agents remain unaffected by the external influence and internal opinion dynamics.

Value change is a necessary condition for transitions

When the interventions are each separately modeled, transitions occur only under the "change values" intervention (Figure 4). This is the deepest leverage point and was examined in Figure 3. The other interventions counterproductively cause a decline in the alternative market share. With the "increase capital" intervention, the additional subsidies cause farmer income to rise (Figure S5) but, since the state aligns with the conv-Mkt, its subsidies provide incentives for conventional farming and thereby increase the conv-Mkt's dominance. Reducing path dependencies has very minor impacts, demonstrating that these processes (economies of scale, resistance to change, and capacity-building rate) are weak relative to the other modeled feedbacks. Regulating power concentration leads to some expected impacts, including lower profit margins and capital for the conv-Mkt and consequently higher farmer capital (Figure S5). However, under this intervention the discursive influence of low-capital actors is heightened (i.e., high-capital actors have relatively less ability to affect discourse), amplifying the effect of each social interaction and thereby causing agents' values to coalesce toward a single value (Figure S5). Due to the initial conditions (median farmer and consumer values of 0.3 [Table S1]), all agents' values converge toward the conventional paradigm, and thus the alternative market share reduces.

When different actors are targeted in the "change values" intervention, it becomes evident that changing values among both farmers and consumers is important to initiate transitions, although consumer values have greater leverage (Figure 5). The higher leverage of consumer values is related to the assumption that the alt-Mkt price is strictly higher than the conv-Mkt price; consumers are opposed to the alt-Mkt's premium and thus require relatively strong alternative values to change their behavior. Farmers, in contrast, benefit from the higher price in the alt-Mkt, so externally driven changes in farmers' values alone do not substantially affect the alternative market share.

Bundling interventions lowers barriers to transitions

It may be difficult in reality to rapidly achieve the value shifts that were tested above (i.e., involving 50% of all farmers and consumers), and it is more plausible that transitions will be driven by multiple interventions that involve both shallow and deep leverage points.[60,69] By engaging with different leverage points, interventions may even mutually support each other to achieve a degree of complementarity.[69] Here we assess how the "shallower" interventions may reduce the level of value change that is necessary to achieve a dominant alternative market, i.e., reduce the level of lock-in.

The most impactful modeled intervention in combination with value changes is to regulate power concentration (Figure 6), i.e., to reduce actors' ability to use their capital to influence values, prices, and decisions. Under this condition, only around 20% of agents' values must change to achieve a dominant alternative market (Figure 6B). Here, we observe a tipping point whereby the alternative market share increases rapidly once the number of affected agents passes a critical threshold (Figure 6A). This is because regulating power concentration enables low-capital agents to more easily affect each other's values, thereby increasing the propagation of discursive influence through the farmer and consumer populations. This demonstrates that the discursive influence of high-capital actors can be a strong inhibitor of system change.

Other combinations of interventions also prove effective in reducing the required value change for a transition, although some degree of value change is always necessary (Figure 6). Increasing capital is the next most impactful intervention, typically reducing the required value change to 25%–35% (Figure 6B). Bundling multiple interventions typically reduces the

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Table 1. Modeled interventions that proxy interventions at different leverage points

Intervention	Model implementation	System characteristic and leverage point depth[a]	Examples of real-world actions and interventions
Increase capital	increase the following parameters by 50%:	parameters (shallow)	increase of state budget allocation to agri-food systems
	(1) state budget (c_{state})—the capital the state agent spends each time step on farmer subsidies		government-assisted programs that build non-economic capital (e.g., rural development schemes, farmer networks)[59]
	(2) consumer income (c_{cons})—the capital available to consumers each time step		redistributive social policies that improve wages and provide social protection mechanisms[60]
Decrease path dependencies	decrease the following parameters by 50%:	feedbacks (shallow)	facilitate land access for young farmers (e.g., farm generational renewal),[61] who tend to be more open to change
	(1) resistance to change (w_3)—the utility derived from continuing previous behavior		programs that support smaller farms and firms (e.g., grants, low-interest loans, technical assistance, cooperative models)
	(2) economies of scale ($r_{scale\text{-}econ}$)—the degree to which an agent's capital reduces their variable expenses		training and extension services that foster access to information, collaboration and peer learning, and investment
	(3) capacity-building rate ($r_{cap\text{-}build}$)—the rate at which capital grows between simulation steps		
Regulate power concentration	decrease the following parameters by 50%:	design (deep)	competition (anti-trust) laws that discourage anticompetitive practices such as mergers and acquisitions or corporate abuses of dominant position[62]
	(1) structural influence ($\beta_{cap\text{-}price}$)—the degree to which agents can use their capital to impact prices		government regulation of firms' public relations and lobbying activities[7]
	(2) discursive influence (α_{disc})—the degree to which agents can use their capital to influence others' values		collaborative decision-making processes (e.g., roundtables or participatory guarantee systems)[63] to distribute decision-making authority
	(3) instrumental influence (w_4)—the degree to which agents' capital affects others' decisions		voting against and protesting harmful practices
Change values	add a strong external discursive influence (strength: c= 4) with an alternative values orientation (v = 1) that affects 50% of the farmers and consumers each time step. The affected agents are randomly selected at the beginning of the simulation. The regular discursive interactions between agents continue	intent (deep)	education and awareness campaigns (from government, media, influencers, or NGOs) that promote sustainable agri-food systems (e.g., exposé documentaries)[64]
			societal crises that expose the negative aspects of conventional food systems (e.g., climate change, drought intolerance, health impacts of pesticides)
			attitudinal spillovers from other issues (e.g., energy, conservation) that increase general attitudes toward sustainability[65]

The parameters modified for each intervention relate to policy-relevant changes but do not directly represent specific (non)governmental programs or policies. For each modeled intervention, the appropriate parameters are perturbed from their baseline values, which are shown in Table S1.
[a]In reference to the leverage points for intervention discussed in Abson et al.[66] and Meadows.[67] Shallow leverage points are interventions that are relatively easy to implement but offer limited potential for transformative change, whereas deep leverage points are more challenging to enact but hold greater potential for driving transformative change.[66]

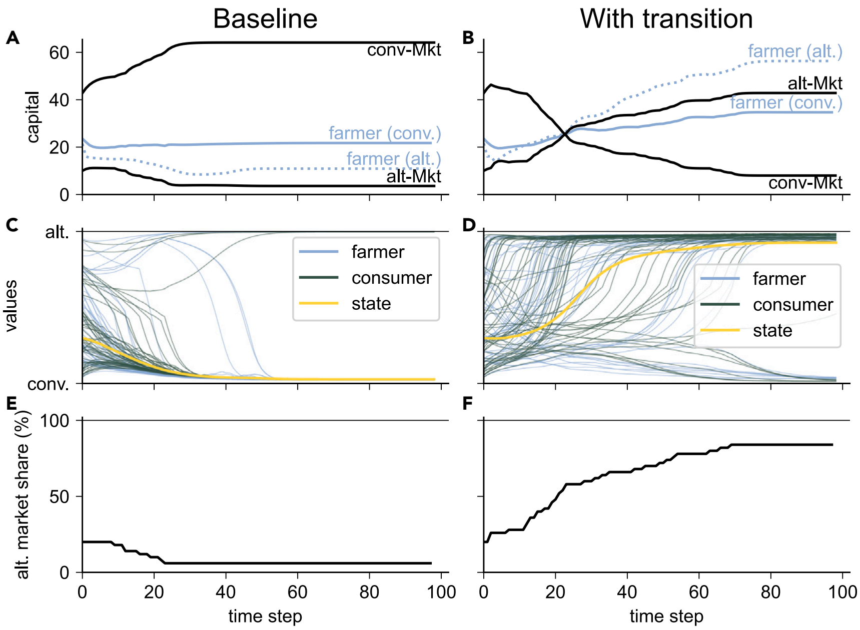

Figure 3. Exemplary model trajectories under baseline conditions and with a transition
The baseline simulation (left-hand plots) represents the initial condition used in subsequent experiments, with median farmer and consumer values of 0.3 and a capital-rich conv-Mkt. The transition simulation (right-hand plots) includes an external discursive influence that pushes the values of 50% of the farmer and consumer agents toward the alternative paradigm (the "change values" intervention in Table 1). In (A) and (B), blue lines represent total capital summed over the farmers that produce for the conventional (solid) and alternative (dashed) markets. In (C) and (D), the thin lines represent individual farmers (blue) and consumers (green). (E) and (F) present the fraction of all trade that flows through the alt-Mkt agent, which is the modeled indicator of a transition. Figures S1–S4 examine additional modeled variables throughout these simulations, including the flows of values and capital, market prices, and farmer and consumer utility calculations.

lock-in below the level with either intervention in isolation (Figure 6C) but rarely creates synergies (i.e., effects that are greater than the sum of their parts; Figure S7). These results demonstrate that the interventions can interact in ways that cause trade-offs in their impacts. This is due to the two-way nature of many modeled feedbacks; for instance, the power mechanisms can reinforce both the conventional and alternative paradigms. Weakening a feedback can thus both help and hinder transitions depending on the state of the system.

DISCUSSION

Aligning capital and values for agri-food transitions

This work emphasizes the intersections of capital and values as mechanisms of power, and thus as key entry points for transformation in agri-food systems. We found that changing actors' values was a necessary condition for transitions to occur (Figure 4), but that bundling additional interventions that regulate power concentration and provide supportive capital can reduce the level of value change required (Figure 6). Although the modeled interventions do not directly represent specific governance instruments, they relate to a range of real-world actions available to different actors (see examples in Table 1).

The crucial role of values in facilitating transitions closely aligns with results of other empirical and modeling studies.[70–72] This result underscores the need to reorient values within heterogeneous populations of actors as well as to coordinate changes throughout the wider agri-food system,[17,73] including both agricultural production and food consumption.[74] Without such coordination, individual-level alternative values can be systemically constrained in their impacts (i.e., attitude-behavior gaps exist), due to factors such as missing markets or agricultural policies that favor conventional paradigms.[75,76] Interventions that aim to shift values should avoid directly imposing values on individuals and instead focus on exposing and promoting food environments that encourage autonomous uptake of sustainability-aligned values[72,77,78] while concurrently reducing harmful influences of incumbent corporate actors.[79]

When values change across a broad enough transect of society, social tipping points can be crossed that catalyze transitions.[80] Our results show that regulating power concentration is the most effective strategy for facilitating these tipping points; in scenarios with stronger power regulation, only 20% of actors' values needed to change to create a dominant alternative market (Figure 6). Without this regulation, roughly double the level of value change was required. This highlights the importance of developing mechanisms to structurally reduce the outsized influence of high-capital actors, in combination with grassroots efforts to change values.[20,81] The figure of 20% aligns with a recent review of social norm diffusion.[82] However, unlike in many other threshold models,[83] the system rarely transitioned to 100% alternative, due to the interactions between interdependent mechanisms, the homophily condition, and heterogeneity in the initialization of the social networks. The tendency to not reach 100% alternative also aligns with empirical evidence that agri-food transitions are likely to involve the coexistence of multiple kinds of practices[60,84] rather than an unequivocal uprooting of conventional paradigms. Social networks are also undeniably a key factor impacting actors' values and transition dynamics; our analysis utilized a static network structure and did not explore the impact of different community configurations. In reality, social networks change over time and may need to fundamentally reconfigure to enable a transition.[85]

The model results suggest that combining interventions that target distinct system components could help to accelerate transitions. This supports other calls for bundling innovations that affect different actors and food-system elements.[11,38,69] Our study is novel in that it quantitatively formalizes the dynamic impacts of interventions at different leverage points, thus helping to integrate technocratic and socio-political perspectives on

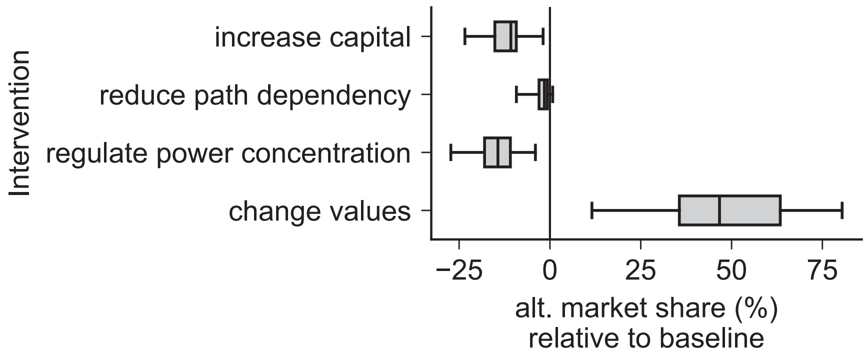

Figure 4. Impacts of individual interventions on the alternative market share

An increased alternative market share (i.e., more farmers and consumers trading with the alt-Mkt agent) is the modeled indicator of a sustainability transition. Interventions are described in Table 1. Outcomes are plotted relative to the baseline scenario, and boxplots show the variability in outcomes across different model parameterizations (see supplemental information). The boxes represent the median and quartiles (25th and 75th percentiles), and the whiskers represent the minimum and maximum values. Figure S5 presents exemplary model trajectories under each intervention.

transitions.[2] The model results also reveal two important considerations when designing coupled interventions. First, there could be risks to operating through shallow leverage points only; the model results (Figure 4) showed that interventions can backfire (i.e., increase the conventional market's dominance) when not paired with changes in actors' values. Reconfiguring power relations is thus not only a problem of corporate power or a lack of sufficient capital but also relies on aligning the beliefs and values of different actors.[1,72] Second, interventions can have complex interactions that lead to either synergies or trade-offs in their combined impacts.[86–89] We found limited evidence of complementarity when implementing multiple interventions, because many feedbacks can benefit both conventional and alternative actors depending on the state of the system. In reality, innovation bundles must be tailored to specific contexts[69]; computational models will thus be useful for exploring how feedbacks may either amplify or undermine the direct impacts of interventions in different contexts.

