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How to conduct more systematic reviews of agent-based models and foster theory development - Taking stock and looking ahead

Sebastian Achter [a], Melania Borit [b], Clémentine Cottineau [c,*], Matthias Meyer [a], J. Gareth Polhill [d], Viktoriia Radchuk [e]

[a] Hamburg University of Technology, Germany
[b] UiT the Arctic University of Norway, Norway
[c] Technological University of Delft, Netherlands
[d] James Hutton Institute, UK
[e] Leibniz Institute for Zoo and Wildlife Research, Germany

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ABSTRACT

Agent-based models (ABMs) are increasingly utilized in ecology and related fields, yet concerns persist regarding the lack of consideration for lessons learned from previous models. This study explores the potential of systematically conducted ABM reviews to contribute to cumulative science and theory development by synthesizing individual ABM findings more effectively. We are conducting a meta-review of ABM reviews to assess current practices, compare them to systematic literature review (SLR) literature recommendations, and evaluate their engagement with theory and theory development. Our analysis of the ecology and social science sample reveals that many reviews are not conducted systematically and lack transparency. The analysis step of SLRs holds significant potential to advance theory development. Reviews primarily focus on model design, while other avenues of theory development receive less attention. Our findings suggest ways to improve current practices and may guide future ABM reviews via benchmarks for methodological decisions and dimensions for advancing theory development.

1. Introduction

Agent-based models (ABMs) are increasingly used to model and study ecological and socio-ecological systems. The main advantages of using ABMs in such contexts are that they can provide realistic representations of the interactions of human actors or other entities in spatial environments, that they foster the modeling of heterogeneity concerning agents and environments, and that they can be used to study complex adaptive systems (Schlüter et al., 2021). In ecology, the advantages of ABMs include their ability to reflect inter- and intra-specific interactions in a spatially explicit way; to intuitively simulate the movement of individuals; and to represent the ability of individuals to adapt to changing environments by adapting their phenotypic traits, such as body mass, physiological state, or health (Backmann et al., 2019; Grimm et al., 2005; Radchuk et al., 2021). These advantages are also reflected in the increasing number of ABM publications across disciplines (Hauke et al., 2017; Heppenstall et al., 2021; Polhill et al., 2019), as well as the special issues devoted to ABMs for the modeling of ecological and socio-ecological systems (Filatova et al., 2013; Grimm and Berger, 2016). Undeniably, ABMs are becoming an ever-growing part of the computational methods toolkit in ecology and related disciplines.

Despite the growing interest in and use of ABMs, researchers have criticized the lack of cumulative progress in the field, particularly concerning the absence of a synthesis that encapsulates the burgeoning number of ABMs on specific case studies. In land-use sciences, O'Sullivan et al. (2016) coined the term "YAAWN syndrome" (Yet Another Agent-based model, Whatever, Nevermind) to describe this phenomenon. This tendency is also observed in other fields involving ABMs, leading to a call for more cumulative science and theory development via ABMs. For example, Lorscheid et al. (2019) point out that the current focus on single cases detracts from general insights at a system level and a more systematic synthesis of knowledge at the agent level.

Literature reviews are helpful in this context because they consolidate current knowledge on multiple dimensions (e.g., disciplinary,

* Corresponding author.
E-mail addresses: sebastian.achter@tuhh.de (S. Achter), melania.borit@uit.no (M. Borit), c.cottineau@tudelft.nl (C. Cottineau), matthias.meyer@tuhh.de (M. Meyer), gary.polhill@hutton.ac.uk (J.G. Polhill), radchuk@izw-berlin.de (V. Radchuk).

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methodological, or topical). They also reduce the risk of "reinventing the wheel" by creating awareness of what has already been accomplished. Reviews represent the forefront of domain knowledge, including its present problems and gaps, and offer a critical assessment of the latest developments. Hence, literature reviews of ABMs may foster learning beyond individual cases and encourage theory development by stimulating the discovery of general patterns at the system level and aligning modeling conventions at the agent level. Indeed, literature reviews can directly address theory development by explicitly comparing and assessing the use of theories in models and by inspecting how models advance the explanatory power of these theories. However, traditional reviews are often criticized for their lack of methodological rigor and their subjective selection of studies (Dijkers, 2009; Doerr et al., 2015).

Systematic literature reviews (SLR) are reproducible[1] and explicit approaches to review the literature on a particular topic and to answer a clearly defined question about this literature. By following a systematic method to identify, select and analyze existing research, they foster transparency, comprehensiveness, and structure (Hiebl, 2021). Conducting SLRs is a longstanding practice in medicine (Tranfield et al., 2003) and has been adopted successively by other disciplines. Reflections on and techniques for conducting SLRs have been widely discussed in various disciplines (Brereton et al., 2007; Keele, 2007; Mallett et al., 2012; Okoli and Schabram, 2010; Sargeant et al., 2006; Tranfield et al., 2003; Xiao and Watson, 2019). However, to our knowledge, no such reflection has been applied to the conduct of ABM reviews specifically.

Hence, this article[2] focuses on whether and how more systematically conducted ABM reviews can contribute to cumulative science and, more specifically, to theory development. For this purpose, our efforts are directed towards two primary contributions. First, we carry out a meta-review to take stock of current ABM literature review practices and compare the practices to recommendations in the literature on SLRs to identify possible improvements. Second, we evaluate the engagement of ABM reviews with theory and theory development. While we could explore these two contributions separately, we investigate them in tandem to highlight the potential for systematic literature reviews to advance cumulative science in the field of ABM research. Furthermore, we compare ABM reviews in ecology with those in social science, especially to identify potential differences in the practices of different but related fields. Based on our meta-review of current ABM review practices, we offer suggestions for improvements and guidance on conducting systematic ABM reviews and create a stepping stone towards the advancement of theory development within the framework of SLRs.

The remainder of this article has the following structure. We start with a background discussion of the existing literature on conducting literature reviews and the benefits and challenges of conducting an SLR for ABMs. We prioritize SLR criteria that support cumulative learning and theory development in ABM research. The subsequent method section explains the design of our meta-review of ABM reviews, including our sample selection and content analysis. Next, we present our results and provide a general overview of how systematic ABM reviews are conducted and how they address theory development. We conclude with a summary of our main findings and contributions.

2. Prior considerations

2.1. Conducting systematic literature reviews

Reviews synthesize scattered knowledge in a field, thereby contributing to cumulative science and establishing a firm foundation for future research endeavors. Reviews integrate the results and perspectives of many studies and "can address research questions with a power that no single study has" (Snyder, 2019, p. 333). The key purposes of reviews include: synthesizing and critiquing existing knowledge; identifying research gaps and problems; evaluating and developing theory; and summarizing the state of the art (Anderson and Lemken, 2023; Baumeister and Leary, 1997). SLRs emerged more recently and have become the "gold standard" in many fields (Davis et al., 2014). They are typically contrasted with traditional narrative reviews because they provide "a methodical, replicable, and transparent approach" (Siddaway et al., 2019, p. 749). While traditional reviews are rather defined by constrasting them with SLRs there are different taxonomies suggested to categorize types of literature reviews (see e.g., Snyder, 2019; University Libraries Temple University, 2023).

SLRs originated from the medical sciences in the 1980s and 1990s, under the direction of A. Cochrane. He suggested reviewing the results of multiple randomized clinical trials (RCTs) with small samples to achieve statistically significant results (Nightingale, 2009). Since then, SLRs have expanded beyond medical science, gaining popularity in the social sciences in particular (Davis et al., 2014). SLRs are considered more comprehensive and transparent than narrative reviews, partly due to their reproducible search of publications in defined databases (Cronin et al., 2008; Hiebl, 2021; Mallett et al., 2012; Tranfield et al., 2003). This process enables researchers to extend their horizon beyond their subject area and citation network (Dixon-Woods et al., 2005; Greyson et al., 2019; Haddaway et al., 2018; Higgins et al., 2019; Robinson and Lowe, 2015). However, the quality of SLRs depends on their search strategy, data extraction, analysis, and reporting. SLRs are costly exercises and, if not done properly, can lead to a shallow representation of the state of literature, beset with similar issues as traditional reviews, disguised under the label of systematicity.

Boell and Cecez-Kecmanovic (2015) raise concerns about the increasing promotion of SLRs as the best way to conduct literature reviews. Even the more transparent reporting associated with SLRs can conceal a subjective and non-replicable extraction of information from the selected papers. They also argue that SLRs risk prioritizing certain forms of scientific knowledge over others (e.g., neglecting non-positivist research), are much more challenging to apply when answering "how" and "why" questions, and may undermine critical thinking and scholarship in general. Moreover, in areas not restricted to RCTs, a major challenge lies in assessing the quality of research findings derived from the papers surveyed in SLRs. As a result, more qualitative approaches have been developed to determine the quality and strength of the findings from different types of studies (Greenhalgh et al., 2004).

Table 1 depicts the three main steps and corresponding elements of conducting an SLR, condensing previous work on how to conduct SLRs (Hiebl, 2021; Shaffril et al., 2021; Tranfield et al., 2003). At the outset, a research question is formulated that supports the entire process (Step 1). The subsequent task of selecting a sample of relevant papers (Step 2) is at the heart of every SLR. The resulting set of papers provides the data that generates new insights. In conclusion, the data is extracted and synthesized, and subsequently presented and interpreted (Step 3). The interdependence of these three steps deserves emphasis.

Bearman et al. (2012) and Hiebl (2021) suggest three desirable attributes of SLRs: reproducibility, traceability, and comprehensiveness. Reproduciblity is achieved by structuring SLRs in "an ordered or methodical way" and not in a "haphazard or random way" (Jesson et al., 2011, p. 12). Traceability pertains to being transparent by explicitly documenting how the sample of research items has been generated, how this sample has been analyzed, and how the analysis was used to reach

[1] In this context we distinguish reproduciblity from replicability as suggested by the National Academies of Sciences E. Medicine, 2019 with the former pertaining to "obtaining consistent results using the same input data, computational steps, methods, code, and conditions of analysis"(p. 46) and the later pertaining to "obtaining consistent results across studies aimed at answering the same scientific question, each of which has obtained its own data" (p. 46) (see also Essawy et al., 2020).

[2] Please note that we utilize the term "article" to refer to our work specifically, while we use the term "paper" to denote the documents included in our literature sample.

Table 1
Main steps and elements of SLRs.

Step	Description
1. Formulate research question(s)	
a. Establish	Formulate, in a first general step, the research question.
b. Circumscribe	Modify and specify the research question in an iterative process, based on the first assessment of material (scoping review).[1]
2. Select a sample	
a. Identify	Select a search strategy (database-driven, journal-driven, gray literature, keywords, forward/backward search).
b. Screen	Select inclusion/exclusion criteria (time-period, citation cut-off, discipline, manual screening, guidance through research question(s)).
c. Assess	Quality assessment (Classification schemas, point-based evaluation, list of excluded papers with a justification of the decision).
d. Report	Transparent disclosure of each process step and the final review sample.
3. Analyze the sample	
a. Extract	Data extraction from reviewed research items; select relevant elements that answer the research question(s).
b. Synthesize	Data synthesis can be done quantitatively (e.g., meta-analysis, bibliometric analysis) or qualitatively (e.g., content-analysis).
c. Present and Interpret	Present and interpret findings.

Notes: [1] Considering which phenomenon is modeled, at which scale and at which level of abstraction, and whether similar phenomena are modeled by other disciplines under different names/concepts.

conclusions. Finally, to be comprehensive, an SLR should cover all relevant research items and search terms, as well as the document content needed to answer the research question (Briner and Denyer, 2012; Rousseau et al., 2008).

Concerning the first step, Tranfield et al. (2003) emphasize that an SLR should be based on one or more thoroughly deliberated and clearly defined research questions. They guide the subsequent research process, in turn influencing the sample selection and analysis steps. In this step, researchers can use their discretion to phrase the research question, thereby limiting its scope to a given period, a specific method, or a particular domain (Hiebl, 2021). Developing a research question is an iterative process that refines the question based on an initial assessment of the material available for review (i.e., for a “scoping review”).

The goal of the second step, the sample selection process, is the production of “an unbiased and representative sample of the existing body of research regarding a specific research question” (Hiebl, 2021, p. 232). Besides articulating the nature of the information sought from the SLR, the research question could stipulate the scope of the review concerning the kinds of documents or more general “research items” covered. Hiebl (2021) makes it clear that researchers should be open to a diversity of potential research items in pursuit of the goal but is also mindful of the quality of the possible sources. The latter approach can lead to a refining of exclusion and inclusion criteria and the research question. The critical point is that each step in this process is disclosed transparently, allowing the reader to understand how the researchers arrived at the final sample of research items to be reviewed by the SLR.

The methods used to analyze the sample in the third step are sensitive to the research question(s). Though there are less standardization and guidance in the literature, two general observations can be made based on Shaffril et al. (2021). First, qualitative research techniques, such as coding, facilitate the extraction of knowledge relevant to the research question from the research items selected for review. The extraction is ideally done independently by two or more authors to ensure reliability (Shaffril et al., 2021). Second, it is essential to adopt a structured approach toward synthesizing the extracted knowledge and to explicitly report on any method used in a process that is inevitably (and perhaps rightly) subject to individual researchers’ interpretations.

2.2. Particularities when reviewing agent-based models

The general framework to conduct SLRs (Table 1) provides a helpful basis to reflect on the current status of ABM review practices. Although the framework for SLRs is intended to apply in diverse research areas, each discipline has idiosyncrasies and challenges to which the process must adjust (Dunne, 2011; Durach et al., 2017).

Achter et al. (2022, p. 519) state that ABMs are “characterized by a much more creative design process depending on individual modeling strategies and a constant iteration between phenomenon, data, conceptual model, and operational model.” Even if multiple models address the same phenomenon, the degrees of freedom granted by the ABM modeling practice in terms of definitions, concepts, formalizations lead to a variety of models and model insights that make the discovery of general patterns an ambitious project.

In ABM contexts, we recommend to reason explicitly about the purpose of the SLR, based on three perspectives.

1. *Design* perspective: How is something modeled?
2. *Insight* perspective: What did we learn from the models?
3. *Effect* perspective: Similar to a classical meta-analysis in medicine and psychology (answers how variables are related to one another and to specific hypotheses)

For example, consider a review that assesses how ABMs reveal the relationship between biodiversity and ecosystem functioning. The design perspective would enhance our knowledge of the way in which biodiversity effects on ecosystem functioning are currently modeled in ABMs. The insight perspective would determine how the stability of ecosystem functioning was affected by biodiversity according to the developed ABMs, for example, which mechanisms are incorporated in the ABMs. The effect perspective would extract correlations, confidence intervals, or effect sizes to measure the strength of the relationship between biodiversity and stability of ecosystem functioning, as revealed by the ABMs.

The diversity of modeling practice creates a variety of ABMs addressing the same phenomenon. This model heterogeneity poses the central challenge of SLRs of ABMs and is further multiplied when progressing, respectively, from the *design* to the *insight* to the *effect* perspective. While it is feasible to contrast different processes and agent classes simulated in different ecosystems via an SLR using the design perspective, the SLR would require a large sample of sufficiently similar models in the target domain. Furthermore, the modeling teams’ design choices influence the insights they gain. Concentrating purely on the insight perspective ignores the potential relevance of design choices in reaching the insights to be reviewed by the SLR. Hence, a meaningful comparison requires linking generated insights and design choices (Heine et al., 2005). While a qualitative comparison of gained insights might be feasible, the value of an effect perspective with an SLR of ABMs is questionable except in highly restricted contexts. Even though the intention is to directly compare the outputs of the models reviewed in the effect perspective, it is not at all clear that these outputs can meaningfully be compared, which is a general concern of meta-analysis studies. Not least among the reasons are issues with semantic heterogeneity, alluded to by Voinov and Shugart (2013), even though there are much more significant challenges associated with the intent of the modeling team, which may not be explicit, and with the question whether the output emerges from the dynamic interactions of heterogeneous agents or is driven by input data. For example, although a model might produce numerical outputs for a variable, the team’s only intention might have been to conduct a pattern-oriented modeling (Grimm and Railsback, 2012) exercise. Though open to debate, it could be argued that the effect perspective requires that all reviewed ABMs be applied to the same case study, with the same purpose, data, and stakeholders. If so, the effect perspective is currently impracticable for SLRs of ABMs. Therefore, the skeptical reader might interpret the effect perspective as idealized objective worth striving for, e.g., by promoting the development and use of building blocks in ABM research (Berger et al., 2023, this issue).

The challenges posed by model heterogeneity for each perspective are also relevant to each stage of an SLR. Terminological variability across disciplines means that a researcher conducting an SLR of ABMs may have "blind spots" when formulating the research question and thereby miss potential contributions. Semantic heterogeneity issues can arise when the same word is used for different phenomena, such as polarization in opinion dynamics models, which can mean fragmentation in the opinion landscape or large opinion distances (Keijzer and Mäs, 2022). A similar issue is diverging definitions and diverging concepts for the same phenomenon. For example, what is known as the *Matthew effect* in sociology and network science is labeled *cumulative advantage* or *increasing returns* in economics.

Early awareness of varying terminologies in the review process is particularly relevant, as ABMs regularly facilitate the integration of multiple disciplines (Adamatti et al., 2014; Axelrod, 2006; Kelly et al., 2013) and synthesize cognitive, social, and environmental elements from diverse academic backgrounds, especially while science, in general, becomes more interdisciplinary (Bursztyn and Purushothaman, 2015; Okamura, 2019; Van Noorden, 2015; Why Interdisciplinarity Research Matters, 2015). Although this is a desirable development, it generally increases the risk of blind spots by missing relevant model implementations in fields that are not within researchers' traditional sphere, and that are reinforced by mostly discipline-specific journal outlets. Hence, *interdisciplinarity* poses specific requirements for the search strategy of a literature review and, at the same time, contributes to the dissemination of findings across disciplinary boundaries. Another problem pertains to various fields' different (or missing) ontologies. Some tools are developed to assist researchers in this regard and to discover potentially important search terms through text mining and keyword co-occurrence networks (Grames et al., 2019).

