Sustainability Science
https://doi.org/10.1007/s11625-024-01551-0

REVIEW ARTICLE

Sustainability transitions in agri-food systems through the lens of agent-based modeling: a systematic review

Alba Alonso-Adame[1,2] · **Jef Van Meensel**[1] · **Fleur Marchand**[1,3] · **Steven Van Passel**[2] · **Siavash Farahbakhsh**[1]

Received: 7 March 2023 / Accepted: 28 July 2024

Abstract
Agri-food systems (AFS) and their value chains are currently under pressure to minimize environmental degradation and secure a more sustainable future. Sustainability transitions are needed to shift from well-established, yet vulnerable systems to more sustainable systems. Agent-based modeling (ABM) as a method to study complex systems is now widely used in transition modeling. We performed a systematic review to analyze the potential of ABM to yield insights into sustainability transitions in AFS. Specifically, we investigated the understanding that agent-based models can support better understanding of sustainability transitions in AFS. We identified potential in participatory modeling methods as well as combining agent-based models with complementary methods. The assessment of the sustainability dimensions was quite balanced between economic and environmental dimensions, but the social dimension was underrepresented. Here, we identify the main features to further advance ABM of sustainability transitions in AFS.

Keywords Agent-based model · Agri-food systems · Environmental dimension · Social dimension · Sustainability transition · Systematic review

Introduction

Agri-food systems (AFS), particularly agriculture, are an important source of greenhouse gas emissions, biodiversity loss, and soil degradation, as well as other significant environmental and social impacts (IPBES 2019; OECD/FAO 2020; Röckstrom et al. 2020; Crippa et al. 2021). With the current production practices and consumption, it is a challenge to find new ways to feed a growing global population without further degrading terrestrial and aquatic ecosystems, depleting non-renewable resources, and accelerating climate change (Poore and Nemecek 2018).

Agri-food systems are complex systems comprising food and non-food agricultural production, e.g., food production, food storage, post-harvest handling, transportation, processing, distribution, marketing, disposal, and consumption. Agri-food supply chains are the resulting networks that involve all actors and activities that deliver products and services in AFS (Borodin et al. 2016; Utomo et al. 2018). Complex adaptive systems follow the organizing principles proposed in Preiser et al. (2018), where they are defined by their elements' interactions that lead to emergent novelties, have adaptive capacities over time in which dynamic processes are non-linear, and their boundaries are contextually determined. Dynamic and diverse agri-food systems call for policies and regulations that contribute to social objectives while ensuring enough flexibility to allow for adaptation and also contributing to a better understanding of the evolving environmental, economic, and social dimensions of sustainability (Thompson et al. 2007).

Efficient pathways within these complex agriculture and food systems that enable a shift toward sustainability need to be identified to help mitigate the environmental and social impacts of AFS (Morrissey et al. 2014; El Bilali 2019; Hoek

---

Handled by Laura Pereira, Stockholm Resilience Centre, Sweden.

✉ Alba Alonso-Adame
alba.alonsoadame@ilvo.vlaanderen.be

[1] Flanders Research Institute for Agriculture, Fisheries, and Food (ILVO), Merelbeke, Belgium

[2] Department of Engineering Management, University of Antwerp, Antwerp, Belgium

[3] Research Institute for Environment and Sustainable Development and Centre for Research On Environmental and Social Change, University of Antwerp, Antwerp, Belgium

et al. 2021). Sustainability transitions in agri-food systems introduce a set of non-linear, durable, multilevel (e.g., individual, population, system) and multi-actor transformation processes that lead food and agricultural practices toward sustainability (Spaargaren et al. 2013; El Bilali 2019). Non-linearity refers to the property of systems where there is no direct relationship between variables and the resulting outcomes. The multi-actor approach is a collaborative process that involves a variety of actors (i.e., roles involved in the AFS such as farmers, advisors, researchers, or policymakers) to address complex problems from multiple perspectives. Sustainability literature sets out promising guidelines to enable AFS to transition toward sustainability (Brunori et al. 2013; Holt-Gimenez and Altieri 2013; Hinrichs 2014; Ingram 2015), but the practice of transitioning itself is not evident. A systemic approach is required to represent the complexity of the context and processes involved (Holtz et al. 2015). Complex systems are difficult to model, as they comprise interdependencies and many types of interactions between their components. More precisely, the concept of a sustainability transition includes the co-evolution of radical processes within established socio-ecological systems on a long-term scale and from a multi-dimensional perspective. Those processes and systems must shift in tandem to meet sustainability objectives of production and consumption (Markard et al. 2012; Tran 2014).

Such transitions cannot be fully understood using typical qualitative sustainability transition frameworks due to the complexities, non-linearity, and interactions involved (Moallemi and Malekpour 2018). Modeling is well suited to provide insights into transitions toward sustainability, but to date such modeling of sustainability transitions in AFS has been generally overlooked in literature (El Bilali 2019, 2020). The system's complexity should represent not only multiple parameters, but also multiple dimensions (e.g., economic, social, environmental), non-linear behaviors, heterogeneity of actors, uncertainties, and stochasticity (Köhler et al. 2018). These uncertainties have different roots, being dynamic (variation over space and time), stochastic (containing inherent randomness), or unobserved from data (Kieu et al. 2020). Further, it is essential to have a correct understanding of the sustainability dimensions as well as a suitable evaluation of the environmental, social, and economic performances of such systems. Without these, it is impossible to gain an overview of system status, especially at the time of transition (Peano et al. 2015).

Given the complexity and the specificities of transition modeling, agent-based modeling (ABM) arises as a potentially suitable method. Agent-based models are computational resources that represent individuals or agents in an environment in which they interact with each other. Agents are their main entity which may be organisms, humans, businesses, institutions, or any entity with a certain behavior and purpose within a system (Railsback and Grimm 2019). The decision-making of agents based on individual behavioral characteristics can realistically lead to collective emergent phenomena (Magliocca 2020). The suitability of ABM to represent complex systems relies on a clear and systematic systems representation, the capacity to make inferences about complex system dynamics, and the capacity to make systematic experiments (Holtz et al. 2015). Among many other methods used in transition modeling (e.g., systems dynamics), ABM simulates system complexity by including heterogeneity in system units, non-linear behaviors, uncertainties and stochasticity, resulting in a successful model of the transition (Grimm et al. 2005; Zheng et al. 2013; Köhler et al. 2018). ABM often includes participatory modeling methods, where the researchers engage with a varied group of stakeholders during the process of creating the model and when performing a decision analysis. Sharing expert knowledge in this way results in a better representation of reality (Basco-Carrera et al. 2017; Voinov et al. 2018; Cuppen et al. 2021). A multiplicity of perspectives also improves the accuracy of understanding such complex processes (Lang et al. 2012; Vermunt et al. 2020). Although ABM has been widely used to study complex systems, little is known about how ABM can be applied to better understand sustainability transitions and potential pathways toward sustainability in agri-food systems. Notable work has been carried out for agent-based modeling research in food–energy–water systems (Magliocca 2020), where suggestions for future research are presented. Nonetheless, there is currently a gap to understand sustainability transitions in AFS using agent-based models.

Here, we investigate the potential and suitability of agent-based modeling for improving our understanding of sustainability transitions in agri-food systems by reviewing a variety of transition models in AFS studies. To do so, we use a sustainability transition characteristics framework covering feedback loops between social and environmental systems, the detection of systemic change, temporal and spatial scales, changes in social values in transitions, diversity and heterogeneity, uncertainty and non-linearity, and multidisciplinary approaches. Furthermore, we analyze generic elements of models such as the representation of sustainability dimensions, sectors within agri-food systems, and complementary methods used in the study, and we examine the key characteristics of sustainability transitions using ABM as transition modeling tool.

Materials and methods

Paper selection

In June 2023, scientific articles on sustainability transitions were found based on keywords in accordance with the recommendations from the Preferred Reporting Items for

Systematic Reviews and Meta Analyses (PRISMA) guidelines (Page et al. 2021). After a first wide search, search fields were narrowed down to “Sustainab* AND (transition OR transform* OR “systemic change”) AND agent based model*”. Sustainab* can refer to either sustainability or sustainable. Similarly, model or modeling was sought using the keyword model*.

A search with these keywords in Scopus and Web of Science databases resulted in 7720 papers in total. The search was then limited to include only journal articles written in English that develop an agent-based model, excluding conference papers, short abstracts, and notes. No time frame exclusion criteria were applied. Literature reviews and other research papers that do not develop an empirical agent-based model were not considered for this study, reducing the number of papers to 5359. After this, 182 duplicate records were eliminated, resulting in 5177 records in total. Of these, 5080 records were not considered relevant to the study based on the exclusion criteria and screening of the title or abstract, further reducing the number to 97 full-text articles assessed for eligibility. Based on reading those articles, another 11 were excluded based on the above criteria. Finally, 86 records were considered suitable for inclusion in the study. Figure 1 shows the flow diagram of the selection process.

Framework of analysis

Information about the 86 reviewed scientific papers retrieved from the systematic review was saved in a database and subjected to qualitative analysis. The database included the following information: (1) paper description including year of publication, sector, scope (e.g., farm level, region level, country level, global), region, agents, participatory, complementary method, and topics studied in the model for