The advantages of modeling power in transitions

Modeling of agri-food systems and analysis of power dynamics are disconnected research domains; models rarely focus on power dynamics between different kinds of food-system actors, while socio-historical analyses rarely utilize the formalism and experimentation possible through modeling. The distinct focuses of these scientific approaches constrains the ability to examine how interventions interact across leverage points.[2] By quantitatively formalizing power dynamics between food-system actors, our study bridges these research fields and offers important benefits for both.

While many conceptualizations of power dynamics are needed,[19] quantitative formalizations like ours could help to extend research on power dynamics in at least two important directions. First, it has been noted that there is a lack of integration of local case study evidence in agri-food transition scholarship.[90] This study used a form of "middle range modeling"[91] to design a model using archetypical patterns from a synthesis of European empirical research.[38] This required abstracting contextual details that qualitative research readily captures but allowed our model to connect empirical observations to broader, recurrent processes relevant for building theory and informing policy.[91,92] Second, discussions around power dynamics typically focus on historical examples of power concentration and/or redistribution.[17,46] Modeling allows for *ex ante* testing of experimental interventions in ways that are not possible through ex-post-historical analysis but are necessary for future agri-food policy reform.[41] In particular, this process-based formalization of agri-food systems provides mechanistic explanations for emergent, system-level outcomes (e.g., sustainability transitions) that are otherwise difficult to study empirically, and thus provides valuable guidance for thinking relationally about and targeting future empirical research on agri-food transitions.

This study also offers opportunities for expanding the range of actors and leverage points considered in simulation models. Many modeling studies have examined how social dynamics can promote and impede technology adoption/diffusion and agri-food transitions[71,93–97] but typically focus on farmer or consumer decisions only. Considering power prompts questions about cross-scale and multiple-actor dynamics. We modeled feedbacks between individual decisions, regional markets, and state subsidies; future studies could build on this to examine pathways for upscaling grassroots innovations that involve actors at different organizational levels.[98] Agroecology, for instance, offers a transformative vision for food-system change in which power and agency play central roles.[23] Yet agroecological transitions have not been comprehensively studied through computational frameworks (but see Ong and Liao[99]). By formalizing knowledge from early exemplars of disruptive solutions such as agroecology, models can be applied to "learn from the future"[41] to examine more transformative scenarios and pathways. Modeling the dynamic institutional contexts that surround individual behavior allows simulation of structural leverage points,[37] thereby mitigating risks of incrementalism in model-based scenario analysis.[41,100] Challenges inevitably exist in representing system states that cannot be hypothesized a priori, so it may be impossible to truly model "transformation," but future work could explore more profound system transitions through endogenous changes in model rules, interactions, and governance modes.[36,101–103]

Some considerations are likely to be particularly relevant when modeling power. Many modeling frameworks already represent "capital" in various forms,[104–106] so adopting a power lens may simply require being explicit about (1) the ways in which actors mobilize their capital to advance their aims (i.e., how actors exercise power) and (2) the directionality toward which capital acts (i.e., the values component). Yet power is inherently intangible and multifaceted[19]; different actors may perceive or experience power differently, and power can draw from many sources and be exercised in different ways.[107] Unlike tangible resources such as water or land, power is often considered to manifest only

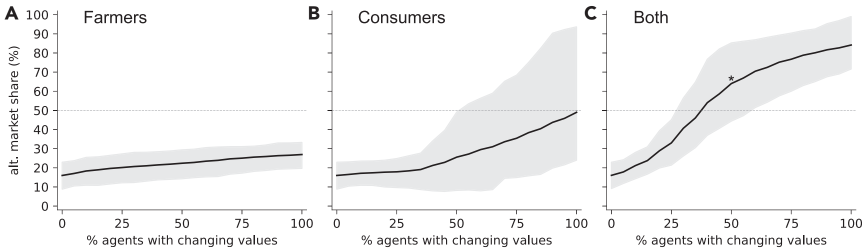

Figure 5. Which actors' values must change to initiate a transition?
This experiment simulates variations of the "change values" intervention that affects (A) farmer values only, (B) consumer values only, and (C) both farmer and consumer values. Lines show the mean outcomes across all model parameterizations, and shading shows the 10th and 90th percentiles across model parameterizations. The star at $x = 50$ in (C) represents the condition modeled in the "change values" experiment in Figure 4.

in relationships,[108] i.e., it cannot be "held," and it may not follow conservation laws that would allow mass or flow balance calculations. Modeling power thus demands clear, context-specific definitions as well as creative measurement approaches. Interventions that disrupt the current balance of power will create winners and losers and, thus, political opposition, while intentionally affecting actors' values may raise ethical concerns. These ambiguities and ethical risks motivate a well-considered normative stance on the distribution of power, as well as reflexivity to examine how researchers' positionality affects the representation and interpretation of power dynamics.[109,110] In this study, we defined a desirable transition as a shift in capital and values toward the alternative paradigm, which we assume offers greater potential for fostering sustainability and equity across supply chains. Yet we do not explicitly model sustainability or equity indicators, nor do we consider the origins of the modeled shifts in actors' values.

Model limitations and future extensions

This paper is a first step toward modeling power in transitions, and there are many opportunities to refine and expand the model scope. Concentration of power within agricultural value chains is a major global concern,[20] and a more detailed representation of the economic network of intermediary firms (e.g., aggregators, wholesalers, retailers) would be necessary to test policies for weakening corporate control. Further, while the dichotomy between the "conventional" and "alternative" is common in discussions of agri-food transitions,[111] many narratives about (un) sustainability exist,[112,113] and hybrid actors and networks often combine different sets of social and ecological values.[38,84,114] Multiple niche innovations may thus simultaneously exist,[115] including community-based food systems that operate outside of formal markets.[116] Further, a well-recognized pathway involves regime actors modifying their practices to adjust to landscape pressures.[117] This has been observed empirically through the conventionalization of organic agriculture,[118] which many argue has limited deeper transitions.[119,120] Better representing these types of pathways would require extending the model to allow multiple niche innovations and dynamic values for market actors.[121]

Given the critical role of values in shaping transition dynamics, effort is needed to elicit stakeholders' values,[72] to understand the impacts of campaigns and interventions,[79] and to construct empirically relevant opinion dynamics models.[82,122] As data on social influence are scarce,[123] empirical calibration would likely require dedicated data collection (e.g., surveys or interviews) to understand the drivers and mechanisms of social influence and behavior change, including their heterogeneity throughout populations and the speed at which they can change. Our model was particularly sensitive to the parameter controlling the discursive influence (i.e., the degree to which capital can be used to impact others' values; Figure S9), underscoring the importance of empirically grounding the opinion dynamics model. Other model parameters have limited influence on the outcomes (Figure S9), so future work could potentially simplify the model structure to represent the most influential processes only. Nevertheless, some potentially influential discursive processes are excluded, such as social norms (i.e., a desire to conform to group behavior), which may further restrict transitions and strengthen tipping points.[123]

Finally, some of the model assumptions and simplifications may not perfectly translate to real-world transition contexts. We assumed that the alt-Mkt price is always higher than the conv-Mkt price, which inhibits behavior change for consumers and may not hold if mechanisms such as "true pricing" are enacted.[71] This assumption also led to a tendency for prices in both markets to increase throughout the simulated transitions (Figure S3), which may not happen in reality and could be refined through more sophisticated economic formulations. For simplicity, the capital of consumers and the state agent were held fixed throughout the simulations, but political and economic fluctuations can strongly affect the capital available for food consumption and food-system interventions. For example, inflation in 2023 caused organic sales in France to reduce by 13%.[124]

Conclusion

Modeling can play a meaningful role in testing transformative solutions to agri-food sustainability challenges provided that modelers pay attention to the ways in which power can both enable and constrain change. This paper proposes an approach for modeling power and demonstrates how transitions may emerge from interactions between capital and values in a simple model of agri-food systems. The results reveal the importance of changing actors' values across the entire food system to catalyze transitions, implying that policy and research may achieve most meaningful change by engaging multiple kinds of actors together, such as farmers, consumers, and value-chain organizations. The results also demonstrate how power can be a double-edged sword; depending on the values of actors in the agri-food system, interventions to reduce power concentration can either facilitate or impede transitions. System change may thus be best achieved by bundling policies and interventions that target incumbent structures and the values that underlie them.

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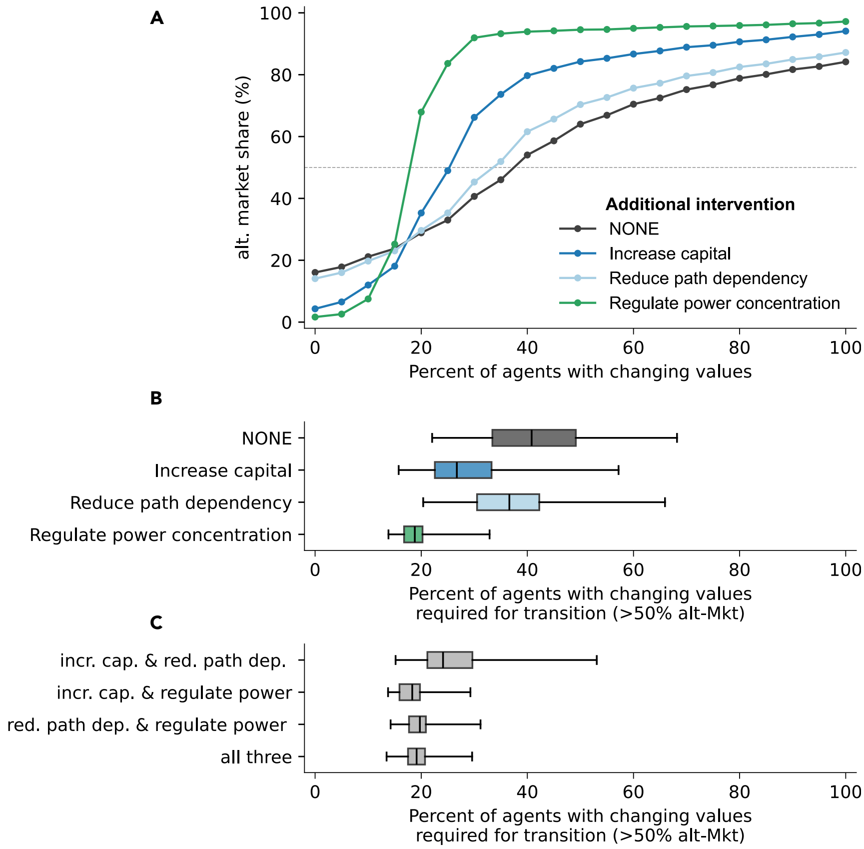

Figure 6. Bundling interventions to reduce the barriers to transition

For (A) and (B), a single intervention is implemented in conjunction with the "change values" intervention (see Table 1). For (C), multiple additional interventions are bundled. The results in (A) when $x = 0$ are equivalent to Figure 4. (A) plots the mean response over all model parameterizations, while (B) and (C) show the variability across model parameterizations. The boxes represent the median and quartiles (25th and 75th percentiles), and the whiskers represent the minimum and maximum values. Figures S6 and S7 formally examine the impacts of bundling interventions.

EXPERIMENTAL PROCEDURES

Formalizing power dynamics through capital and values

This study applies an agency-based interpretation of power wherein power draws from resources and manifests in social relations.[15,45] We use two key variables to operationalize this conception: capital and values.

Capital describes the bundles of material and non-material resources that actors draw from in their social practices and interactions.[44,45] Agri-food systems relate to multiple forms of capital,[125] including economic, natural, human, infrastructural, and social capital. These types of capital are also intertwined[126] as, for instance, actors can leverage their social capital to build economic capital and vice versa. As capital can be accumulated by actors, it reinforces itself and its (re)distribution throughout society provides a useful lens for describing (changing) social structures[126,127] such as systemic lock-ins and transitions. The model presented here does not differentiate between different types of capital, and thus "capital" represents an aggregate proxy for these bundles of resources.