More generally, theoretical concepts that appear similar at some level of abstraction can become critically different when formalized (Muelder and Filatova, 2018; Scholz et al., 2019). Such terminological complications are best captured while scoping the literature at the step of research question formulation. Terminological complications can then be addressed during the analysis or in the previous sampling step through a systematic inclusion/exclusion of specific terms in the search or screening step. Indeed, when it comes to sampling, there is no agreement about what "agent-based models" are called! The terms "multi-agent systems," "individual-based models," and "agent-based social simulations" have all been used. This terminological variety can be utilized as an inclusion/exclusion criterion if it resembles disciplinary boundaries. However, if not consciously considered, it may result in a biased sampling process.

In the analysis stage, some issues caused by model heterogeneity are somewhat ameliorated through standardized documentation protocols such as ODD (Grimm et al., 2020), ODD + D (Müller et al., 2013), and ODD+2D (Laatabi et al., 2018), which offer beneficial ways to structure the analysis and explicitly consider model heterogeneity. McAlpine et al. (2021, p.253) observe that "the ODD + D framework offers a valuable approach to extracting and understanding model development and comparison across studies" and promote a broader adoption of this framework among other ABM modelers.

Although SLRs follow a common framework (Table 1), this section illustrates the idiosyncrasies of such a review for the ABM field. Particularly, model heterogeneity is a property of the ABM field, which is believed to delay its cumulative progress and which, at the same time, demands considerable attention through all three phases of an SLR of ABMs. Attending to these challenges enables those who conduct an SLR of ABMs to foster systematic learning beyond individual cases and nourish the grounds for theory development.

2.3. Developing theory using reviews of agent-based models

In general, a problem with theory development is the ongoing philosophy of science debate on what a theory is. Essentially, it depends on the position as to whether theories must be expressed in formal language, and to whether they are to be evaluated exclusively against empirical data. When it comes to modeling, this matter is further complicated by the debate on whether a model as such is a theory (e.g., Balzer et al., 2001), and/or the extent to which models should or can use theories (e.g., Smaldino et al., 2015). Antosz et al. (2023, this issue) more explicitly contrast the ways in which a theory is something that goes *into* a model and/or something that comes *out* of it.

Theory development can be a guiding principle to overcome a disconnected case-by-case modeling practice and to empower cumulative science in ABM research. Defining theory, especially in an interdisciplinary field, usually sparks heated debates. Nevertheless, while agreement on a formal definition is problematic, there are certain common denominators that make it a sound guiding principle. (1) A theory explains systems and their behavior and provides an abstract understanding of a phenomenon using a scientific method. This need for generalization helps to transfer case-by-case knowledge to generalized knowledge. (2) Whether derived inductively or deductively, a theory embodies collected, consolidated, and proven (not yet falsified) knowledge about a phenomenon over time. The need to consolidate knowledge forces research to further confront heterogeneity in models. (3) Developing theory is an established and universally accepted goal in science. Therefore, it is an implicit goal of most research endeavors.

Theory development with simulation models is promoted from different angles. Grimm et al. (2005) establish the practice of pattern-oriented modeling by finding observable patterns that characterize the system under investigation, thus guiding the design of the model structure by finding, in turn, mechanisms and agent characteristics that reproduce these observable patterns. In this process, as part of the model structure, different theories at an agent level are compared against how well they can reproduce the observed patterns. Consequently, complex systems theories can be seen as "sets of conceptually simple mechanisms that produce different dynamics and outcomes in different contexts" (p. 991). Furthermore, theories can also be contrasted on a system level more directly (Radchuk et al., 2016). According to Hedström and Ylikoski (2010), explaining how a phenomenon can be simulated in an ABM is itself considered theory development.

Davis et al. (2007) explain that a hesitancy to utilize simulation methods for theory development originates from "a lack of clarity about the method and its related link to theory development" (p. 480). They argue that the method is especially useful to advance "simple theories" that attest to a weak but readily existing theoretical understanding of the underlying phenomenon. These theories must be more fully developed concerning the precision of constructs, grounded propositions, and a theoretical logic that links the constructs and boundary assumptions. In such situations, simulations are well suited to enhance theoretical precision by elaborating and exploring the underlying mechanisms in a virtual laboratory and incorporating concepts of other theories. Similarly, Smaldino et al. (2015) promote the merit of ABMs as an additional tool in the methodological toolkit for theory development. The necessity of formalization helps to clarify terms and conditions imposed by a hypothesis of either theoretical or empirical origin. It facilitates a transparent benchmark to compare empirical results or general patterns. Sun et al. (2016) argue that, preferably, simple ABMs should be used for theory development, as unnecessary empirical details may congest a model and hinder the goal of theory development. However, if the ability for out-of-sample predictions depends on a model's structural realism, an optimal level of model complexity between oversimplifying and overspecifying is critical (Grimm et al., 2005). Nevertheless, it remains an ongoing debate whether the goals of prediction and theory testing with models are comparable (Tredennick et al., 2021).

The contribution of reviews to theory development is increasingly

Table 2
Dimensions for theory development with ABM reviews.

Nr.	Name	Description	Example
Modeling perspective			
Dim-1	Model element comparison	Comparing the elements included in the reviewed models creates an overview of the entities and processes used to explain and reproduce a phenomenon. This is a way to compare the ability of different models (e.g., behavioral models) to simulate a given pattern, which can lead to theory development.	Castro et al. (2020, p. 14, see table 5) In this example, the inclusion of different markets and policies is analyzed.
Dim-2	Description of mechanisms	Analyzing the mechanisms included in the reviewed models creates a list of candidates to explain a phenomenon.	(Thober et al., 2018, p. 7, see table 5) Mechanisms and causal chains of the socio-ecological feedbacks of climate ABMs are compared.
Theory used			
Dim-3	Discussion of theories used	Analyzing theories included in the model or used as a framework to select model elements and mechanisms provides an opportunity for theory testing. Their comparison in the review can lead to theory development.	Groeneveld et al. (2017, p. 44, see Figure 4) The frequency of different behavioral theories is visualised and discussed.
Dim-4	Discussion of alternative formalizations	How conceptual components are implemented and formalized can vary considerably (Muelder and Filatova, 2018). Drawing attention to alternative formalizations provides an opportunity to align community knowledge and theory development.	Flache et al. (2017) The authors discuss alternative implementations of ideal-type models of social influence.
Beyond understanding single cases			
Dim-5	Generalization	By using models that address the same phenomenon in various settings, areas, or periods, a systematic literature review can identify the common elements necessary to develop theory through generalization.	Malishev and Kramer-Schadt (2021, p. 10, see Figure 1) The categories used to analyze models form a generalization of movement models.
Dim-6	Identify gaps and research avenues	An extensive review of ABMs on a particular topic should highlight blind spots in the existing literature and suggest future research avenues. This contributes to theory development by suggesting unexplored entities, activities, interactions, or mechanisms to explain the phenomenon under investigation.	(Egli et al., 2019, p. 6) The studied models of resilience show a focus on single-mechanism approaches.
Dim-7	Theory development as an explicit focus	In some cases, the review has the explicit goal of developing theory; ABMs are reviewed to explain a system and its behavior and to provide a more general understanding of a phenomenon.	Grimm (1999, p. 140, see Figure 5) A diagram shows the mutual relationships between bottom-up and top-down approaches in ecological modeling.

recognized (Durach et al., 2017; Paul and Criado, 2020; Post et al., 2020; Webster and Watson, 2002). In their editorial, Post et al. (2020) proclaim the untapped potential of literature reviews to advance theory. SLRs show significant potential in advancing research with agent-based models by combining the insights of individual cases, thereby promoting theory development.

For this article's purpose, we suggest seven dimensions on the basis of which ABM reviews can contribute to theory development (Table 2). Here, the term "dimension" is used to describe different angles through which SLRs can contribute to theory development in the context of ABMs.

2.3.1. *Modeling perspective*

First, one can assess and compare ABMs in a SLR from a modeling perspective. A very basic step is to collect and compare the different elements used in the models (*Dim-1*). Here, the review systematically compares elements and submodels of the ABMs, such as the properties of the agents, the environment, and corresponding processes. On the one hand, these comparisons help consolidate previous modeling efforts and document existing implementations, providing ABM researchers with templates and sources of inspiration. On the other hand, such comparisons also shed light on reasoning behind different model design decisions, both in theoretical and empirical terms. In this line, Webster and Watson (2002) highlight the contribution of reviews in the realm of theory development from the perspective of conceptual modeling. To develop a deeper understanding of a phenomenon, they "reason and justify" the design of corresponding models based on their examination of past research. As a next step in the analysis of models we suggest the description of mechanisms as a relevant design component (*Dim-2*). The emergent properties of an ABM arise from the interaction of model elements. Although interactions often follow from direct causal relationships of the model elements, they are subject to design choices. We refer to them as mechanisms if an interacting system of model elements represents, in the aggregate, an independent (dynamic) aspect of the phenomenon (e.g., in foraging models, the animals' movement process as opposed to the interactions required for the model's functioning).

2.3.2. *Theory used*

Second, one can review ABMs concerning theories used. A first step here is the purely descriptive comparison of the used theories (*Dim-3*). Such an analysis can include a reflection on the model assumptions in terms of which theories were chosen and on systematic differences in their produced model outputs. Other than the emphasis on the competition between theories, the integration of theories can also be a feature of such an analysis (Gigerenzer, 2017), being particularly relevant to ABM research given the possibility of using theories on multiple levels of a model (see for example Rai and Robinson, 2015; Secchi and Cowley, 2020; Smith and Conrey, 2007). Beyond the application of theories, their formalization is a crucial step for ABMs (*Dim-4*). Theories are often not presented in a formal language, especially in the social sciences. Hence they must be formalized when developing a computational model (Schlüter et al., 2017; Schwarz et al., 2020). Previous research shows that the same verbal theories can be implemented in distinct ways (Muelder and Filatova, 2018), influencing the model output. Learning about varying formalizations of theories contribute to a better understanding of the potential implications of using a specific theory.

2.3.3. *Beyond understanding single cases*

Finally, SLRs of ABMs can serve as valuable tools for refining our current comprehension of phenomena or topics. They offer a multifaceted approach to advancing and consolidating knowledge beyond the analysis of single cases. Firstly, SLRs enable the generalization of existing knowledge, such as identifying common elements (*Dim-5*), which helps establish a foundational understanding. Secondly, these reviews play a pivotal role in spotlighting gaps in the literature and proposing avenues for future research (*Dim-6*), thereby contributing to theory development by uncovering unexplored facets like entities, activities, interactions, or mechanisms. Thirdly, some reviews explicitly aim at theory development (Paul and Criado, 2020). For instance, when examining ABMs that analyze a specific class of systems and their behavior, the primary goal may be to develop a broader, more comprehensive theory. In such cases, these reviews explicitly prioritize theory development as a research objective (Dim-7).

Collectively, the table provides an overview of seven distinct but non exclusive dimensions potentially employed in systematic literature reviews of ABMs. These dimensions can serve as analytical criteria for evaluating and categorizing the objectives and outcomes of such reviews. In our systematic literature review, we remain agnostic about defining theory. Instead, based on the seven dimensions introduced, we focus on what authors *claim* about the relationships between their review of the literature and the development of theory.

3. Method

Our meta-review aims to take stock of ABM literature reviews published to date, focusing on how these reviews are conducted and how they address theory development. Our research question is:

> *Which share of ABM reviews follow established recommendations concerning the different steps of conducting systematic literature reviews, and how do ABM reviews engage in theory development?*

We consider the different terminologies for *agent-based modeling*, including individual-based modeling used in ecology and multi-agent systems prevalent in the engineering and computer science domains. As multi-agent systems also describe physical or software agents, we explicitly limit our search to the context of simulations. No previously published article has attempted a systematic analysis of the structure of ABM reviews. Hence, we pay special attention to obtaining an exhaustive list of ABM reviews as no benchmark is available to assess the list's comprehensiveness. Consequently, to reduce the risk of a biased sample set, we adopt a broad search approach and refrain from the early use of filters in the identification process. Instead, we use an elaborate screening process to classify the identified records of our database search into relevant and non-relevant groups of ABM reviews per research objective. This results in a comprehensive list of 127 papers representing ABM reviews across disciplines. We only select a subset of these papers, benchmarking the ABM reviews from ecology and the social sciences due to their similarities in modeling practice and understanding of theory. We follow a content-analytical approach for an in-depth analysis of the papers by developing and applying a comprehensive questionnaire that includes multiple-choice and open-text answers. A detailed description of the sampling process and questionnaire development for the content-analysis follows.

3.1. Sample selection

We started with a database-driven search strategy in Web of Science and Scopus, the two most comprehensive multidisciplinary databases (Bar-Ilan, 2018). We commenced the keyword search by testing different keyword combinations and search logics across several iterations. We assessed the keyword string's robustness to balance comprehensiveness and analyzability (see step 1 Table E1). Scanning the results of different keyword searches, we noticed a high share of noise in the search results, which we were unable to remove through terminological adaptation or other search filters. An exclusion based on the year of publication, the number of citations, or other comparable properties was not considered either. Therefore, we decided that a manual screening of the identified records was necessary to reach a reliable sample of papers. We only excluded records of the document type "conference review". Appendix Table E1 and the flowchart in Fig. 1, which follows the guidelines of the PRISMA standard (Page et al., 2021), provide a detailed description of the sample selection process.

To ensure the comprehensiveness of our search process while keeping the workload manageable, we decided on a two-step database-driven strategy. We first used a narrow keyword search, restricting the results by including *TS*[3] = *("literature review" OR "systematic review")* in the search string. The search resulted in 671 records after removing duplicates. We developed a classification schema on a subsample (n = 200) of the records to determine which records were suitable for our review (see Step 2, Table E1). This classification was used to screen all 671 records by the first author's reading of the title, the abstract and, if necessary, the full text. We decided to include only records of Class1 ("Review as the main research method only on ABMs") for further assessment. Consequently excluding records of Class 2 to 7, which contain papers that endanger diluting our analysis for different reasons (e.g. when the literature review includes other simulation paradigms or covers unrelated definitions of "agent-based"). The first author performed the classification step, with the inclusion of co-authors' opinions in feedback discussions. A detailed description of the search string for the databases Web of Science and Scopus, as well as the reasoning behind our decision and a robustness test are disclosed in the supplementary material A0.

A broadening of the search string by replacing the *TS = ("literature review" OR "systematic review")* with *TS = ("review")* resulted in 3026 additional records from both databases after duplicate removal. For our purpose, a quick sampling indicated eligible papers among these results. Therefore, to safeguard the comprehensiveness of our sample set, we screened only the titles of these 3026 additional records to identify their fit to Class1. To ensure the reliability of this process, two authors not involved in the previous narrow search classified the 671 records of the narrow search based only on the title with "yes" (part of Class1), "no" (not part of Class1), or "maybe" (inconclusive, discuss in team and/or read abstract). The comparison of the two authors' results to the screening of the first author, whose decision was based on a reading of the title, the abstract, and the full text, allowed us to evaluate the reliability of the decision based on the title only. We found that the error of falsely excluding an eligible record was 0.8% and, therefore, acceptably small (see Step 6, Table E1). Additional statistical intercoder reliability measures confirmed the validity of the process. The full counting method showed 90% agreement, the partial counting method showed 95% agreement, and Fleiss Kappa showed 63% agreement. Concerning the last measure, which considers chance agreement, a value between 61% and 80% represents a substantial agreement strength (Landis and Koch, 1977).

Hence, for the narrow keyword search, we compared the independent assessments of three of the authors and discussed deviations in the group by skimming the abstract or full text to reach a final decision. Ultimately, we selected 51 records for the final dataset based on the narrow keyword search. For the selection from the broad database search, we partitioned the 3026 records into three equally sized batches. The three authors independently made the inclusion/exclusion decision based only on the title. Again, records could be coded with "In/Out/Maybe." All documents coded with "yes" or "maybe" were discussed in the group by skimming the abstract or the full text to reach a final decision. Moreover, we solicited the opinion of a group of experienced agent-based modelers on ABM reviews they were familiar with, which added five papers to the final dataset (with duplicates removed). Finally, we performed a further search in a selection of simulation-specific journals, which did not produce any papers not covered by our previous search. Ultimately, we allocated 76 documents from the broad keyword search to the final dataset, which resulted in 127 eligible ABM reviews not restricted by time or discipline overall.

The spectrum of ABM modeling practices among the disciplines represented by the 127 studies is broad, as is their relationship to theory. We selected papers from ecology and the social sciences for our assessment because both disciplinary groups show similarities regarding modeling practices, given the overlap of human and ecological systems, and are recognizable by collaborations between the disciplines.

[3] Searches for topic terms in the following fields within a record: Title, abstract, Author Keywords, and Keywords Plus®.

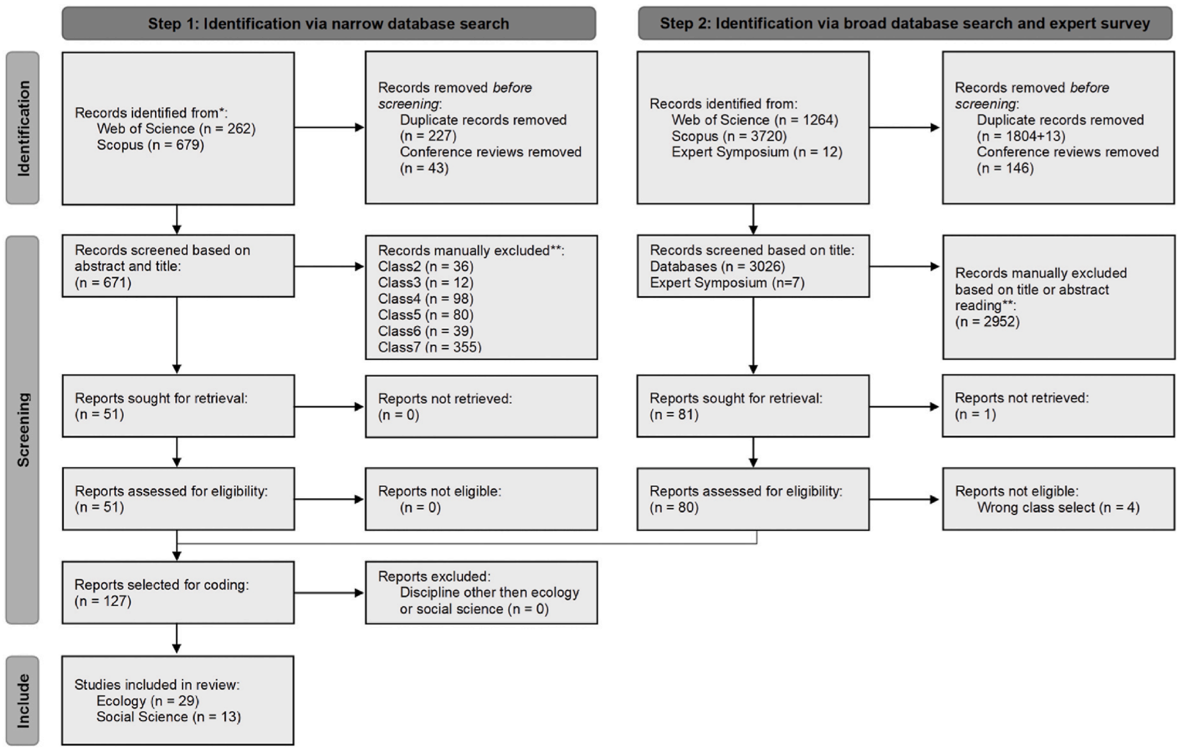

Fig. 1. Sampling process according to PRISMA statement.
Notes: All steps from the list of records of the database search to the list of final sample are disclosed in supplementary data A1.

