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Research

Governance in social-ecological agent-based models: a review

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ABSTRACT. Analyzing governance is particularly important for understanding and managing social-ecological systems (SES). Governance systems influence interactions between actors and the ecological system and are in turn influenced by the changes that occur in the actors' and ecological systems. Agent-based models (ABM) are well adapted for studying SES, for exploring interactions and the resulting collective behavior and for predicting the results of management processes. Considering the potential of ABM to analyze SES, we performed a literature review of the modeling of governance in ABM of SES and highlight the perspectives and challenges surrounding this issue. Our results show in particular that a significant share of the literature is not explicitly based on theories supporting the modeling of governance and actors' decision making. Regarding the conceptualization of governance, formal and informal institutions are rarely represented compared with diverse modes of governance. The governance modes that are mostly modeled are state interventions whereas the community-based and market-based modes of governance are scarcely represented. Finally, the overview of how interactions between governance and SES are operationalized in ABM highlights two main forms of implementation of governance: variable-based and agent-based implementations. The corresponding sets of models differ in terms of main theoretical background, types of governance modes represented or presence of interactions. Therefore, we recommend moving toward a greater diversity in the representation of governance and toward a better implementation of the dynamics of models, which can be facilitated by the explicit use of theories supporting the modeling of governance and the decision making of actors and by the representation of governance as an agent.

Key Words: *agent-based model; decision making; governance; review; social-ecological system*

INTRODUCTION

Social-ecological systems (SES) are tightly linked units of humans and nature in mutual interaction (Berkes et al. 2003). Examples of SES include fisheries (Schlüter et al. 2014), agricultural and food systems (Rivera-Ferre et al. 2013), forests (Fischer 2018), or landscapes (Duguma et al. 2015). Because they are essential for humanity, interest in these systems and in their governance has grown significantly. Indeed, the rise in tensions between the ecological and social worlds has become of increasing concern: water pollution, loss of biodiversity, sea-level rise, increase in global epidemics, spread of pests, and deforestation (FAO 2011).

Whereas social and ecological systems were usually studied separately, more and more studies are now focussing on both systems in an integrated way (e.g., Pollnac et al. 2010, Cinner et al. 2012, Zhang et al. 2013, Martín-López and Montes 2015, Schoon and Van der Leeuw 2015). To understand and analyze these complex interacting systems, a study of governance is particularly important to help identify adequate management options (Ostrom 2007). Governance "is [a] process by which the repertoire of rules, norms, and strategies that guide behaviour within a given realm of policy interactions are formed, applied, interpreted, and reformed" (McGinnis 2011:171). Different types of governance are characterized in the diverse fields and approaches of social sciences, e.g., polycentric and monocentric governance, market-based governance, self-governance or democratic administration (Ostrom 2010, McGinnis 2011, Carlisle and Gruby 2019). We focus in particular on informal institutions, formal institutions, and modes of governance following Williamson (2000).

Governance forms part of the social system together with individual actors, groups of actors, and organizations. The analysis of governance involves studying this social system and the feedback between the social system and the ecological system. Indeed, governance systems influence the behavior of individuals or groups, and individuals or groups choose modes of governance, thus making it necessary to understand how these individuals or groups behave. Moreover, governance systems can have a direct impact on other systems as well as indirect impacts that require prior understanding of the links between systems to characterize the effects of governance. Therefore, to analyze governance in SES one has to consider its characteristics and to examine the actors and the links between the ecological system, the actors, and the governance system.

Although these systems are complex and the modeling approach fundamentally reductionist, simulation-based tools are particularly relevant for improving our understanding of the factors and processes leading to the sustainability of SES as complex adaptive systems (Müller-Hansen et al. 2017, Schulze et al. 2017). Indeed, because SES are invariably dynamic and complex due to non-linear interdependencies between ecological and social systems and due to the emergence of macro-scale effects arising from individual behavior (Anderies et al. 2019, Mathias et al. 2020), simulation-based models are suitable tools to represent them. These tools can also be used for management or decision support in an uncertain context, considering the evolutionary nature of SES and examining various possible strategies (Rounsevell et al. 2012, Filatova et al. 2013, Anderies et al. 2019). In particular, studying governance in SES modeling is important. First, although many studies in the field of SES modeling have examined human-environment interactions, the focus has been on understanding the ecological rather than the social dynamics, and several authors now stress the importance of a better representation of the social system (Groeneveld et al.