Values, as applied in this paper, describe the relative importance that actors attach to different functions of agri-food systems, such as producing food, supporting biodiversity, or enhancing socio-economic well-being. Actors' values toward these goals influence their social practices[128] (e.g., soil management or consumption decisions) and thus collectively shape the direction toward which the system is oriented.[66] Values can therefore be key leverage points for transformation.[129] For simplicity, we conceptualize values as varying along a single, continuous spectrum that ranges from "conventional" ($v = 0$) to "alternative" ($v = 1$). This spectrum is explained in the main body of the article. Some nuance is of course lost with this one-dimensional simplification, as we cannot explore relationships between different forms of alternative agri-food networks,[14,130] but this approach provides a grounding from which additional dimensions could be included in further work.

Within this conceptual model, a transition is described by a systemic shift in actors' production and consumption practices toward those that embody the alternative paradigm, thereby changing the dominant supply chains that link producers and consumers. An actor's practices emerge from the interactions between their own and others' capital and values. Both dimensions, and their distribution throughout the system, are therefore necessary entry points for understanding transitions.

Overview of the agent-based model

The following model description aligns with the ODD (overview, design concepts, details) protocol,[131–133] which is a standardized approach for describing agent-based models.

Purpose and patterns

The purpose of the model and analysis is to explore sets of interacting processes that may generate transitions to alternative agri-food systems. The design of the model was informed by a recent meta-study that characterized the actors and power-laden interactions that reoccur across diverse agri-food systems in Europe.[38] We used the outcomes of this meta-study in two principal ways: (1) to inform the model structure, i.e., which actors are modeled, their roles, and how they interact; and (2) to inform the scenario design and hypothesized dynamics, such that the model experiments have the capacity to represent the diversity of network configurations found empirically. Although the model is not calibrated to represent a particular context, it thus most closely describes European agri-food systems. Specifically, the model was parameterized to generate a degree of lock-in to conventional markets under baseline conditions and to allow a potential for transition when actors' values change toward the alternative paradigm. Further details on the parameterization approach and quantification of these patterns are provided in the supplemental information.

Entities, state variables, and scales

As the goal is to examine social interactions between agri-food actors, several types of agents are modeled: farmers, consumers, market actors, and the state. The model represents populations of heterogeneous farmer and

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consumer agents, two distinct kinds of market agent (alt-Mkt and conv-Mkt), and a single state agent.

The agents are characterized by two primary state variables: capital and values. Capital (c) is a non-negative, continuous variable representing the (non)material resources that actors draw from in their social practices and interactions (e.g., money, information, social connections, prestige). Values (v) is a continuous variable representing the relative importance that agents attach to different functions of agri-food systems, and ranges from "conventional" ($v = 0$) to "alternative" ($v = 1$). Conventional values represent valuing food primarily as a commodity, whereas alternative values represent the social, ecological, and cultural qualities embedded in food. Capital and values are dynamic throughout the simulation, with several exceptions: the conv-Mkt agent has fixed $v = 0$, the alt-Mkt has fixed $v = 1$, and the state agent and consumer agents have fixed capital defined by external parameters (see Table S1).

Each simulated time step conceptually represents one year, and the model is run for 100 discrete time steps. For simplicity, all model processes operate at the same temporal resolution, though it is noted that these processes operate at different frequencies in reality (e.g., consumers make more frequent purchasing decisions than farmers' production decisions). The model is therefore not used to make inferences regarding the speed of change. There is no spatial representation in the model.

Process overview and scheduling

After initialization (see "initialization and social network generation"), five main processes sequentially operate each time step:

(1) Calculation of prices
(2) Farmer and consumer decision-making
(3) Resolving the market
(4) Updating agents' capital
(5) Updating agents' values

The following section describes the concepts underlying the model as a whole. The subsequent sections outline the key assumptions in the design and implementation of each process, as well as their theoretical and empirical bases.

Design concepts

Basic principles

The model addresses the question of how to transition to a more sustainable agri-food system through the lenses of resilience and sustainability transitions. At the system level, the model is based on the premise that mutually reinforcing social feedbacks can both impede change (i.e., promote "lock-ins" or undesirable resilience)[11,12] and drive change (e.g., through social tipping points in which a minority of actors can affect system-wide patterns).[82] At the level of agent interactions, these feedbacks are encoded using the concepts of "types" or "facets" of power,[46] namely instrumental influence, structural influence, and discursive influence (see Figure 1). The model is particularly novel in that it quantitatively represents these types of power, which are typically discussed qualitatively.

Emergence

The primary emergent outcome is the fraction of trade flowing through the alt-Mkt, which is interpreted as an indicator of the degree of transition toward sustainability. This outcome emerges from the distributed decisions of the farmer and consumer agents. These agents' decisions are driven by several dynamic factors (capital returns, value alignment, previous behavior, and market agents' capital), so many modeled mechanisms collectively contribute to the emergent outcome.

Adaptation

Each time step, each farmer and consumer agent chooses to trade with either the conventional or alternative market (process 2). These decisions are a form of direct objective seeking and are driven by internal decision models that represent the agents' utility gains from several factors. Each agent chooses the option with the highest utility value (see "objectives" below). The state agent has one adaptive behavior: the balance of subsidies provided to farmers trading with the conventional and alternative markets. This is also a form of direct objective seeking, where the state's objective is to subsidize agriculture that aligns with its values. Market agents use their capital to influence prices in their favor but do not explicitly make their own decisions.

Objectives

The objective measure used by farmers and consumers is encoded in a multi-objective utility function comprising four elements: capital returns, value alignment, previous behavior, and market agents' capital. The first three elements are conceptually internal to the agents' decision-making processes, whereas the final element (market agents' capital) represents external forces from market agents that impact farmer/consumer decisions in ways beyond the other modeled mechanisms. The state agent's subsidy balance is not modeled using an explicit utility function, but it is assumed that the balance of subsidies is linearly proportional to the state's values at each time step.

Learning

Agents do not adapt their decision-making methods as a consequence of their experience.

Prediction

The agents' adaptive behavior is not based on any explicit or implicit predictions.

Sensing

All agents are fully aware of their own values and capital. The farmer and consumer agents are fully aware of the prices and subsidies they will receive and pay. Within each modeled discursive interaction, agents (farmers, consumers, and the state) observe others' values and capital in relation to their own. There is no uncertainty in sensing.

Interaction

The modeled interactions are summarized in Figure 2. Agents directly interact through their discursive interactions (process 5), wherein they use their own capital and values to influence others' values. These interactions are bidirectional (i.e., agents i and j both simultaneously influence each other) and occur at each time step between all i-j agent pairs within the social network. Farmers and consumers also directly interact with the market agents at each time step through bidirectional exchanges of capital through trade (process 4). The state also directly interacts with each farmer by providing subsidies (process 4), which is a one-way interaction process. Mediated interaction occurs within two different processes: (1) in the formation of market prices (process 1), agents' relative capital impacts the payoffs that the different agent types receive; and (2) when resolving the market (process 3), imbalances in the number of farmers and consumers choosing the alt-Mkt result in behavioral switches.

Stochasticity

In the initialization (see "initialization and social network generation" below), farmer and consumer heterogeneity is created by sampling their values from probability distributions and randomly generating social connections. This creates variability within the initial conditions when using different random seeds, thereby representing uncertainty in these features. Within the simulation, stochasticity is used in several ways. Farmer and consumer utility functions (process 2) include a small random component that represents the effects of non-modeled factors. When updating agents' values (process 5), the order in which the updating occurs is randomized so that some agents do not always execute before others. A convergence analysis is conducted to determine the number of simulation replications such that the results are not unduly impacted by within-model stochasticity (see supplemental information).

Collectives

There are no explicit collective entities in the model. Upon initialization, farmers and consumers are allocated to communities of like-minded individuals, but these communities have no collective properties of their own. During the simulation, agents are separated at each time step into those trading with conventional and alternative markets, but these again do not have their own collective properties or impact the modeled processes.

Observation

At each time step, the primary observed outcome is the fraction of trade that flows through the alt-Mkt agent (i.e., the fraction of farmers and consumers that trade with the alt-Mkt). To facilitate model understanding (presented in Figures 3 and S1–S5), several additional variables are tracked at each time step, including: each agent's capital and values (which can be averaged separately for those trading with each market type); the farm-gate and retail prices within the alt-Mkt and conv-Mkt; the farmers' and consumers' relative utilities for trading with each market; the total flows of capital between agent types; and the total net discursive influence between each agent type (e.g., the sum of all influence from the alt-Mkt to farmers).

Initialization and social network generation

Key assumptions

- Community structure, with some links between communities
- Some individuals are more connected than others
- Actors associate more frequently with their own kind (e.g., consumers with consumers)

Description

The model is initialized with populations of farmer and consumer agents, two market agents, and one state actor. The numbers of farmers and consumers, as well as the initial levels of capital and values for each actor, are set by external parameters (Table S1). At the beginning of the simulation, all farmers and all consumers have the same capital but heterogeneous values. We model the heterogeneity of values using a single parameter for each agent type, which represents the median value within the farmer or consumer population. We uniformly sample 50% of the agents' values both below and above the median. This thus generates a distribution of values wherein, regardless of the median parameter, some agents' values may be at both extremes of the [0,1] interval. This explains why the alternative market share rarely tends to either 0 or 1 (Figure 5).

Farmers and consumers are connected by social networks, which are constructed at initialization and do not evolve. The model represents direct connections within the farmer and consumer populations (i.e., farmer-farmer and consumer-consumer links) as well as connections between the two populations (farmer-consumer links). The function of the networks throughout the simulation is to propagate discursive influence between the agents, so a link between two agents denotes an active social tie through which value-laden information is shared. This conceptually represents all familial, friendship, and spatial neighborhood networks, both in-person and online; however, we do not explicitly distinguish between different types of social ties.

To initialize the networks, we first allocate agents to a set of equal-sized communities in each population. We then generate within-community connections using the Barabasi-Albert model, which uses a preferential attachment algorithm to generate a scale-free network containing some well-connected individuals.[134] This approach captures the heterogeneity in individual connectivity, reflecting the presence of key individuals with a high number of connections. While the Barabasi-Albert model does not inherently incorporate spatial constraints, we introduce spatial or group-related separation by probabilistically adding connections between communities, such that individuals from different communities are less likely to be connected than individuals in the same community[135,136] and actors have more connections with their own kind (i.e., farmer-consumer connections are less likely). The result is a nested network structure with two kinds of agents and communities within each agent population. An example is shown in Figure S8. This structure leverages the scale-free properties within communities and incorporates spatial or social group distinctions through controlled inter-community connections, thus balancing the need to represent both well-connected individuals and the spatial or social segregation observed in real-world networks.

Finally, values are assigned to the agents based on their community, such that the communities tend to contain like-minded agents. This is accomplished by sorting the randomly generated values and sequentially assigning them to agents by community.

Empirical and theoretical basis

Social interactions are important for spreading values and practices and have been extensively studied within both farmer and (food) consumer populations[137–139] as well as in simulation models.[140] Many real-life social networks exhibit a community structure, such that there are distinct well-connected subgroups between which there are fewer interactions (e.g., representing villages or social groups).[135] It is also often observed that certain individuals play outsized roles as "innovation champions"[141] and thus can be considered as having more social ties within their community.

Process 1: Calculating prices

Key assumptions

- Agents use their capital to influence prices in their favor (structural influence)
- The alt-Mkt prices are influenced by previous imbalances between supply and demand
- The alt-Mkt prices are strictly higher than the conv-Mkt prices
- The alt-Mkt agent does not use its capital to influence prices in its favor

Description

To represent the flows of capital within the value chains requires assigning quantitative values to the farmer-Mkt and Mkt-consumer interactions. In the model, trade is a zero-sum interaction in which one actor loses a specific amount of capital and the other gains the same amount (e.g., a consumer buying food and a retailer's gross income). In real-world agri-food systems, money (economic capital) is the prevailing form of capital that defines trade relations. We do not explicitly model economic variables, i.e., capital, as operationalized in the model, is a more general construct that incorporates other relevant qualities such as information and prestige. For simplicity, we nevertheless use the word "price" to describe the quality of each trade relation. The term "market" is also used to represent the totality of organizations and businesses in the value chains between farmers and consumers, and we consider the market agents to each possess a level of capital that represents their political, economic, and organizational resources.

Four prices are successively calculated at each time step. The prices correspond to the two markets (conventional and alternative) and the two stages of the modeled value chain, farmer-Mkt (i.e., farm-gate price) and Mkt-consumer (i.e., retail price). We assume that all agents receive the same price at each point in time.