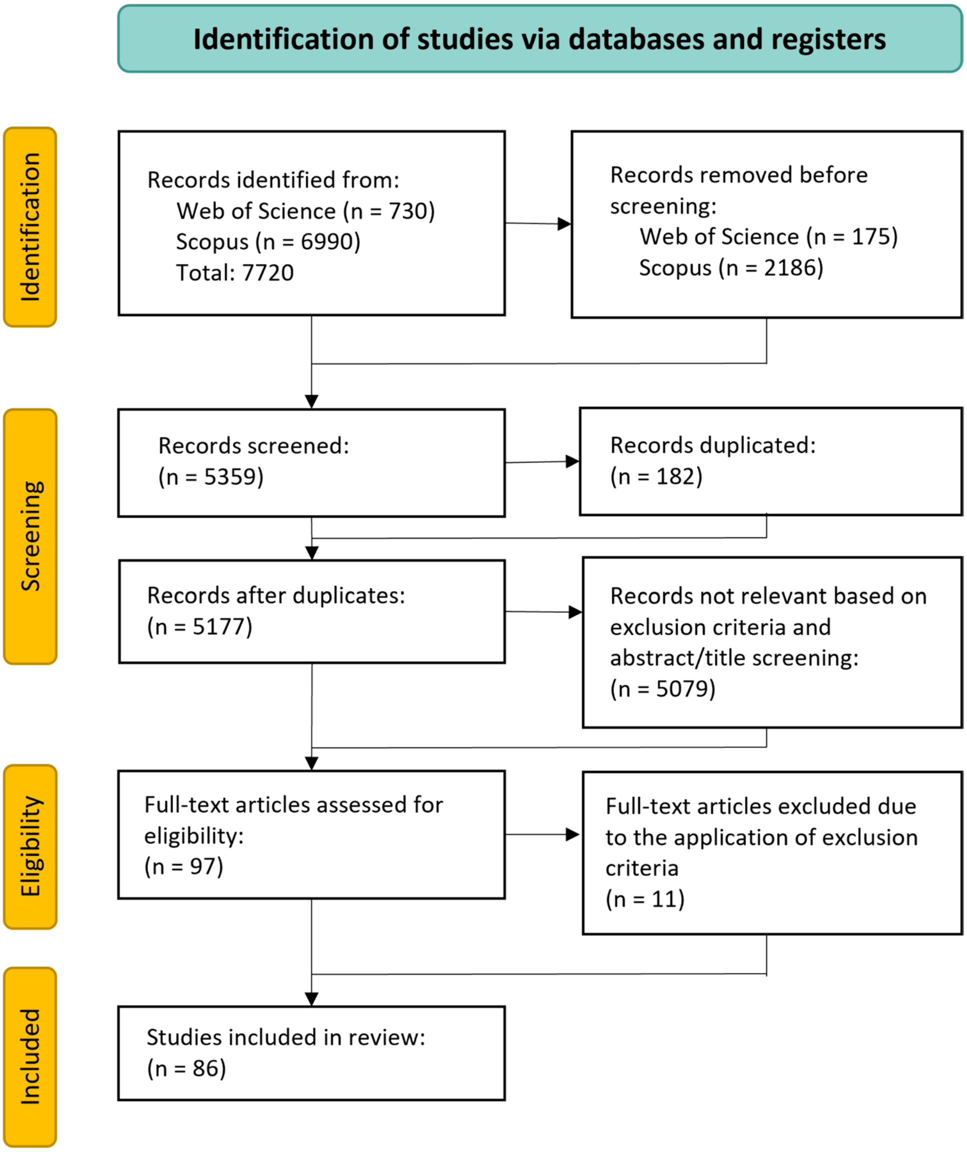

Fig. 1 Diagram of the systematic review following the PRISMA guidelines. The records screened corresponded mostly to other sectors out of the scope of this systematic review such as energy. Other articles were discarded in the screening based on the exclusion criteria because sustainability transition and agent-based modeling have to be both included in the eligible articles

sustainable transition; (2) sustainability dimensions included in the model; and (3) the notion of suitability of ABM in agri-food systems as a transition modeling tool based on the framework proposed (see below).

Descriptive data of reviewed papers is useful to provide an overview of the sustainability transition field in AFS, e.g., when it started to become popular in research and what elements are present in the studies. Therefore, elements regarding both publication records (e.g., year of publication) and elements included in the model (e.g., types of agents) were considered.

For a more comprehensive analysis, we selected 13 papers out of the total 86 papers in the review to deepen the characteristics of sustainability transitions. All agri-food system publications ($n = 8$) were included in this selection of 13 representative papers. For papers concerning neighboring sectors, we selected one paper, amounting to five papers, one for each sector in agriculture, fisheries, consumption, land use, and distribution. These representative studies from other sectors were chosen due to their explicit focus on sustainability dimensions as well as their comprehensive modeling approaches, which serve as the modeling benchmark for those sectors.

Characteristics of sustainability transitions

To discuss the potential of an ABM approach to sustainability transitions, a set of characteristics for sustainability transitions was used. These characteristics originate from different frameworks such as Köhler et al. (2018), Polhill et al. (2016), Preiser et al. (2018), Peter and Swilling (2014), and Köhler et al. (2019). Köhler et al. (2018) elaborate a framework for features in transition modeling methods; Polhill et al. (2016) research characteristics of socio-ecosystem systemic changes; Preiser et al. (2018) enunciate the characteristics of complex adaptive systems; Peter and Swilling (2014) develop a complexity-based framework for modeling transitions to sustainability; and finally, Köhler et al. (2019) indicate sustainability transition characteristics. Through comparing and integrating the characteristics of both transition modeling and complex systems transitions characteristics, we elaborated a complete framework of characteristics of sustainability transitions that are used in this paper to evaluate their representation in agri-food systems studies using agent-based modeling.

The seven characteristics of sustainability transitions emerged from the previously mentioned papers are described below:

1. Feedback loops: Feedbacks between the social and environmental systems are featured in sustainability transitions, which are mainly defined by the interactions among their different elements (Preiser et al. 2018). Complex systems such as agri-food systems include various elements: technologies, markets, environment, policies, and supply and distribution chains (Köhler et al. 2019).
2. Sources and detection of systemic change: In complex systems, the concept systemic change refers to a significant change in the system (i.e., inclusion of new elements, drop of old elements, adaptation of elements, and reconfiguration of interactions between elements), either in the behavior of relevant actors or the structure of the system (Köhler et al. 2018). These are not by default perceived as "shocks" in the system, because they can occur gradually in a system (Polhill et al. 2016). Both changes in the re-organization of the value chain as well as technological adaptations to environmental issues are needed to understand and foster sustainability transitions (Gaitán-Cremaschi et al. 2019). Systemic change can be driven endogenously (i.e., from the arising of new institutions, rules or norms within the system) or exogenously (i.e., climate change, external shocks). Public policy plays a central role in shaping the transitions, for instance by means of regulations and subsidies (Köhler et al. 2019). It is important to state what is the intention of the transition, or the emergence of the model. For some studies, systemic change is detected because the model simulates a phenomenon that is already known in the real world. In other cases, the systemic change is detected while exploring diverse outcomes in the model generated by external shocks. Context-dependency of sustainability transitions implies that the systemic components might change when their context changes (Preiser et al. 2018). Studies of sustainability transitions simulate the real world and, hence, adaptation to these context changes is crucial. In this regard, it is relevant to observe how systemic changes are measured in the outcome metrics.
3. Temporal and spatial scales: Sustainability transitions are long-term processes. Sustainable innovations usually require a long time to evolve from their first stage as an emergence in niches to diffusion. Spatial scales in modeling can elucidate the timings and sequences of transitions and clarify why niches upscale in certain contexts given that regional scales act as nodes in networks interacting with other scales. Transitions can thus define the spatial dimensions relying on how actors develop interactions over space (Coenen et al. 2012). Moreover, long-term processes are needed to unlock existing systems and overcome resistance to change. Transitions can be categorized into different phases: predevelopment, take-off, acceleration, and stabilization (Köhler et al. 2019). Thus, it is relevant to include a specific timescale of such transition processes. On the other hand, sustainability transitions are multi-dimensional processes that

consider change at and across spatial scales (Markard et al. 2012). The spatial scale of the model delimits the system, i.e., individual, region, country, or global (Köhler et al. 2018); and cross-scale, cross-sector, cross-level, and inter-institutional (Peter and Swilling 2014).

4. Changes in social values and norms: Variation and adaptation in the decision-making of agents, as well as changes in their social values and norms are expected in a regime shift toward sustainability transition (Geels 2011; Moore et al. 2014). Social norm change can occur due to external interventions such as policy incentives or environmental variations; however they repeatedly may develop spontaneously (Andrighetto and Vriens 2022). Social interactions as well as learning and adaptation should be well represented in transition models, where they can evolve within the system to create feedback loops leading to complex dynamics (Parker et al. 2003). Depending on the complexity level of the model, this could be represented in a more sophisticated or more simplified way.
5. Diversity and heterogeneity: Transitions include a variety of groups of actors (producers, consumers, etc.), and each actor can also be heterogeneous (e.g., producers that follow different strategies, consumers that make different food choices). Diversity and heterogeneity among elements and actor attributes are some of the main characteristics of complex systems that should be present in sustainability transition models.
6. Open processes, uncertainties, and non-linearities: Unpredictable events, such as the development of radical innovations, influence transitions. These events might change the direction of the transition depending on how reactive the system is. Since transition pathways are manifold (Geels and Schot 2007; Rosenbloom 2017), the future is open-ended (Köhler et al. 2019). Non-linearities emerge in agent-based models from the interactions present in complex systems (Coronese et al. 2023). The non-linear aspect of innovation processes, political processes, and socio-cultural processes might evidence uncertainty in the system (Köhler et al. 2019).
7. Multidisciplinary approach: To integrate multiple perspectives from different knowledge domains as well as to achieve adaptive and innovative capacity, participatory-based modeling is highly encouraged in sustainability transitions (Hinrichs 2014; Conti et al. 2021). Participatory approaches are important for representing decision-making and understanding the interests of agents (Delmotte et al. 2013), building up potential scenarios considering multidisciplinary perspectives (Delmotte et al. 2016), assisting policy decision-making toward sustainable systems (Bailey et al. 2019), developing a model that can be used by all involved experts to inform about improvements for the models (Moallemi et al. 2020), and to reduce ambiguity by helping stakeholders understand the models' representation (Martin et al. 2018). The concept of sustainability is particularly argued, which causes disagreements about the most well-fitted transition pathways among involved actors (Köhler et al. 2019). As sustainability transitions may pose a threat to the most powerful industries (e.g., energy) and rooted structures, the interest of actors for the direction and speed of transition may differ between each actor group (Köhler et al. 2019). Moreover, a combination of ABM with other methods could integrate complementary perspectives in the model and support decision and policymaking (Halog and Manik 2011).

Results

Descriptive data of papers

Use of agent-based model approaches in sustainability transitions in agri-food systems is not quite recent, with the first publications dating to 2006. Nonetheless, from 2015 onward, the number of publications increased considerably. The majority of articles ($n = 57$) were published from 2018 onward (Fig. 2).

Different sectors within the agri-food systems were found in the systematic review using an ABM approach (i.e., agriculture, fisheries, consumption, land use, and distribution). Accordingly, the range of agents in the models includes humans (typically producers and consumers) as well as environmental elements (land use). The scope of the model varied between different sectors, with regional level being the most common among all (Fig. 3).

Complementary methods to ABM were identified in 51 articles out of the total reviewed records, where the methods were either coupled to the agent-based model or complemented the model results. The most frequently used ones were geographic information system ($n = 12$ in agriculture, $n = 15$ in land use, $n = 3$ in agri-food), role-playing games ($n = 2$ in agriculture, $n = 4$ in land use), Bayesian network ($n = 2$ in land use, $n = 1$ in agriculture, $n = 1$ in agri-food, $n = 1$ in fisheries), and life cycle analysis ($n = 2$ in agriculture and $n = 1$ in consumption). Focusing on the 13 selected papers, 5 papers out of 8 in the agri-food sector included a complementary method, but they presented a wide variety of methods (i.e., system dynamics, discrete event simulation, geographic information systems (GIS), Bayesian network, and robust optimization). The remaining 35 research articles did not include any complementary method.