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2017, Schulze et al. 2017). Although governance is an important part of the social system, most reviews of SES models dealing with the social system focused on actors and not on governance. Second, governance is the subject of growing interest in the SES field (Herrero-Jáuregui et al. 2018): research on SES increasingly focuses on governance and the definitions of SES considering the role of institutions and governance (e.g., Glaser et al. 2008).

Among the different approaches in modeling, agent-based models (ABM) are well adapted for studying SES and for exploring interactions and the resulting collective behavior (Gotts et al. 2019). They are dynamic tools that highlight SES feedback (Janssen et al. 2008, Heckbert et al. 2010, Schulze et al. 2017). Agent-based models are computational systems with autonomous entities (agents) in an environment. Agents with heterogeneous characteristics have a dynamic behavior and interact with each other and with the environment. Outcomes at the system scale emerge from these individual interactions. Agent-based models are useful not only for analysing SES or predicting management results (Rounsevell et al. 2012, Schulze et al. 2017), but also for highlighting emergent behavior resulting from governance dynamics.

Several reviews have shown the relevance of ABM in studying SES, with a focus on the decision-making processes of the actors (An 2012, Groeneveld et al. 2017, Müller-Hansen et al. 2017, Huber et al. 2018), on the transparency and comprehensiveness of the models (Schulze et al. 2017), or on their initialization (Kremmydas et al. 2018). Janssen and Ostrom (2006) have analysed the challenges related to ABM for the study of governance in SES, focusing on the conditions under which cooperative solutions are sustained. Nevertheless, their review is not focused on describing the modes of governance represented in ABM and their implementation. To the best of our knowledge, no review has concentrated specifically on the formalization of the governance component, from conceptualization to implementation, and the interactions between governance, actors, and the ecological system. Thus, considering the potential of ABM to analyze SES, we aim to provide a review of the modeling of governance in social-ecological ABM and to highlight the perspectives and challenges surrounding this issue. The review provides an initial entry point for agent-based modelers and the broader community of SES modelers with an overview of how the SES ABM integrate governance. Furthermore, the review is more generally of interest to researchers working on SES governance because it discusses the potential of ABM in analyzing the governance of SES.

Our objective is pursued by adopting a literature review approach. After describing the methodology used in this study, we present the results of the review, focusing on the conceptualization of governance, on its implementation, and on the links between governance and other systems within the SES. Finally, we discuss the findings and offer a conclusion: (1) we emphasize that a significant share of the literature is not explicitly based on theories to support the modeling of governance processes and interactions or actor decision making. (2) Moreover, we underline that institutions, although important in the field of SES, are scarcely modeled and that the governance modes that are mostly modeled are state interventions, whereas community-based and market-based modes of governance are rarely represented. Finally, we provide (3) an overview of how interactions between governance and other systems within an SES are operationalized in ABM; and (4) highlight two types of implementation of governance: agent-based and variable-based implementation. The corresponding sets of models differ in terms of the main theoretical background, the types of governance modes represented, or the presence of interactions.

METHODS

Literature search: protocol and criteria

We conducted a review of the peer-reviewed literature identified in the database *Scopus* (https://www.scopus.com). We limited the literature reviewed to published articles and articles in press written in English. The articles selected include in their title, abstract, or keywords one or more terms from each of the following groups: (1) ABM group: terms linked to agent-based modeling; (2) SES group: terms linked to social-ecological systems; and (3) GOV group: terms linked to governance. In the ABM group, terms were: agent-based, multi-agent, agent based, multiagent, or abm. We focused only on models self-identified by authors as applying to an SES. We followed Herrero-Jáuregui et al. (2018) describing the literature on SES and Schulze et al. (2017) reviewing ABM of SES to define our search commands. Thus, the SES group included the terms: socio-ecological, social-ecological, and socio-ecosystem. The set of terms for the GOV group was established in an iterative way. We first conducted a search with the ABM and SES groups and found 172 documents. We then established a list highlighting terms related to governance with the highest occurrence. On this basis, the GOV group included govern, manag, rule, institution, polit, and polic in the final search command in Scopus:

TITLE-ABS-KEY (("agent-based" OR "multi-agent" OR “abm” OR "agent based" OR "multi agent") AND ("social-ecological" OR "socio-ecological" OR “socio-ecosystem” OR "human-environment") AND (govern* OR manag* OR institution* OR polic* OR rule* OR polit*)) AND DOCTYPE (ar) AND (LIMIT-TO (LANGUAGE , "English"))

We compiled a list of 128 documents (on 19/10/2020) and refined the list based on the following criteria:

- Criterion 1: inclusion of an agent-based model. We selected only articles that describe an agent-based model and excluded reviews, frameworks, software or cyber-infrastructure descriptions. 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. Thus, 47 articles were excluded.

At the end of the process, 45 articles were selected for the analysis (an article was removed because of many difficulties coding it, see Appendix 1 for the list of selected articles). Note that, like any keyword-based bibliographic research, some biases exist because relevant papers may not include the keywords used for the research.

Data extraction and analysis

As a guideline for the analysis, we focused on how governance is conceptualized, formalized, implemented, and linked to other systems in social-ecological ABM. We first concentrated on the conceptualization of governance: (1) what are the theories underlying the modeling of governance and actors' decision making and (2) which links exist between the conceptualisation of governance, algorithms, and the factors influencing the decision-making process? The aim was to characterize the diversity of theories employed, to highlight the links between them and the theories of actors' decision-making processes, and to describe the types of governance and decision-making processes used. Second, we focused on the implementation of governance in SES models. We especially aimed to identify the different forms of implementation and to observe differences and similarities regarding the conceptualization of governance, its links with other systems, and the diversity of agents. Finally, the last part concerns the links, both the types and the direction, between systems. The objective was to describe and quantify these links.

To gather all the information needed to examine these issues, we created a transversal questionnaire following three axes: the representation of governance, the description of the diverse decision-making processes of actors, and the links between the ecological systems, the governance system, and the actors (see Appendix 2 for the detailed questionnaire).

We read the full texts of the selected articles and coded them. The first part of the coding frame is based on overview criteria such as source, year of publication, subject, and type of research. The second part is developed on the basis of the aforementioned questions. All co-authors tested the questionnaire on eight articles to make the coding robust. Disagreement on certain responses allowed us to clarify the questions and response items and thus to improve the coding.

Table 1. Number of peer-reviewed publications according to Scopus search terms (on 19/10/2020). As per normal Boolean search rules, the specific phrase within quotation marks will be found and an asterisk will highlight any word that begins with the root/stem of the word truncated by the asterisk. Social-ecological systems (SES) search command refers to: ("social-ecological") OR ("socio-ecological") OR ("socio-ecosystem") OR ("socioecosystem"). The agent-based model (ABM) search command refers to: ("agent-based") OR ("multi-agent") OR abm OR ("agent based") OR ("multi agent"). The governance (GOV) search command refers to: (govern* OR manag* OR institution* OR polic* OR rule* OR polit*).

Search terms or commands	Publication counts
SES command	9503
social-ecological	5871
socio-ecological	3772
socio-ecosytem	65
socioecosystem	12
GOV command	5,201,077
govern*	881,440
manag*	2,807,633
institution*	667,504
polic*	1,000,717
rule*	493,502
polit*	510,301
ABM command	39,669
ABM and SES command	172
ABM and GOV command	11,930
SES and GOV command	6542
SES and GOV and ABM command	128

RESULTS

Overview

Occurrence of governance in the selected literature
More than one-quarter of the articles presenting an ABM for SES (ABM + SES command) do not provide any reference to governance, management, or public policies (see Table 1). Moreover, one-third of the articles in the final search command (SES + ABM + GOV command) were excluded because they did not ultimately integrate governance. A close examination of the articles that were excluded reveals that the models are proposed to support governance, public policy decision making, or systems management but do not integrate governance in the model.