In the following equations, X denotes price, c denotes capital, the α parameters represent fixed and variable markups taken by the Mkt agents, and the β parameters control the sensitivity of the prices to the influences of capital and supply-demand imbalances. The alt-Mkt and conv-Mkt agents are shortened to *cMkt* and *aMkt*, respectively.

The prices are calculated as follows. It is noted that the functional representations are highly stylistic and are designed simply to quantitatively represent the qualitative key assumptions listed above. The specific functional forms assume that prices are a linear combination of their component factors.

(1) The farm-gate price in the conventional market, $X_{frmr\text{-}cMkt}$, is driven by the capital differential between the conv-Mkt agent and the farmer agents (the total over all farmers), such that a relatively powerful conv-Mkt leverages its capital to drive farm-gate prices downwards. The capacity of the conv-Mkt agent to exercise structural influence is controlled by the $\beta_{cap\text{-}price}$ parameter, such that as $\beta_{cap\text{-}price} \rightarrow 0$ the price becomes uninfluenced by the market agent and as $\beta_{cap\text{-}price} \rightarrow 1$ the market agent can drive the farm-gate price to zero (when $c_{cMkt} \gg c_{frmr}$). The functional form ensures that the price remains non-negative.

$$X_{frmr\text{-}cMkt} = 0.5 + \beta_{cap\text{-}price}\left(\frac{c_{frmr}}{c_{cMkt}+c_{frmr}} - 0.5\right) \quad \text{(Equation 1)}$$

(2) The farm-gate price in the alternative market, $X_{frmr\text{-}aMkt}$, is calculated as the sum of two components: (1) a proportional markup above the conventional farm-gate price; and (2) a perturbation representing the effect of residual supply in the previous time period, such that supply shortfalls (i.e., excess demand) increase subsequent alt-Mkt prices, and vice versa. The residual is defined in the section "resolving the market." It is assumed that the supply-demand imbalances cannot cause the alternative farm-gate price to drop below the conventional farm-gate price.

$$X_{frmr\text{-}aMkt} = \max\left(X_{frmr\text{-}cMkt},\ \alpha_{alt\text{-}markup} * X_{frmr\text{-}cMkt} - \beta_{resid} * resid_{t-1}\right) \quad \text{(Equation 2)}$$

(3) The retail price in the conventional market, $X_{cMkt\text{-}cons}$, is calculated as the sum of two components: (1) a fixed, absolute margin above the farm-gate price; and (2) an additional margin driven by the capital differential between the conv-Mkt and consumers, such that a relatively powerful conv-Mkt leverages its capital to drive retail prices upward.

The capacity of the conv-Mkt to exercise structural influence is controlled by the $\beta_{cap\text{-}price}$ parameter in a similar way to Equation 1, such that an all-powerful market agent ($c_{cMkt} \gg c_{cons}$) can increase the retail price by $0.5 * \beta_{cap\text{-}price}$.

$$X_{cMkt\text{-}cons} = X_{frmr\text{-}cMkt} + \alpha_{margin} + \beta_{cap\text{-}price} * \max\left(0, \left(\frac{c_{cMkt}}{c_{cMkt}+c_{cons}} - 0.5\right)\right) \quad \text{(Equation 3)}$$

(4) The retail price in the alternative market, $X_{aMkt\text{-}cons}$, is calculated as a fixed, absolute margin above the alternative farm-gate price. Similar to the farm-gate price in the alternative market, it is assumed that the alternative retail price cannot drop below the conventional retail price.

$$X_{aMkt\text{-}cons} = \max\left(X_{cMkt\text{-}cons}, X_{frmr\text{-}aMkt} + \alpha_{margin}\right) \quad \text{(Equation 4)}$$

Empirical and theoretical basis

There are at least three mechanisms through which capital-rich corporations are able to exercise market power.[7,63] The first is by influencing commodity prices. There is evidence of such behavior in United States dairy markets (though it can be mitigated with collective action in cooperatives)[142] and mixed evidence in Europe.[143] The second is through bargaining power, whereby big firms have a large leverage in negotiations and, due to potentially exploitative contracts and the absence of alternatives, can create relations of dependence.[144] The third is through governance, where there is evidence of corporations setting rules (e.g., quality standards) for how food is produced.[46,145] All three of these mechanisms describe forms of structural influence, i.e., actors influencing the option space of other actors. The level of structural influence in the model is controlled by the parameter $\beta_{cap\text{-}price}$ in Equations 1 and 3.

The alternative market, as conceptualized in this article, is predicated on embedding non-economic qualities into the valuation of food. Such quality attributes can take many forms in reality,[130] including those based on place (e.g., local), ecological management (e.g., organic), or social equity (e.g., fair trade). There is therefore inherently a higher quality of capital embedded in the alt-Mkt, which provides some justification for the assumption that alt-Mkt prices are strictly higher. Further, governance in alternative markets often aims for democratic decision making across the supply chain,[38] reducing the incentive for price gouging. Nevertheless, it is reasonable to assume based on basic economic theory that demand surpluses(/deficits) will increase(/decrease) prices in the alternative market.

Process 2: Farmer and consumer decision making

Key assumptions

- Farmer and consumer decisions are driven by value alignment, capital returns, previous behavior, and market agents' capital (instrumental influence)
- Farmers and consumers have linear, multiobjective utility functions, and they select the option that maximizes their utility

Description

Each time step, farmers and consumers decide which market they will trade with. This is a binary decision, i.e., agent i's decision at time t is given by $D_{i,t} \in \{0, 1\}$ where 0 and 1 represent the conv-Mkt and alt-Mkt, respectively. We do not model direct producer-consumer trade, although this is to an extent represented through the alternative market actor. Farmer and consumer decisions are driven by four components: value alignment, capital returns, previous behavior, and market agents' capital. We utilize a linear, weighted, multiobjective utility function to represent these components. For agent i at time t, the general form of the utility function for a particular market ($xMkt$) is

$$U_{i,t}^{xMkt} = w_1 * abs(v_{i,t} - v_{xMkt}) + w_2 X_t^{xMkt} + w_3 B_{i,t-1} + w_4 \frac{c_t^{xMkt}}{c_t^{cMkt} + c_t^{aMkt}} + \varepsilon_{i,t} \quad \text{(Equation 5)}$$

where $w_1 \ldots w_4$ represent the weights allocated to the four components, v is the agent's values ($0 \le v \le 1$), X ($X \ge 0$) is the capital return (composed of the price plus any subsidy), B is an indicator representing the agent's previous behavior ($B \in \{0, 1\}$), c is capital, and ε is a small random term added to the utility to represent uncertainty both internal and external to the decision-making process. The weights are consistent for all farmers and consumers and do not change over time (see Table S1). The resulting utility value is unitless, as it represents a weighted aggregation of the benefit derived from the four components that each have different units. Three of these components are bounded by [0,1] and so represent a consistent scale, whereas capital returns (X) are technically unrestricted in scale, but under the tested model settings never exceed 1.65. The equation takes slightly different forms for farmers and consumers, as farmers seek to maximize their economic returns and consumers seek to minimize their costs. Each agent selects the option that maximizes their utility, and it is assumed that farmers and consumers are fully aware of the subsidies and prices they will receive/pay.

Empirical and theoretical basis

The farmers' and consumers' utility functions depict a form of rational decision making (i.e., *Homo economicus*). This has widely acknowledged limitations[146]; however, the function includes, in transparent ways, the key features that we wish to represent and that are present in other behavioral theories, such as the theory of planned behavior[147] and habitual behavior.[148]

In particular, an agent's values represent their subjective judgment of the relative desirability of the conv-Mkt and alt-Mkt (i.e., their attitude), which is formed by their interactions with their peers (i.e., subjective norms). Attitudes and norms have been shown to exert strong influences on farmer decision making in Europe.[138] Perceived behavioral control "is influenced by the farmer's assessment of affordability, risks, necessary farming skills, farm structural issues, and so forth,"[93] which are encompassed in the capital return component.

The influence of an agent's previous behavior aligns more closely with other theories such as habitual learning (and the consumat approach),[149] as the implication is that values and relative capital returns need to differ above some dissatisfaction threshold to motivate behavior change. The utility penalty for diverging from previous behavior also conceptually incorporates the uncertainties associated with changing behavior as well as the sunk costs of technology investments.[12]

The fourth component proxies the ways in which a market agent's capital impacts decision making beyond values and prices. This component constitutes the representation of instrumental influence in the model, i.e., actors using their resources to directly impact others' practices. The level of instrumental influence is controlled by the parameter w_4. We note that truly "direct" influence on decisions is rare in agri-food systems, except in situations of extreme coercion, and may in reality operate through a range of mechanisms, for instance convenience and access[50]; capital-rich retailers have many stores with long opening hours and prominent advertising, which together influence consumer behavior independently of product prices and socio-ecological values. Similar accessibility mechanisms exist for farmers, as capital-rich value chains have established logistics and processes that make trade organizationally simple and therefore desirable even if it does not align with a farmer's values or offer favorable prices.

Process 3: Resolving the market

Key assumptions

- The alternative market share is the limiting factor of supply and demand
- Agents who wish to participate in the alt-Mkt but have no matching buyer/seller revert to the conv-Mkt
- The most undecided agents revert to the conv-Mkt first

Description

The alt-Mkt is assumed to be regional in nature,[150] requiring both willing producers and consumers to function. The alternative market share is therefore dictated by the limiting factor of supply or demand. For example, if 60% of consumers choose the alt-Mkt but only 20% of producers, the alt-Mkt market share is 20%. As there is no available alt-Mkt supply for 40% of the consumers, they must participate in the conv-Mkt. There is thus a distinction between agents' decisions (D; the outcome of the utility calculation) and their behavior (B), which also requires the availability of appropriate markets. The overall difference between farmers' and consumers' decisions is directly used to calculate the residual production, which impacts subsequent prices in the alternative market:

$$resid_t = \frac{1}{N_f}\sum_{f=1}^{N_f}\mathbb{I}(D_{f,t} = alt.) - \frac{1}{N_c}\sum_{c=1}^{N_c}\mathbb{I}(D_{c,t} = alt.) \quad \text{(Equation 6)}$$

In the case of a market imbalance (i.e., $resid_t \neq 0$), the following algorithm is used to determine which agents' behavior (B) must deviate from their decisions (D): (1) sort agents based on their relative utility for the alt-Mkt (i.e., $Utility(alt.Mkt) - Utility(conv.Mkt)$); (2) sequentially select agents with the lowest relative utility (i.e., the weakest preference for the alt-Mkt) until the market imbalance is resolved; (3) revert the behavior of these selected agents to trade with the conv-Mkt.

Empirical and theoretical basis

The availability of supportive markets is a well-known barrier to upscaling alternative value chains in Europe and elsewhere.[73,151,152] There is also emerging evidence in places such as France that organic producers are resorting to selling their products without organic labels as a result of decreasing consumer demand due to inflation and mistrust.[124]

Process 4: Updating agents' capital

Key assumptions

- Agents allocate some fraction of their capital to lobby/influence others
- Agents have both fixed and variable costs
- Economies of scale reduce the rate of variable costs
- The state subsidizes farmers whose practices align with its values

Description

At time t, the capital of agent i is updated using the following general form:

$$c_{i,t+1} = (r_{cap\text{-}build} - \alpha_{lobby})c_{i,t} + IN_{i,t} - OUT_{i,t} \quad \text{(Equation 7)}$$

where $r_{cap\text{-}build}$ ($r_{cap\text{-}build} > 1$) is an interest rate representing capacity-building, α_{lobby} ($0 < \alpha_{lobby} < 1$) is the fraction of capital used for influencing other agents' values, and IN and OUT refer respectively to the inflows and outflows of capital from trade, expenses, and subsidies. This formulation therefore assumes that agents divide their capital between lobbying to spread their values within their networks (parameter α_{lobby}) and building their own capacity ($1 - \alpha_{lobby}$). As we do not model heterogeneous or evolving yields or demand, the in- and outflows due to trade simply correspond to the calculated prices (Equations 1, 2, 3, and 4).

Agents' expenses (E) (e.g., representing personnel costs, labor, and agricultural inputs) have fixed and variable components, with the rate of variable costs exhibiting economies of scale based on the agent's capital (relative to the total capital summed across all agents).

The level of subsidies (S) that a farmer receives is linearly proportional to the alignment of their behavior ($B_{i,t}$, where 0 and 1, respectively, represent conventional and alternative) with the state's values. This reflects the tendency of state policies to support some forms of agriculture more than others (e.g., Europe's Common Agricultural Policy historically supported agricultural intensification by providing subsidies based on production levels).[153]

The capital updating equations for each agent type are thus as follows. Parameter values are given in Table S1.