The code of the simulation model was available in 33 scientific papers, and three papers indicated that the model was available upon request (Fig. 4). Community repositories such as Comses were often used to upload and review the

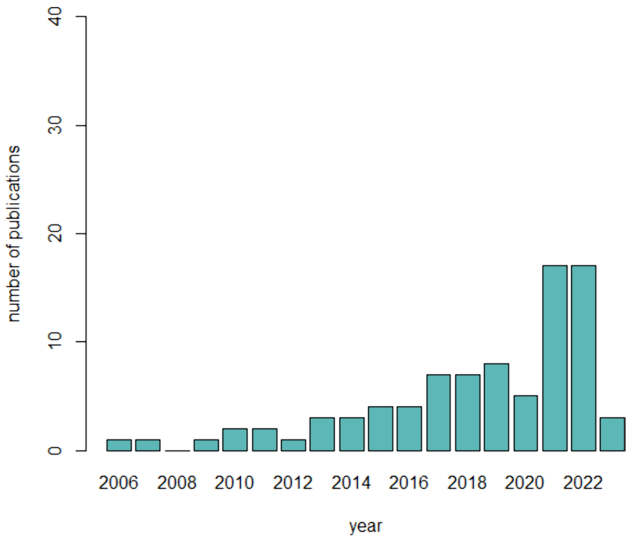

Fig. 2 Distribution of the year of publication of 86 reviewed papers concerning sustainability transition in agri-food systems using agent-based models

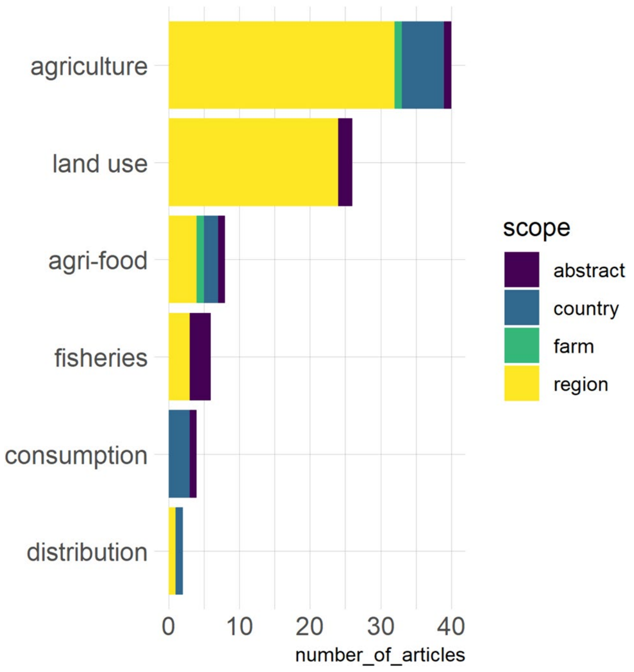

Fig. 3 Scope of the models from the 86 reviewed papers in the systematic review

models in publications. 45 papers attached documentation of their models in their publication as supplementary material, mainly following the standard ODD + D (Müller et al. 2013).

Participatory approaches were slightly common through all of the 86 reviewed papers (Fig. 5). However, distribution and consumption papers did not include participatory approaches. On the other hand, 38% of agri-food papers included participatory approaches ($n = 3$, out of 8), in contrast to 25% of agriculture papers ($n = 10$, out of 40) and 42% of land use ($n = 11$, out of 26). Finally, Fig. 6 presents an overview of the sustainability dimensions that are included in the final selection of articles. Economic and environmental were the most studied dimensions, while the social dimension appears more often coupled to the environmental one. 60% of all articles included all three dimensions simultaneously.

Characteristics of sustainability transitions

In total, 86 papers were retrieved. Below, we highlight the 13 representative papers that showcase the great potential of agent-based models in modeling and understanding transitions. These 13 papers encompass various sectors and areas, including agri-food (8 papers), as well as agriculture, consumption, distribution, fisheries, and land use (one for each). Table 1 offers an overview of these 13 representative papers.

Feedback loops

All models represent varied feedbacks between social and environmental agents. However, papers of agri-food sector that had little to no representation of the environmental dimension could not represent remarkable feedback loops between social and environmental agents. Thus, these

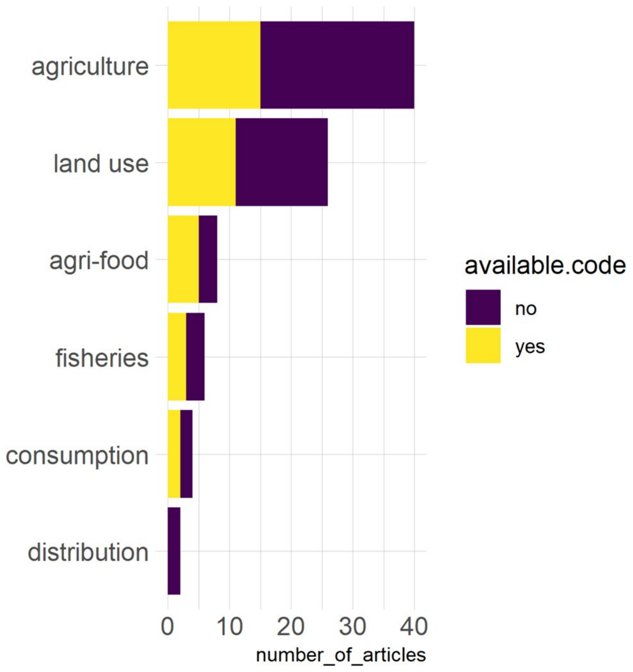

Fig. 4 Availability of the code in the 86 reviewed papers in the systematic review. Codes available upon request were interpreted as available ones

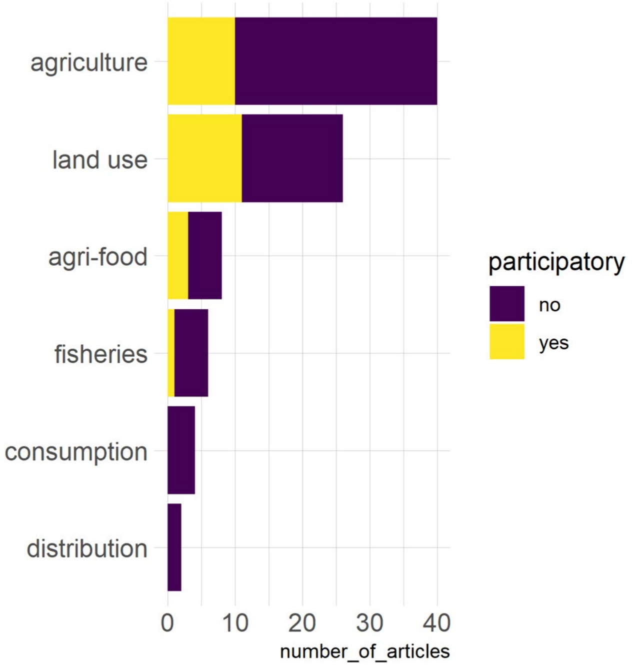

Fig. 5 Presence of participatory approaches in models from the 86 reviewed papers in the systematic review

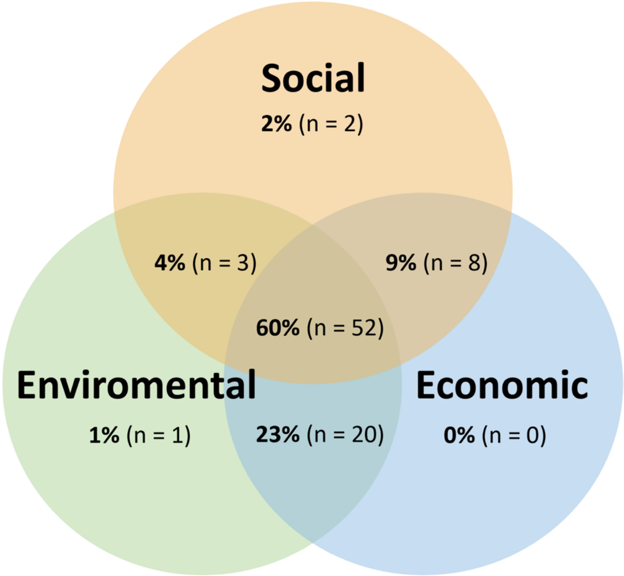

Fig. 6 Dimensions included in the analysis of the selected final records

papers only considered the main feedback loops between agents. Other agri-food models considered how consumers' decision-making affects the overall ecological, social, and environmental performance of the system (Taghikhah et al. 2021). Models by Shaaban et al. (2021) portrayed the cooperation between agents and trade-offs in ecosystem services. Other feedback loops like demographic herds influenced by agent's consumption, especially sheep meat, were represented in Günther et al. (2021). Lastly, Dobbie et al. (2018) presented food access and availability depending on the type of agent. The study of Fernandez-Mena et al. (2020) included a great variety of feedback loops, since the topic of study was focused on circularity and material flows. They included varied farming activities (i.e., crop fertilization, crop production, feed exchanges, livestock production, local flows and transportation, food processing, nitrogen flows, greenhouse gas emissions, food waste and by-product exchanges, and bioenergy production). In our selected papers, the environmental dimension was explicitly displayed when the model included producers (i.e., farmers), fishers, or landscape. Otherwise, agri-food papers that did not consider any of these represented the environment usually as an external shock as in van Voorn et al. (2020).

Papers concerning other sectors such as agriculture, consumption, distribution, fisheries, and land use also included feedback loops between social and environmental agents when these two dimensions are present. In Catarino et al. (2021), weather variability and spatial variability of soils affect farming strategies. Moreover, for one kind of farmer, a specific fava bean crop had a positive effect on the annual economic performance, as well as meeting the legumes demand had a positive influence on socio-economic performance. In addition, in Schlüter et al. (2021), fish population defines fishers' catch, together with fishers' skills and ability to go out fishing. In these simulations, the loss of catch under unpredictable fishing circumstances can be partially balanced through repeated interventions. Lastly, in Becu et al. (2014), memory of past cultivated locations was found to reveal to some extent farmers' decisions around the cultivation location, since kinship relations influence the diffusion of farming knowledge as well as how farming practices are organized.

Processes and relationships of economic, social, and environmental aspects are unevenly developed in the models. Economic dynamics are well represented in most agri-food papers; however, even though some studies include social and environmental processes, these are usually represented as an outcome or as a fundamental change in an scenario. For instance, in Van Voorn et al. (2020) and Dobbie et al. (2018), they mainly represent social networks of agents. Günther et al. (2021) and Fernandez-Mena et al. (2020) represent environmental dynamics for biomass regrowth and grazing, and nitrogen flows and greenhouse gas emissions among others, respectively. Furthermore, in Dobbie S. et al. (2018) they represent the environmental dynamics of extraction of wood and water resources using common pool theory.