According to Herrero-Jáuregui et al. (2018), "governance" is one of the 10 most frequently used keywords in SES articles (articles found in Scopus with the terms socio-ecosystem, social-ecological system, and socio-ecological system). However, the term is not one of the most frequently used keywords in the papers we reviewed. Still, the inclusion of diverse terms used to describe governance in our search command (the GOV search command included govern, manag, rule, institution, polit, and polic) allowed us to identify the papers that included a governance component but did not refer to the "governance" keyword. Of the 128 documents, only 24 documents included in their title, abstract, or keywords the term "governance," whereas 89 included "manag," 48 included "polic," 23 included "institution," 10 included "polit," and 9 included "rule."

Sources
The journals with the highest number of publications and the most frequently cited sources in our set of articles were *Environmental Modelling and Software* and *Ecology and Society*. These journals are interdisciplinary, which highlights the specificity of the subject studied (governance and modeling of SES). Nervertheless, they are mainly anchored in the fields of ecology, ecological modeling, and environmental engineering (source: SCImago Journal Rank). This is in line with the results of Herrero-Jáuregui et al. (2018), according to whom, 62% of SES studies are conducted by researchers whose primary field lies in the natural sciences, whereas 30% of studies are conducted by social scientists. Additionally, our research focused on articles using formal models. It explains, for example, why the *International Journal of the Commons*, an interdisciplinary journal dedicated to furthering the understanding of institutions for the use and management of resources that are (or could be) used collectively, although well-suited to our subject and embedded in the SES research community, is not present in the selected articles.

Software
Three-quarters of the articles provided the reader with information on the platform or language used for the model. NetLogo was the most commonly used platform (50%), compared with Repast (16%), Java or CORMAS (9% and 6%, respectively). One-third of the authors justify their choice within the article. NetLogo is often chosen because it is "particularly well suited for

modelling complex systems developing over time" and "it provides the interface control tools [...] to set the parameters and scenarios of the model, and display simulation results" (Hu et al. 2010:58). Its language is simple (Van Schmidt et al. 2019), and the environment is user friendly (Martin and Schlüter 2015).

Types of social-ecological systems (SES) and dynamics of ecological systems

In our research, agricultural systems dominated and were represented in one-quarter of the models (e.g., Barnaud et al. 2008, Caillault et al. 2013). Then, other types of SES modeled are, by order of importance, pastoralism (e.g., Gross et al. 2006), forestry (e.g., Huber et al. 2017), and fisheries (e.g., Klein et al. 2017). As Herrero-Jáuregui et al. (2018) found in empirical studies of SES, the most frequently analyzed topics concerned the exploitation of ecological systems. In the models reviewed, ecological systems were always implemented dynamically. Three types of models have been identified: transition rules, parametric equations, and differential equations. The model most frequently used is that of differential equations.

Conceptualization of governance

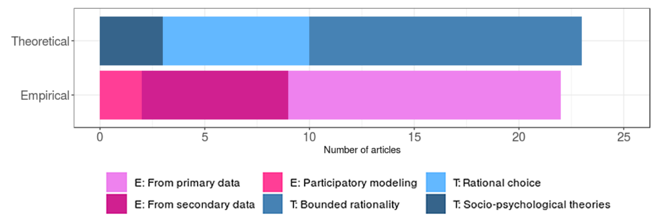
Although half of the articles have a theoretical background, one-quarter of the articles do not mention it explicitly. Most articles with a theoretical background refer to theories developed in the field of economics. These theories are generally grounded in neoclassical economics (60%), in which the environmental and natural resource management problems are approached from the perspective of market dysfunction (e.g., environmental economics in Huber et al. 2013; game theory in Sugiarto et al. 2017 or Tilman et al. 2018; evolutionary game theory in Nhim et al. 2019). Other theories used belong to the field of institutional economics, e.g., Wang et al. 2013 and Holzhauer et al. 2019, or Rasch et al. 2016, who used the theory of collective action (Ostrom 2003). First, the theories employed are based on decision-making theories of individuals or groups such as rational choice theory, bounded rationality or socio-psychological theories. Second, they can be applied to different types of governance. We make a distinction between informal institutions, formal institutions, and modes of governance (Williamson 2000). Modes of governance is divided into three main forms: community-based, market-based, and state-based (Lemos and Agrawal 2006). We analyze the conceptualization of governance through these two dimensions: the decision-making theories used in models and the modes of governance represented.