For farmer i trading with $xMkt$ at time t:

$$c_{i,t+1} = (r_{cap\text{-}build} - \alpha_{lobby})c_{i,t} + X_{frmr\text{-}xMkt,t} + S_{i,t} - E_{i,t} \quad \text{(Equation 8)}$$

where

$$S_{i,t} = \frac{c_{state} * r_{subsidy}}{N_{frmr}} * (1 - |v_{state,t} - B_{i,t}|) \quad \text{(Equation 9)}$$

$$E_{i,t} = E_{frmr\text{-}min} + c_{i,t} * r_{frmr\text{-}exp} * \left(1 - r_{scale\text{-}econ} * \frac{c_{i,t}}{\sum_{agents} c_{a,t}}\right) \quad \text{(Equation 10)}$$

For market actor $xMkt$ (i.e., either alt-Mkt or conv-Mkt) at time t:

$$c_{i,t+1} = (r_{cap\text{-}build} - \alpha_{lobby})c_{i,t} - X_{frmr\text{-}xMkt,t} + X_{cons\text{-}xMkt,t} - E_{xMkt,t} \quad \text{(Equation 11)}$$

where

$$E_{xMkt,t} = E_{mkt\text{-}min} + c_{xMkt,t} * r_{mkt\text{-}exp} * \left(1 - r_{scale\text{-}econ} * \frac{c_{xMkt,t}}{\sum_{agents} c_{a,t}}\right) \quad \text{(Equation 12)}$$

For simplicity and due to the focus on the agricultural component of food systems in this study, we treat consumer and state capital as exogenous, so this process runs for the farmers and market actors only. Because food expenditure is a small component of consumers' overall budgets in industrialized countries, it makes less sense to endogenize consumer capital, which also would considerably increase the complexity of the model (e.g., as consumers' and farmers' economic preferences are inherently opposed). We leave this and the exploration of endogenous transitions in the influence of state actors as an exercise for future research (e.g., see Jung and Lake[101]).

Empirical and theoretical basis

Allocating income between savings and expenditure is a common microeconomic construct. Studies of agri-food transitions in Europe have revealed the ubiquity of "capital building" as a strategy employed by agri-food actors during transitions[38] as well as the importance of lobbying and protest to increase the legitimacy of novel practices and influence state policies.[17,154] Corporations also frequently have dedicated budgets for lobbying.

State actors play a strong role in supporting particular types of agriculture, and there is substantial evidence in Europe that state support historically favored agricultural intensification[47,155] but has progressively changed over time in response to evolving societal pressures and narratives.[153] State subsidies can thus be described as providing more support to activities that align with prevailing values.

Process 5: Updating agents' values

Key assumptions

- Values are impacted by both personal interactions and societal narratives
- Market agents influence farmer and consumer values
- All agents influence the state's values
- Agents are more strongly influenced by opinions close to their own (homophily)
- The magnitude of influence scales with the capital allocated to it (discursive influence)
- Capital-rich agents are less sensitive to discursive influence

Description

To model the social influence between two agents, we apply a model that is grounded by two key assumptions: (1) homophily, i.e., individuals are more strongly influenced by others with similar opinions; and (2) capital-rich agents have larger social influence and are themselves less sensitive to others' influence. This model differs from the widely applied relative agreement model of Deffuant et al.,[156] as we do not adopt a threshold maximum opinion difference for any influence to occur but allow influence to scale inversely (quadratically) with opinion distance so that all agents can affect each other. We also do not model agents' opinion certainty and instead replace this construct with capital, such that high-capital agents have larger social influence.

Specifically, we apply the following equation to update the values of agent j under influence from agent i:

$$v_{j,t+1} = v_{j,t} + \mu_{disc}\left(\frac{L_{i,t}}{L_{i,t}+c_{j,t}}\right)^{\alpha_{disc}}(1 - |v_{i,t} - v_{j,t}|)^2(v_{i,t} - v_{j,t}) \quad \text{(Equation 13)}$$

where μ_{disc} is a scaling parameter controlling the overall strength of discursive influence (i.e., the general stubbornness of beliefs[136]), L_i is the lobbying effort of agent i, and α_{disc} ($0 < \alpha_{disc} < 1$) specifies the sensitivity of social influence to the lobbying effort. The α_{disc} parameter thus represents and controls the strength of discursive influence in the model, i.e., actors' ability to use their capital to influence others' values. The lobbying effort of agent i is calculated as $\alpha_{lobby} * c_{i,t}/k_i$, where k_i is the number of agents to whom agent i is connected (i.e., their degree in the full influence network).

The direction of social influence in Equation 13 is determined by the final term, $v_{i,t} - v_{j,t}$, while all three components together determine the magnitude of influence. The first term, $L_{i,t}/(L_{i,t} + c_{j,t})$, controls the effect of lobbying, such that capital-rich actors have larger social influence ($L_{i,t}$), but the effect on the receiving agent is moderated by the receiving agent's capital ($c_{j,t}$). The second and third components both depend on the agents' value alignment and have opposing effects, which respectively represent homophily ($1 - |v_{i,t} - v_{j,t}|$) and ensure that agents with equal values do not influence each other (i.e., if $v_i - v_j = 0$, we wish to ensure that $v_{j,t+1} = v_{j,t}$). The reason for the quadratic form in the middle term is to maintain the property that influence is stronger between closely aligned opinions (i.e., homophily), which the third term otherwise counteracts.

To represent diffuse social norms and influence, we model a single "media" entity whose opinion is the mean of all farmer and consumer values, weighted by their respective capitals. The media is not an actor per se, operating outside of the regular social networks and simultaneously impacting all agents' values (farmers, consumers, and the state). The strength of this influence ($L_{i,t}$ in the above equation) is set using an external parameter, α_{media}, which defines the total strength of media relative to word-of-mouth in each of the farmer and consumer populations (it is 30% in the baseline parameterization). The strength of the media's influence on state values is equal to the sum of its effects on the farmers and consumers.

For the "change values" intervention (described in Table 1 and applied in Figures 3, 4, 5, and 6), a percentage of farmers and/or consumers are randomly selected at the beginning of the simulation to be affected by the external discursive influence. This fraction is set by the EI_{frac} parameter in Table S1. At each time step, these agents are subject to the external influence in addition to the regular agent-agent interactions. The external influence is modeled in the same way as agent-agent influences, with a strength of $EI_{strength}$ ($L_{i,t}$ in Equation 13) and value orientation of 1 ($v_{i,t}$ in Equation 13).

Empirical and theoretical basis

Opinion formation is complex and is influenced both by information provided by personal interactions and through the mass media.[157] In farming communities, diffuse narratives such as the "good farmer" are pervasive and frequently perpetuate an ideology in which yield is the key status symbol.[47,51,150] Farmers also frequently learn from and follow others' land-use practices.[136] Consumers' consumption decisions are also heavily driven by personal social influences (e.g., surrounding veganism and organic consumption).[158,159] Beyond personal influence, mass media plays a strong role in channeling public opinion around food and agriculture[76] as well as transmitting values between otherwise socially disconnected communities.[33]

Individuals have a tendency to associate with like-minded people (i.e., homophily).[160] Such structures can lead to polarization of opinions.[161] Individuals are also more strongly influenced by the opinions of well-respected others (in our case, those with high capital), such as "important referent individuals,"[147] "championing farmers,"[141] or those with "political legitimacy."[46] This represents the notion of discursive influence described in Figure 1.

Social influence also flows from individuals and organizations to the state, as in democratic societies the government responds to public opinion conveyed through mechanisms such as voting, protest, and lobbying. Similarly to the tendency for individuals to be more strongly influenced by well-respected others, the values embodied in governmental policies are often more strongly swayed by capital-rich actors.[20,46] This is known as elite capture and is another empirical example of discursive influence scaling with capital.

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Tim G. Williams (tgwilnz@gmail.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

- The article does not utilize specific empirical data. Data underlying the figures in this paper will be shared by the lead contact upon request.
- All original code has been deposited in the COMSES model library at https://www.comses.net/codebases/6ac188eb-f817-4d73-85d6-9fd051ed5a77/releases/1.0.0/.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization, T.G.W. and P.H.V.; methodology, T.G.W., C.B., V.D., N.R.M., N.M., M.D.A.R., C.Z., and P.H.V.; software, T.G.W.; formal analysis, T.G.W.; writing – original draft, T.G.W.; writing – review & editing, T.G.W., C.B., V.D., N.R.M., N.M., M.D.A.R., C.Z., and P.H.V.; visualization, T.G.W.; funding acquisition, P.H.V.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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REFERENCES

1. Béné, C. (2022). Why the Great Food Transformation may not happen – A deep-dive into our food systems' political economy, controversies and politics of evidence. World Dev. *154*, 105881. https://doi.org/10.1016/j.worlddev.2022.105881.
2. Dorninger, C., Abson, D.J., Apetrei, C.I., Derwort, P., Ives, C.D., Klaniecki, K., Lam, D.P., Langsenlehner, M., Riechers, M., Spittler, N., and von Wehrden, H. (2020). Leverage points for sustainability transformation: a review on interventions in food and energy systems. Ecol. Econ. *171*, 106570. https://doi.org/10.1016/j.ecolecon.2019.106570.
3. Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., et al. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet *393*, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.
4. Baker, P., Lacy-Nichols, J., Williams, O., and Labonté, R. (2021). The political economy of healthy and sustainable food systems: An introduction to a Special Issue. Int. J. Health Pol. Manag. *10*, 734–744. https://doi.org/10.34172/ijhpm.2021.156.
5. Leclère, D., Obersteiner, M., Barrett, M., Butchart, S.H.M., Chaudhary, A., De Palma, A., DeClerck, F.A.J., Di Marco, M., Doelman, J.C., Dürauer, M., et al. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature *585*, 551–556. https://doi.org/10.1038/s41586-020-2705-y.
6. Tubiello, F.N., Rosenzweig, C., Conchedda, G., Karl, K., Gütschow, J., Xueyao, P., Obli-Laryea, G., Wanner, N., Qiu, S.Y., Barros, J.D., et al.

(2021). Greenhouse gas emissions from food systems: building the evidence base. Environ. Res. Lett. *16*, 065007. https://doi.org/10.1088/1748-9326/ac018e.