Although the kinds of theories used and conceptions of theory differ, we expect a level of tension that not only allows a meaningful comparison but also has the potential to propel a leap forward by interdisciplinary learning. Lastly, the expertise of the author team lies in ecology, sociology, economy, geography, and management. Therefore, in the last step of our sampling process, we selected 42 ABM reviews from ecology (n = 29) and the social sciences (n = 13) for our study. We took advantage of the WoS categories and WoS areas to allocate the individual articles to disciplinary groups. This categorization is represented in the supplementary material A1. The resulting breakdown of the 127 articles into their respective disciplinary groups is illustrated in Appendix C.5.

3.2. Sample analysis

The content analysis aims to extract particular aspects of the papers in our sample set that are relevant to our research question. Table 3 depicts the complete step model for the content analysis. We combined a deductive and inductive approach to develop the questionnaire.

We first developed a list of questions that address our formulated research questions from various angles. On the one hand, questions are deductively derived from literature and our prior considerations (see section 2). Hiebl (2021), who investigated the practice of the systematic sampling process in management reviews, exerted a major influence on our questionnaire. On the other hand, we derived questions inductively by examining the papers identified as our sample set.

We arranged and charted the developed questions into the first draft of a workable questionnaire. It was further expanded with coding guidelines, including working definitions, the terminology used, the provision of anchor examples, and specifying coding rules, to reduce subjectivity among the coders. We tested the resulting questionnaire draft with seven researchers (five of whom are part of the author team) on four randomly selected papers of our sample set. We compared the coding results, analyzed all detected differences among the coders (see supplementary data A2), and discussed the results in multiple workshops, thus producing several revisions of the draft questionnaire. The variety of perspectives and the joint discussions of diverging codes objectify the coding results by articulating the researcher's subjective understanding of questions and expected answers, creating an awareness of alternative interpretations (no statistical agreement measures were applied at this stage). As a result, the questionnaire (see Appendix A for an exemplary table of complete coding book, and supplementary data A6 for the applied excel tool) for the content analysis was subdivided into three parts, pooling questions according to the three steps of a systematic literature review.

- Formulate the research question: 2 questions and 2 items.
- Select a sample: 30 questions and 43 items.
- Analyze the sample: 7 questions and 22 items.

The coding of the entire sample set was done by two of the authors. In this step, we performed rigorous reliability checks of the questionnaire. First, in another iteration, the two researchers applied the latest revision of the questionnaire to five randomly selected ecology papers of the sample set. They compared the coding results of each questionnaire item. For the first two parts of the questionnaire, the authors achieved an average percentage agreement rate of 91%, measured as the share of matching answers. For the third part of the questionnaire, an average percentage agreement rate of 75% was achieved (see supplementary data A3). These percentage agreement measures are not sufficient to judge the validity of coding results as they do not account for chance agreement (Lombard, 2002). Nevertheless, they suggest an adequate alignment of the two researchers' coding. Additionally, they indicate problematic items that require a revision of the question or coding guidelines to better align the researchers, which was done based on the identified disagreements. Hence, after another questionnaire revision focusing on the coding guidelines, the two researchers independently coded all 29 ecology papers. The larger sample enabled a quantitative measurement of the questionnaire's validity.

Each item was evaluated individually (Feng, 2015) based on three

Table 3
Content-analytical step model.

Stages	Steps
Initialization	A. Develop a list of questions to address the RQ(s). • Deductively from literature. • By screening the review papers. • Through creative workshops and discussions.
Identification	B. Draft a structured questionnaire. • Select and arrange questions. • Chart the questionnaire layout.
	C. Define coding guidelines. • Define and interpret terminology. • Provide anchor examples. • Specify coding rules.
	D. Preliminary coding of selected review papers by multiple authors (with increasing rigor).
	E. Compare codes and calculate intercoder agreement measures (make use of multiple measures).
	F. Revise questions and coding guidelines based on detected differences and misunderstandings. (For an iterative revision, go back to Step B and repeat the steps from there.)
Completion	G. Final working through of the set of review papers by two researchers acting independently.
	H. Resolve coding misalignments and contingent interpretations.
	I. Present the final coding results

measurements (see supplementary data A4): Cohen's Kappa, Gwet's AC1, and percentage agreement rate. Considered individually, each measurement does not allow for a reliable coding assessment (details and discussions on the limitations of the three measurements are presented in supplementary data A0). When the measures suggest different conclusions about an item's validity, we provide reasons for our choices (supplementary data A4).

The resulting intercoder reliability analysis showed that nine items were unreliable. These items are Q1, Q2, Q33.1, Q33.2, Q33.3, Q33.4, Q33.6, Q34.2, and Q36.4 (see Appendix C.4), they refer to the formulation of the research question, how the review contributes to theory development, the purpose of the review, and the methods used in the analysis. The two authors discussed each difference in the coding in a consequential manner until an agreement was reached, leading to a final revision of the coding guidelines and the question formulations for these items. Also for items that demonstrated a sufficient agreement rate, differences were resolved between the two authors. Lastly, both researchers coded the remaining ABM reviews of the social sciences. Again, differences were resolved in alignment meetings, resulting in a final and aligned coding of all 42 selected ABM reviews (supplementary data A5).

4. How systematic are current ABM reviews?

4.1. Use of research questions

In the following sections we present our results on how systematically ABM reviews are conducted. Concerning the use of research questions, we find in our total sample of 42 records only 10 papers (24%) that explicitly formulate a research question while 13 papers (31%) at least state the aim or objective of their study. Ecology performs better concerning both aspects (see Appendix D.2). 19 papers do not explicitly specify the aim of the reviews. Overall, the observation that many reviews do not clearly state their aim should raise some concern, especially considering that the research questions or objectives provide a focal point for the whole review process and methodological choices. We thus identify a clear opportunity for improvement in future work.

The papers that include research questions formulate more than one research question, ranging from two ([072] - Parrish & Viscido, 2005)][4] up to seven ([050] - Lorig et al., 2021). Most of the time these research questions address various aspects of a theme from different angles, in the sense of "how is a certain phenomenon modeled with ABMs in discipline X," including questions such as parameter specification ([105] - Groeneveld et al., 2017; [034] - Magliocca, 2020; [103] - Parker et al., 2003; [109] - Thober et al., 2018). In other cases, the research questions are more interrelated. This could be the case in subquestions ([015] - Hansen et al., 2019) or in questions building on each other ([054] - Berger et al., 2008). The two social science reviews ([031] - Gu and Blackmore, 2015; [050] - Lorig et al., 2021) only ask questions about "how something is modeled." Although these questions are also incorporated in ecology reviews, certain questions address more general issues (e.g., in [015] - Hansen et al. (2019): "How has ABM contributed to an understanding of energy transitions?"). Overall, some research questions denote a mainly descriptive approach and future reviews should strive to move beyond the simple question of how something is modeled.

4.2. Identifying the literature sample

Our analysis of the sampling process of ABM reviews reveals that it often lacks transparency, is quite diverse in search approaches and databases used, and is rather limited (see Table 4).

Although transparency is fundamental for reproducibility and supports a key argument for conducting SLRs, our first finding is that most papers reviewed are unclear about how their review sample was constituted. Unclear sampling is common in both ecology papers (59%) and social science papers (62%). Untabulated results show that this observation is more frequent in earlier reviews, although still present among recent papers.

Reviews disclosing their sampling method also tend to disclose their search terms and terminological variations (e.g., searching for "agent-based" and "individual-based" models, as well as "multi-agent systems"). Still, approximately half of the authors who include terminological variation do not test for robustness. This is most likely a flaw by omission (the search string being relegated to the supplementary material without a note in the main text) rather than a deliberate decision.

[4] All articles in our sample are referred to by their ID in the format "[XXX] – (Reference)", to distinguish them from other references. The list containing the articles' IDs is presented separately, in Appendix B.

Table 4
Identifying the literature sample.

Question	Ecology		Social Sciences		Total	
	Yes	No	Yes	No	Yes	No
[Q3] To which principal search approaches can the review paper be assigned?[1]						
Journal-Driven	2 (0,07)	27 (0,93)	0 (0,00)	13 (1,00)	2 (0,05)	40 (0,95)
(public) Database-Driven	10 (0,34)	19 (0,66)	4 (0,31)	9 (0,69)	14 (0,33)	28 (0,67)
Seminal-Work-Driven	1 (0,03)	28 (0,97)	1 (0,08)	12 (0,92)	2 (0,05)	40 (0,95)
Others	3 (0,10)	26 (0,90)	0 (0,00)	13 (1,00)	3 (0,07)	39 (0,93)
Approach is unclear	17 (0,59)	12 (0,41)	8 (0,62)	5 (0,38)	25 (0,60)	17 (0,40)
[Q4] Have keywords or the search-string been disclosed?[2]	10 (0,34)	(1 + 18) (0,66)	4 (0,31)	(0 + 9) (0,69)	14 (0,33)	28 (0,67)
[Q5] Did the keyword search consider terminological issues, e.g., varying terms among (sub)disciplines or differing meanings of abstract concepts?[3]	9 (0,31)	(2 + 18) (0,69)	2 (0,15)	(2 + 9) (0,85)	11 (0,26)	31 (0,74)
[Q6] Is the process of determining the final keywords/search-string disclosed, e.g., showing its robustness?[4]	4 (0,14)	(7 + 18) (0,86)	2 (0,15)	(2 + 9) (0,85)	6 (0,14)	36 (0,86)
[Q8] Have the references of found research items been searched for further relevant research items?	2 (0,07)	27 (0,93)	2 (0,15)	11 (0,85)	4 (0,10)	38 (0,90)
[Q9] Have the citations of initially found research items been searched for further relevant research items?	2 (0,07)	27 (0,93)	2 (0,15)	11 (0,85)	4 (0,10)	38 (0,90)
[Q11] If a database-driven search approach was conducted, which database(s) is (are) used?[5,6]						
Not mentioned	0 (0,00)	(11 + 18) (1,00)	0 (0,00)	(4 + 9) (1,00)	0 (0,00)	42 (1,00)
Scopus	3 (0,10)	(8 + 18) (0,90)	2 (0,15)	(2 + 9) (0,85)	5 (0,12)	37 (0,88)
Web of Science	8 (0,28)	(3 + 18) (0,72)	3 (0,23)	(1 + 9) (0,77)	11 (0,26)	31 (0,74)
Google Scholar	3 (0,10)	(8 + 18) (0,90)	1 (0,08)	(3 + 9) (0,92)	4 (0,10)	38 (0,90)
Others	2 (0,07)	(9 + 18) (0,93)	4 (0,31)	(0 + 9) (0,69)	6 (0,14)	36 (0,86)
[Q12] Have additional research items been included in the review sample based on the authors' prior knowledge or expert recommendations (e.g., by reviewers)?	3 (0,10)	26 (0,90)	0 (0,00)	13 (1,00)	3 (0,07)	39 (0,93)

Notes: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$. [1]A review could also be assigned multiple search approaches, hence the "yes"-column for ecology does not add up to the 29 papers. The three search approaches in the category "others" are labeled: "own (non-public) database," "expert driven," "symposium driven." [2,3,4]The answer "No" is divided into ("No" + "No keyword search applied"). [5]A list of the other databases used can be found in Appendix D.8. [6]The answer "No" is divided into ("No" + "No database search applied").

By contrast, [002] - An (2012) discusses the choice of terms included/excluded from the expression as well as their Boolean connectors, justifying that they "did not use 'AND' to connect the two parts because this is too restrictive and many relevant papers […] are filtered out" (p.27). Similarly, [051] - Bourceret et al. (2021) relates an iterative set of steps to reach the final list: a process of trial and error common to everyday research experience. Regarding robustness, [034] - Magliocca (2020) identifies "a target set of 11 known articles […] to represent the full expected range of ABM publications in the [Food-Energy-Water-Systems] research domain" (p.3). These target articles are used to initiate and refine the search expression: "the search repeated until all articles in the target set were contained in the search results" (p.4). We therefore advocate that these are good examples to enhance transparency and robustness in ABM reviews.

We identify multiple approaches that coexist to generate samples. Firstly, even though database-driven searches are the dominant method (n = 14), our small sample included papers that used journal-driven (n = 2, in combination with a database-driven approach), seminal-work-driven (n = 2), and other search methods (n = 3). The oldest papers in our sample ([001] - Grimm, 1999 [132] - Van Winkle, Rose and Chambers, 1993); tend to be the least systematic, potentially because of the state of bibliometrics at the time. Database-driven searches are more frequent in social science (50%) than in ecology (33%). Among reviews that used a database-driven search approach, we identified the use of many databases, especially in social science papers. Beyond the usual suspects (Web of Science is used in 11 papers, Scopus in 5 papers, and Google Scholar in 4 papers), the authors made use of ScienceDirect (n = 3); ProQuest (n = 2); PubMed (n = 2) and 21 other sources (such as NBER papers, Wiley Online Library, Elsevier, or the medrxiv, chemrxiv and biorxiv repositories), which were sometimes aggregated through a search engine. This applies to [050] - Lorig et al. (2021), which used COVIDScholar.org to find published and preprint papers containing ABMs of the Covid-19 pandemic. Overall, we note a large database diversity with a database landscape dominated by major publishers and search engines.

Finally, the sampling process reported in our reviewed papers is usually limited to a database-driven search. Only four papers resort to a snowball technique (i.e., looking for additional references in the citations and/or cited items), whereas three mentioned the addition of research items based on prior knowledge or expert recommendations. [109] - Thober et al. (2018) integrates both techniques with an iterative database search in their review of environment-migration models. These methods are less easily automated, but they can complement keyword-based sampling techniques to ensure that as much of the relevant literature as possible is covered.

We found useful examples of sampling methods and thorough reporting, including sources, search expressions, and robustness checks. Nonetheless, these examples are too few compared to the number of papers included in our review. Most flaws are by omission. The resulting lack of reporting and transparency could easily be fixed in the future.

4.3. *Screening and assessing the literature sample*

Concerning the subsequent activity of screening and assessing the identified sample, the results in Table 5 show that the "No" columns largely outweigh their "Yes" counterparts. This suggests trivial steps that reviewers of agent-based models can take to improve the reproducibility and transparency of the processes used to screen the sample of papers. Despite setting a low bar where we did not confirm reproducibility based on disclosed criteria for inclusion and exclusion reported in the reviews [Q14], less than 40% of both ecology and social science reviews disclosed criteria. Concerning the remaining questions in Table 5, the most crucial point is the need for authors to be explicit that the criterion in question has or has not played a role in the screening process and a few additional sentences in the manuscript should be able to address this.

In more detail, the most straightforward information that authors could be encouraged to provide to promote reproducibility pertains to the period covered by the search [Q21-Q23]. Those that did are in a clear minority. Although the authors of papers such as [109] - Thober et al. (2018) state that they do not restrict the date range of the search – which at least is explicit – it is important to disclose the date on which the search was made; "the beginning of 2018," used in paper ([015] - Hansen et al., 2019, p. 43) is better than nothing, although vaguer than the ideal. The reasoning behind any time-related screening should also be disclosed as it may be relevant to any follow-up activity. For example, [001] - Grimm (1999) and [054] - Berger et al. (2008) both review developments in the literature over a ten-year period since the date of a previous review.

More qualitatively, disclosing criteria about the source of the material will also provide the reader a better chance of reproducing the screening. A matter not covered by our questions was screening by accessibility; [015] - Hansen et al. (2019) excluded paywalled papers, while [014] - Utomo et al. (2018, p. 795) stipulated that the papers "must be accessible to the wider academic community" – wording that could well have the same meaning but risk alternative interpretations. Other papers in our sample explicitly excluded literature reviews ([054] - Berger et al., 2008; [131] - Malishev and Kramer-Schadt, 2021; [014] - Utomo et al., 2018), and some used a discipline as an inclusion or exclusion criterion ([001] - Grimm, 1999; [121] - Jager and DeAngelis, 2018; [107] - Matthews et al., 2007).

Only one ecology paper ([015] - Hansen et al., 2019) used citation rates in conjunction with the paper source; the authors of the review included the most highly-cited conference paper returned by their search. Publication rates, citations, and practices differ from one discipline to another (Harzing and Alakangas, 2015; Meyer et al., 2018) and, more importantly, by gender (Mayer and Rathmann, 2018) – especially since it seems that male authors are somewhat more inclined to cite themselves than female authors (King et al., 2017). Hence, using citation and journal metrics as screening criteria is problematic.