Decision-making theories: from perfect rationality to social psychology theories

The actors' decision-making processes mainly concern the choice between different productive activities and the allocation of resources. The activities can be agricultural activities (choice of crops or farming practices), forestry activities, or non-agricultural activities. The resources to be allocated are mainly land, labor, and money. In a smaller proportion of articles, decisions are made about the extraction of resources (e.g., fish, timber, water). Other types of behaviors are more rarely analyzed such as travel itineraries or locations of residence. In only one article do the decisions relate to a political process. In the work of Guzy et al. (2008), actors classify public policies according to ecological and economic criteria. Actors' behaviors are mainly individual: aggregated actors are found in only four articles.

In the papers reviewed, the decision-making processes of the actors can derive from theoretical frameworks (in the fields of economics, sociology, and psychology) or from empirical input (e.g., data derived, participatory modeling; see Fig. 1). The formalization of decision-making processes is empirical in a little less than half of the articles. In these articles, three types of data sources for the formalization were found: primary data, secondary data, and participatory modeling. The primary data represent the most important source of empirical formalization (62% of empirical sources). The other half of the articles were based on theoretical frameworks.

Fig. 1. Origin of the decision-making processes used for actors. Numbers do not necessarily add up to 45 because 1 article may use several categories at the same time or because an assessment was not possible for some articles.



The theories employed use assumptions concerning the behavior of humans such as, for example, the rationality of humans or their cognitive capacity (Vatn 2005). The literature on SES management includes a large number of behavioral theories (Schlüter et al. 2017). Because of the importance and diversity of decision-making processes and theories, several authors have already reviewed and analyzed this topic from angles other than SES ABM including governance: decision models used in agent-based simulations of coupled human and natural system dynamics (An 2012), decision making in agent-based land-use models (Groeneveld et al. 2017), decision making in European agricultural ABM (Huber et al. 2018), human behavior and decision making in earth system models (Müller-Hansen et al. 2017), as well as agent-based modeling for agricultural policy evaluation (Kremmydas et al. 2018).

In ABM, the decision-making model is mainly grounded in rational choice theory (An 2012), and although a few decision-making theories have been formalized in SES modeling, agent decision making has often been based on simple assumptions (Jager et al. 2000). In 30% of the reviewed articles with theoretical decision making, the agents' choices were based on rational choice theory. This theory assumes that agents make decisions according to their preferences and goals. Omniscient and perfectly rational agents maximize their expected outcomes, originally stated as their economic profit under resource constraint. Rational choice theory uses the concept of utility. Introduced by Bernoulli, the concept of utility is used to model value, linking income and the concept of satisfaction. Well-being, consumption, and the preservation of the environment can also be considered in the concept of utility. For example, in the work of Agrawal et al. (2013), the utility function of households involves different attributes: consumption of the extracted firewood, leisure and utility from adhering to institutional rules, or community norms regarding firewood extraction. The theory of expected utility, developed by Von Neumann and Morgenstern, is a theory of decision making in a risky environment, which considers the incidence of cognitive biases in decision-making processes, e.g., Tilman et al. (2018) that include risk aversion of fishers in their decision-making processes. The concept of utility is used in 16% of models and always includes other attributes in addition to money.

However, other theories introduce cognitive biases into rational decision-making processes. Simon's research on bounded rationality highlights that rationality is limited in terms of an agent's cognitive capacity and available information (Schilirò 2018). Rational choice and bounded rationality theories are widely used in models of natural resource management (Schlüter et al. 2017). In 57% of the articles in which decision making is based on theoretical assumptions, the decision-making processes refer to the bounded rationality concept. Its applications can be broad, ranging from the simple addition of a constraint while remaining in a neoclassical paradigm (e.g., Agrawal et al. 2013), to a redefinition of the decision-making process (e.g., Caillault et al. 2013).