Table 1 Overview of the 13 selected papers representing agri-food sustainability transitions' characteristics

Sector	Author(s) and year	Case study	Topic of study
Agriculture	Catarino et al. (2021)	Crop livestock integration	Local diversification of crops and relocation of animal feeding in collaboration between farmers
Agri-food	Mcgarraghy et al. (2022)	Wheat value chain	Strategic interventions on power structure of food value chains
Agri-food	Taghikhah et al. (2021)	Organic wine	Consumer preferences and socio-environmental issues leading to more organic wine production and consumption
Agri-food	Shaaban et al. (2021)	Supply–demand mismatches in four CSA farms	Cooperation for supply-driven demand and demand-driven supply
Agri-food	Günther et al. (2021)	Herd pastoralism and calorie requirements	Herd dynamics and consumption patterns influenced by the dietary composition and environmental disruptions
Agri-food	Achmad et al. (2021)	Rice supply-chain food security	Optimization of food hub location and food network to maintain food security under COVID
Agri-food	Fernandez-Mena et al. (2020)	Alternative scenarios of material flows in agriculture	Leverages for more circularity through different sustainable solutions
Agri-food	Van Voorn et al. (2020)	Food value chain resilience	Re-organization of networks for efficiency and resilience to shocks
Agri-food	Dobbie et al. (2018)	Food security	Interactions between households and the environment leading to the emergence of community food availability
Consumption	Thomopoulos et al. (2021)	Behavioral change toward plant-based diets	Behavioral changes toward plant-based diets
Distribution	Mittal and Krejci (2019)	Food hubs	Efficiency-enhancing practices into food hub warehousing operations
Fisheries	Schlüter et al. (2021)	Governance in small-scale fisheries	Interventions to shift from hierarchical fisher–fish buyer arrangements to cooperative arrangements
Land use	Becu et al. (2014)	Shifting cultivation	Transformation of savannah woodland into a shifting cultivation savannah landscape

Sources and detection of systemic change

Sources of change in the selected 13 papers are varied. Five agri-food papers consider actions in the value chain the source of change (e.g., strategic interventions or optimization of the food value chain), while two of them focus on environmental pressures and one paper considers farming practices leading to changes to other actors in the value chain (e.g., environmental disruptions or rainfall variation, and material flow exchanges, respectively). Endogenous sources of change are represented here by a re-structuration of food value chains or networks, consumers' preferences, cooperation among actors, sustainable farming practices, and population growth. On the other hand, exogenous causes in the selected papers are mainly focused on environmental pressures, such as rainfall variability originating from climate change or disease spread such as COVID.

For the other selected papers in the sectors of agriculture, consumption, distribution, fisheries and land use, we found varied sources of systemic change. We found the following endogenous sources of these papers as these main groups: behavioral changes, collaboration between farmers, adopting new practices, or transformation of landscape. On the other hand, the classification of the exogenous causes of systemic changes are: environmental and socio-economic shocks such as crises, and interventions. Both endogenous and exogenous sources of change will determine agents' decision-making, which results in the systemic change needed for a sustainability transition.

Systemic change is measured in the selected papers through a set of outcomes. However, the studied outcomes highly depend on the topic of study and the systemic change. For instance, in the agri-food sector paper, Dobbie et al. (2018) use a set of outcomes to measure food security that are suitable to capture this, such as the percentage of households with calorie deficit, the households' food security itself, mean annual grain output per household, mean proportion of households with access to farmland, and the proportion of each agent's job.

Few papers mentioned environmental, social, and economic impacts as a specific outcome, as well as economic, social, and ecological performance as in Catarino et al.

(2021), where they measure gross margin and economic efficiency of production as economic performance, workload of crop management operations as social impact, and N use and total amount of active ingredients in pesticides applied as environmental impact, among others.

In all selected papers, including both agri-food and other sectors, varied outcomes based on the specific systemic change they research are observed in the simulations. For example, to measure behavioral changes toward plant-based diets, Thomopoulos et al. (2021) present as outcomes consumers' perception level of meat consumption, number of vegetarian and meat-based diets, and the adaptive resistance to change.

All models are flexible enough to represent a change in the context. Agent-based modeling papers focusing on agri-food systems always present at least two scenarios to study, where the context significantly changes from one to another. Three papers considered three scenarios, while one paper investigated eight different scenarios (Fernandez-Mena et al. 2020). One conceptual paper, even at the first stages of the modeling cycle, presented five different food value chain case studies to analyze with the agent-based model (McGarraghy et al. 2022). Other papers like van Voorn et al. (2020) study different network configurations instead of formal scenarios for food value chain resilience (i.e., three network modes: preference, random, and weighted) and four different types: block, inverse pyramid, hourglass, and diamond).

Papers from other sectors also represent changes in the context through scenario simulations. In Thomopoulos et al. (2021), they introduce frequent crises in the model to observe how consumers change their decisions toward diets. Becu et al. (2014) studied two scenarios: one for the transformation of savannah woodland into a shifting cultivation savannah landscape, and the other for changes in the landscape and socio-demographic structure. Meanwhile, the studies of Catarino et al. (2021), Schlüter et al. (2021), and Mittal and Krejci (2019) simulated three scenarios, with two of them representing baseline scenarios. Papers in our systematic review that included a baseline scenario could not only represent a change in the context, but also compare the current situation with future scenarios of interest.

Temporal and spatial scales

Time and space representations of complex systems are a key aspect of ABM. Out of the eight agri-food sector papers, four focused on a regional scale, while only one paper considered a farm-level scale. One paper developed a model based on an abstract scale, which focused on food value chain resilience to shocks (van Voorn et al. 2020), and two focused on country-level systems. Concerning the timescale in the model, the minimum temporal scale considered in a simulation was 12 months in the re-organization of food value chain paper of van Voorn et al. (2020), while the maximum time represented was 50 years in a paper analyzing the dynamics of a pre-industrial herder settlement (Günther et al. 2021).

The majority of papers in agriculture, consumption, distribution, fisheries, and land use sectors represented a regional scope, while only one paper represented an abstract scale. This paper was focused on behavioral changes toward plant-based diets, where depicting a spatial scale could be of minor relevance (Thomopoulos et al. 2021).

In Shaaban et al. (2021), it is stated that there is currently a research gap in modeling approaches that can display dynamics on local and global scales. However, few papers showed multiple spatial scales in their models. For instance, in the MAELIA multi-agent platform in Catarino et al. (2021), simulation results were aggregated at varied spatio-temporal scales, thus allowing the validation of the model. Furthermore, in Fernandez-Mena et al. (2020), researchers connect the agro-ecological practices at farm scale with the local scale through flows among farms for the scenario design, which could be used to achieve circularity at both scales with synergies in the environmental performance. In Dobbie et al. (2018), food stability takes multiple scales into account through a function that links global and individual factors. The authors state that this conceptualization of food security taking national and local perspectives into account could address scale mismatches in socio-ecological systems.

The time span detailed in these models are particularly broad, ranging from 2 days in the case of food warehouse operations (Mittal and Krejci 2019) to 60 years for landscape transformations (Becu et al. 2014). In addition, in models like Taghikhah et al. (2021), different temporal scales were represented in the same model, from short to long term.

Systemic changes are often gradual and concatenate events that arise in a favorable regime in a determined region (Geels 2011). Even though the time span in models was varied, McGarraghy et al. (2022) indicated that they focus on current value chains, claiming that this will be still valid at least until 2030, after which uncertainty will be too high for the development of a suitable model.

Changes in social values and norms

Changes in social values and norms were slightly underrepresented in the selected models, but some researched topics take adaptations of social values and norms into account. Selected papers of agri-food sector include the decision-making change of agents under different scenarios. In Taghikhah et al. (2021), where they represent four different agents in the wine industry (i.e., wine farmers, winemakers, retailers, and consumers), the behavior was highly variable depending on the interactions among agents. The agent's interactions in this model condition the decision-making of others, being highly integrated. In Shaaban et al. (2021), the agents have adaptation behavior evolution throughout the model and different scenarios for supply-driven demand and demand-driven supply. Two agri-food papers argued that they do not properly capture some aspects such as the behavioral aspects of agents (van Voorn et al. 2020; Günther et al. 2021). One agri-food paper uses an ABM-robust optimization approach to optimize agents' decision-making (Achmad et al. 2021). The most well-integrated case is found in Fernandez-Mena et al. (2020), where eight scenarios are built upon each one of the eight different farmers' behaviors.

Following the agriculture paper, in Catarino et al. (2021) they study the behavioral change through the scenarios. The consumption model developed in Thomopoulos et al. (2021) was primarily focused on changing perspective toward a certain topic such as plant-based diets, where changes in social norms are the core of the study. For the distribution paper, the model represents changes in social values through the emergence of the scheduling behavior based on how satisfied they are with the outcomes of past decisions (Mittal and Krejci 2019). In the fisheries model of Schlüter et al. (2021), the feedbacks between loyalty and cheating behavior of fishers lead to a social norm of what is an acceptable behavior. Lastly, we found that the analyzed land use paper includes a memory behavior for land area cultivation that may change (Becu et al. 2014).

Although six papers did not indicate which behavioral theories they use for the decision-making of agents, the studied models showed variety among the behavioral theories used. Specifically, they use cognition theory (Tenenberg and Knobelsdorf 2014), theory of planned behavior (Ajzen 1991), alphabet theory (Zepeda and Deal 2009), goal framing theory (Lindenberg and Steg 2007), argumentation theory (Bourguet et al. 2013), common pool resource theory (Ostrom 1990; Schlager 2004), principal agent theory (Jensen and Meckling 1976), information theory (Ulanowicz et al. 2009), multi-attribute utility theory (Dyer 2005), and heuristic approach to represent the decision-making of agents. Moreover, four models combined different theories and approaches in the decision-making of their agents.

Diversity and heterogeneity

Every model represented in the final selection of articles represent diverse and heterogeneous agents. At least three different actors from the agri-food value chain were represented in the models. All papers concerning agri-food sector represented many and diverse actor groups in the models. Three studies represented five or more actors of the value chain, with the type of models being represented by longer whole value chains, including farmers, winemakers, retailers, and consumers in Taghikhah et al. (2021), farmers, foresters, retailers, inhabitants, policymakers, and others in Shaaban et al. (2021), and producer, collector, processor, retailer, and consumer in McGarraghy et al. (2022). Two papers represent a short value chain in settlements, where they have producers and the population as consumers (Dobbie et al. 2018; Günther et al. 2021). Thus, the agri-food value chain was quite well represented, with six studies including producers, five including processors and/or distributors, and six papers including consumers as agents. The heterogeneity of these agents differ among papers. Some studies differ among agents based on their market, either organic or conventional (Taghikhah et al. 2021), their capital, i.e., financial, human, social, natural, physical, cultural (Shaaban et al. 2021), different jobs (Achmad et al. 2021), and different water, fuel, and food needs (Dobbie et al. 2018). In Fernandez-Mena et al. (2020), the farms are very heterogeneous, with eight different kinds of farming styles that have different values of variables such as area, number of livestock, and percentages of varied crops. The study of McGarraghy et al. (2022) explains that they use a cognitive map that will allow them to capture the behavior and interactions between actors to help them to differ among agents.