In addition to the questions in Table 5, papers can be screened based on their content, which is a more subjective and qualitative criterion that merits disclosure. In ABM literature, the content could pertain to the method and/or the phenomenon. Concerning the method, several papers ([054] - Berger et al., 2008; [124] - Castro et al., 2020; [001] - Grimm, 1999; [121] - Jager and DeAngelis, 2018; [034] - Magliocca, 2020; [014] - Utomo et al., 2018), for example, required that screened papers include an implemented model and/or exclude purely methodological papers or those only presenting conceptual models or frameworks. A challenging aspect of ABM literature, and again a feature of its interdisciplinarity, is the lack of agreement about what an agent – and hence an agent-based model – is (Gilbert and Troitzsch, 2005). This means authors should be explicit about what they understand an ABM to be when screening based on the method. Turning to this phenomenon, few papers ([111] - DeAngelis and Diaz, 2019; [005] - Hellweger and Bucci, 2009; [050] - Lorig et al., 2021 [100] - Werner et al., 2001); define the target system used for screening. Others ([054] - Berger et al., 2008; [121] - Castro et al., 2020; [116] - Egli et al., 2019; [031] - Gu and Blackmore, 2015; [124] - Jager and DeAngelis, 2018; [045] - McAlpine et al., 2021; [014] - Utomo et al., 2018), by contrast, stipulate a broader requirement for the screened papers by relating it to the topic under investigation.

Only [099] - Chekmareva (2016) explicitly state that they include publications written in a language other than English (in this case, Russian). Writing in the field of medical literature, Linares-Espinos et al. (2018) note that SLRs are typically restricted to English-language documents, as well as that not restricting them by language involves a dramatic increase in workload. Of relevance to environmental systems is that where screening is based on phenomena and/or target systems primarily located outside the Anglosphere, it is arguably more challenging to scientifically defend exclusion based on the English language. Most of the ABM reviews in our sample were not explicit about the English language restriction, and we assume that it is only mentioned where search results returned non-English sources. The best practice when documenting SLRs is to be explicit about any language-based screening, even if it is done for pragmatic reasons.

4.4. *Reporting of the sampling process and its results*

The lack of *transparency* observed previously is also noted when analyzing the reporting of the sampling process, with similar practices between the disciplines. Table 6 shows that nearly half of both the ecology and social science papers did not disclose the sampling process. All papers revealing this process, irrespective of the field, did so in the main text, with a few that included the information in the appendix or in supplementary material. The practice of reporting the date on which the literature search was performed is similar for ecology and the social sciences, amounting to only 17% and 15% of the papers, respectively. Only two papers use the PRISMA statement (Preferred Reporting Items

Table 5
Screening and assessing the literature sample.

Question	Ecology		Social Sciences		Total	
	Yes	No	Yes	No	Yes	No
[Q14] Have inclusion and/or exclusion criteria for the sample selection been disclosed?[1]	11 (0,38)	18 (0,62)	5 (0,38)	8 (0,62)	16 (0,38)	26 (0,62)
[Q15] Are (peer-reviewed) "journal papers" explicitly reported as being included in the review sample?	4 (0,14)	25 (0,86)	3 (0,23)	10 (0,77)	7 (0,17)	35 (0,83)
[Q16] Are working or conference papers explicitly reported as being included in the review sample (whether peer-reviewed or not)?	2 (0,07)	27 (0,93)	2 (0,15)	11 (0,85)	4 (0,10)	38 (0,90)
[Q17] Are books or book chapters explicitly reported as being included in the review sample?	2 (0,07)	27 (0,93)	1 (0,08)	12 (0,92)	3 (0,07)	39 (0,93)
[Q18] Is other gray literature (e.g., organizational or governmental reports, speeches, urban plans, and so on) explicitly reported as being included in the review sample?	1 (0,03)	28 (0,97)	0 (0,00)	13 (1,00)	1 (0,02)	41 (0,98)
[Q19] Have citation rates played a role in the sample selection?	1 (0,03)	28 (0,97)	0 (0,00)	13 (1,00)	1 (0,02)	41 (0,98)
[Q20] Are journal quality measures used as inclusion or exclusion criteria?	0 (0,00)	29 (1,00)	0 (0,00)	13 (1,00)	0 (0,00)	42 (1,00)
[Q21] Is the final point in time for the inclusion of items in the review disclosed?	6 (0,21)	23 (0,79)	3 (0,23)	10 (0,77)	9 (0,21)	33 (0,79)
[Q22] Is a specific period of time, other than the final point in time, chosen as inclusion/exclusion criteria?	4 (0,14)	25 (0,86)	1 (0,08)	12 (0,92)	5 (0,12)	37 (0,88)
[Q23] Regarding the previous question, is the reason for the chosen period of time disclosed?[2]	2 (0,07)	27 (0,93)	0 (0,00)	13 (1,00)	2 (0,05)	40 (0,95)
[Q29] Are languages other than English explicitly considered?[3]	0 (0,00)	(26 + 3) (1,00)	1 (0,08)	(8 + 4) (0,92)	1 (0,02)	41 (0,98)

Notes: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$. [1]Is answered with "Yes" if any criteria are disclosed that demonstrate the selection process to the reader. However, for this review, they are not tested for completeness and reproducibility. [2]The two disclosed reasons for choosing a period of time are (1) Another review dating back several years and (2) another book reviewing literature published in 1998. [3]The answer "No" is divided into ("No, not explicitly considered" + "No, only restricted to English").

Table 6
Reporting of the sampling process.

Questions	Ecology		Social Sciences		Total	
	Yes	No	Yes	No	Yes	No
[Q27] Where has the sampling process been disclosed?						
Main text (method section)	15 (0,52)	14 (0,48)	6 (0,46)	7 (0,54)	21 (0,50)	21 (0,50)
Footnote	0 (0,00)	29 (1,00)	1 (0,08)	12 (0,92)	1 (0,02)	41 (0,98)
Appendix	5 (0,17)	24 (0,83)	1 (0,08)	12 (0,92)	6 (0,14)	36 (0,86)
Supplementary material	3 (0,10)	26 (0,90)	2 (0,15)	11 (0,85)	5 (0,12)	37 (0,88)
Not at all	14 (0,48)	15 (0,52)	7 (0,54)	6 (0,46)	21 (0,50)	21 (0,50)
Other	0 (0,00)	29 (1,00)	0 (0,00)	13 (1,00)	0 (0,00)	42 (1,00)
[Q13] Is the date reported on which the literature search was performed?	5 (0,17)	24 (0,83)	2 (0,15)	11 (0,85)	7 (0,17)	35 (0,83)
[Q26] Have multiple researchers been involved in the selection process?[1,2]	(2 + 20) (0,76)	(6 + 1) (0,24)	(3 + 8) (0,85)	(2 + 0) (0,15)	33 (0,79)	9 (0,21)
[Q28] Does the review paper disclose that the titles, abstracts, author-provided keywords, and/or full text have been used for the selection of research items?[3]	6 (0,21)	23 (0,79)	4 (0,31)	9 (0,69)	10 (0,24)	32 (0,76)
[Q30] Has a list of the papers finally included in the review been disclosed separately?	8 (0,28)	21 (0,72)	4 (0,31)	9 (0,69)	12 (0,29)	30 (0,71)
[Q31] Is the complete list of records from before the screening and assessment stage disclosed (raw results of the identification stage)?	1 (0,03)	28 (0,97)	0 (0,00)	13 (1,00)	1 (0,02)	41 (0,98)

Note: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$. [1]The answer "Yes" is divided into ("Yes" + "Seems so, but not explicitly disclosed") and "No" is divided into ("No" + "Does not seem so, but not explicitly disclosed"). [2]Although the papers involve multiple researchers in the selection process, none use intercoder reliability measures. [3]We do not differentiate whether this was in the identification, screening or the assessment step.

for Systematic Reviews and Meta-Analyses) (Page et al., 2021).

Almost one-third of the ecology papers and half of the social science papers disclose the use of titles, abstracts, author-provided keywords, and/or the full text to select research items, regardless whether in the identification, screening, or assessment step. Hence, in the case of two-thirds of the ecology papers and half of the social science papers, it is not known what part of the reviewed texts was used to select research items. This hinders reproducibility.

Almost 40% of the ecology papers and half of the social science papers separately disclose a list of the papers eventually included in the review. Still, only one ecology paper (but none of the social science papers) reports the complete list of records before the screening and assessment stage. Possible reasons for this could be the length of these lists or the non-recognition of its relevancy for transparency and reproducibility.

The literature reviews' sample size varies between the disciplines (see Fig. 2). Note that we did not count the items but only recorded the number if explicitly reported in the paper. The lack of transparency also extends to the issue of how many researchers engaged in selecting items, regardless of the discipline. It seems that multiple researchers were involved in two-thirds of both ecology papers and social science papers, but this is not explicitly stated. Considering the biases inherent in the involvement of multiple coders, we believe that it is vital that reviews mention both the number of researchers involved in the selection process and the use of intercoder reliability measures (as a minimum stating that "any conflicts were resolved by consensus between the authors"). Similar attention should also be paid when multiple researchers engaged in the analysis (e.g., if a coding schema is applied).

4.5. Analysis of the review sample

Two-thirds of the ecology and social science reviews use an unstructured approach when analyzing the items selected for review (see Table 7). The rest use a structured analysis. Except for one social science paper that uses bibliometric analysis, no paper uses quantitative analysis methods like scientific mapping or meta-analysis. By structured analysis, we mean any explicitly organized approach based on, for example, previous research, theory, recommended protocols, or an approach that emerged from the data as such. Most papers in our sample use structures like a codebook or a questionnaire. However, few provide details on how this structure was developed. The Overview, Design concepts and Details (ODD) protocol to describe ABMs was used only once in a social

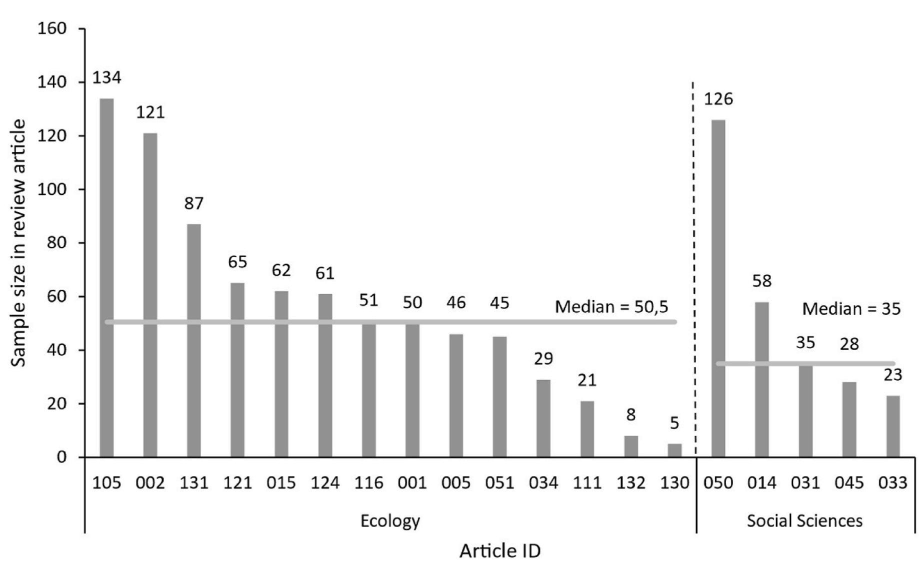

Fig. 2. Sample size in ABM reviews if reported in paper [Q32].

Table 7
Methods for analysis of the sample set.

Question	Ecology		Social Sciences		Total	
	Yes	No	Yes	No	Yes	No
[Q36] What general method is used to analyze the sample dataset?						
Bibliometric analysis	0 (0,00)	29 (1,00)	1 (0,08)	12 (0,92)	1 (0,02)	41 (0,98)
Scientific mapping	0 (0,00)	29 (1,00)	0 (0,00)	13 (1,00)	0 (0,00)	42 (1,00)
Meta-analysis	0 (0,00)	29 (1,00)	0 (0,00)	13 (1,00)	0 (0,00)	42 (1,00)
Structured comparison[1]	9 (0,31)	20 (0,69)	3 (0,23)	10 (0,77)	12 (0,29)	30 (0,71)
Unstructured comparison	20 (0,69)	9 (0,31)	10 (0,77)	3 (0,23)	30 (0,71)	12 (0,29)
[Q38] Are differences in the hardware or software infrastructure, or other technological specifics considered in the analysis/comparison of the papers?	3 (0,10)	26 (0,90)	1 (0,08)	12 (0,92)	4 (0,10)	38 (0,90)

Notes: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$. [1]Structured comparison includes, e.g., a coding book as in content-analysis, an ODD protocol, or any other classification schemas.

science paper ([045] - McAlpine et al., 2021). A structure taken from a previous review was also used only once, this time in an ecology paper ([054] - Berger et al., 2008).

As transparency and reproducibility should not stop when analysis starts, we recommend the following established practices from qualitative/mixed data analysis (Krippendorff, 2018; Miles and Huberman, 1994; Thyer, 2009) for this specific review phase. These practices include but are not limited to (1) developing clear coding instructions that incorporate everything that transpired during their development; (2) testing of the finalized instructions on several different coders; (3) coder training (ideally, content analysts should not also be coders); (4) leaving an audit trail (logs and records concerning research methods and made decisions); (5) reporting details related to coders and analysts, including their preconceptions and assumptions; (6) ensuring that the interpretations of data are empirical, logical, and replicable; (7) documenting how interpretations evolved; (8) cross-checking interpretations by several analysts; and (9) establishing a chain of evidence that is linked to different data sources or peer-debriefings (with peers who are not part of the study). An opportunity for criticism of not only the results but also of how the results were arrived at should be a feature of a review. However, such a high degree of transparency is accompanied by an increased workload, which must be considered when planning the review.

Lastly, differences in the hardware or software infrastructure or other technological specifics considered in the analysis were only recorded in three ecology papers ([051] - Bourceret et al., 2021; [005] - Hellweger and Bucci, 2009 [023] - Wallentin, 2017); and one social science paper ([050] - Lorig et al., 2021).

4.6. Minimum standards for good practice

For an assessment of how systematic ABM literature reviews currently are, we select a set of items from our questionnaire we consider as a minimum standard for good practice. During each of the three steps of an SLR, we evaluated how current ABM reviews compare with respect to these criteria. Although they do not strictly define an SLR, we regard them as a set of good practices based on current SLR knowledge, which are vital to ensure rigorous scientific research when conducting literature reviews that offer value for any review study. For the phase of question formulation, we assessed the proportion of all reviews that clearly formulated a research question, aim, or objective. For the sample selection step, we considered whether the paper documented the search strategy transparently and in a reproducible manner, for example, by reporting diverse inclusion/exclusion criteria (see Appendix F for details on the questions used to assess the sample selection phase). Finally, for the analysis step, the analysis could not be unstructured if the review was to be classified as complying with good practice.

Overall, only five ABM reviews complied with our minimum criteria for SLRs across all three steps (Fig. 3), three of which were in ecology (10%) ([111] - DeAngelis and Diaz, 2019; [034] - Magliocca, 2020 [107] - Matthews et al., 2007); and two in social science (15%) ([050] - Lorig et al., 2021; [045] - McAlpine et al., 2021). The reviews in ecology and the social sciences, respectively, differed remarkably at the step of the research question formulation; whereas most social science reviews did not formulate research questions, ecological reviews of ABMs did. However, for both research fields, most of our criteria were not met at the sample selection step, thus constituting the main "bottleneck" that precluded reviews from being labeled SLRs. Interestingly, seven (6%) out of all studies self-defined as SLRs ([065] - Dawid and Delli Gatti, 2018; [031] - Gu and Blackmore, 2015; [015] - Hansen et al., 2019; [050] - Lorig et al., 2021; [034] - Magliocca, 2020; [045] - McAlpine et al., 2021; [109] - Thober et al., 2018), three in ecology and four in social science. Importantly, there is a mismatch between those studies that self-defined as SLRs and those that were defined as SLRs according to our criteria; only three of the seven reviews that self-defined as SLRs were defined as SLRs according to our criteria ([050] - Lorig et al., 2021; [034] - Magliocca, 2020; [045] - McAlpine et al., 2021). In other words, not only is the proportion of SLRs exceptionally low across all reviews, but the studies that self-defined as SLRs often did not satisfy our expectations of the sample selection step or/and the analysis step. In general, this denotes a lack of a mutual understanding of what constitutes an SLR.

5. Theory development with ABM reviews

5.1. Theory development addressed in the research questions

As a first indicator of the level at which theory development is considered in ABM reviews, we use the acknowledgment of theory when these reviews formulate research questions (see Appendix D.3). According to our criteria, 6 of the 23 reviews (26%) pose a research question that addresses theory development. When comparing ecology and social science, most studies addressing theory development in their research question are found in ecology.

How exactly is theory addressed in these research questions? [051] - Bourceret et al. (2021) and [105] - Groeneveld et al. (2017) investigate the underlying theories of modeling governance processes and human decision-making, respectively. Both papers describe identified theories and how they are used in the models. Notably, [105] - Groeneveld et al. (2017) illustrates how the use of different theories developed over time. Apart from investigating how established concepts and theories on plant competition are considered in ABMs, [054] - Berger et al. (2008) indicates how empirical, theoretical, and simulation work can improve the understanding of the plant competition phenomenon. Another approach to view theory is to determine whether the goal of the models is theoretical insight or simulation for practical purposes such as policy decisions ([103] - Parker et al., 2003). Lastly, the review's objective can be to assess what has been learned from ABMs in a domain or about a phenomenon involving established theoretical knowledge ([001] - Grimm, 1999; [033] - Revay and Cioffi-Revilla, 2018). Generalizing from these observations, we find that theory is addressed (1) by determining which theories underpin modeling decisions and how they

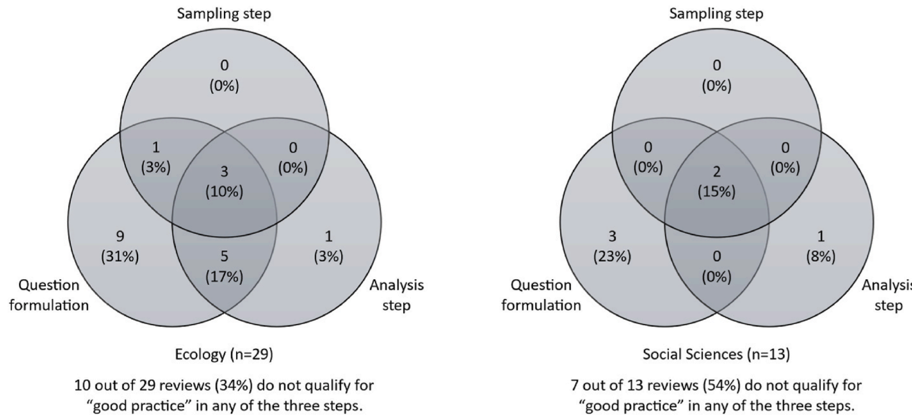

Fig. 3. Venn diagrams showing which papers follow "good practice" along the three SLR steps.
Note: Percentages refer to sample size. Therefore, reviews not qualifying for "good practices" in any of the three steps are not shown. E.g., 10 out of 29 reviews in ecology do not qualify for "good practice" in any of the three steps.

achieve this, (2) by contrasting the theoretical and empirical research orientations of ABMs, and (3) by adding and comparing ABM-generated theoretical insights to established theory.