The last set of articles using theories to model decision-making processes of actors refers to the literature on social psychology. Decision theories, such as the theory of planned behavior (Ajzen 1991), the theory of normative conduct (Cialdini et al. 1991) or social learning theory (Bandura 1977), focus on specific aspects of decision-making processes such as the influence of norms, learning effects, judgement of consequences, repetition, or conditioning effects on behavior.

In the articles that mention theories relating to governance, i.e., half of the articles, actors' decision making is more often based on theoretical than on empirical processes, whether for theories grounded in neoclassical economics or for theories grounded in institutional economics.

Modes of governance

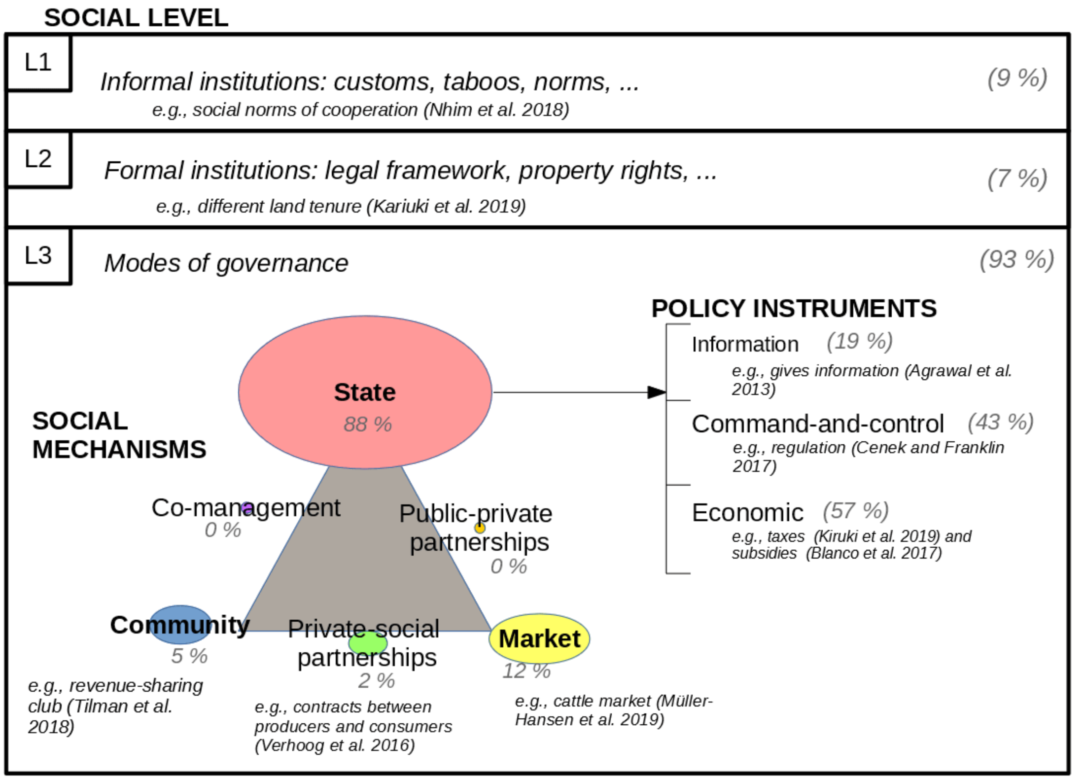
To characterize the modes of governance represented in models, we used different typologies. Williamson (2000) distinguished four levels of social analysis. The top level is the level of informal institutions such as customs, taboos, or norms. Rules are unwritten and unofficial. For instance, Nhim et al. (2019) analyzed how the social norms of cooperation and punishment of non-cooperators evolved. The second level consists of formal institutions, e.g., legal frameworks, property rights, and other written and official rules. An example is represented by the work of Kariuki et al. (2018), who analyzed the impact of different land-tenure allocations (between communal, private, and government) on the behavior of the system. The third level refers to how actors formally interact with each other in a given formal and informal institutional environment. Different modes of governance frame these interactions. The last level deals with the allocation of resources. The first three levels relate to governance, and the social level more widely represented is the governance level, in almost all articles. Nevertheless, a few articles integrate the formal and informal institutions in their models (see Fig. 2).