Agri-food systems were found to be either of longer value chains (including intermediaries such as retailers, managers, etc.) or shorter ones like those from villages in which they are self-sufficient, mainly in low-income countries. Therefore, we have papers such as that by Shaaban et al. (2021), where six different sorts of agents are depicted, in contrast to other papers such as that by Günther et al. (2021), where the herders and the cattle shape the whole agri-food value chain of the studied region.

On the other hand, we find diversity and heterogeneity among the papers of other sectors. In the case of agriculture, Catarino et al. (2021) represented seven types of farmers with diversity of farming strategies, five of them with crops and the two others with livestock. The consumer paper only has one agent that has few variables (Thomopoulos et al. 2021). Some represent only one agent that is highly heterogeneous among its peers (e.g., a model that only represents farmers, but with quite diversified attributes and decision rules (cfr. Mittal and Krejci 2019; Schlüter et al. 2021) whose model includes producer and food hub managers characterized by static and dynamic state variables with four types of agents, and fishers with different reliability, loyalty to patron/coop, and fishing skills, fish buyers, and fish stock, respectively). Other models representing only one agent were less heterogeneous, such as those by Thomopoulos et al. (2021) and Becu et al. (2014), where agents were distinguished by few parameters.

Several aspects of heterogeneity are often included in the agents' decision-making; however, behavioral heterogeneity is less well integrated (Magliocca 2020). For instance, some key parameters of farmers influencing their decision-making and thus steering environmental impacts in the system are information exchange, environmental awareness, and access to environmental information (Lan and Yao 2019). Nevertheless, they were seldom included in the reviewed models.

Open processes, uncertainties, and non-linearities

Some variety was observed in how well the models incorporate uncertainties. ABM can deal with uncertainty through sensitivity analysis using a one-factor-at-a-time analysis (OFAT) like in van Voorn et al. (2020) and Taghikhah et al. (2021). Other methods to consider uncertainty in the models are Bayesian belief networks, as used in Shaaban et al. (2021), robust optimization as in Achmad et al. (2021), and consistency analysis to reduce stochastic uncertainty with an estimation of parameter effects on simulation results as in Dobbie et al. (2018). This sensitivity analysis enables an assessment of the degree to which the uncertainty in the output of a model can be related to different input sources, such as the non-linearity of interactions across scales (Lippe et al. 2019). Only one paper did not mention uncertainties.

On the other hand, other sector papers also include uncertainties in their studies. As in agri-food sector papers, other studies also include sensitivity analysis for key parameters such as that by Mittal and Krejci (2019). Moreover, Thomopoulos et al. (2021) perform a sensitivity analysis of the ratio between frequency of crises and communication campaigns, initial proportion of vegetarians, radius of crises, progression over time of the resistance rate, resistance to communication campaigns, and influence of neighbors. Three papers did not mention or include uncertainty analyses in their study.

All 13 selected articles represented non-linear behavior. The models studied in the selected records showed a non-linear behavior under the studied scenarios, which means that the changes in the outcomes are not the result of a proportional change in any of the inputs. For instance, the agri-food paper of Shaaban et al. (2021) researches human–environment interactions representing complex social–ecological systems with adaptive behavior, which is non-linear. However, most of the papers did not explicitly mentioned non-linearity in their outcomes, although they are in fact non-linear.

Multidisciplinary approach

When used in combination with modeling, participatory research can support the process of learning and co-creating for both farmers and stakeholders (Delmotte et al. 2016). From the selected 13 papers, only four mentioned explicitly that they follow a participatory approach, or include a certain level of participation with stakeholders even when it was not explicitly labeled as "participatory". Out of these four papers that follow a participatory approach, three belonged to the agri-food sector.

In Shaaban et al. (2021), researchers use an extensive participatory approach throughout the whole study. First, it allows to account for individuals and the collective needs of stakeholders regarding ecosystem services, which makes it possible to map it in the model using GIS. The main advantage of such approach is the inclusion of cultural realities of diverse communities and landscapes. Moreover, the outcomes of the model are discussed with the stakeholders to evaluate the accuracy of the model.

On the other hand, studies like Catarino et al. (2021) focused their participatory approach on scenario simulation. The simulated scenarios were developed considering stakeholders' knowledge on limitations and feasible solutions. Calibration, validation, and analysis of results were also done in participation with stakeholders.

Discussion

Although sustainability transitions in agri-food systems have been overlooked in the past (El Bilali 2019), they have gained more visibility in sustainability transition research in recent years (Elsner et al. 2023). Our systematic review demonstrates how ABM studies represent, and are used for the analysis of, all characteristics of sustainability transitions, which indicates that these models can account for the complex features in AFS. In this section, the potential of ABM to deal with these characteristics is discussed based on our analysis of the 13 selected papers.

Feedback loops

ABM is used to represent the economic, social, and environmental dimensions. To achieve transformative change in AFS, sustainability dimensions must be regarded simultaneously in an integrative perspective as well as include their mutual interactions (Matthews et al. 2005; Preiser et al. 2018; El Bilali and Probst 2018; Nogueira et al. 2019; Allen et al. 2019). The inclusion of environmental and social dimensions as outcomes or scenarios seems more prevalent in the observed agent-based models. Some of the selected papers only take into account specific aspects within sustainability dimensions. Separating dimensions from sustainability transitions may create an artificially narrow perspective of AFS, which calls for the improvement of the representation of processes and relationships within sustainability dimensions. For instance in the study by Catarino et al. (2021), environmental variables such as grasslands and livestock dynamics would have captured the demand for feed (Catarino et al. 2021). Combining other methods such as life cycle analysis with ABM may help to quantify the different impacts of processes in the agent-based model and link this information back to the agents, which in turn would influence their behavior (Baustert and Benetto 2017).

ABM has the potential to incorporate feedback loops within and among agents, between varied sustainability dimensions, and between initial conditions and outputs (Sun et al. 2016; Miyasaka et al. 2017; Marvuglia et al. 2018). This is also possible through other methods such as system dynamics (SD), though not on all of the different cross-level interactions at once. SD models represent dynamics on the system level (Voinov et al. 2018) without micro-level interactions and can be used to identify dominant drivers for the system structures and boundaries for transitions (Nabavi et al. 2017). It is recommended that SD represent the system explicitly to avoid overlooking important socio-economic processes (Nabavi et al. 2017). Although SD represented as causal loop diagrams can illustrate alternative system states and simulate transitions among them, they are insufficient regarding their capacity to include emergent phenomena from a bottom-up approach as opposed to ABM (Hoekstra et al. 2017). Even though SD are also suitable to represent socio-ecological dynamics, they falter in addressing socio-ecological heterogeneity and spatial trade-offs compared to ABM (Miyasaka et al. 2017), which might be solved by coupling them to ABM (Lane and Oliva 1998; Nabavi et al. 2017; Ding et al. 2018; McGarraghy et al. 2022). In the study of Taghikhah et al. (2021), the interactions offered by a combination of ABM and SD give insights into social sustainability dynamics for both consumers and farmers.

Nonetheless, a deep reflection on the sustainable nature of transitions is lacking, especially in relation to social aspects such as social justice (Köhler et al. 2019; El Bilali et al. 2021; Hebinck et al. 2021). For instance, although organic and agroecological practices are becoming more environmentally friendly, these transitions do not necessarily take social justice into consideration (Lamine et al. 2019).

Sources and detection of systemic change

ABM allows for the representation of emerging effects of systemic change through varied sorts of indicators for different sustainability dimensions. When all sustainability dimensions are included in the agent-based model, trade-offs between sustainability dimensions can be detected. Performance indicators could be useful to understand the overall effect of change in different dimensions and to help policymakers (Zheng et al. 2013).

Being able to study the effects of different future scenarios in several sustainability dimensions is a strength of ABM to represent complex systems as well as to account for the uncertainties of future pathways (Abdel-Aal et al. 2020). In AFS, many unknown context changes may appear in the future, which makes ABM ideal in this regard. As Geels (2011) indicated, more attention should be paid to multi-regime interactions for sustainability transitions, which could benefit from using ABM.

Temporal and spatial scales

ABM can represent several spatial scales and interactions among scales. In domains such as disease transmissions, ABM following a multiple scale space–time patterns has been proven to validate spatially explicit models assessing the impacts on both micro and macroscales (Kang and Aldstadt 2019). In our systematic review, multiple scale modeling with explicit time and space has only been observed in few agri-food papers.

The coupling of ABM with spatial data is necessary to build up spatial structures in dynamic models, which takes intertwined consequences into account. In the systematic review, GIS is frequently used in land use models for spatial representation.

An advantage of agent-based models is that they are flexible to represent processes that require either a longer time span, such as landscape transformations, or shorter temporal scales. Furthermore, they can combine multiple timescales in one model. In such cases, insight into long-term processes like land use transitions can be obtained by using a multi-scale modeling approach that incorporates both social and biophysical dynamics (Evans and Kelley 2008). However, the understanding of a system in the past cannot guarantee the prediction of future behaviors and long-system dynamics in a complex system (Peter and Swilling 2014).

Changes in social values and norms

Literature points out that ABM currently have limited consideration of social learning, risk aversion, social norms, or social aspects contributing to social norms, in contrast to natural system components that often appear in models (Rounsevell and Arneth 2011; Rounsevell et al. 2014; Magliocca 2020). This has been reported as a limitation in few reviewed papers (van Voorn et al. 2020; Schlüter et al. 2021). In sectors such as fisheries, standard models generally do not fully capture the social dimension, which calls for improving the understanding of fisher behavior and representation (Lindkvist et al. 2020; Wijermans et al. 2020). In reality, however, social factors have a significant impact on farming systems that can be comparable to economic or agronomic factors. Moreover, it is a challenge to include this behavioral decision-making for numerous sorts of agents across sectors (Magliocca 2020). As indicated in Wijermans et al. (2023), reflecting critically on what type of decision-making fits the model by determining relevant sustainability dimensions in the given context could enrich socio-ecological models.

To increase diversity in decision-making and integrate social interactions in ABM, a combination of existing modeling approaches could solve this (Huber et al. 2018). Nevertheless, social and environmental factors influencing the decision-making of agents are already represented through ABM. In the study of Yan et al. (2019), the bottom-up ABM approach was successful in the deep understanding of driving factors and changing process in socio-ecological systems. Characterization and parametrization are needed to model agents' behavior, but this carries challenges in assessing behaviors through empirical observation (Yan et al. 2019). Surveys, expert knowledge, interviews, and participatory approaches are helpful methods to include the behavior characteristics in ABM (Smajgl et al. 2011; Marvuglia et al. 2022).