7. Clapp, J. (2021). The problem with growing corporate concentration and power in the global food system. Nat. Food *2*, 404–408. https://doi.org/10.1038/s43016-021-00297-7.
8. Webb, P., Benton, T.G., Beddington, J., Flynn, D., Kelly, N.M., and Thomas, S.M. (2020). The urgency of food system transformation is now irrefutable. Nat. Food *1*, 584–585. https://doi.org/10.1038/s43016-020-00161-0.
9. IPES-Food (2016). From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems. International Panel of Experts on Sustainable Food systems (CGIAR).
10. Bernard, B., and Lux, A. (2017). How to feed the world sustainably: an overview of the discourse on agroecology and sustainable intensification. Reg. Environ. Change *17*, 1279–1290.
11. Oliver, T.H., Boyd, E., Balcombe, K., Benton, T.G., Bullock, J.M., Donovan, D., Feola, G., Heard, M., Mace, G.M., Mortimer, S.R., et al. (2018). Overcoming undesirable resilience in the global food system. Glob. Sustain. *1*, e9. https://doi.org/10.1017/sus.2018.9.
12. Conti, C., Zanello, G., and Hall, A. (2021). Why are agri-food systems resistant to new directions of change? A systematic review. Global Food Secur. *31*, 100576. https://doi.org/10.1016/j.gfs.2021.100576.
13. Béné, C., and Abdulai, A.-R. (2024). Navigating the politics and processes of food systems transformation: guidance from a holistic framework. Front. Sustain. Food Syst. *8*, 1399024. https://doi.org/10.3389/fsufs.2024.1399024.
14. Williams, T.G., Bürgi, M., Debonne, N., Diogo, V., Helfenstein, J., Levers, C., Mohr, F., Stratton, A.E., and Verburg, P.H. (2024). Mapping lock-ins and enabling environments for agri-food sustainability transitions in Europe. Sustain. Sci. *19*, 1221–1242. https://doi.org/10.1007/s11625-024-01480-y.
15. Avelino, F. (2017). Power in Sustainability Transitions: Analysing power and (dis)empowerment in transformative change towards sustainability. Environ. Policy Gov. *27*, 505–520. https://doi.org/10.1002/eet.1777.
16. Görg, C., Brand, U., Haberl, H., Hummel, D., Jahn, T., and Liehr, S. (2017). Challenges for social-ecological transformations: Contributions from social and political ecology. Sustainability *9*, 1045. https://doi.org/10.3390/su9071045.
17. Rossi, A., Bui, S., and Marsden, T. (2019). Redefining power relations in agrifood systems. J. Rural Stud. *68*, 147–158. https://doi.org/10.1016/j.jrurstud.2019.01.002.
18. Rutting, L., Vervoort, J., Mees, H., Pereira, L., Veeger, M., Muiderman, K., Mangnus, A., Winkler, K., Olsson, P., Hichert, T., et al. (2022). Disruptive seeds: a scenario approach to explore power shifts in sustainability transformations. Sustain. Sci. *18*, 1117–1133. https://doi.org/10.1007/s11625-022-01251-7.
19. Avelino, F. (2021). Theories of power and social change. Power contestations and their implications for research on social change and innovation. J. Political Power *14*, 425–448. https://doi.org/10.1080/2158379X.2021.1875307.
20. IPES-Food (2023). Who's Tipping the Scales? The growing influence of corporations on the governance of food systems, and how to counter it.
21. Montenegro de Wit, M., Canfield, M., Iles, A., Anderson, M., McKeon, N., Guttal, S., Gemmill-Herren, B., Duncan, J., van der Ploeg, J.D., and Prato, S. (2021). Editorial: Resetting Power in Global Food Governance: The UN Food Systems Summit. Development *64*, 153–161. https://doi.org/10.1057/s41301-021-00316-x.
22. D'Odorico, P., Carr, J.A., Davis, K.F., Dell'Angelo, J., and Seekell, D.A. (2019). Food inequality, injustice, and rights. Bioscience *69*, 180–190. https://doi.org/10.1093/biosci/biz002.
23. Anderson, C.R., Bruil, J., Chappell, M.J., Kiss, C., and Pimbert, M.P. (2019). From Transition to Domains of Transformation: Getting to Sustainable and Just Food Systems through Agroecology. Sustain. Sci. Pract. Pol. *11*, 5272. https://doi.org/10.3390/su11195272.
24. Holtz, G., Alkemade, F., de Haan, F., Köhler, J., Trutnevyte, E., Luthe, T., Halbe, J., Papachristos, G., Chappin, E., Kwakkel, J., and Ruutu, S. (2015). Prospects of modelling societal transitions: Position paper of an emerging community. Environ. Innov. Soc. Transit. *17*, 41–58. https://doi.org/10.1016/j.eist.2015.05.006.
25. Kok, M.T., Alkemade, R., Bakkenes, M., van Eerdt, M., Janse, J., Mandryk, M., Kram, T., Lazarova, T., Meijer, J., van Oorschot, M., et al. (2018). Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation: A global scenario-study. Biol. Conserv. *221*, 137–150. https://doi.org/10.1016/j.biocon.2018.03.003.
26. Brown, C., Holzhauer, S., and Metzger, M.J. (2018). Land managers' behaviours modulate pathways to visions of future land systems. Reg. Environ. Change *18*, 831–845.
27. Kremmydas, D., Athanasiadis, I.N., and Rozakis, S. (2018/7). A review of Agent Based Modeling for agricultural policy evaluation. Agric. Syst. *164*, 95–106. https://doi.org/10.1016/j.agsy.2018.03.010.
28. Teeuwen, A.S., Meyer, M.A., Dou, Y., and Nelson, A. (2022). A systematic review of the impact of food security governance measures as simulated in modelling studies. Nat. Food *3*, 619–630. https://doi.org/10.1038/s43016-022-00571-2.
29. Gottschamer, L., and Walters, J.P. (2023). The dynamics of sustainability transitions: An archetype for transformation. Environ. Innov. Soc. Transit. *49*, 100767. https://doi.org/10.1016/j.eist.2023.100767.
30. Köhler, J., De Haan, F., Holtz, G., Kubeczko, K., Moallemi, E., Papachristos, G., and Chappin, E. (2018). Modelling Sustainability Transitions: An Assessment of Approaches and Challenges. J. Artif. Soc. Soc. Simulat. *21*. https://doi.org/10.18564/jasss.3629.
31. Steger, C., Hirsch, S., Cosgrove, C., Inman, S., Nost, E., Shinbrot, X., Thorn, J.P., Brown, D.G., Grêt-Regamey, A., Müller, B., et al. (2021). Linking model design and application for transdisciplinary approaches in social-ecological systems. Global Environ. Change *66*, 102201. https://doi.org/10.1016/j.gloenvcha.2020.102201.
32. van Daalen, C., Dresen, L., and Janssen, M.A. (2002). The roles of computer models in the environmental policy life cycle. Environ. Sci. Pol. *5*, 221–231. https://doi.org/10.1016/s1462-9011(02)00040-0.
33. Condie, C.M., Alexander, K.A., Fulton, E.A., Vince, J., and Condie, S.A. (2022). Reducing socio-ecological conflict using social influence modelling. Sci. Rep. *12*, 22002. https://doi.org/10.1038/s41598-022-26570-8.
34. Bodirsky, B.L., Chen, D.M.-C., Weindl, I., Soergel, B., Beier, F., Molina Bacca, E.J., Gaupp, F., Popp, A., and Lotze-Campen, H. (2022). Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100. Nat. Food *3*, 341–348. https://doi.org/10.1038/s43016-022-00500-3.
35. van Zanten, H.H.E., Simon, W., van Selm, B., Wacker, J., Maindl, T.I., Frehner, A., Hijbeek, R., van Ittersum, M.K., and Herrero, M. (2023). Circularity in Europe strengthens the sustainability of the global food system. Nat. Food *4*, 320–330. https://doi.org/10.1038/s43016-023-00734-9.
36. Bourceret, A., Amblard, L., and Mathias, J.-D. (2021). Governance in social-ecological agent-based models: a review. Ecol. Soc. *26*, art38. https://doi.org/10.5751/ES-12440-260238.
37. Davidson, M.R., Filatova, T., Peng, W., Verbeek, L., and Kucuksayacigil, F. (2024). Simulating institutional heterogeneity in sustainability science. Proc. Natl. Acad. Sci. USA *121*, e2215674121. https://doi.org/10.1073/pnas.2215674121.
38. Williams, T.G., Bui, S., Conti, C., Debonne, N., Levers, C., Swart, R., and Verburg, P.H. (2023). Synthesising the diversity of European agri-food networks: A meta-study of actors and power-laden interactions. Global Environ. Change *83*, 102746. https://doi.org/10.1016/j.gloenvcha.2023.102746.
39. Bui, S., Cardona, A., Lamine, C., and Cerf, M. (2016). Sustainability transitions: Insights on processes of niche-regime interaction and regime

reconfiguration in agri-food systems. J. Rural Stud. *48*, 92–103. https://doi.org/10.1016/j.jrurstud.2016.10.003.

40. Leblond, N., and Trottier, J. (2016). Performing an Invisibility Spell: Global Models, Food Regimes and Smallholders. Int. J. Sociol. Agric. Food *23*. https://doi.org/10.48416/ijsaf.v23i1.127.
41. Valencia, V., Bennett, E.M., Altieri, M., Nicholls, C., Pas Schrijver, A., and Schulte, R.P.O. (2022). Learning from the future: mainstreaming disruptive solutions for the transition to sustainable food systems. Environ. Res. Lett. *17*, 051002. https://doi.org/10.1088/1748-9326/ac6ad9.
42. Benton, T.G. (2023). Academics can do more to disrupt and reframe the solution space for food system transformation. Nat. Food *4*, 928–930. https://doi.org/10.1038/s43016-023-00876-w.
43. IPES-Food (2015). The new science of sustainable food systems: Overcoming barriers to food systems reform.
44. Scoones, I. (1998). Sustainable Rural Livelihoods: A Framework for Analysis (Institute for Development Studies).
45. Navarro, Z. (2006). In search of a cultural interpretation of power: The contribution of Pierre Bourdieu. IDS Bull. *37*, 11–22. https://doi.org/10.1111/j.1759-5436.2006.tb00319.x.
46. Clapp, J., and Fuchs, D. (2009). Agrifood corporations, global governance, and sustainability: a framework for analysis. In Corporate Power in Global Agrifood Governance, pp. 1–26.
47. Vanloqueren, G., and Baret, P.V. (2008). Why are ecological, low-input, multi-resistant wheat cultivars slow to develop commercially? A Belgian agricultural 'lock-in' case study. Ecol. Econ. *66*, 436–446. https://doi.org/10.1016/j.ecolecon.2007.10.007.
48. Dries, L., Reardon, T., and Swinnen, J.F.M. (2004). The Rapid Rise of Supermarkets in Central and Eastern Europe: Implications for the Agrifood Sector and Rural Development. Dev. Pol. Rev. *22*, 525–556. https://doi.org/10.1111/j.1467-7679.2004.00264.x.
49. Meynard, J.-M., Charrier, F., Fares, M., Le Bail, M., Magrini, M.-B., Charlier, A., and Messéan, A. (2018). Socio-technical lock-in hinders crop diversification in France. Agron. Sustain. Dev. *38*, 54. https://doi.org/10.1007/s13593-018-0535-1.
50. Hjelmar, U. (2011). Consumers' purchase of organic food products. A matter of convenience and reflexive practices. Appetite *56*, 336–344. https://doi.org/10.1016/j.appet.2010.12.019.
51. Vermunt, D.A., Wojtynia, N., Hekkert, M.P., Van Dijk, J., Verburg, R., Verweij, P.A., Wassen, M., and Runhaar, H. (2022). Five mechanisms blocking the transition towards 'nature-inclusive'agriculture: A systemic analysis of Dutch dairy farming. Agric. Syst. *195*, 103280.
52. Corporate Europe Observatory (2023). Sabotaging EU Pesticide Reduction Law (SUR). Pesticide industry lobby's reckless assault on biodiversity and health. https://corporateeurope.org/en/2023/11/sabotaging-eu-pesticide-reduction-law-sur.
53. Lamine, C. (2011). Transition pathways towards a robust ecologization of agriculture and the need for system redesign. Cases from organic farming and IPM. J. Rural Stud. *27*, 209–219. https://doi.org/10.1016/j.jrurstud.2011.02.001.
54. Elzen, B., Geels, F.W., Leeuwis, C., and van Mierlo, B. (2011). Normative contestation in transitions 'in the making': Animal welfare concerns and system innovation in pig husbandry. Res. Pol. *40*, 263–275. https://doi.org/10.1016/j.respol.2010.09.018.
55. Menary, J., Collier, R., and Seers, K. (2019). Innovation in the UK fresh produce sector: Identifying systemic problems and the move towards systemic facilitation. Agric. Syst. *176*, 102675. https://doi.org/10.1016/j.agsy.2019.102675.
56. Richards, C., Bjørkhaug, H., Lawrence, G., and Hickman, E. (2013). Retailer-driven agricultural restructuring—Australia, the UK and Norway in comparison. Agric. Hum. Val. *30*, 235–245. https://doi.org/10.1007/s10460-012-9408-4.
57. Magrini, M.-B., Anton, M., Cholez, C., Corre-Hellou, G., Duc, G., Jeuffroy, M.-H., Meynard, J.-M., Pelzer, E., Voisin, A.-S., and Walrand, S. (2016). Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. Ecol. Econ. *126*, 152–162. https://doi.org/10.1016/j.ecolecon.2016.03.024.
58. Bijman, J., Iliopoulos, C., Poppe, K. Gijselinckx, C, Hagedorn, K., Hanisch, M., Hendrikse, G.W.J., Kühl, R., Ollila, P., Pyykkönen, P., and van der Sangen, G. (2012). Support for Farmers' Cooperatives: Final Report (library.wur.nl).
59. Baumgart-Getz, A., Prokopy, L.S., and Floress, K. (2012). Why farmers adopt best management practice in the United States: a meta-analysis of the adoption literature. J. Environ. Manag. *96*, 17–25. https://doi.org/10.1016/j.jenvman.2011.10.006.
60. De Schutter, O. (2017). The political economy of food systems reform. Eur. Rev. Agric. Econ. *44*, 705–731. https://doi.org/10.1093/erae/jbx009.
61. Coopmans, I., Dessein, J., Accatino, F., Antonioli, F., Bertolozzi-Caredio, D., Gavrilescu, C., Gradziuk, P., Manevska-Tasevska, G., Meuwissen, M., Peneva, M., et al. (2021). Understanding farm generational renewal and its influencing factors in Europe. J. Rural Stud. *86*, 398–409. https://doi.org/10.1016/j.jrurstud.2021.06.023.
62. IPES-Food (2017). Too big to feed: Exploring the impacts of mega-mergers, consolidation and concentration of power in the agri-food sector.pdf. International Panel of Experts on Sustainable Food Systems.
63. Debonne, N., van Vliet, J., Metternicht, G., and Verburg, P. (2021). Agency shifts in agricultural land governance and their implications for land degradation neutrality. Global Environ. Change *66*, 102221. https://doi.org/10.1016/j.gloenvcha.2020.102221.
64. Ma, J., Seenivasan, S., and Yan, B. (2020). Media influences on consumption trends: Effects of the film Food, Inc. on organic food sales in the U.S. Int. J. Res. Mark. *37*, 320–335. https://doi.org/10.1016/j.ijresmar.2019.08.004.
65. Truelove, H.B., Carrico, A.R., Weber, E.U., Raimi, K.T., and Vandenbergh, M.P. (2014). Positive and negative spillover of pro-environmental behavior: An integrative review and theoretical framework. Global Environ. Change *29*, 127–138. https://doi.org/10.1016/j.gloenvcha.2014.09.004.
66. Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., von Wehrden, H., Abernethy, P., Ives, C.D., Jager, N.W., and Lang, D.J. (2017). Leverage points for sustainability transformation. Ambio *46*, 30–39. https://doi.org/10.1007/s13280-016-0800-y.
67. Meadows, D.H. (1997). Places to intervene in a system. Whole Earth Rev. *91*, 78–85.
68. Williams, T.G., Guikema, S.D., Brown, D.G., and Agrawal, A. (2020). Assessing model equifinality for robust policy analysis in complex socio-environmental systems. Environ. Model. Software *134*, 104831. https://doi.org/10.1016/j.envsoft.2020.104831.
69. Barrett, C.B., Benton, T., Fanzo, J., Herrero, M., Nelson, R., Buckler, E.S., Cooper, K.A., Culotta, I., Fan, S., Gandhi, R., et al. (2020). Socio-technical Innovation Bundles for Agri-Food Systems Transformation: A Nature Sustainability Expert Panel Report. Report of the International Expert Panel on Innovations to Build Sustainable, Equitable, Inclusive Food Value Chains. Nature Sustainability.
70. Gosnell, H., Gill, N., and Voyer, M. (2019). Transformational adaptation on the farm: Processes of change and persistence in transitions to 'climate-smart' regenerative agriculture. Global Environ. Change *59*, 101965. https://doi.org/10.1016/j.gloenvcha.2019.101965.
71. Davis, N., Dermody, B., Koetse, M., and van Voorn, G. (2024). Identifying personal and social drivers of dietary patterns: An agent-based model of Dutch consumer behavior. J. Artif. Soc. Soc. Simulat. *27*. https://doi.org/10.18564/jasss.5020.
72. Martin, A., O'Farrell, P., Kumar, R., Eser, U., Faith, D.P., Gomez-Baggethun, E., Harmackova, Z., Horcea-Milcu, A.I., Merçon, J., Quaas, M., et al. (2022). Chapter 5: The role of diverse values of nature in visioning and transforming towards just and sustainable futures. In Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, M. Christie, P. Balvanera, U.