Throughout the literature, there are different ways of classifying the modes of governance. Lemos and Agrawal (2006) identified three main types of governance modes: community-based, state-based, and market-based modes of governance. Community-based modes of governance are represented in only two articles. The perceived strength of these modes is the deployment of solidarity relationships and time- and place-specific knowledge embodied in communities. Tilman et al. (2018) presented an example of self-governance with a revenue-sharing club of fishers who were involved in reinsurance and management of the resources. The profit of the fishers depended, among other things, on their own fishing efforts and on the efforts of the other club members as well as on the split coefficient of the revenue sharing. Market-based modes of governance are also rarely represented in models, i.e., in only 12% of articles that model modes of governance. They are systems of exchange between sellers and buyers in which regulation is frequently based on prices, sometimes on quantities (Commaille and Jobert 2019). The state-based modes of governance are the more widely represented type, in 88% of articles that model modes of governance. State-based modes of governance can be further characterized by the corresponding type of policy instrument: command-and-control, economic instruments, information (Villamayor et al. 2019). Economic instruments are modeled in 57% of articles that model state-based modes of governance, mostly represented by taxes (e.g., Gross et al. 2006) and subsidies (e.g., Van Schmidt et al. 2019). Command-and-control instruments such as legislation, permits, and quotas (e.g., Klein et al. 2017) are the second more commonly represented policy instruments, in 43% of articles that model state-based modes of governance. Command-and-control instruments and economic instruments were considered in neoclassical economics as the only options to correct market failures/externalities. In the traditional classification of policy instruments, information is also a state-based instrument. In the study by Agrawal et al. (2013), the organization agent sends each household a signal indicating the sustainable level of resource extraction based on its assessment of the forest.

The three hybrid modes of governance are co-management (between state and community), public-private partnerships (between state and market), and private-social partnerships (between market and community; Lemos and Agrawal 2006). Of the articles reviewed, only one presented a hybrid form, the private-social partnership. In the article by Verhoog et al. (2016), agricultural firms, waste-water treatment facilities, and consumers negotiated biogas contracts (quantity and price of the biogas), depending on the demand and supply of biogas, and on the prices in markets external to the biogas system. Contracts were used as an input to arrive at capacities at which to construct new digesters, cleaners, and biogas pipelines.

The crossover between the theories employed and the proposed typology shows that the articles that do not mention theories model state-based modes of governance, particularly command-and-control instruments, more than the other articles do. The modes of governance based on the market and private-social partnerships are mainly modeled in articles referring to institutional theories, e.g., in Verhoog et al. (2016) biogas contracts between producers and consumers were analyzed through the Institutional Analysis and Development (IAD) framework of Ostrom (2011). Nevertheless, these articles referring to institutional theories also modeled command-and-control and economic instruments, e.g., Gross et al. (2006) who

Fig. 2. Typology of governance and examples from the review of the literature: three levels of governance analysis. The size of the circles depends on the representation of the mode in the articles reviewed. Bold type indicates the main modes and normal type, the hybrid form. Percentages do not necessarily add up to 100% because one paper may use several categories at the same time. Adapted from Williamson (2000), Lemos and Agrawal (2006), Driessen et al. (2012), and Villamayor-Thomas et al. (2019).



addressed questions about institutions that provide subsidies and collect taxes. Finally, the articles mentioning the neoclassical trend are largely dominated by models representing economic policy instruments (e.g., Klein et al. 2017).

Implementation of governance: agent-based modeling versus variable-based modeling of governance

In the articles reviewed, governance was either modeled by an agent or a variable:

1. In the case of agent-based modeling of governance, agents are modeled with characteristics, objectives, decision-making processes, possibility of interactions, and sets of actions. Governance actors represented by an agent have the capacity to make decisions, to interact, and to adapt as an actor can. This type of implementation of governance was found in one-third of the articles. A governance agent can represent a municipality (e.g., Acevedo et al. 2008, Gaube et al. 2009), policymakers (e.g., Bitterman and Bennett 2016), federal managers, the state (e.g., Kline et al. 2017), or the government (e.g., Liu et al. 2013).