Diversity and heterogeneity

ABM includes heterogeneity by representing varied types of agents. In cases such as technology adoption, both agent heterogeneity and spatial interdependencies are crucial for emergent phenomena toward transition, and consequently, heterogeneity and diversity in the model components should be explicitly treated (Parker et al. 2003). Heterogeneity may change throughout the simulation due to agent learning and demographic changes, which can affect model outcomes and overall performance (Wilensky and Rand 2015). Hence, it highlights the relevance to include behavioral heterogeneity in ABM, which could be done by integrating behavioral theories in the model. However, ABM highly depend on the initial conditions of agents and their designed behaviors (Manson et al. 2020), which has been stated as a limitation in a reviewed publication (Shaaban et al. 2021).

Explicitly modeling supply chains is an advantage of ABM that clarifies how agents interact with each other, as well as how sector trends can arise from their varied decision-making. As observed in the systematic review, this explicit modeling of supply chains is emerging in ABM for socio-ecological systems, especially for AFS, which indicates a need to close this research gap (Magliocca 2020).

In Utomo et al. (2018), production was found to be the most represented activity in the agri-food supply chain. This limits the study of how the activities of the AFS value chains are bridged (El Bilali 2019; Hebinck et al. 2021). Nevertheless, a focused study of at least two activities of the agri-food supply chain can still provide valuable insights regarding sustainability transitions. Other transition studies with multisector perspectives in related sectors such as energy may also benefit from the study of sustainable transitions in AFS (Hebinck et al. 2021).

Data availability could constrain how well agents can be distinguished (McGarraghy et al. 2022). Limited data can lead to an oversimplification of the models (Robinson et al. 2018; McDowall and Geels 2017; Miyasaka et al. 2017; Magliocca 2020). However, agent-based models are not required to be highly data intensive. A set of assumptions and theories, as well as stylized facts can represent decision-making mechanisms without quantitative data (Müller et al. 2013). Still, when presented with a choice between simplification or overlooking agent heterogeneity, simplification is deemed to be preferred (Rounsevell et al. 2014). For example, in the case of Dobbie et al. (2018), simulation outcomes were consistent with observations and literature despite the simplifications of the model, reflecting important dynamics from reality.

Open processes, uncertainties, and non-linearities

As Morgan et al. (1990) stated, without any uncertainty analysis in a model, especially for large and complex ones, the meaning of the model outcomes is unclear. However, ABM is demonstrated to be suitable to handle uncertainties in agri-food systems transitions and most of them include sensitivity analyses. Other modeling methods, such as econometric ones, fail to capture non-linear systems (Mehdizadeh et al. 2022). Interactions in complex systems can define how well the system can confront uncertain disturbances; nonetheless, the behavior of complex, non-linear systems is unpredictable to some extent (Schouten et al. 2013).

Multidisciplinary approach

ABM has shown potential to understand transitions in complex systems while supporting a participatory, interdisciplinary approach (Hansen et al. 2019). Interdisciplinary frameworks that synthesize and integrate links between disciplines can also be adequate for AFS to support the understanding of socio-ecological systems like in Schlüter et al. (2019). However, more attention should be given to the degree of participation and how this benefits the modeling.

It is highly recommended to follow a participatory approach, especially in AFS sustainability transition papers using ABM, as that these tend to be broad, multidisciplinary systems. We observe in our results that including participatory approaches or collaborative modeling is beneficial. For instance, the CHANOS model (Mialhe et al. 2012), developed to test the effects of decision-making of farmers on land use change, can also be used as a decision support tool, where participants can discuss the model outcomes related to determined factors such as behavioral, policy, and environmental change (Mialhe et al. 2012). In this regard, following good code publishing practices could be done in specific modeling journals such as Environmental Modelling & Software or by keeping modeling notebooks, which helps to communicate and share models' results (Ayllón et al. 2021).

The combination of ABM with other methods can increase the power of these analyses. Filatova et al. (2016) conclude that the greatest insight into regime shifts would be provided when a hybrid approach with other methods is used. Coupled models show enhanced representation of processes through a clear identification of component interactions and processes (Robinson et al. 2018). For instance, the integrative outcomes of the coupled ABM–GIS model developed in Castella et al. (2005) provided policymakers with a decision-making support tool that inspired stakeholders. Furthermore, a combination of participatory future narratives with ABM in AFS contributes to a more accurate system representation (Shaaban et al. 2023), which can be useful for facilitating transition processes. Agri-food models could benefit from using complementary methods adapted to the needs of the simulation.

Issues that could pose a challenge in the developing of ABM are specific skillset requirements, access to relevant databases containing reliable data, and the steep learning curves for software tools. Collaboration can address some of these issues, e.g., working within a team that comprises individual skills and experience and creating interdisciplinary collaborations between computer and social scientists.

Lastly, a reasonable amount of time is required to complete the modeling process (Holtz et al. 2015; Hansen et al. 2019; Guo et al. 2020). Even though some papers state limitations of the model indicating that agents could be more complete, or that models are oversimplified to reduce complexity (Köhler et al. 2019), this does not entirely illustrate a limitation. Although complexity is a broadly discussed concept, ABM has to capture the core characteristics among system entities to provide insights (Manson et al. 2012).

Conclusions

The present systematic research highlights the potential found in ABM to understand sustainability transitions in AFS. Agent-based modeling has shown great potential to enable understanding of the characteristics of sustainability transitions, specifically in the context of agri-food systems. Encouraging modeling sustainability transitions research in agri-food systems using an ABM approach is highly desired to address this research topic. Furthermore, a combination of ABM with other powerful methods, depending on the needs of the model (e.g., GIS, system dynamics, Bayesian networks, and the like), results in great insights into agri-food systems' transitions and could add on improving the representation of relevant socio-ecological dynamics.

Even though we highlight the potential of ABM as a method to understand sustainability transitions, there are limitations worth considering, such as its dependence on initial inputs, assumptions of agent behavior, and the need for a better representation of social norms. Given the uncertainty of sustainability transitions and the mentioned limitations, ABM is often not predictive. Therefore, model results should be treated as a projection rather than an accurate prediction of sustainability transitions. Moreover, developing an ABM, gathering data, and validating results with experts requires a significant amount of time. Yet, this clashes with the need to timely address sustainability transitions.

This study takes the first step toward understanding the transition modeling of a complex system where a sustainable transition is still demanded. Research on sustainability transitions in agri-food systems should focus on the aspects mentioned to contribute novel and valuable insights for the field. Periodic research to reflect on the status of sustainability transition research would help to meet the urgent need for transitions toward sustainability in agri-food systems and integrate the latest insights. The outcomes of agent-based modeling research will help to identify efficient and successful strategies for sustainability transitions within the agri-food sector.

Funding The authors acknowledge the financial support for this project provided by transnational funding bodies, partners of the H2020 ERA-NETs SUSFOOD2 and CORE Organic Cofund, under the Joint SUSFOOD2/CORE Organic Call 2019 for FOODLEVERS project, and from the European Union's Horizon 2020 Framework Programme for Research and Innovation under Grant Agreement no 101000527 for RUSTICA project.

Declarations

Conflict of interest The authors declare that no competing financial interest influenced the work reported in this document.

References

Abdel-Aal M, Haltas I, Varga L (2020) Modelling the diffusion and operation of anaerobic digestions in Great Britain under future scenarios within the scope of water-energy-food nexus. J Clean Prod. https://doi.org/10.1016/j.jclepro.2019.119897

Achmad ALH, Chaerani D, Perdana T (2021) Designing a food supply chain strategy during COVID-19 pandemic using an integrated agent-based modelling and robust optimization. Heliyon. https://doi.org/10.1016/j.heliyon.2021.e08448

Ajzen I (1991) The Theory of Planned Behaviour. Organ Behav Hum Decis Process 50:179–211

Allen P, Robinson M, Butans E, Varga L (2019) Innovations for sustainable lifestyles: an agent-based model approach. Sustain Sci 14:341–354. https://doi.org/10.1007/s11625-018-0593-y

Andrighetto G, Vriens E (2022) A research agenda for the study of social norm change. Philos Trans R Soc Math Phys Eng Sci 380:20200411. https://doi.org/10.1098/rsta.2020.0411

Ayllón D, Railsback SF, Gallagher C et al (2021) Keeping modelling notebooks with TRACE: good for you and good for environmental research and management support. Environ Model Softw 136:104932

Bailey RM, Carrella E, Axtell R et al (2019) A computational approach to managing coupled human–environmental systems: the POSEIDON model of ocean fisheries. Sustain Sci 14:259–275. https://doi.org/10.1007/s11625-018-0579-9

Basco-Carrera L, Warren A, van Beek E et al (2017) Collaborative modelling or participatory modelling? A framework for water resources management. Environ Model Softw 91:95–110. https://doi.org/10.1016/j.envsoft.2017.01.014

Baustert P, Benetto E (2017) Uncertainty analysis in agent-based modelling and consequential life cycle assessment coupled models: a critical review. J Clean Prod 156:378–394. https://doi.org/10.1016/j.jclepro.2017.03.193

Becu N, Raimond C, Garine E et al (2014) Coupling environmental and social processes to simulate the emergence of a savannah landscape mosaic under shifting cultivation and assess its sustainability. JASSS J Artif Soc Soc Simul. https://doi.org/10.18564/jasss.2397

Borodin V, Bourtembourg J, Hnaien F, Labadie N (2016) Handling uncertainty in agricultural supply chain management: a state of the art. Eur J Oper Res 254:348–359. https://doi.org/10.1016/j.ejor.2016.03.057

Bourguet J-R, Thomopoulos R, Mugnier M-L, Abécassis J (2013) An artificial intelligence-based approach to deal with argumentation applied to food quality in a public health policy. Expert Syst Appl 40:4539–4546. https://doi.org/10.1016/j.eswa.2013.01.059

Brunori G, Barjolle D, Dockes AC et al (2013) CAP reform and innovation: the role of learning and innovation networks. EuroChoices 12:27–33. https://doi.org/10.1111/1746-692X.12025

Castella J-C, Trung TN, Boissau S (2005) Participatory simulation of land-use changes in the northern mountains of Vietnam: the combined use of an agent-based model, a role-playing game, and a geographic information system. Ecol Soc 10:art27. https://doi.org/10.5751/ES-01328-100127

Catarino R, Therond O, Berthomier J et al (2021) Fostering local crop-livestock integration via legume exchanges using an innovative integrated assessment and modelling approach based on the MAELIA platform. Agric Syst. https://doi.org/10.1016/j.agsy.2021.103066

Coenen L, Benneworth P, Truffer B (2012) Toward a spatial perspective on sustainability transitions. Res Policy 41:968–979. https://doi.org/10.1016/j.respol.2012.02.014