5.2. Purpose of the review

All but two reviews strongly focus on the design characteristics of ABMs, which address how something is modeled (Table 8). Only 48% apply an insight perspective while none of the review papers adopt an effect perspective. Two studies from ecology that do not adopt a design perspective, apply only an insight perspective. Although intersections are not shown in the table, 18 of the ABM reviews combine the design and insight perspectives, going beyond the review of design choices by considering new insights and lessons generated by the models. The previous section showed that theory development is addressed in research questions by reviewing how theory is used as input for the model design and how theoretical insights are generated as output of the models. The reflection of this dualism resides in the ABM review perspectives. While the design perspective focuses on theory as input for the models, the insight perspective considers theoretical insights as output of the models. Therefore, the imbalance between the design and insight perspectives reflects the disparity between theory utilization and theory development.

Review papers that concentrate on summarizing and comparing design aspects of the models select their sample papers according to different criteria, which should be reflected in the research question and realized in the sampling process. Choices are frequently based on, among others, the phenomenon under investigation (e.g., Covid-19 ([050] - Lorig et al., 2021), migration ([045] - McAlpine et al., 2021; [109] - Thober et al., 2018), or governance ([051] - Bourceret et al., 2021)), an essential submodel or subprocess (e.g., decision-making ([002] - An, 2012; [111] - DeAngelis and Diaz, 2019; [105] - Groeneveld et al., 2017), animal movement ([006] - Tang and Bennett, 2010), or energy budgets ([131] - Malishev and Kramer-Schadt, 2021)), or a research community/domain (e.g., wildlife ecology and management ([004] - McLane et al., 2011), agri-food supply chains ([014] - Utomo et al., 2018), or spatial sciences ([061] - Torrens, 2010)). While [050] - Lorig et al. (2021), for example, includes all ABMs that model the Covid-19 phenomenon, [002] - Chen (2012) selects decision-making submodels within the domain of coupled human and natural systems for the review.

The way design aspects of models are compared varies considerably and depends on the analysis method applied. Most studies use an unstructured analysis method. As a result, differences in design choices are not reported as transparently as possible, potentially lacking the overall quality criteria expected of a systematic analysis. Comparisons can be made paper by paper (e.g., [105] - Groeneveld et al., 2017 [050] - Lorig et al., 2021); or by a preceding grouping of the models into model types (e.g., [002] - An, 2012; [017] - Hunter et al., 2017), which are then compared. For those papers that apply a structured analysis, the analysis of design aspects is organized in terms of predefined dimensions, for example, based on a codebook ([051] - Bourceret et al., 2021; [050] - Lorig et al., 2021 [034] - Magliocca, 2020); or dimensions of the ODD protocol ([045] - McAlpine et al., 2021). Therefore, the analysis becomes more commensurable and transparent if appropriately reported. Furthermore, model designs can be assessed anywhere between the operational or conceptual model levels. We did not find any reviews that compare program code-level designs, but [065] - Dawid and Delli Gatti (2018) and [053] - Flache et al. (2017) describe characteristics of different model types in formulaic form. However, there is a general tendency to answer the "how is something modeled" question at the conceptual end of the spectrum.

The focus on the design perspective reflects the challenge to learn and build on previously developed models, which, if not done, risks inflation of unconnected ABM studies (O'Sullivan et al., 2016), thereby forfeiting the opportunity of cumulative progress. Analyzing and comparing the design of ABMs are a logical consequence of encountering this issue and can help to initiate the reuse of building blocks in the future (Berger et al., 2023, this issue). However, ABM reviews must go beyond the design aspects of models and consider the insights generated by these models to contribute to more general theoretical issues and position ABM contributions in the context of studies using other methodical approaches.

Several reviews combine the design and insight perspectives, which – as we found – are realized in diverse ways. Among others, certain studies might separate the two perspectives into distinct sections (e.g., [124] - Castro et al., 2020; [056] - DeAngelis & Mooij, 2005; [121] - Jager and DeAngelis, 2018). In this regard, [056] - DeAngelis and Mooij, 2005 – reviewing ABMs of ecological and evolutionary processes – offers an excellent example of the utilization of this structure. The authors of this paper describe general design characteristics along five axes and classify models into the main types of the studied biological processes. They continue by summarizing the insights generated by these model types and by assessing these studies' deeper, more profound impact. Interestingly, they return the discussion to the design perspective by selecting six representative papers and scrutinizing their design characteristics in more detail. Another approach is to individually discuss design and insight issues for each paper (e.g., [054] - Berger et al., 2008; [057] - Heckbert et al., 2010; [107] - Matthews et al., 2007; [063] - Schuler et al., 2011). While this approach eases the conveyance of the relationship between design decisions and generated insights, it complicates the identification of generalizations of such links. Nevertheless, an excellent example of how generalizing can succeed is offered by [054] -

Table 8
[Q34] Purpose of the review.

Questions	Ecology		Social Sciences		Total	
	Yes	No	Yes	No	Yes	No
What is the purpose of the review?						
Design perspective: How is something modeled?	27 (0,93)	2 (0,07)	13 (1,00)	0 (0,00)	40 (0,95)	2 (0,05)
Insight perspective: What did we learn from the models?	14 (0,48)	15 (0,52)	6 (0,46)	7 (0,54)	20 (0,48)	22 (0,52)
Effect perspective: Like classical meta-analysis in medicine and psychology.	0 (0,00)	29 (1,00)	0 (0,00)	13 (1,00)	0 (0,00)	42 (1,00)

Notes: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$.

Berger et al. (2008), which reviews spatially explicit ABMs of plant competition. It groups the reviewed papers in model classes according to an existing classification schema with the addition of three new (more recent) modeling approaches. Within these classes and in an alternating manner, the description of the models refers to design aspects of the individual models and that of the model class. Similarly, insights into individual ABMs are presented and generalized with reference to the advantages and disadvantages of each model class.

The usual review sequence starts with the design aspects and then links relevant insights in the subsequent step. Only [033] - Revay and Cioffi-Revilla (2018) uses a reversed sequence. It identifies five thematic classes in which evolutionary ABMs can be categorized. For each of these classes, it briefly summarizes each model and the insights generated regarding each class. In a subsequent chapter, it discusses the design of evolutionary algorithms in the models but disconnect them from the previously discussed thematic classes.

Combining design and insight perspectives allows us to carefully disentangle the link between design decisions and emerging macro-behavior. In this way, ABM reviews can play a part in managing the heterogeneity of ABMs and support the merging of ABM-generated insights with those of other methods. To deal with the complexity of ABMs, a structured analysis of the design aspects and their relation to generated insights can be of future value. Studies must consider which design aspects at what level of detail are required to answer the research questions that address the insight perspective. Doing so is time consuming but worthwhile, and feasible when adopting more structured review approaches.

5.3. *Dimensions of theory development*

Each paper in our sample tackles theory development concerning at least one of the seven dimensions presented in Table 2. ABM reviews in ecology are most likely to address three theory dimensions in a single study. ABM reviews in social science, by contrast, are more likely to focus on only one dimension (see Fig. 4). As Table 9 shows, the dimensions “model element comparison (Dim-1),” “description of mechanisms (Dim-2),” and “identification of gaps and research avenues (Dim-6)” are most prominent in ABM reviews. Hence, they are also the dimensions most frequently co-occurring in the reviews. The reviews rarely address the remaining dimensions, including the “discussion of alternative formalizations (Dim-4),” which is only discussed once in a social science review.

We do not notice a conspicuous difference in cultivating theory development when comparing the five reviews classified as systematic ([111] - DeAngelis and Diaz, 2019; [050] - Lorig et al., 2021; [034] - Magliocca, 2020; [107] - Matthews et al., 2007 [045] - McAlpine et al., 2021); with the remaining reviews of our sample. Instead, we discern a similar representation of the addressed dimensions in the entire sample. Research gaps are discussed in all five of the systematically conducted ABM reviews. A comparison of model elements is made by four ([111] - DeAngelis and Diaz, 2019; [050] - Lorig et al., 2021; [034] - Magliocca, 2020 [045] - McAlpine et al., 2021); of the five reviews. Additionally, [045] - McAlpine et al., 2021 elaborates on the theories used, while [050] - Lorig et al. (2021) and [111] - DeAngelis and Diaz (2019) describe mechanisms. We therefore conclude that the systematic

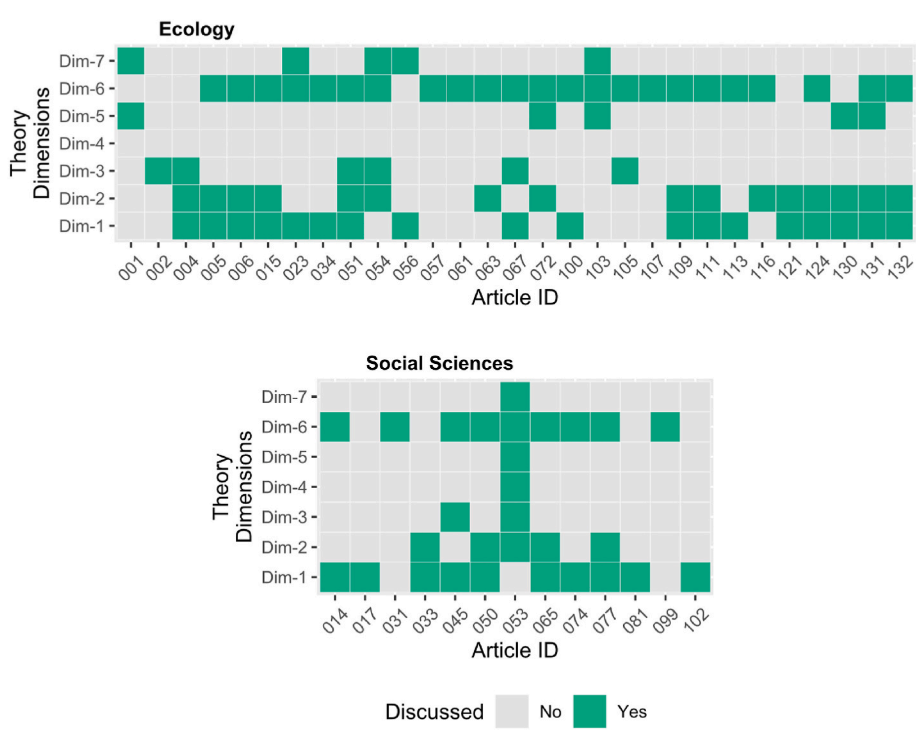

Fig. 4. Combination of theory dimensions per ABM review.

Table 9
[Q33] Addressing theory development in ABM reviews.

Question	Ecology		Social Sciences		Total	
	Yes	No	Yes	No	Yes	No
How did the review add to theory development?						
Model element comparison (Dim-1)	18 (0,62)	11 (0,38)	10 (0,77)	3 (0,23)	28 (0,67)	14 (0,33)
Description of mechanisms (Dim-2)	16 (0,55)	13 (0,45)	5 (0,38)	8 (0,62)	21 (0,50)	21 (0,50)
Discussion of used theories (Dim-3)	6 (0,21)	23 (0,79)	2 (0,15)	11 (0,85)	8 (0,19)	34 (0,81)
Discussion of alternative formalizations (Dim-4)	0 (0,00)	29 (1,00)	1 (0,08)	12 (0,92)	1 (0,02)	41 (0,98)
Generalization (Dim-5)	5 (0,17)	24 (0,83)	1 (0,08)	12 (0,92)	6 (0,14)	36 (0,86)
Identification of gaps and research avenues (Dim-6)	23 (0,79)	6 (0,21)	9 (0,69)	4 (0,31)	32 (0,76)	10 (0,24)
Theory development as an explicit focus (Dim-7)	5 (0,17)	24 (0,83)	1 (0,08)	12 (0,92)	6 (0,14)	36 (0,86)

Notes: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$. Papers typically address multiple theory dimensions; hence, Yes-columns do not add up to the number of reviewed papers. All papers address theory development on at least one of the dimensions.

conduct of an ABM review does not seem to make *per se* contributions to theory development. Next, we examine how the theory development dimensions are addressed and exemplify the results based on selected review papers.

5.3.1. *Modeling perspective*

Directly tied to the comparison of model elements is our definition of mechanisms as the causal connection of model elements corresponding to subsystems of a phenomenon. We find that two theory dimensions, namely model element comparison (Dim-1) and description of mechanisms (Dim-2) are among those regularly addressed and that co-occur most frequently (e.g., [050] - Lorig et al., 2021; [006] - Tang and Bennett, 2010).

Model element comparison (Dim-1). The reviews in our sample offer a variety of styles to compare model elements, among others, in terms of comprehensiveness, use of visualization, selection of elements, or depth of description. Model element comparisons are often merely undertaken as a narrative description of the elements that are used, while other reviews apply a more quantitative data-driven approach to their comparisons. One of our sample's most comprehensive model element comparisons is found in [050] - Lorig et al. (2021, see its entire section 4), which offers several examples. Its structured analysis is a commendable example of the direction in which the transparency of ABM reviews should develop. The review is clearly defined as an investigation of models of the Covid-19 pandemic. The represented elements in these models are comprehensively listed and quantified, and the comparison is supported with visualizations. Additionally, the review exemplifies how the comparison of model elements and the description of mechanisms are connected, as they analyze all possible elements included in the simulation of transmission mechanisms. Another example of a commendable quantitative data-driven comparison with a narrative report is [034] - Magliocca (2020). The author of this paper compares model elements in their review on integrating human behavior into food-energy-water models. Besides a narrative comparison, they also provide quantitative insights into the number of reviewed papers that included certain model elements. They also visualize the relationship between the model's spatial extent and the time steps used (p.10-13).

An example of a narrative style to compare model elements is provided by [121] - Jager and DeAngelis (2018). Instead of introducing a comprehensive list of model elements, only a few main model elements are discussed, seemingly those that cause significant changes in outcomes, insights, or assumptions. As with any analysis, a transparent presentation and description of model elements (and of mechanisms) is only a first step before commencing with the interpretation of findings. Reviews with the purpose of combining the design and insight perspectives are of value. [121] - Jager and DeAngelis (2018) show how to go beyond a mere description of the compared model elements and, instead, examine the different outcomes they lead to. The next-generation ABM reviews should combine transparent and descriptive reporting while deriving insights about the ranges of outcomes caused by different model designs. Another example of a narrative comparison style is [131] - Malishev and Kramer-Schadt (2021). The authors review ABMs of animal movement with a specific focus on how energetic mechanisms (metabolism in the wider sense) are integrated into the models as connectors of multiple model elements and scales. They describe and compare the design of the ABMs regarding three themes (foraging and local habitat selection, memory and cognition, and home range occupancy and dispersal potential), within which they compare the model elements. They also explicitly compare selected element types across all reviewed papers in a comprehensive table (p.3-10) which is an excellent example for a visualization of a systematic comparison, while a more detailed and narrative description is presented in the text.

5.3.2. *Description of mechanisms (Dim-2)*

The reviews address mechanisms to varying degrees, ranging from a few paragraphs ([124] - Castro et al., 2020 [004] - McLane et al., 2011); to dedicated sections ([131] - Malishev and Kramer-Schadt, 2021; [006] - Tang and Bennett, 2010). The prominence of each mechanism's discussion depends on the addressed phenomenon or topic and, therefore, cannot be used as a quality criterion. In certain circumstances, a short paragraph might suffice. An example of the latter is [004] - McLane et al. (2011), which compares different mechanistic approaches to animal-movement rules expressed in different variations of the random walk theory. The authors of this review introduce the different variations and briefly discuss what goes into the selection decision. By contrast, [006] - Tang and Bennett (2010) devote their entire review to modeling animal movement dynamics in ABMs. They offer deeper insights into the mechanisms. Another example is [054] - Berger et al. (2008), who examine how different ABM modeling approaches (mechanistically) represent plant competition. Competition is a key process in natural populations and communities and different theories address plant competition in ABMs in several ways, which is the central focus of this review. In sum, although reviews can have a variety of goals, the comprehensiveness with which mechanisms are addressed depends on the particular purpose of each review.

The description of mechanisms ranges from the conceptual level to the operational level. The ABM reviews in our sample are almost without exception located at the conceptual end of the spectrum. For example, [005] - Hellweger and Bucci (2009) describes the different mechanisms through which microbe populations can produce or maintain heterogeneity due to their high growth and turnover rates. The mechanisms are discussed in the context of the biological phenomenon and are presented as an essential consideration for the simulation model. With a focus on the insights that can be derived from models, [072] - Parrish and Viscido, 2005 review ABMs that address fish schooling. Their goal is to understand the mechanisms used in the model to produce the schooling behavior of fish. They describe these mechanisms on a conceptual/theoretical level and focus on insights that can be derived from the models (only insight, no design perspective). A different approach is adopted by [109] - Thober et al. (2018) who review ABMs of migration.

They use a conceptual diagram to illustrate the elements represented in migration models and their interconnectedness. This conceptual basis facilitates the discussion of the combination of elements that represent migration decisions (aka mechanisms). In another example [050] - Lorig et al. (2021) review ABM Covid-19 models and compare the different implementations of transmission mechanisms. By comparing a range of factors included in the transmission mechanisms (e.g., age, distance, density), that influence infection probability, they remain on a distinctly conceptual level. Although we find no review that strictly compares mechanisms at the level of formalization, [053] - Flache et al. (2017) is an example that moves toward the operational end of the spectrum. The authors review ABMs of social influence and distinguish between three different ideal types of social influence. Although they discuss the theoretical origin of this distinction, they also compare the implementation of these "basic" mechanisms in a formulaic format.