Pascual, B. Baptiste, and D. González-Jiménez, eds. (IPBES secretariat). https://doi.org/10.5281/zenodo.6522326.

73. Gava, O., Povellato, A., Galioto, F., Pražan, J., Schwarz, G., Quero, A.L., Iragui, U.Y., Massa, C.A., Zīlāns, A., and Carolus, J. (2022). Policy instruments to support agroecological transitions in Europe. EuroChoices *21*, 13–20. https://doi.org/10.1111/1746-692x.12367.

74. Ericksen, P., Stewart, B., Dixon, J., Barling, D., Loring, P., Anderson, M., and Ingram, J. (2012). The value of a food system approach. In Food security and global environmental change (Routledge)), pp. 45–65.

75. Virginie, A., Roberta, D., Jean-Loup, L., Gun, R., Barbara, T., Matthew, G., Beatrice, B., Davide, M., Duboys de Labarre, M., Jelena, F., et al. (2022). European food quality schemes in everyday food consumption: An exploration of sayings and doings through pragmatic regimes of engagement. J. Rural Stud. *95*, 336–349. https://doi.org/10.1016/j.jrurstud.2022.09.009.

76. Vanloqueren, G., and Baret, P.V. (2009). How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. Res. Pol. *38*, 971–983. https://doi.org/10.1016/j.respol.2009.02.008.

77. Thaler, R.H., and Sunstein, C.R. (2008). Nudge: Improving Decisions about Health, Wealth, and Happiness (Yale University Press).

78. Ferrari, L., Cavaliere, A., De Marchi, E., and Banterle, A. (2019). Can nudging improve the environmental impact of food supply chain? A systematic review. Trends Food Sci. Technol. *91*, 184–192. https://doi.org/10.1016/j.tifs.2019.07.004.

79. Norman, J., Kelly, B., Boyland, E., and McMahon, A.-T. (2016). The impact of marketing and advertising on food behaviours: Evaluating the evidence for a causal relationship. Curr. Nutr. Rep. *5*, 139–149. https://doi.org/10.1007/s13668-016-0166-6.

80. Aschemann-Witzel, J., and Schulze, M. (2023). Transitions to plant-based diets: the role of societal tipping points. Curr. Opin. Food Sci. *51*, 101015. https://doi.org/10.1016/j.cofs.2023.101015.

81. Blesh, J., Mehrabi, Z., Wittman, H., Kerr, R.B., James, D., Madsen, S., Smith, O.M., Snapp, S., Stratton, A.E., Bakarr, M., et al. (2023). Against the odds: Network and institutional pathways enabling agricultural diversification. One Earth *6*, 479–491. https://doi.org/10.1016/j.oneear.2023.03.004.

82. Everall, J.P., Donges, J.F., and Otto, I.M. (2023). The Pareto effect in tipping social networks: from minority to majority. Preprint at EGUsphere. https://doi.org/10.5194/egusphere-2023-2241.

83. Zeppini, P., Frenken, K., and Kupers, R. (2014). Thresholds models of technological transitions. Environ. Innov. Soc. Transit. *11*, 54–70. https://doi.org/10.1016/j.eist.2013.10.002.

84. Lamine, C., Renting, H., Rossi, A., Wiskerke, J.S.C. (han), and Brunori, G. (2012). Agri-Food systems and territorial development: innovations, new dynamics and changing governance mechanisms. In Farming Systems Research into the 21st Century: The New Dynamic, I. Darnhofer, D. Gibbon, and B. Dedieu, eds. (Springer Netherlands), pp. 229–256. https://doi.org/10.1007/978-94-007-4503-2_11.

85. Lenton, T.M., Benson, S., Smith, T., Ewer, T., Lanel, V., Petykowski, E., Powell, T.W.R., Abrams, J.F., Blomsma, F., and Sharpe, S. (2022). Operationalising positive tipping points towards global sustainability. Glob. Sustain. *5*, 1–32. https://doi.org/10.1017/sus.2021.30.

86. Williams, T.G., Dressler, G., Stratton, A.E., and Müller, B. (2021). Ecological and financial strategies provide complementary benefits for smallholder climate resilience: insights from a simulation model. Ecol. Soc. *26*, art14. https://doi.org/10.5751/ES-12207-260214.

87. Cirillo, C., Györi, M., and Veras Soares, F. (2017). Targeting social protection and agricultural interventions: The potential for synergies. Global Food Secur. *12*, 67–72. https://doi.org/10.1016/j.gfs.2016.08.006.

88. Saleth, R.M., and Dinar, A. (2009). The impact of multiple policy interventions on food security. J. Pol. Model. *31*, 923–938. https://doi.org/10.1016/j.jpolmod.2009.08.001.

89. Alt, M., Bruns, H., DellaValle, N., and Murauskaite-Bull, I. (2024). Synergies of interventions to promote pro-environmental behaviors – A meta-analysis of experimental studies. Global Environ. Change *84*, 102776. https://doi.org/10.1016/j.gloenvcha.2023.102776.

90. Melchior, I.C., and Newig, J. (2021). Governing Transitions towards Sustainable Agriculture—Taking Stock of an Emerging Field of Research. Sustain. Sci. Pract. Pol. *13*, 528. https://doi.org/10.3390/su13020528.

91. Magliocca, N.R., van Vliet, J., Brown, C., Evans, T.P., Houet, T., Messerli, P., Messina, J.P., Nicholas, K.A., Ornetsmüller, C., Sagebiel, J., et al. (2015). From meta-studies to modeling: Using synthesis knowledge to build broadly applicable process-based land change models. Environ. Model. Software *72*, 10–20. https://doi.org/10.1016/j.envsoft.2015.06.009.

92. Schlüter, M., Orach, K., Lindkvist, E., Martin, R., Wijermans, N., Bodin, Ö., and Boonstra, W.J. (2019). Toward a methodology for explaining and theorizing about social-ecological phenomena. Curr. Opin. Environ. Sustain. *39*, 44–53. https://doi.org/10.1016/j.cosust.2019.06.011.

93. Kaufmann, P., Stagl, S., and Franks, D.W. (2009). Simulating the diffusion of organic farming practices in two New EU Member States. Ecol. Econ. *68*, 2580–2593. https://doi.org/10.1016/j.ecolecon.2009.04.001.

94. Coronese, M., Occelli, M., Lamperti, F., and Roventini, A. (2024). Towards sustainable agriculture: behaviors, spatial dynamics and policy in an evolutionary agent-based model (Laboratory of Economics and Management (LEM) (Sant'Anna School of Advanced Studies, Pisa, Italy), pp. 2024/05.

95. Zagaria, C., Schulp, C.J., Zavalloni, M., Viaggi, D., and Verburg, P.H. (2021). Modelling transformational adaptation to climate change among crop farming systems in Romagna, Italy. Agric. Syst. *188*, 103024. https://doi.org/10.1016/j.agsy.2020.103024.

96. Xu, Q., Huet, S., Perret, E., and Deffuant, G. (2020). Do farm characteristics or social dynamics explain the conversion to organic farming by dairy farmers? An agent-based model of dairy farming in 27 French cantons. J. Artif. Soc. Soc. Simulat. *23*. https://doi.org/10.18564/jasss.4204.

97. Deffuant, G., Huet, S., and Amblard, F. (2005). An individual-based model of innovation diffusion mixing social value and individual benefit. Am. J. Sociol. *110*, 1041–1069. https://doi.org/10.1086/430220.

98. Bennett, E.M., Biggs, R., Peterson, G.D., and Gordon, L.J. (2021). Patchwork Earth: navigating pathways to just, thriving, and sustainable futures. One Earth *4*, 172–176. https://doi.org/10.1016/j.oneear.2021.01.004.

99. Ong, T.W.Y., and Liao, W. (2020). Agroecological transitions: a mathematical perspective on a transdisciplinary problem. Front. Sustain. Food Syst. *4*, 91.

100. Barreiro-Hurle, J., Bogonos, M., Himics, M., Hristov, J., Pérez-Domínguez, I., Sahoo, A., Salputra, G., Weiss, F., Baldoni, E., and Elleby, C. (2021). Modelling transitions to sustainable food systems: Are we missing the Point? EuroChoices *20*, 12–20. https://doi.org/10.1111/1746-692x.12339.

101. Jung, D.F., and Lake, D.A. (2011). Markets, Hierarchies, and Networks: An Agent-Based Organizational Ecology. Am. J. Pol. Sci. *55*, 972–990.

102. Polhill, J.G., Filatova, T., Schlüter, M., and Voinov, A. (2016). Modelling systemic change in coupled socio-environmental systems. Environ. Model. Software *75*, 318–332. https://doi.org/10.1016/j.envsoft.2015.10.017.

103. Ghorbani, A., and Bravo, G. (2016). Managing the commons: a simple model of the emergence of institutions through collective action. Int. J. Nanobiotechnology Pharm. *10*, 200–219.

104. Epstein, J.M., and Axtell, R. (1996). Growing artificial societies: social science from the bottom up.

105. Murray-Rust, D., Brown, C., van Vliet, J., Alam, S.J., Robinson, D.T., Verburg, P.H., and Rounsevell, M. (2014). Combining agent functional types, capitals and services to model land use dynamics. Environ.

Model. Software *59*, 187–201. https://doi.org/10.1016/j.envsoft.2014.05.019.

106. Harrison, P.A., Holman, I.P., Cojocaru, G., Kok, K., Kontogianni, A., Metzger, M.J., and Gramberger, M. (2013). Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe. Reg. Environ. Change *13*, 761–780. https://doi.org/10.1007/s10113-012-0361-y.

107. Arora, S., and Glover, D. (2017). Power in practice: insights from technography and actor-network theory for agricultural sustainability.

108. Foucault, M. (1990). Politics, Philosophy, Culture: Interviews and Other Writings, 1977-1984, 1st ed. (Routledge).

109. Finlay, L. (1998). Reflexivity: An Essential Component for All Research? Br. J. Occup. Ther. *61*, 453–456. https://doi.org/10.1177/030802269806101005.

110. Williams, T.G., Brown, D.G., Guikema, S.D., Logan, T.M., Magliocca, N.R., Müller, B., and Steger, C.E. (2022). Integrating equity considerations into agent-based modeling: A conceptual framework and practical guidance. J. Artif. Soc. Soc. Simulat. *25*. https://doi.org/10.18564/jasss.4816.

111. Dumont, A.M., Gasselin, P., and Baret, P.V. (2020). Transitions in agriculture: Three frameworks highlighting coexistence between a new agroecological configuration and an old, organic and conventional configuration of vegetable production in Wallonia (Belgium). Geoforum *108*, 98–109. https://doi.org/10.1016/j.geoforum.2019.11.018.