Conti C, Zanello G, Hall A (2021) Why are agri-food systems resistant to new directions of change? A systematic review. Glob Food Secur 31:100576. https://doi.org/10.1016/j.gfs.2021.100576

Coronese M, Occelli M, Lamperti F, Roventini A (2023) AgriLOVE: agriculture, land-use and technical change in an evolutionary, agent-based model. Ecol Econ 208:107756

Crippa M, Solazzo E, Guizzardi D et al (2021) Food systems are responsible for a third global anthropogenic GHG emissions. Nature Food 2:198–209

Cuppen E, Nikolic I, Kwakkel J, Quist J (2021) Participatory multi-modelling as the creation of a boundary object ecology: the case of future energy infrastructures in the Rotterdam Port industrial cluster. Sustain Sci 16:901–918. https://doi.org/10.1007/s11625-020-00873-z

Delmotte S, Lopez-Ridaura S, Barbier J-M, Wery J (2013) Prospective and participatory integrated assessment of agricultural systems from farm to regional scales: comparison of three modeling approaches. J Environ Manag 129:493–502. https://doi.org/10.1016/j.jenvman.2013.08.001

Delmotte S, Barbier J-M, Mouret J-C et al (2016) Participatory integrated assessment of scenarios for organic farming at different scales in Camargue, France. Agric Syst 143:147–158. https://doi.org/10.1016/j.agsy.2015.12.009

Ding Z, Gong W, Li S, Wu Z (2018) System dynamics versus agent-based modeling: a review of complexity simulation in construction waste management. Sustainability 10(7):2484. https://doi.org/10.3390/su10072484

Dobbie S, Schreckenberg K, Dyke JG et al (2018) Agent-based modelling to assess community food security and sustainable livelihoods. JASSS. https://doi.org/10.18564/jasss.3639

Dyer JS (2005) MAUT - multi-attribute utility theory. Multiple criteria decision analysis: state of the art surveys. Springer, pp 265–292

El Bilali H (2019) Research on agro-food sustainability transitions: a systematic review of research themes and an analysis of research gaps. J Clean Prod 221:353–364. https://doi.org/10.1016/j.jclepro.2019.02.232

El Bilali H (2020) Transition heuristic frameworks in research on agro-food sustainability transitions. Environ Dev Sustain 22:1693–1728. https://doi.org/10.1007/s10668-018-0290-0

El Bilali H, Probst L (2018) Towards an integrated analytical framework to map sustainability transitions in food systems. AGROFOR. https://doi.org/10.7251/AGRENG1702015T

El Bilali H, Strassner C, Ben Hassen T (2021) Sustainable agri-food systems: environment, economy, society, and policy. Sustainability 13:6260. https://doi.org/10.3390/su13116260

Elsner F, Herzig C, Strassner C (2023) Agri-food systems in sustainability transition: a systematic literature review on recent developments on the use of the multi-level perspective. Front Sustain Food Syst 7:1207476. https://doi.org/10.3389/fsufs.2023.1207476

Evans TP, Kelley H (2008) Assessing the transition from deforestation to forest regrowth with an agent-based model of land cover change for south-central Inidiana (USA). Geoforum 39:819–832

Fernandez-Mena H, MacDonald GK, Pellerin S, Nesme T (2020) Co-benefits and trade-offs from agro-food system redesign for circularity: a case study with the fan agent-based model. Front Sustain Food Syst 4:41. https://doi.org/10.3389/fsufs.2020.00041

Filatova T, Polhill JG, van Ewijk S (2016) Regime shifts in coupled socio-environmental systems: review of modelling challenges and approaches. Environ Model Softw 75:333–347. https://doi.org/10.1016/j.envsoft.2015.04.003

Gaitán-Cremaschi D, Klerkx L, Duncan J et al (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

Geels FW (2011) The multi-level perspective on sustainability transitions: responses to seven criticisms. Environ Innov Soc Transit 1:24–40. https://doi.org/10.1016/j.eist.2011.02.002

Geels FW, Schot J (2007) Typology of sociotechnical transition pathways. Res Policy 36:399–417

Grimm V, Revill E, Berger U et al (2005) Pattern-oriented modeling of agent-based complex systems: lessons from ecology. Science 310:987–991

Günther G, Clemen T, Duttmann R et al (2021) Of animal husbandry and food production: a first step towards a modular agent-based modelling platform for socio-ecological dynamics. Land 10:1366. https://doi.org/10.3390/land10121366

Guo M, van Dam KH, Touhami NO, Nguyen R, Delval F, Jamieson C, Shah N (2020) Multi-level system modelling of the resource-food-bioenergy nexus in the global south. Energy 197:117196. https://doi.org/10.1016/j.energy.2020.117196

Halog A, Manik Y (2011) Advancing integrated systems modelling framework for life cycle sustainability assessment. Sustainability 3:469–499. https://doi.org/10.3390/su3020469

Hansen P, Liu X, Morrison GM (2019) Agent-based modelling and socio-technical energy transitions: a systematic literature review. Energy Res Soc Sci 49:41–52. https://doi.org/10.1016/j.erss.2018.10.021

Hebinck A, Klerkx L, Elzen B et al (2021) Beyond food for thought: directing sustainability transitions research to address fundamental change in agri-food systems. Environ Innov Soc Transit 41:81–85. https://doi.org/10.1016/j.eist.2021.10.003

Hinrichs CC (2014) Transitions to sustainability: a change in thinking about food systems change? Agric Hum Values 31:143–155. https://doi.org/10.1007/s10460-014-9479-5

Hoek AC, Malekpour S, Raven R et al (2021) Towards environmentally sustainable food systems: decision-making factors in sustainable food production and consumption. Sustain Prod Consum 26:610–626. https://doi.org/10.1016/j.spc.2020.12.009

Hoekstra A, Steinbuch M, Verbong G (2017) Creating agent-based energy transition management models that can uncover profitable pathways to climate change mitigation. Complexity 2017:1–23. https://doi.org/10.1155/2017/1967645

Holt-Gimenez E, Altieri MA (2013) Agroecology, food sovereignty, and the newgreen revolution. Agroecol Sust Food 37:90–102. https://doi.org/10.1080/10440046.2012.716388

Holtz G, Alkemade F, de Haan F et al (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

Huber R, Bakker M, Balmann A et al (2018) Representation of decision-making in European agricultural agent-based models. Agric Syst 167:143–160. https://doi.org/10.1016/j.agsy.2018.09.007

Ingram J (2015) Framing niche-regime linkage as adaptation: an analysis of learning and innovation networks for sustainable agriculture across Europe. J Rural Stud 40:59–75. https://doi.org/10.1016/j.jrurstud.2015.06.003

IPBES (2019) IPBES 2019: Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat, Bonn, Germany

Jensen MC, Meckling WH (1976) Theory of the firm: managerial behavior, agency costs and ownership structure. J Financ Econ 3:305–360. https://doi.org/10.1016/0304-405X(76)90026-X

Kang J-Y, Aldstadt J (2019) Using multiple scale spatio-temporal patterns for validating spatially explicit agent-based models. Int J Geogr Inf Sci 33:193–213. https://doi.org/10.1080/13658816.2018.1535121

Kieu L-M, Malleson N, Heppenstall A (2020) Dealing with uncertainty in agent-based models for short-term predictions. R Soc Open Sci 7:191074. https://doi.org/10.1098/rsos.191074

Köhler J, De Haan F, Holtz G et al (2018) Modelling sustainability transitions: an assessment of approaches and challenges. JASSS. https://doi.org/10.18564/jasss.3629

Köhler J, Geels FW, Kern F et al (2019) An agenda for sustainability transitions research: state of the art and future directions. Environ Innov Soc Transit 31:1–32. https://doi.org/10.1016/j.eist.2019.01.004

Lamine C, Darnhofer I, Marsden TK (2019) What enables just sustainability transitions in agrifood systems? An exploration of conceptual approaches using international comparative case studies. J Rural Stud 68:144–146. https://doi.org/10.1016/j.jrurstud.2019.03.010

Lan K, Yao Y (2019) Integrating life cycle assessment and agent-based modeling: a dynamic modeling framework for sustainable agricultural systems. J Clean Prod. https://doi.org/10.1016/j.jclepro.2019.117853

Lane DC, Oliva R (1998) The greater whole: Towards a synthesis of system dynamics and soft systems methodology. Eur J Oper Res 107(1):214–235. https://doi.org/10.1016/S0377-2217(97)00205-1

Lang DJ, Wiek A, Bergmann M et al (2012) Transdisciplinary research in sustainability science: practice, principles, and challenges. Sustain Sci 7:25–43. https://doi.org/10.1007/s11625-011-0149-x

Lindenberg S, Steg L (2007) Normative, gain and hedonic goal frames guiding enviromental behavior. Soc Issues 63:117–137. https://doi.org/10.1111/j.1540-4560.2007.00499.x

Lindkvist E, Wijermans N, Daw TM et al (2020) Navigating complexities: agent-based modeling to support research, governance, and management in small-scale fisheries. Front Mar Sci 6:733. https://doi.org/10.3389/fmars.2019.00733

Lippe M, Bithell M, Gotts N et al (2019) Using agent-based modelling to simulate social-ecological systems across scales. GeoInformatica 23:269–298. https://doi.org/10.1007/s10707-018-00337-8

Magliocca NR (2020) Agent-based modeling for integrating human behavior into the food–energy–water nexus. Land 9:519. https://doi.org/10.3390/land9120519

Manson SM, Sun S, Bonsal D (2012) Agent-based modeling and complexity. In: Heppenstall A, Crooks A, See L, Batty M (eds) Agent-based models of geographical systems. Springer, Dordrecht, pp 125–139

Manson S, An L, Clarke KC et al (2020) Methodological issues of spatial agent-based models. JASSS. https://doi.org/10.18564/jasss.4174

Markard J, Raven R, Truffer B (2012) Sustainability transitions: an emerging field of research and its prospects. Res Policy 41:955–967. https://doi.org/10.1016/j.respol.2012.02.013

Martin G, Allain S, Bergez J-E et al (2018) How to address the sustainability transition of farming systems? A conceptual framework to organize research. Sustainability 10:2083. https://doi.org/10.3390/su10062083

Marvuglia A, Navarrete Gutiérrez T, Baustert P et al (2018) Implementation of agent-based models to support life cycle assessment: a review focusing on agriculture and land use. AIMS Agric Food 3:535–560. https://doi.org/10.3934/agrfood.2018.4.535

Marvuglia A, Bayram A, Baustert P et al (2022) Agent-based modelling to simulate farmers' sustainable decisions: farmers' interaction and resulting green consciousness evolution. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.129847

Matthews RB, Polhill JG, Gilbert N, Roach A (2005) Integrating Agent-Based Social Models And Biophysical Models, p 7