5.3.3. Theory used

Reviews of ABMs often involve the discussion of theories that are used in the models. Some reviews comprehensively discuss the theories used, while others only briefly mention them. However, understanding the theories used in ABMs is crucial to assess the model's validity, and can also uncover differences in model design and output linked to deeper theoretical assumptions. Alternative formalizations of a theory, however, are found to be discussed in only one review.

Discussion of used theories (Dim-3). An example of an ecological study that discusses used theories in ABMs is [002] - An (2012). They discuss theories that are related to human decision-making in coupled human and natural systems. However, the comprehensiveness and centrality of theory in the discussion vary, depending on the decision-making type. Similarly, [051] - Bourceret et al. (2021) review the use of theories to model governance in socio-ecological ABMs, and find that more than half of the decision-making processes are modeled in accordance with theoretical assumptions. They dedicate an entire section to this issue and refer to other reviews on decision-making in ABMs (including [002] - An, 2012). Another study concerns the theoretical foundation of human decision-making in ABMs ([105] - Groeneveld et al., 2017). Its authors address the use of decision theories in one of their four research questions, and attribute a prominent role to this topic in their paper. The paper serves as a commendable example of how to describe the use of theories, and also provides a quantitative analysis of the frequency at which theories are used and how this use developed over time.

In the context of plant competition, [054] - Berger et al. (2008) analyze the concepts represented in existing ABMs, differences in their level of detail, and missing components. They also refer to the neglect of testing theoretical assumptions, which should be integral to the development of theories. [054] - Aerts (2020) discusses the use of theory in the context of the conceptual design of ABMs for flood risk assessment, focusing on behavioral theories. They also spend an entire subsection on the issue and place the theories in a conceptual design of a flood risk ABM.

In social science, [045] - McAlpine et al., 2021 review ABMs of migration and slavery and reports on each reviewed paper's theoretical basis and its use of decision models. However, the theories are only briefly mentioned in a single paragraph and, compared to the ecology reviews, are not comprehensively described. [053] - Flache et al. (2017), by contrast, introduce and compares theories that form the basis of four ideal-type models. While this comparison is not very comprehensive, it is explicitly addressed along with the empirical foundations of the ideal types.

We can conclude that some reviews extend beyond the description of theories used by contrasting their role in ABM studies. In the context of social ecological systems, this challenge underscores the broader issue of creating theories that bridge scales from individual agents to the larger social or ecological systems they are part of. [002] - An (2012) emphasizes the inherent complexity and challenges in realistically simulating human decision-making, a crucial facet for effectively coupling human and natural systems. Similarly, [054] - Berger et al. (2008) find modelers paying insufficient attention to agents' adaptation to the environment, and their modification of it. Nevertheless, more often reviews emphasize the advantages of embracing disciplinary and theoretical diversity ([002] - An, 2012; [051] - Bourceret et al., 2021; [105] - Groeneveld et al., 2017; [045] - McAlpine et al., 2021), an often-missing prerequisite for advancing cross-level theory development in literature reviews.

Alternative formalizations (Dim-4). [053] - Flache et al. (2017) is the only ABM review that explicitly considers alternative formalizations. While defining three ideal types of social influence models, it attributes an entire subsection to discuss alternative implementations of each ideal type. Although this review is not a textbook case of discussing an alternative formalization of an established theory, it is the only one that remotely falls in this category. Each of these ideal types of social influence models can be seen as a theory, and the paper continues by discussing their formal implementation. However, this is done narratively and not by demonstrating different formalizations.

5.3.4. Beyond understanding single cases

Our analysis reveals that generalizations are primarily made in a qualitative fashion. While discussions regarding research gaps and prospective avenues are common, their depth and extent vary considerably. In contrast, the explicit treatment of theory development, if addressed at all, tends to be presented in a rather generic manner.

Generalization (Dim-5). We find that five ecology reviews and only one social science review generalize findings. Generalization in the context of ABM reviews refers to the ability to generalize findings across multiple studies, either statistically using quantitative methods or narratively. The latter can include the use of qualitative methods. As our results on the analysis methods used and the non-existing engagement with an effect perspective show, we do not find the required application of statistical methods to generalize findings across ABM studies. However, we find that the narrative form captures generalizations by applying qualitative methods across multiple studies. This manifests in the identification of patterns (e.g., [103] - Parker et al., 2003; [072] - Parker et al., 2003), the discovery of relationships (e.g., [131] - Malishev and Kramer-Schadt, 2021; [130] - Mortensen et al., 2021), or the more abstract discussion of how ABMs contribute to generalization in a specific discipline (e.g., [001] - Grimm, 1999; [103] - Parker et al., 2003).

[072] - Parrish and Viscido (2005) devotes a single paragraph to list several generalizations about the traffic rules of fish schools (p.70-72). [103] - Parker et al. (2003) describes general insights into how theory development can be achieved with ABMs (p.325-326). Its authors do not address the generalization of a specific phenomenon, but of theory development in general.

[130] - Mortensen et al. (2021) review ABMs that incorporate the impact of sound on marine animals. They use insights into spatial effects revealed by the ABMs to improve an existing framework used to evaluate how marine mammal behavior changes when exposed to acoustic disturbances (PCAD-framework – Population Consequences of Acoustic Disturbance). [131] - Malishev and Kramer-Schadt (2021) conceptualizes animal movement by incorporating it in ABMs through a hierarchical structure (see p.10).

By asking the question on what has been learned about general theoretical issues in population ecology, [001] - Grimm (1999) examines whether a unified theory has emerged. [053] - Flache et al. (2017) review ABMs of social influence, and its authors generalize three ideal-types of models with specific properties. The development of ideal types is an interesting step that can be undertaken after classifying models. Creating ideal types is an established procedure in qualitative social science and can be a helpful tool of the analysis step in SLRs (see for example Kluge, 2000). The procedure defines variables to distinguish the model classes based on certain core characteristics and describes them in an idealized form. Based on these descriptions, the variables can be contrasted without being overwhelmed by the models' heterogeneity.

Research gaps (Dim-6). Identifying research gaps and future research avenues, including current challenges, is the most frequently addressed theory development dimension. Overall, 32 of the 42 ABM reviews in our sample address this issue to varying degrees, with 79% and 69% of the sampled reviews in ecology and social science, respectively. This issue and the related research gaps, avenues and challenges are mostly addressed in the concluding discussion or similar sections at the end of the papers. The scope of these conclusions varies and ranges between a few paragraphs (e.g., [124] - Castro et al., 2020; [045] - McAlpine et al., 2021), a significant part of the discussion (e.g., [050] - Lorig et al., 2021), or a dedicated section (e.g., [054] - Berger et al., 2008; [053] - Flache et al., 2017). While the earlier ABM reviews identified research gaps and covered the ABM method in general (e.g., [132] - Van Winkle et al., 1993), the recent reviews address gaps and research avenues regarding the phenomena (e.g., [109] - Thober et al., 2018). This dimension is rarely the central focus of the review. However, [014] - Utomo et al. (2018) is an interesting exception. Its authors start by analyzing the use of ABMs in agri-food supply chain research, and then compare this use with the general research landscape of agri-food supply chains to identify gaps and future research avenues for ABMs.

Theory development as an explicit focus (Dim-7). Reviews of ABMs often discuss their contribution to theory development. However, only six review papers, including one in social science, explicitly address theory development. In these reviews, the discussion mostly remains at a generic level and covers how ABMs can or should participate more generally in theory development.

One review paper on population ecology identifies pragmatic and paradigmatic motivations, of which only the latter makes provision for theoretical synthesis (theory development). [001] - Grimm (1999) finds that only 30% of the papers fall into the latter category, concluding that ABMs must be directed at theory. [054] - Berger et al. (2008) recommend the "theory development cycle" by Grimm and Railsback (2005). All potential theories and submodels that explain population-level patterns should be compared to determine how they reproduce multiple empirically observed patterns of plant interaction, iteratively refining the theories in this manner. [023] - Wallentin (2017) focuses on spatially explicit ABMs in ecology and discusses their contribution to theories as a general challenge confronting ABMs. Furthermore, the author discuss the role of Big Data in a theoretical context and conclude that data-driven spatial simulation can link large empirical datasets to ecological theory. Similarly, [056] - DeAngelis and Diaz (2019) draw attention to spatially explicit ABMs that not only investigate the consequences of local interactions on the population level, but also contribute to ecological theory. Lastly, [053] - Flache et al. (2017) acknowledge the problem that many ABMs "fail to identify how they add to insights of earlier work" (para. 3.2). The paper proposes three directions for future theoretical work that reviews should address. These directions include the comparison of alternative operationalizations under the same theoretical assumption, the comparison of different theoretical approaches to a phenomenon, and the investigation of the way in which various micro-level mechanisms stem from fundamental principles, which may vary depending on the specific conditions.

6. Discussion and conclusion

The ABM landscape is often case-specific and tends to neglect the importance of incorporating insights and experiences from previous models into new models. This is an issue that leads to an accumulation of models without or, in the best case, with slow theoretical progress. However, conducting thorough literature reviews can help solve this problem. Given this context, we examine the current practices of reviewing ABMs and provide recommendations.

Based on our findings, there are several concerns regarding the current practice of ABM literature reviews that should be considered for future research and practices. Although only a fraction of the examined ABM reviews claims to be conducted systematically, transparency and reproducibility should be a concern of any research project in order to foster cumulative science. We can attest to a gap between current practice and SLR principles.

There might be various reasons for this situation. Researchers conducting ABM reviews might not be convinced of the usefulness of SLRs and do not always realize that their benefits outweigh the increased effort. Furthermore, the absence of established guidelines for ABM researchers and a lack of pressure from reviewers and editors may amplify this problem. It could also be due to a lack of training and awareness of SLRs in the ABM community. Indeed, the academic backgrounds of ABM researchers differ considerably, and alternative practices of reviewing the literature may exist in their "home disciplines."

We believe this article promotes the benefits of SLRs. It provides authors, reviewers, and editors an anchor point for advice and discussion. Besides the detailed assessment of the current state of ABM reviews and the presentation of a range of practices, we highlight certain key activities and related issues that should be considered in future review endeavors. Table 10 summarizes the main findings from various stages of an SLR and offers selected recommendations.

Concerning the first review step, a thoroughly deliberated research question supports the entire research process. It establishes which of the three perspectives (design, insight, effect) the review addresses. It can also help researchers assess how heterogeneity among published models impacts their review results and how they may take it into account in the research process. During the early phase of establishing the research question and determining its scope and specifications, it is possible to consider terminological issues while scoping the literature.

The sampling process often lacks transparency, both in ecology and social science. When conducting SLRs, it is crucial to consider alternative terminologies during the sample selection process, as it heavily depends on semantic matching. To find relevant papers, the search term in ABM reviews typically has two general components. The first component limits the search results to papers that apply an agent-based modeling approach. Since there are a variety of synonyms used for "agent-based modeling" in different communities (e.g., "individual-based modeling" or "multi-agent simulation"), their consideration in the search string is crucial for the comprehensiveness of results. The second component of the search term is usually related to the investigated phenomenon or system. At times, a too detailed and specific search string may fall short of adequately capturing the diversity of phenomena and models. Hence, using a broader search string might be unavoidable to ensure the inclusion of all relevant papers. Consequently, one must apply a more elaborate screening process to separate relevant from non-relevant papers beyond semantics. In this regard, see the procedure in this article as an example of how to use categorization and inter-rater reliability measures. Currently, we find that using inter-coder reliability measures or even transparent reporting of who engages in the selection process is mostly lacking and needs improvement.

During sample selection, a close inspection of the conceptual or implemented model might be necessary. Although reporting standards like the ODD protocol and online platforms like Comses Network, 2023 are regarded as good practices for disclosing the model code, not every paper satisfies these criteria. Older papers rarely hold up to these standards. If the code is not sufficiently disclosed, this potentially impairs trust in the models. Here, a codebook or a questionnaire are reasonable instruments to include for quality considerations in the sampling process and to further narrow down the final sample set, e.g., by excluding studies that do not disclose their program code. Given the review-specific form of such measures, their transparent disclosure is essential.

Regarding sample selection, we recommend addressing standard criteria like time range, source types, or other database-specific criteria,

Table 10
Summary of the current practices and recommendations.

Step and Related Activities	Current Practice	Recommendations and Issues To Be Considered
1. Formulate research question(s)		
Use of research question(s).	Only 10 papers formulate a research question (24%), 13 state the aim of the paper (31 %).	- What is the exact research question? - What are alternative formulations of the research question, and what are their respective implications for the project (including sampling and analysis decisions)?
Relationship to theory development.	About 14% of the reviews address theory development in their research questions.	- Does the review provide the opportunity to develop theory (underlying theories, theoretical insights generated by ABM, etc.)? - Which of the three perspectives (design, insight, effect) does the review address?
2. *Select a sample*		
Select and identify the literature sample.	The sampling process often lacks transparency (60% unclear sampling approach).	- Have the appropriate databases been chosen? - What alternative terminologies must be considered for the sample selection process? - Consider the variety of synonyms used for “agent-based modeling” in different communities (e.g., “individual-based modeling” or “multi-agent simulation”). - What is an appropriate search term for the investigated phenomenon/system? - Has the robustness of the search/search string been demonstrated? - How can the search strategy ensure completeness and potentially be complemented (e.g., snowballing, experts, etc.)?
Assess the literature sample.	Fewer than 40% of the reviews disclose the criteria used for sample selection.	- Which inclusion and/or exclusion criteria were used for the sample selection? - What is the reviewed time period, and what are the reasons for choosing it? - Use journal metrics cautiously in interdisciplinary fields, considering their limitations. - If content-specific criteria are used, be especially mindful of reproducibility.
Report on the sampling process.	About 50% of the papers do not report sampling information.	- Is the disclosed sampling process detailed enough for it to be reproducible? - How many researchers engaged in the sampling process, and how can reliability measures be used?
3. *Analyze the sample*		
Extract and synthesize data.	About 71% of the papers use an unstructured analysis.	- Which methods to analyze the sample are preferred? - What are the possibilities of systematic data extraction and synthesis from the sample? - Can the presentation be structured, e.g., using the ODD protocol or other standards? - How can heterogeneity be addressed best? - Can best practices from qualitative/mixed data analysis studies be utilized?
Present the results.		- Can visualizations support the narrative of the review?

whether applied or not, making the results readily reproducible. In the course of this, authors can also disclose at which point in the sampling process the inclusion/exclusion criteria were applied, for example, during the identification, screening, or assessment phases, if this adds to the traceability of the resulting sample. Authors can exploit state-of-the-art materials and established guidelines. Standards like the Prisma statement (“Preferred Reporting Items for Systematic Reviews and Meta-Analyses”) offer explicit guidelines and checklists to ensure a sufficient minimum level of reporting (Moher et al., 2009; Page et al., 2021). Furthermore, different disciplines require registering an SLR before it is conducted (Prospero,[5] Cochrane[6]), an exercise also conceivable for ABM reviews.

SLRs are often defined as having “complete” samples. However, given the comprehensiveness of available literature and challenges due to the interdisciplinarity of ABMs, completeness might not be the only appropriate criterion. The “representativeness” of the sample legitimizes the findings if the characteristics of the sample are considered during the analysis. Most importantly, the authors should be explicit about their final sample choice so that the readers can independently judge the reliability of the review. An astonishing 40% of the ecology and 50% of social science reviews do not disclose their final literature sample, which is an issue any literature review should resolve. It is essential to distinguish the literature in the final sample from other literature accompanying the paper.

While the sampling process aims to create a suitable dataset, analyzing the data generates insights. This second aspect appears to be neglected. Many of the ABM-specific challenges of conducting SLRs pertain to the analysis step. Hence, we pay attention to the knowledge discovery process based on a systematically selected sample, especially concerning theory development. Such a focus sets this article apart from other “advice-giving” work on how to conduct an SLR. Our results show that for both disciplines, more effort and rigor should go into the analysis step of ABM literature reviews.

Leveraging existing protocols and procedures from the ABM literature can aid the analysis phase. Standards for model documentation, such as ODD (or ODD + D)), may help, particularly concerning the design perspective (Grimm et al., 2020). These standards have provided a helpful basis for determining categories and comparing the ABMs (e.g., [045] - McAlpine et al., 2021). Observed patterns or stylized facts can also structure such an analysis (Heine et al., 2005; Meyer, 2011). McAlpine et al., 2021 highlight that the broader use of documentation standards would pave the way for more systematic reviews of ABMs and support advancements in the respective fields. Whether the ODD protocol is used to create an adapted codebook or questionnaire or if information from the applied ODD protocol forms the database for the analysis depends on the individual case. Likewise, guidelines for conducting and reporting simulation experiments (Lorscheid et al., 2012) could support the purpose of systematic reviews concerning the “insight perspective.” In addition, the TRACE documentation framework, which serves as a modeling notebook, can also be of great value (Ayllón et al., 2021), similar to other standards (Achter et al., 2022). Finally, the systematic comparison of heterogeneous models benefits from initiatives promoting reusable building blocks in ABM (e.g., Berger et al., 2023, this issue).

While the sample of ABMs will typically exhibit heterogeneity regardless of the chosen perspectives, handling this complexity becomes more challenging as we move from the design to the insight to the effect perspective. Indeed, the models may differ in how they implemented different processes and modeled the specific ecosystems, for example, forests, or grasslands (design perspective). These design differences may lead to diversity in the behavior and outcomes of the model (insight perspective) and eventually result in variations in specific model outputs, such as the coefficient of variation of biomass (effect perspective). It is essential to extract the relevant information from papers based on the review’s purpose.[7] However, tracing the differences in outcomes and

[5] https://www.crd.york.ac.uk/PROSPERO/.
[6] https://community.cochrane.org/review-production/production-resources/proposing-and-registering-new-cochrane-reviews.
[7] Model Intercomparison projects in other disciplines, such as ISIMIP and AgMIP, may offer useful materials on which to base more rigorous and/or standardized approaches to comparing agent-based models.

outputs back to design choices and interpretations of the target system can be challenging. Hence, the extent to which model heterogeneity should be addressed in a review depends not only on its general level but also on the purpose of the review. This requires careful consideration at the beginning of an ABM review study and throughout its execution. The lack of structured analyses in most assessed ABM reviews deserves attention and is recommended as a focus of future ABM review studies.