112. Béné, C., Oosterveer, P., Lamotte, L., Brouwer, I.D., de Haan, S., Prager, S.D., Talsma, E.F., and Khoury, C.K. (2019). When food systems meet sustainability–Current narratives and implications for actions. World Dev. *113*, 116–130.

113. Weber, H., Poeggel, K., Eakin, H., Fischer, D., Lang, D.J., Wehrden, H.V., and Wiek, A. (2020). What are the ingredients for food systems change towards sustainability?—Insights from the literature. Environ. Res. Lett. *15*, 113001. https://doi.org/10.1088/1748-9326/ab99fd.

114. Gaitán-Cremaschi, D., Klerkx, L., Duncan, J., Trienekens, J.H., Huenchuleo, C., Dogliotti, S., Contesse, M.E., and Rossing, W.A.H. (2019). Characterizing diversity of food systems in view of sustainability transitions. A review. Agron. Sustain. Dev. *39*, 1. https://doi.org/10.1007/s13593-018-0550-2.

115. Bui, S. (2021). Enacting Transitions—The Combined Effect of Multiple Niches in Whole System Reconfiguration. Sustain. Sci. Pract. Pol. *13*, 6135. https://doi.org/10.3390/su13116135.

116. Vivero-Pol, J. (2017). Food as Commons or Commodity? Exploring the Links between Normative Valuations and Agency in Food Transition. Sustain. Sci. Pract. Pol. *9*, 442. https://doi.org/10.3390/su9030442.

117. Geels, F.W., and Schot, J. (2007). Typology of sociotechnical transition pathways. Res. Pol. *36*, 399–417. https://doi.org/10.1016/j.respol.2007.01.003.

118. Jaffee, D., and Howard, P.H. (2010). Corporate cooptation of organic and fair trade standards. Agric. Hum. Val. *27*, 387–399.

119. Constance, D.H., Choi, J., and Lyke-Ho-Gland, H. (2008). Conventionalization, bifurcation, and quality of life: Certified and non-certified organic farmers in Texas. Journal of Rural Social Sciences *23*.

120. Guthman, J.H. (2000). Agrarian dreams? The paradox of organic farming in California.

121. Bergman, N., Haxeltine, A., Whitmarsh, L., Köhler, J., Schilperoord, M., and Rotmans, J. (2008). Modelling socio-technical transition patterns and pathways. J. Artif. Soc. Soc. Simulat. *11*, 1–32.

122. Gestefeld, M., and Lorenz, J. (2023). Calibrating an opinion dynamics model to empirical opinion distributions and transitions. J. Artif. Soc. Soc. Simulat. *26*. https://doi.org/10.18564/jasss.5204.

123. Jager, W., Guijarro-Berdiñas, B., Bouman, L., Antosz, P., Alonso-Betanzos, A., Salt, D., Polhill, J.G., Rodríguez-Arias, A., and Sánchez-Maroño, N. (2024). Simulating the role of norms in processes of social innovation: Three case studies. J. Artif. Soc. Soc. Simulat. *27*, 6. https://doi.org/10.18564/jasss.5168.

124. Girard, L. (2023). Le bio en pleine désaffection : «Certains producteurs n'affichent plus le logo pour ne pas faire fuir le client». Le Monde.

125. FAO (2023). The State of Food and Agriculture 2023 – Revealing the True Cost of Food to Transform Agrifood Systems (FAO). https://doi.org/10.4060/cc7724en.

126. Bourdieu, P. (1986). The forms of capital. In Handbook of Theory and Research for the Sociology of Education, J. Richardson, ed. (Greenwood), pp. 241–258.

127. Anheier, H.K., Gerhards, J., and Romo, F.P. (1995). Forms of Capital and Social Structure in Cultural Fields: Examining Bourdieu's Social Topography. Am. J. Sociol. *100*, 859–903. https://doi.org/10.1086/230603.

128. Gould, R.K., Soares, T.M., Arias-Arévalo, P., Cantú-Fernandez, M., Baker, D., Eyster, H.N., Kwon, R., Prox, L., Rode, J., Suarez, A., et al. (2023). The role of value(s) in theories of human behavior. Curr. Opin. Environ. Sustain. *64*, 101355. https://doi.org/10.1016/j.cosust.2023.101355.

129. Chan, K.M.A., Agard, J., Liu, J., Aguiar, A.P.D., Armenteras, D., Boedhihartono, A.K., Cheung, W.W.L., Hashimoto, S., Pedraza, G.C.H., Hickler, T., et al. (2019). Chapter 5. Pathways towards a Sustainable Future. In Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, E.S. Brondízio, J. Settele, S. Díaz, and H.T. Ngo, eds. (IPBES secretariat), p. 108. https://doi.org/10.5281/zenodo.3832099.

130. Renting, H., Marsden, T.K., and Banks, J. (2003). Understanding Alternative Food Networks: Exploring the Role of Short Food Supply Chains in Rural Development. Environ. Plann. *35*, 393–411. https://doi.org/10.1068/a3510.

131. Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S.K., Huse, G., et al. (2006). A standard protocol for describing individual-based and agent-based models. Ecol. Model. *198*, 115–126.

132. Grimm, V., Railsback, S.F., Vincenot, C.E., Berger, U., Gallagher, C., Deangelis, D.L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., et al. (2020). The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. J. Artif. Soc. Soc. Simulat. *23*.

133. Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., and Schwarz, N. (2013). Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. Environ. Model. Software *48*, 37–48. https://doi.org/10.1016/j.envsoft.2013.06.003.

134. Barabasi, A.L., and Albert, R. (1999). Emergence of scaling in random networks. Science *286*, 509–512. https://doi.org/10.1126/science.286.5439.509.

135. Girvan, M., and Newman, M.E.J. (2002). Community structure in social and biological networks. Proc. Natl. Acad. Sci. USA *99*, 7821–7826. https://doi.org/10.1073/pnas.122653799.

136. Sun, Z., and Müller, D. (2013). A framework for modeling payments for ecosystem services with agent-based models, Bayesian belief networks and opinion dynamics models. Environ. Model. Software *45*, 15–28. https://doi.org/10.1016/j.envsoft.2012.06.007.

137. Gaitán-Cremaschi, D., Klerkx, L., Aguilar-Gallegos, N., Duncan, J., Pizzolón, A., Dogliotti, S., and Rossing, W.A. (2022). Public food procurement from family farming: A food system and social network perspective. Food Pol. *111*, 102325. https://doi.org/10.1016/j.foodpol.2022.102325.

138. Swart, R., Levers, C., Davis, J.T., and Verburg, P.H. (2023). Meta-analyses reveal the importance of socio-psychological factors for farmers' adoption of sustainable agricultural practices. One Earth *6*, 1771–1783. https://doi.org/10.1016/j.oneear.2023.10.028.

139. Dedeurwaerdere, T., De Schutter, O., Hudon, M., Mathijs, E., Annaert, B., Avermaete, T., Bleeckx, T., de Callataÿ, C., De Snijder, P., Fernández-Wulff, P., et al. (2017). The governance features of social enterprise

and social network activities of collective food buying groups. Ecol. Econ. *140*, 123–135. https://doi.org/10.1016/j.ecolecon.2017.04.018.

140. Will, M., Groeneveld, J., Frank, K., and Müller, B. (2020). Combining social network analysis and agent-based modelling to explore dynamics of human interaction: A review. Socio-Environmental Systems Modelling *2*, 16325. https://doi.org/10.18174/sesmo.2020a16325.

141. Klerkx, L., Aarts, N., and Leeuwis, C. (2010). Adaptive management in agricultural innovation systems: The interactions between innovation networks and their environment. Agric. Syst. *103*, 390–400. https://doi.org/10.1016/j.agsy.2010.03.012.

142. Cakir, M., and Balagtas, J.V. (2012). Estimating market power of U.s. dairy cooperatives in the fluid milk market. Am. J. Agric. Econ. *94*, 647–658. https://doi.org/10.1093/ajae/aar136.

143. Koppenberg, M., and Hirsch, S. (2022). Output market power and firm characteristics in dairy processing: Evidence from three EU countries. J. Agric. Econ. *73*, 490–517. https://doi.org/10.1111/1477-9552.12460.

144. Adams, T., Gerber, J.-D., Amacker, M., and Haller, T. (2019). Who gains from contract farming? Dependencies, power relations, and institutional change. J. Peasant Stud. *46*, 1435–1457. https://doi.org/10.1080/03066150.2018.1534100.

145. Konefal, J., Mascarenhas, M., and Hatanaka, M. (2005). Governance in the Global Agro-food System: Backlighting the Role of Transnational Supermarket Chains. Agric. Hum. Val. *22*, 291–302. https://doi.org/10.1007/s10460-005-6046-0.

146. Levine, J., Chan, K.M., and Satterfield, T. (2015). From rational actor to efficient complexity manager: Exorcising the ghost of Homo economicus with a unified synthesis of cognition research. Ecol. Econ. *114*, 22–32. https://doi.org/10.1016/j.ecolecon.2015.03.010.

147. Ajzen, I. (1991). The theory of planned behavior. Organ. Behav. Hum. Decis. Process. *50*, 179–211. https://doi.org/10.1016/0749-5978(91)90020-T.

148. Graybiel, A.M. (2008). Habits, rituals, and the evaluative brain. Annu. Rev. Neurosci. *31*, 359–387. https://doi.org/10.1146/annurev.neuro.29.051605.112851.

149. Jager, W., and Janssen, M. (2012). An updated conceptual framework for integrated modeling of human decision making: The Consumat II. In workshop Complexity in the Real World @ ECCS, pp. 1–18. https://api.semanticscholar.org/CorpusID:59434512.

150. Ambrosius, F.H., Kramer, M.R., Spiegel, A., Bokkers, E.A., Bock, B.B., and Hofstede, G.J. (2022). Diffusion of organic farming among Dutch pig farmers: An agent-based model. Agric. Syst. *197*, 103336. https://doi.org/10.1016/j.agsy.2021.103336.

151. Morel, K., Revoyron, E., San Cristobal, M., and Baret, P.V. (2020). Innovating within or outside dominant food systems? Different challenges for contrasting crop diversification strategies in Europe. PLoS One *15*, e0229910. https://doi.org/10.1371/journal.pone.0229910.

152. Mier y Terán Giménez Cacho, M., Giraldo, O.F., Aldasoro, M., Morales, H., Ferguson, B.G., Rosset, P., Khadse, A., and Campos, C. (2018). Bringing agroecology to scale: key drivers and emblematic cases. Agroecology and Sustainable Food Systems *42*, 637–665. https://doi.org/10.1080/21683565.2018.1443313.

153. Galli, F., Prosperi, P., Favilli, E., D'Amico, S., Bartolini, F., and Brunori, G. (2020). How can policy processes remove barriers to sustainable food systems in Europe? Contributing to a policy framework for agri-food transitions. Food Pol. *96*, 101871. https://doi.org/10.1016/j.foodpol.2020.101871.

154. van der Ploeg, J.D. (2020). Farmers' upheaval, climate crisis and populism. J. Peasant Stud. *47*, 589–605. https://doi.org/10.1080/03066150.2020.1725490.

155. Pe'er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Müller, R., Bontzorlos, V., Clough, D., Bezák, P., Bonn, A., et al. (2019). A greener path for the EU Common Agricultural Policy. Science *365*, 449–451. https://doi.org/10.1126/science.aax3146.

156. Deffuant, G., Amblard, F., Weisbuch, G., and Faure, T. (2002). How can extremism prevail? A study based on the relative agreement interaction model. J. Artif. Soc. Soc. Simulat. *5*.

157. Sîrbu, A., Loreto, V., Servedio, V.D.P., and Tria, F. (2017). Opinion dynamics: Models, extensions and external effects. In Understanding Complex Systems Understanding complex systems (Springer International Publishing), pp. 363–401. https://doi.org/10.1007/978-3-319-25658-0_17.

158. Phua, J., Jin, S.V., and Kim, J.J. (2020). The roles of celebrity endorsers' and consumers' vegan identity in marketing communication about veganism. J. Market. Commun. *26*, 813–835. (jay). https://doi.org/10.1080/13527266.2019.1590854.

159. Persaud, A., and Schillo, S.R. (2017). Purchasing organic products: role of social context and consumer innovativeness. Market. Intell. Plann. *35*, 130–146. https://doi.org/10.1108/MIP-01-2016-0011.

160. McPherson, M., Smith-Lovin, L., and Cook, J.M. (2001). Birds of a feather: Homophily in social networks. Annu. Rev. Sociol. *27*, 415–444. https://doi.org/10.1146/annurev.soc.27.1.415.

161. Moernaut, R., Mast, J., Temmerman, M., and Broersma, M. (2022). Hot weather, hot topic. Polarization and sceptical framing in the climate debate on Twitter. Inf. Commun. Soc. *25*, 1047–1066. https://doi.org/10.1080/1369118x.2020.1834600.