McDowall W, Geels FW (2017) Ten challenges for computer models in transitions research: Commentary on Holtz et al. Environ Innov Soc Transit 22:41–49. https://doi.org/10.1016/j.eist.2016.07.001

McGarraghy S, Olafsdottir G, Kazakov R et al (2022) Conceptual system dynamics and agent-based modelling simulation of interorganisational fairness in food value chains: research agenda and case studies. Agriculture 12:280. https://doi.org/10.3390/agriculture12020280

Mehdizadeh M, Nordfjaern T, Klöckner CA (2022) A systematic review of the agent-based modelling/simulation paradigm in mobility transition. Technol Forecast Soc Chang 184:122011. https://doi.org/10.1016/j.techfore.2022.122011

Mialhe F, Becu N, Gunnell Y (2012) An agent-based model for analyzing land use dynamics in response to farmer behaviour and environmental change in the Pampanga delta (Philippines). Agric Ecosyst Environ 161:55–69. https://doi.org/10.1016/j.agee.2012.07.016

Mittal A, Krejci CC (2019) A hybrid simulation modeling framework for regional food hubs. J Simul 13:28–43. https://doi.org/10.1057/s41273-017-0063-z

Miyasaka T, Le QB, Okuro T et al (2017) Agent-based modeling of complex social–ecological feedback loops to assess multi-dimensional trade-offs in dryland ecosystem services. Landsc Ecol 32:707–727. https://doi.org/10.1007/s10980-017-0495-x

Moallemi EA, Malekpour S (2018) A participatory exploratory modelling approach for long-term planning in energy transitions. Energy Res Soc Sci 35:205–216. https://doi.org/10.1016/j.erss.2017.10.022

Moallemi EA, Kwakkel J, de Haan FJ, Bryan BA (2020) Exploratory modeling for analyzing coupled human-natural systems under uncertainty. Glob Environ Chang. https://doi.org/10.1016/j.gloenvcha.2020.102186

Moore M-L, Tjornbo O, Enfors E et al (2014) Studying the complexity of change: toward an analytical framework for understanding deliberate social-ecological transformations. Ecol Soc 19:art54. https://doi.org/10.5751/ES-06966-190454

Morgan MG, Henrion M, Small M (1990) Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press

Morrissey JE, Mirosa M, Abbott M (2014) Identifying transition capacity for agri-food regimes: application of the multi-level perspective for strategic mapping. J Environ Policy Plan 16:281–301. https://doi.org/10.1080/1523908X.2013.845521

Müller B, Bohn F, Dreßler G et al (2013) Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. Environ Model Softw 48:37–48. https://doi.org/10.1016/j.envsoft.2013.06.003

Nabavi E, Daniell KA, Najafi H (2017) Boundary matters: the potential of system dynamics to support sustainability? J Clean Prod 140:312–323. https://doi.org/10.1016/j.jclepro.2016.03.032

Nogueira C, Pinto H, Marques JF (2019) Innovative and transition potential of intentional sustainable communities: towards an exploratory conceptual model. Cid Comunidades E Territ. https://doi.org/10.15847/citiescommunitiesterritories.dec2019.039.art07

OECD/FAO (2020) OECD-FAO Agricultural Outlook 2020-2029. FAO/OECD, Rome, Paris

Ostrom E (1990) Governing the commons. Cambridge University Press

Page MJ, McKenzie JE, Bossuyt PM et al (2021) The PRISMA 2020 statement: an updated guideline for reporting sustematic reviews. BMJ 372:n71

Parker DC, Manson SM, Janssen MA et al (2003) Multi-agent systems for the simulation of land-use and land-cover change: a review. Ann Assoc Am Geogr 93:314–337. https://doi.org/10.1111/1467-8306.9302004

Peano C, Tecco N, Dansero E et al (2015) Evaluating the Sustainability in Complex Agri-Food Systems: The SAEMETH Framework. Sustainability 7:6721–6741. https://doi.org/10.3390/su7066721

Peter C, Swilling M (2014) Linking Complexity and Sustainability Theories: Implications for Modeling Sustainability Transitions. Sustainability 6:1594–1622. https://doi.org/10.3390/su6031594

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

Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science 360:987–992. https://doi.org/10.1126/science.aaq0216

Preiser R, Biggs R, De Vos A, Folke C (2018) Social-ecological systems as complex adaptive systems: organizing principles for advancing research methods and approaches. Ecol Soc 23:art6. https://doi.org/10.5751/ES-10558-230446

Railsback SF, Grimm V (2019) Agent-based and individual-based modeling: a practical introduction, 2nd edn. Princeton University Press, Princeton, NJ

Robinson DT, Di Vittorio A, Alexander P et al (2018) Modelling feedbacks between human and natural processes in the land system. Earth Syst Dyn 9:895–914. https://doi.org/10.5194/esd-9-895-2018

Röckstrom J, Edenhofer O, Gaertner J, DeClerck F (2020) Planet-proofing the global food system. Nature Food 1:3–5

Rosenbloom D (2017) Pathways: An emerging concept for the theory and governance of low-carbon transitions. Glob Environ Chang 43:37–50

Rounsevell MDA, Arneth A (2011) Representing human behaviour and decisional processes in land system models as an integral component of the Earth system. Glob Environ Chang 21:840–843

Rounsevell MDA, Arneth A, Alexander P et al (2014) Towards decision-based global land use models for improved understanding of the Earth system. Earth Syst Dyn 5:117–137. https://doi.org/10.5194/esd-5-117-2014

Schlager E (2004) Common-pool resource theory. Environmental governance reconsidered: challenges, choices, and opportunities. MIT Press, Cambridge, MA, pp 145–175

Schlüter M, Haider LJ, Lade SJ, Lindkvist E, Martin R, Orach K, Wijermans N, Folke C (2019) Capturing emergent phenomena in social-ecological systems: an analytical framework. Ecol Soc 24(3):11. https://doi.org/10.5751/ES-11012-240311

Schlüter M, Lindkvist E, Basurto X (2021) The interplay between top-down interventions and bottom-up self-organization shapes opportunities for transforming self-governance in small-scale fisheries. Mar Policy. https://doi.org/10.1016/j.marpol.2021.104485

Schouten M, Opdam P, Polman N, Westerhof E (2013) Resilience-based governance in rural landscapes: experiments with agri-environment schemes using a spatially explicit agent-based model. Land Use Policy 30:934–943. https://doi.org/10.1016/j.landusepol.2012.06.008

Shaaban M, Schwartz C, Macpherson J, Piorr A (2021) A conceptual model framework for mapping, analyzing and managing supply-demand mismatches of ecosystem services in agricultural landscapes. Land 10:131. https://doi.org/10.3390/land10020131

Shaaban M, Voglhuber-Slavinsky A, Dönitz E et al (2023) Understanding the future and evolution of agri-food systems: a combination of qualitative scenarios with agent-based modelling. Futures 149:103141. https://doi.org/10.1016/j.futures.2023.103141

Smajgl A, Brown DG, Valbuena D, Huigen MGA (2011) Empirical characterisation of agent behaviours in socio-ecological systems. Environ Model Softw 26:837–844

Spaargaren G, Oosterveer P, Loeber A (eds) (2013) Food practices in transition: changing food consumption, retail and production in the age of reflexive modernity. Routledge

Sun Z, Lorscheid I, Millington JD et al (2016) Simple or complicated agent-based models? A complicated issue. Environ Model Softw 86:56–67. https://doi.org/10.1016/j.envsoft.2016.09.006

Taghikhah F, Voinov A, Shukla N et al (2021) Integrated modeling of extended agro-food supply chains: a systems approach. Eur J Oper Res 288:852–868. https://doi.org/10.1016/j.ejor.2020.06.036

Tenenberg J, Knobelsdorf M (2014) Out of our minds: a review of sociocultural cognition theory. Comput Sci Educ 24:1–24. https://doi.org/10.1080/08993408.2013.869396

Thomopoulos R, Salliou N, Abreu C et al (2021) Reduced meat consumption: from multicriteria argument modelling to agent-based social simulation. Int J Food Stud 10:133–149. https://doi.org/10.7455/IJFS/10.1.2021.A1

Thompson J, Millstone E, Scoones I et al (2007) Agri Food Systems Dynamics: pathways to sustainability in an era of uncertainty. STEPS Working Paper 4, pp 1–71

Tran M (2014) Modeling sustainability transitions on complex networks. Complexity 19:8–22. https://doi.org/10.1002/cplx.21492

Ulanowicz RE, Goerner SJ, Lietaer B, Gomez R (2009) Quantifying sustainability: resilience, efficiency and the return of information theory. Ecol Complex 6:27–36. https://doi.org/10.1016/j.ecocom.2008.10.005

Utomo DS, Onggo BS, Eldridge S (2018) Applications of agent-based modelling and simulation in the agri-food supply chains. Eur J Oper Res 269:794–805. https://doi.org/10.1016/j.ejor.2017.10.041

van Voorn G, Hengeveld G, Verhagen J (2020) An agent based model representation to assess resilience and efficiency of food supply chains. PLoS ONE. https://doi.org/10.1371/journal.pone.0242323

Vermunt DA, Negro SO, Van Laerhoven FSJ et al (2020) Sustainability transitions in the agri-food sector: how ecology affects transition dynamics. Environ Innov Soc Transit 36:236–249. https://doi.org/10.1016/j.eist.2020.06.003

Voinov A, Jenni K, Gray S et al (2018) Tools and methods in participatory modeling: selecting the right tool for the job. Environ Model Softw 109:232–255. https://doi.org/10.1016/j.envsoft.2018.08.028

Wijermans N, Boonstra WJ, Orach K et al (2020) Behavioural diversity in fishing: towards a next generation of fishery models. Fish Fish 21:872–890. https://doi.org/10.1111/faf.12466

Wijermans N, Scholz G, Chappin É et al (2023) Agent decision-making: the elephant in the room - enabling the justification of decision model fit in social-ecological models. Environ Model Softw 170:105850. https://doi.org/10.1016/j.envsoft.2023.105850

Wilensky U, Rand W (2015) An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo. MIT Press, Cambridge, MA

Yan H, Pan L, Xue Z et al (2019) Agent-based modeling of sustainable ecological consumption for grasslands: a case study of Inner Mongolia, China. Sustainability 11:2261. https://doi.org/10.3390/su11082261

Zepeda L, Deal D (2009) Organic and local food consumer behaviour: alphabet theory. Int J Consum Stud 33:697–705. https://doi.org/10.1111/j.1470-6431.2009.00814.x

Zheng C, Liu Y, Bluemling B et al (2013) Modeling the environmental behavior and performance of livestock farmers in China: an ABM approach. Agric Syst 122:60–72. https://doi.org/10.1016/j.agsy.2013.08.005