Finally, the ABM community can gain valuable insights by exploring other methodical fields that prioritize measurement theories when utilizing established theoretical constructs in surveys or experiments. Adding bibliometric analyses to the analysis toolkit can assist in identifying connections between models and tracking design advancements (e.g., Hauke et al., 2017; Meyer et al., 2009). This, in turn, can aid in identifying and utilizing reusable building blocks. Furthermore, resulting citation networks paired with word-occurrence analyses can help to determine the frontiers of terminology, theories, concepts, and formalizations. Similarly, scientific mapping offers a starting point for reviews (Chen, 2017), saving time in selecting papers and providing greater capacity for in-depth comparisons of models through more specific research questions.

Our study also shows that ABM reviews already engage in theory development. However, our findings concerning the different dimensions adopted in ABM reviews confirm a strong focus on the design aspects of models. Neglected focus on the insight perspective indicates the enormous potential of future ABM reviews. The complexity of ABMs makes a design comparison vital, especially when not all sampled ABMs are built upon standard scaffolding. A design analysis should more frequently form the basis for discussing the results and insights that the ABMs generate. Although 43% of the ABM reviews combine design and insight perspectives, the link between them is rarely explicitly addressed.

In our sample, theory development is rarely addressed in the research question, although more often in ecology. The observation that this is seldom done explicitly indicates that researchers do not strongly link the practice of conducting literature reviews to the opportunity for theory development. However, this does not mean that reviews of ABMs do not enage in theory development at all. Considering the proposed seven dimensions for theory development, we find that ABM reviews already engage in this endeavor. We aim to promote greater awareness and encourage more careful consideration of these dimensions. Ecology is slightly ahead in addressing theory development across all dimensions, except for model element comparison, where social science reviews have a higher share. The dimensions that exhibit a strong correlation with the design perspective are the ones that appear most frequently.

Establishing connections between design aspects and model insights may be supported by analysis methods that provide a more structured approach to extracting information from models. They also help to retrace model design choices and outputs to theoretical assumptions to test, expand, or explore their limitations. We find that ABM reviews currently refrain from discussing theory or their implications for theory. More often, what is examined is the extent to which theories are used to inspire model designs. Reviewing the use of theories to provide a state-of-the-art overview helps a community understand the underlying assumptions in which the models are rooted. We could interpret this as theory development through a more reflective choice of theoretical assumptions.

As with all studies, it is important to consider the limitations inherent in this research. First, our study is limited in that it only covers two disciplines. Subsequent research endeavors can broaden the scope of our study to encompass additional disciplines, and are invited to utilize and expand the sample in our article. Similarly, our definition of theory development is oriented toward ecology and social science. Lastly, analyzing and coding the papers in our sample required subjective judgments, albeit we tried to minimize such subjectivity to the best of our abilities. For this reason and given the plurality of understanding among researchers regarding what a theory is, we focus on describing the status quo concerning theory development and refrained from giving more explicit recommendations in this context.

In summary, our aim with this study is to contribute to advancing and consolidating the ABM field, particularly concerning theory development. We aim to promote more transparent and cumulative research using SLRs. We offer a way forward by reflecting on the current role of literature reviews in ABM research and addressing existing gaps and challenges. We hope that our practical recommendations for conducting ABM SLRs and synthesizing their phases can be valuable to future researchers, helping them navigate the extensive body of scientific knowledge and fostering a culture of cumulative research.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to improve language and grammar. After using this tool/service, the author (s) reviewed and edited the content as needed and take full responsibility for the publication's content.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the data and code used in the article are available on GitHub. The link is shared in the acknowledgments section.

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Appendix G. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2023.105867.

Appendix A Deductively and inductively generated codes and their answer types

Item No.	Question	Answer type
Q0	Is the paper explicitly described as a systematic literature review?	yes/no
Part 1 - Research Question		
Q1	Is a research question explicitly formulated?	yes/no/Not as questions, but explicit aim or objective
Q2	Is theory development addressed in the research question (or in a research aim or research objective)?	yes/no
Part 2 - Sample selection		
Identify- Approach		
Q3	To which principal search approaches can the review paper be assigned?	Single choice + Open coding
Identify - Keywords		
Q4	Have keywords or the search-string been disclosed?	yes/no/no keyword search
Q5	Did the keyword search consider terminological issues, e.g., varying terms among (sub)disciplines or differing meanings of abstract concepts?	yes/no/no keyword search
Q6	Is the process of determining the final keywords/search-string disclosed, e.g., showing its robustness?	yes/no/no keyword search
Identify - Search procedure		
Q7	Have specific, pre-defined journals been searched?	yes/no
Q8	Have the references of found research items been searched for further relevant research items?	yes/no
Q9	Have the citations of initially found research items been searched for further relevant research items?	yes/no
Q10	How many databases have been used in the sample selection process?	integer or "n/a"?
Q11	If a database-driven search approach was conducted, which database(s) is (are) used?	Multiple choice
	n/a	yes/no
	Scopus	yes/no
	Web of Science	yes/no
	Google Scholar	yes/no
	Others [separate multiple inputs with ";"]	"no"/Open coding
Q12	Have additional research items been included in the review sample based on the authors' prior knowledge or expert recommendations (e.g., by reviewers)?	yes/no
Q13	Is the date reported on which the literature search was performed?	yes/no
Screen/Assess - Inclusion/Exclusion criteria		
Q14	Have inclusion and/or exclusion criteria for the sample selection been disclosed?	yes/no
Q15	Are (peer-reviewed) "journal papers" explicitly reported as being included in the review sample?	yes/no
Q16	Are working or conference papers explicitly reported as being included in the review sample (whether peer-reviewed or not)?	yes/no
Q17	Are books or book chapters explicitly reported as being included in the review sample?	yes/no
Q18	Is other gray literature (e.g., organizational or governmental reports, speeches, urban plans, etc.) explicitly reported to be included in the review sample?	yes/no
Q19	Have citation rates played a role in the sample selection?	yes/no
Q20	Are journal quality measures used as inclusion or exclusion criteria?	yes/no
Q21	Is the final point in time for the inclusion of items in the review disclosed?	yes/no
Q22	Is a specific time-period, other than the final point in time, chosen as inclusion/exclusion criteria?	yes/no
Q23	Regarding the previous question, is the reason for the chosen time-period disclosed?	yes/no
Q24	If disclosed, what is the chosen time period?	integer or "n/a"
Q25	Have other inclusion/exclusion criteria been used? If yes, which?	"No"/Open coding
Q26	Have multiple researchers been involved in the selection process?	yes/no/seems so (not exactly disclosed)/not mentioned
Report - Process		
Q27	Where has the sampling process been disclosed?	Single choice + Open coding
Q28	Does the review paper disclose that the titles, abstracts, author-provided keywords, and/or full text have been used for the selection of research items?	yes/no/partially
Q29	Are languages other than English explicitly considered?	Yes/No, explicitly restricted to English/No, not explicitly considered
Report - Results		
Q30	Has a list of the papers finally included in the review been disclosed separately?	yes/no
Q31	Is the complete list of records from before the screening and assessment stage disclosed (raw results of the identification stage)?	yes/no
Q32	How many papers are included in the (final) review sample?	integer or "n/a"
Part 3 - Analysis		
Q33	How did the review add to theory development?	Multiple choice
	Description of or new insights about mechanisms used	yes/no
	Model element comparisons (agent type, environment structure or submodel combinations)	yes/no
	Generalization derived from the review which add to theory development beyond mere description	yes/no
	Identification of gaps and research avenues	yes/no
	Discussion of alternative formalizations (aka operationalizations) beyond the mere recognition of their existence	yes/no
	Discussion of theories used beyond the mere recognition of their existence	yes/no
	Theory development as an explicit focus of the review analysis	yes/no
	Others [separate multiple inputs with ";"]	Open coding
Q34	What is the purpose of the review?	Multiple choice
	Design perspective: How is something modeled?	yes/no
	Insight perspective: What did we learn from the models?	yes/no
	Effect perspective: Similar to classical meta-analysis in medicine and psychology.	yes/no
	Other perspective [separate multiple inputs with ";"]	Open coding
Q35	Does the review claim to go beyond summarizing available knowledge? If yes, state in which respect?	Open coding
Q36	What general method is used to analyze the sample dataset?	Multiple choice
	Bibliometric analysis	yes/no

(*continued on next page*)

(*continued*)

Item No.	Question	Answer type
	Scientific mapping	yes/no
	Meta-analysis	yes/no
	*Structured comparison (*e.g., *coding book as in content-analysis, ODD-protocol or any other classification schemas)*	yes/no
	Unstructured comparison	yes/no
	Others [separate multipl inputs with ";"]	Open coding
Q37	Referring to the previous question, what tools are used for the methods referred to in Q37.1-Q37.6 above?	Open coding
Q38	Are differences in the hardware or software infrastructure, or other technological specifics considered in the analysis/comparison of the papers?	yes/no
Q39	Did we learn anything else to improve systematic literature reviews?	Open Coding

Appendix B. Sample lists

Appendix B.1. Sample list complete (n = 127)

Abraham, Y. S., Zhao, Z., Anumba, C. J., & Asadi, S. (2017). Exploring agent-based modeling for human-centered energy consumption prediction. Paper presented at the Construction Research Congress 2018, New Orleans, Louisiana.

Adleberg, J. M., Catlett, C. L., Rothman, R. E., Lobner, K., & Hsieh, Y.-H. (2017). Novel applications of agent-based modeling in emergency medicine research–A systematic literature review. The American journal of emergency medicine, 35 (12), 1971–1973.

Aerts, J. C. (2020). Integrating agent-based approaches with flood risk models: A review and perspective. Water Security, 11, 100,076.

Agostinho, N. B., Wherhli, A. V., & Adamatti, D. F. (2021). A Systematic Review to Multiagent Systems and Regulatory Networks. In Y. Dong, E. Herrera-Viedma, K. Matsui, S. Omatsu, A. González Briones, & S. Rodríguez González (Eds.), Distributed Computing and Artificial Intelligence, 17th International Conference (Vol. 1237, pp. 231–240). Cham: Springer International Publishing.

Alotaibi, M. F., & Ibrahim, D. M. (2018, 2018). Agent-Based Simulation for Coordination Emergency Response: A Review Study. Paper presented at the 1st International Conference on Computer Applications and Information Security (ICCAIS) 2018.

An, L. (2012). Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecological Modeling, 229, 25–36.

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Appendix B.2. Final sample Ecology and Social Science (n = 42)

Ecology

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Appendix C Additional analysis

Appendix C.1 Top ten journals containing ABM reviews

Journal title	Number of papers
Ecological Modeling	7
Lecture Notes in Computer Science	4
Journal of Artificial Societies and Social Simulation	3
Advances in Intelligent Systems and Computing	3
Renewable & Sustainable Energy Reviews	2
Geography Compass	2
Agricultural Systems	2
Ecology and Society	2
Procedia Computer Science	2
Journal of Computational Social Science	2

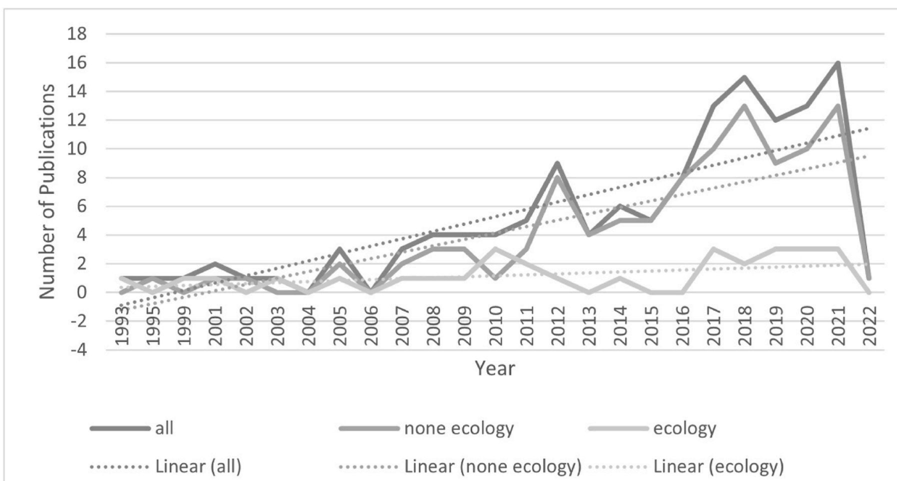
Note: Based on the papers in our complete sample (n = 127) and their associated WoS category. All remaining journals are represented by only one paper in our sample.

Appendix C.2 Ecology journals containing ABM reviews

Journal title	Number of papers
Ecological Modeling	7
Geography Compass	2
Ecology and Society	2
Energy research & social science	1
Land	1
Perspectives in Plant Ecology, Evolution and Systematics	1
Annual Review of Ecology, Evolution, and Systematics	1
Annals of the New York Academy of Sciences	1
Water Science and Technology	1
Water Security	1
Sarsia	1
Annals of the Association of American Geographers	1
Environmental Modeling and Software	1
Landscape Ecology	1
Frontiers in Ecology and Evolution	1
Environment and Planning B-Planning & Design	1
Ecological Complexity	1
Journal of Animal Ecology	1
Wiley Interdisciplinary Reviews-Climate Change	1
OIKOS	1
Transactions of the American Fisheries Society	1

Note: Based on the papers in our complete sample (n = 127) and their associated WoS category.

Appendix C.3 Development of ABM review papers across time



Appendix C.4 Critical intercoder reliability measures and respective explanation

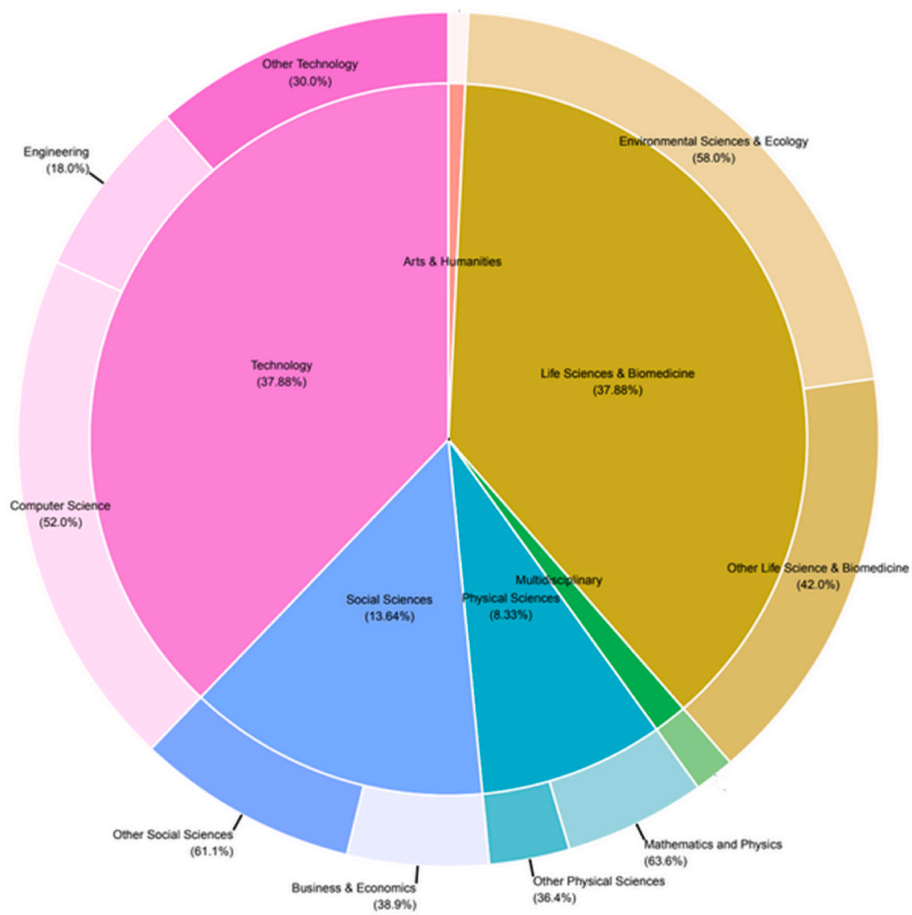
Item	Question	Kappa	AC1	%-agg.	Explanation
Q1	Is a research question explicitly formulated?	0,16	0,10	0,39	R2 was more liberal about what counts as a research question or a similar objective/aim. We went with the more conservative perspective of R1. RQ must be able to guide the research process and not only answer to the "what the paper does" but also to "why something is done" (not the method-"why" but the reason/justifying-"why").
Q2	Is theory development addressed in the research question (or in a research aim or research objective)?	0,04	0,28	0,46	Logical result of diverging interpretations of Q1. R1 was more conservative selecting the research question or objective resulting in a more frequent selection of "No", consequently, R1 more often selected "no research question" to answer Q2 instead of "No", the latter indicating there was a research question or objective that did not address theory development.
Q33.1	Did the review add to theory development? (Mechanism description)	0,14	0,16	0,57	Triggered an in-depth discussion of the coding guidelines. Each case that was coded differently was individually discussed until an agreement was reached.
Q33.2	Did the review add to theory development? (Model element comparison)	0,08	0,07	0,54	Triggered an in-depth discussion of the coding guidelines. Each case that was coded differently was individually discussed until an agreement was reached.

(*continued on next page*)

(*continued*)

Item	Question	Kappa	AC1	%-agg.	Explanation
Q33.3	Did the review add to theory development? (Generalization)	0,03	0,60	0,71	Triggered an in-depth discussion of the coding guidelines. Each case that was coded differently was individually discussed until an agreement was reached.
Q33.4	Did the review add to theory development? (Research gaps)	−0,08	0,08	0,50	Triggered an in-depth discussion of the coding guidelines. Each case that was coded differently was individually discussed until an agreement was reached.
Q33.6	Did the review add to theory development? (Theories used)	0,18	0,47	0,68	Triggered an in-depth discussion of the coding guidelines. Each case that was coded differently was individually discussed until an agreement was reached.
Q34.2	What is the purpose of the review? (Insight perspective)	−0,03	−0,10	0,39	Triggered an in-depth discussion of the coding guidelines. Each case that was coded differently was individually discussed until an agreement was reached.
Q36.4	What general method is used to analyze the sample dataset? (Structured comparison)	0,10	0,10	0,54	Triggered an in-depth discussion of the coding guidelines. Each case that was coded differently was individually discussed until an agreement was reached.

Appendix C.5 Share of ABM review paper across WoS research area



Appendix D Additional coding results

Appendix D.1[Q0] Explicit use of the label "systematic literature review"

Question	Ecology		Social		Total	
	Yes	No	Yes	No	Yes	No
Is the paper explicitly described as a systematic literature review?	3 (0,10)	26 (0,90)	4 (0,31)	9 (0,69)	7 (0,17)	35 (0,83)

Notes: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$.

Appendix D.2[Q1] Use of research questions

Question	Ecology		Social		Total	
	Yes	No	Yes	No	Yes	No
Is a research question explicitly formulated?[1]	(8 + 10) (0,62)	11 (0,38)	(2 + 3) (0,38)	8 (0,62)	23 (0,55)	19 (0,45)

Notes: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$. The answer "Yes" is divided into ("Yes" + "Not as question, but explicit aim or objective").

Appendix D.3[Q2] Research question's reference to theory development

Question	Ecology		Social Sciences		Total	
	Yes	No	Yes	No	Yes	No
Is theory development addressed in the research question (or in a research aim or research objective)?[1]	5 (0,17)	(13 + 11) (0,83)	1 (0,08)	(4 + 8) (0,92)	6 (0,14)	36 (0,86)

Notes: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$. [1]The answer "No" is divided into ("No" + "No research question").

Appendix D.4[Q7] Search restriction based on selected journals

Question	Ecology		Social		Total	
	Yes	No	Yes	No	Yes	No
Have specific, pre-defined journals been searched?	2 (0,07)	27 (0,93)	0 (0,00)	13 (1,00)	2 (0,05)	40 (0,95)

Notes: The underlying sample sizes are: $n_{ecology} = 29$, $n_{social} = 13$, $n_{total} = 42$.

Appendix D.5[Q24] If disclosed, what is the chosen time-period?

- [001] 1990–1999
- [014] until February 2016
- [015] No restriction
- [034] until June 2020
- [045] 1999–2019
- [050] until October 1, 2020
- [054] 1997-02.2007
- [105] 2000–2013
- [109] No restriction
- [131] 1991–2019

Appendix D.6. [Q25] Have other inclusion/exclusion criteria been reported?

Legend

- Time property (not found here)
- {Source property}$_1$
- {Content property – Method}$_2$
- {Content property - Phenomenon}$_3$

For ecology

- [001] "71 papers were discarded because they were {not about a certain model per se (e.g., reviews}$_1$ {or methodological papers)}$_2$, {not ecological (e.g., behavioral)}$_1$, or {not individual-based as defined at the beginning}$_2$ of the Introduction."
- [005] IBMs for microbes; {models of single individuals that are not upscaled are excluded; restricted to the lowest trophic level, bacteria and phytoplankton}$_3$.
- [015] "Another 23 results were then eliminated for failure to meet the original criterion of containing either of the terms in the title."; {paywall}$_1$.
- [034] "The abstracts of the publications returned in the search results were next screened using basic exclusion criteria. Articles were excluded if they did not (1) {include ABM as at least one modeling approach used}$_2$, and (2) {present an implementation of a model or model formalization}$_2$."
- [051] "A second round of screening was performed using the full text of each remaining article. Articles were primarily screened to determine if at least two sectors were explicitly considered in the ABM and/or overall modeling approach. The {article must have addressed the research questions related to interactions and/or trade-offs between two or more food, energy, or water sectors}$_3$."
- [054] "Criterion 1: inclusion of an agent-based model. We selected only articles that {describe an agent-based model and excluded}$_2$ r{eviews}$_1$, {frameworks, software or cyberinfrastructure descriptions}$_2$. Thus, 35 articles were excluded. Criterion 2: inclusion of a governance component in the model. {We excluded articles that do not have a governance component in their model}$_3$. Thus, 47 articles were excluded."
- [100] "When selecting agent-based models for our review, {preference was given to the models at the municipal level}$_3$ {that have a detailed description of agents, their behavior and rules of interaction, accompanied by a visual diagram of the conceptual model}$_2$. At the same time, an

important criterion was considered the {availability of information about testing the models on actual data for a specific municipality}$_2$. It means that {abstract theoretical agent-based models that are intended for practical use were deliberately excluded}$_2$ from the review."

- [107] "Each publication was evaluated by two persons by title and abstract to determine which articles did not match our general criteria (i.e., a {modeling study}$_2$, {but not related to land use research}$_1$)."
- [111] "Only publications describing ABMs {in which migration decisions in rural contexts are influenced by at least one environmental factor}$_3$, e. g., rainfall. {We excluded urban-urban migration as well as constantly moving societies including pastoralists, hunters and gatherers}$_3$."
- [116] "(1) main objective is to simulate {residential choice in the context of urban development}$_3$, (2) they are {spatially explicit and based on agent-based modeling techniques or microsimulation (MSM) modeling}$_2$."
- [121] "We excluded 29 papers, because {no ABM or results were presented}$_2$, or because the ABM was not used to study resilience}$_3$. Since we were only interested in model applications to ecological and social-ecological systems, we {excluded articles investigating systems related to economy (n = 10), technology and human safety (n = 10), sociology (n = 3), medicine (n = 2) or other systems (n = 3) }$_1$."
- [124] "Scanned many Google Scholar pages for titles to see if the respective studies addressed the themes, offered {a concrete and innovative model}$_2$, and were {relevant for climate policy}$_3$—until the success rate dropped to zero, that is, the next and various subsequent Google Scholar pages did not return any relevant ABM studies of climate policy. From the thus obtained set, we read the abstracts, which further reduced the number of relevant studies significantly."
- [131] {Excluded reviews}$_1$
- [132] {Only paper from one symposium}$_1$

For social

- [014] "Firstly, the article must be {accessible to the wider academic community}$_1$. Secondly, the article must {feature a complete ABS model rather than simply an unimplemented conceptual ABS model}$_2$. Thirdly, we {excluded literature review papers}$_1$. Fourthly, we {excluded articles that focus only on nonhuman actors and articles in which the keywords only appear in the reference section}$_3$. Finally, the {article must address research questions related to supply chain topics}$_3$."
- [031] Exclusion through certain keywords (see Table 2); based on manual screening checking "An article is considered relevant if it (a) {applies or considers an agent-based approach}$_2$ and (b) the {focus of the ABMS is a facet of the HE system}$_3$. The exclusion terms were selected due to their high incidence of co-occurrence in search results with Components 1 and 2 on a case-by-case basis," from this manual search they also determined the exclusion keywords in Table 2.
- [045] "The studies needed to meet two criteria pertaining to (1) the {study topic}$_3$ and (2) the {study methodology}$_2$." Both are defined in more detail in the paper."
- [050] Uses an ABSS model that {allows for investigating the spread of Covid-19}$_3$, i.e., a {micro-level model where the identity and status of each individual can be tracked throughout the simulation}$_3$; Article describes the {simulation model and the transmission process}$_3$; For each model and each team of authors, only the latest version of the preprint or, if existing, the peer reviewed article is included.

Appendix D.7[Q37] Open coding results regarding the tools used for structuring the analysis

Ecology

- [001] Criteria to scan papers.
- [005] Codebook
- [034] Codebook
- [051] Transversal questionnaire
- [054] Classification for structure taken from a previous review.
- [107] Standard questionnaire.
- [111] (Self-developed) conceptual framework for classification and questionnaire (see table 2)
- [124] Use several categories/segmentations (see tables) to quantify the results on which basis they are discussed in depth.
- [132] A priori structure related to the topic of the paper.

Social

- [045] Questions from the ODD + D protocol. The questionnaire is reviewed by co-authors and applied by only one of the authors.
- [050] Codebook (https://www.epress.ac.uk/JASSS/workspace/2020.190.2/5/5appendix.pdf).
- [077] Self-developed Codebook.

Appendix D.8. Other databases used

Other databases used for ecology are [ProQuest] and [ScienceDirect]. Other databases used for social are [ABI/INFORMS; Academic Search Complete; Business Source Complete; Science Direct], [ACM Digital Library; Proquest; Science Direct Journals; SpringerLink; EBSCO MegaFile Premier; Wiley Online Library; Computer and Applied Sciences Complete; Engineering Village; Oxford Journals Online; Sages; Google], [PubMed; MathSci; arXiv], [PubMed; Elsevier; medrxiv; Social Science Research Network; OtherXiv; Dimensions Publications; biorxiv; Dimensions Clinical Trails; preprints.org collection on Covid-19 and Sars; PsyArXiv; OSF; chemrxiv; The National Bureau of Economic Research; CORD-19; Dimensions Data Sets; COVIDScholar Submission; CrossRef; SSRN; Lens Patents; NBER]

Please note, some databases are double counted (e.g., "the National Bureau of Economic Research" and "NBER"). As they are reported like this in the original source, we did not correct it.

Appendix E Detailed description of the sample selection process

Table E.1
Detailed description of sample selection process (inspired by Aguinis et al., 2018)

Step	Procedure
1	**Identification: Find search string for database search:** • Try different terminologies for "agent-based modeling." ◦ *agent-based* ◦ *agent-based social* ◦ *individual-based* ◦ *multi-agent* ◦ *model* ◦ *simulation* ◦ *system* • Try different terminologies for "literature review." ◦ *review* ◦ *literature review* ◦ *systematic review* • Conduct robustness tests by varying terminologies and search operators and wildcards (see appendix for detail on robustness test). • We decided on a narrow database search which leads to 671 records (after removing duplicates) that can be screened manually. ◦ Search string WoS: ***TS = ("agent-based" AND simulation*) OR ("agent-based" AND model*) OR ("agent-based" AND system*) OR ("individual-based" AND simulation*) OR ("individual-based" AND model*) OR ("individual-based" AND system*) OR ("multi-agent" AND simulation*) OR ("multi-agent" AND model*) OR ("multi-agent" AND system*))*** ***AND TS = ("literature review" OR "systematic review")*** ◦ Search string Scopus: ***TITLE-ABS-KEY(("agent-based" AND simulation*) OR ("agent-based" AND model*) OR ("agent-based" AND system*) OR ("individual-based" AND simulation*) OR ("individual-based" AND model*) OR ("individual-based" AND system*) OR ("multi-agent" AND simulation*) OR ("multi-agent" AND model*) OR ("multi-agent" AND system*))*** ***AND TITLE-ABS-KEY("literature review" OR "systematic review")*** • We add a broad database search which leads to 3026 records (after removing duplicates) for which we apply another screening process based on the insights gained from the manual screening of the narrow database search. ◦ Search string WoS: ***TS = ("agent-based" AND simulation*) OR ("agent-based" AND model*) OR ("agent-based" AND system*) OR ("individual-based" AND simulation*) OR ("individual-based" AND model*) OR ("individual-based" AND system*) OR ("multi-agent" AND simulation*) OR ("multi-agent" AND model*) OR ("multi-agent" AND system*))*** ***AND TS = ("review")*** ◦ Search string Scopus: ***TITLE-ABS-KEY(("agent-based" AND simulation*) OR ("agent-based" AND model*) OR ("agent-based" AND system*) OR ("individual-based" AND simulation*) OR ("individual-based" AND model*) OR ("individual-based" AND system*) OR ("multi-agent" AND simulation*) OR ("multi-agent" AND model*) OR ("multi-agent" AND system*))*** ***AND TITLE-ABS-KEY("review")***
2	**Development of screening criteria based on narrow keyword search:** • To develop a comprehensive and unbiased sample we refrained from using generic exclusion criteria such as citation rates, disciplines, a time range, source types, etc. • Instead, one author read a sample of 200 abstracts and developed in multiple iterations a classification schema for the records on which basis we could decide which records to include and exclude. • The final version of the classification schema was discussed and revised with the help of the co-authors. Class 1. Review as the main research method only on ABM[8] (n = 51): *Conducting a literature review is the central method in the paper and therefore responsible for the main contributions. The review solely focuses on ABMs.* Class 2. Review not on ABM alone but, e.g., includes other simulation techniques (n = 36): *Review is conducted on multiple simulations techniques such as discrete event simulation, system dynamics or others besides ABM.* Class 3. Reviews of ABM method and methodology (n = 12): *Those papers that review ABM specific methods* (e.g., *the application of the ODD protocol) or combinations of ABMs with specific methods, techniques or platforms* (e.g., *digital-twin, virtual reality, or machine learning). Does not include reviews in which methodological questions are addressed, among others, in the analysis.*[9] Class 4. A review is used for the development of a (single) ABM (n = 98). *Papers that conduct a review to collect information that are subsequently, but in the same paper, used to design, calibrate or specify a model.* Class 5. The topic of ABM comes up because of a review (n = 80). *Reviews in which ABMs appear in the final sample as part of a more general finding,* e.g., *when a search for simulation models in general or a subfield in which ABM is applied as one method, among others.* Class 6. When an ABM or the review only plays a minor role in the record (n = 39). *Also excludes introductions to ABM, unless they put a review of current ABMs in the centre of their introduction.* Class 7. Unrelated topics and physical multi-agent technologies (n = 355). *E.g., papers concerning agents as drugs in a medical context, physical multi-agent technologies or generally multi-agent systems with little overlap to simulations.* • Class 1 is treated as inclusion criteria, while classes 2–7 are treated as exclusion criteria. Note that the class 1 is mutually exclusive with respect to classes 2–7, while classes 2–7 are not mutually exclusive among each other.
3	**Final selection narrow keyword search:** • Author A assigns classes 1–7 to all 671 records found in the narrow keyword search by reading title and abstract, and if necessary, reading the full text. • As only Class 1 is defined as inclusion criteria, 51 records are selected for the final dataset.
4	**Calibrating the screening process for narrow and broad keyword search:**

(*continued on next page*)

[8] Used from here on as a placeholder for agent-based, individual-based and multi-agent modeling if not specified otherwise.
[9] Excludes those papers that review ABM methodology or (specific methods). Not those that review ABM models which are then analyzed for methodological categories (e.g., A. McAlpine et al., 2021).

Table E.1 (*continued*)

Step	Procedure
	• To accelerate the screening process for the 3026 records found in the broad keyword search, we test if an inclusion or exclusion decision is possible by only reading the title. • Author A makes the inclusion/exclusion-decision for the 671 records found in the narrow keyword search by reading the title and abstract, and if necessary, reading the full text. Class 1 is treated as inclusion criteria, while classes 2–7 are treated as exclusion criteria. • Two co-authors B and C independently repeat the inclusion/exclusion-decision for the 671 records of the narrow keyword search by only reading the title. • The records are coded with "In/Out/Maybe" and then evaluated by applying three intercoder reliability measures: ○ Full counting: 90% ○ Partial counting: 95% ○ Fleiss Kappa: 63% (following Landis and Koch (1977) represents a value between 61% and 80%: a substantial agreement strength) • The reliability measures indicate a satisfactory agreement rate. • Therefore, we: ○ Use the classification schema as inclusion/exclusion-criteria. ○ Base our inclusion/exclusion-decision for the 3026 records found in the broad keyword search only on reading the title.
5	**Final selection narrow keyword search:** • Comparing the independent assessment of authors A, B and C, we notice the following results: ○ 89% (599) of the records are classified identical. ○ 11% (72) have mixed classification and are discussed among authors A, B, and C, based on a skimming of the full text for a final classification. • 51 of the records (7,6%) are selected for the final dataset.
6	**Final selection broad keyword search:** • We partition the 3026 records into three equally sized batches. Each author (A,B,C) independently makes the inclusion/exclusion-decision only based on the title. Records can be coded with "In/Out/Maybe." • A closer look at the direction of the deviations in the intercoder reliability test gives additional security that the selection based only on titles is reliable. As a false exclusion poses the central thread in the screening process, we quantify that error: ○ 14 out of 671 records were marked "no" by one author while ending up being included in the final list. ○ For these 14 records the authors classified 16*x*"No", 26*x*"Maybe"or"Yes" ("Maybe" treated like "Yes" since assessed by the group again). ○ The probability of a false exclusion is P (14|671) x P (16|42) = 0,8%, which is an acceptable error rate we would not expect to bias the results of our study. • Comparing the independent assessment of authors A, B and C, we notice the following results: ○ 90% (2726) are coded with "no". ○ 1% (52) are coded with "yes". ○ 8% (254) are coded with "maybe". • All records coded with "yes" or "maybe" are discussed among authors A, B, and C, based on a skimming of the abstract or full text for a final decision. • One record could not be retrieved, while four records initially selected were excluded later during the analysis since a detailed reading uncovered an initially false classification. • 71 of the records (2,3%) are selected for the final dataset.
7	**Expert additions:** • In the context of a symposium on ABM and theory development we asked multiple experts in the field of ABM about additional reviews that are not yet in our list. • We received 12 suggestions that we subjugated to the decision-criteria. • 5 of the papers are selected for the final dataset.
8	**Specific journal search:** • To make sure we would not miss any papers that might be missing in the databases, we additionally performed searches in simulation specific journals. ○ Journal of Artificial Societies and Social Simulation. ○ Environmental Modeling & Software. ○ Simulation Modeling Practice and Theory. ○ Journal of Simulation. • We did not find any additional papers not already covered by one of the previous searches.

Appendix F. Assessment criteria for good practices based on SLRs resembled by our questionnaire

Set of necessary conditions (following and AND-logic) to be considered a systematic review paper

Regarding question formulation.

- [Q1] Research question, objective, or aim need to be formulated.

Regarding sampling phase:

- [Q3] Replicable search approach is chosen.
- [Q4] + [Q11] Transparency in general search parameter.
- [Q14] Inclusion/Exclusion-criteria are reported (other than publication date).
- [Q21] Inclusion/Exclusion-criteria publication date is disclosed.
- [Q30] List of finally included papers is disclosed.

Regarding analysis phase:

- [Q36] Analysis cannot be unstructured.

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