2. In the case of variable-based modeling of governance, governance is implemented as a set of variables (state variables or parameters), e.g., market support (e.g., Acosta-Michlik and Espaldon 2008) or boat speed limits (e.g., Chion et al. 2013). This form is found in 80% of the articles.

These different forms of implementing governance may reflect varying willingness in terms of the representation of governance. In fact, agents are able to perceive the environment, interact with it, and communicate with each other (Ferber and Perrot 1995). They can assess situations and make decisions on the basis of a set of rules. They may execute various behaviors and have relationships with other agents (Bonabeau 2002). Thus, the implementation of governance as an agent may be more adapted, even if this does not guarantee it, to represent an internal structure of governance more complex than a set of variables. The following paragraphs highlight similarities and differences between the articles according to the type of governance modeling (summarized in Table 2).

Similarities in number of actor types and in actors' decision-making processes

The actors' decision-making process does not appear to be linked to the types of modeling of governance. Approximately 29% of the reviewed articles consider optimization for representing rational behavior (27% and 32% of articles using variable-based and agent-based governance, respectively). The remaining cases use some type of behavioral heuristics such as the probability of decisions based on criteria, choice of the best alternatives, and reaching a threshold, all used in the same proportion. These results, and all those that follow, concern articles whose authors

Table 2. Number of articles for each characteristic and in parentheses the percentage of the total per form of governance implemented. Comparison between forms of implementation: similarities (S) and differences (D). Numbers do not necessarily add up to 45 or 100% because 1 article may use several categories at the same time or because an assessment was not possible for some articles.

Characteristics of articles	Variable-based governance	Agent-based governance	Comparison
Total number	35	12	
Different types of actors	7 (21%)	2 (18%)	S
Decision-making process: optimization algorithm	11 (32%)	3 (27%)	S
Decision-making process: use of financial/ecologic/social factors	30/23/14 (88%/68%/41%)	8/6/5 (73%/55%/45%)	S
Theoretical background in neoclassical economics/ institutional economics	12/5 (34%/14%)	2/3 (17%/25%)	D
Governance represented by state/others	26/8 (84%/25%)	11/0 (100%/0%)	D
Policy instruments: command-and-control/economic instruments/information	12/16/4 (44%/62%/15%)	4/5/3 (36%/45%/27%)	D
Bidirectionnal links with actors/the ecological system	5/0 (15%/0%)	4/2 (36%/18%)	D

self-identified the subject as relating to SES. We found that the use of optimization was less important in the papers modeling the governance of SES than in articles focusing on a specific type of SES such as land-use models studied by Groeneveld et al. (2017), or agricultural models studied by Kremmydas et al. (2018). In fact, these authors found that 40% and 60%, respectively, of the articles they reviewed used optimization in decision making.

Regardless of the specific evaluation procedure or the theory used to describe mechanisms, different factors can influence the decision-making processes. These factors are also not influenced by the types of governance modeling. The most important factor considered in decisions is the financial factor, seen in approximately 80% of the articles (88% for variable-based governance articles and 73% for agent-based governance articles). The second-most important factor is the ecological factor, used in 62% of the articles (68% and 55%, respectively). Lastly, the social factor can represent the influence exerted by specific individuals or by a group of agents on the other actors. In 42% of the articles, social influence is reported, either by individual or collective actors (45% for variable-based governance articles and 41% for agent-based governance articles). In only one model is this influence both individual and collective. Social influence is principally collective; 18% of all articles mention individual influence and in 27%, collective influence. For instance, the governance agent may be influenced by the number of land managers that benefit from the subsidies (Holzhauer et al. 2019), or agents may be influenced by both collective and individual actors through the total harvest rate of all agents and by a random agent to whom they compare their income (Tilman et al. 2018).

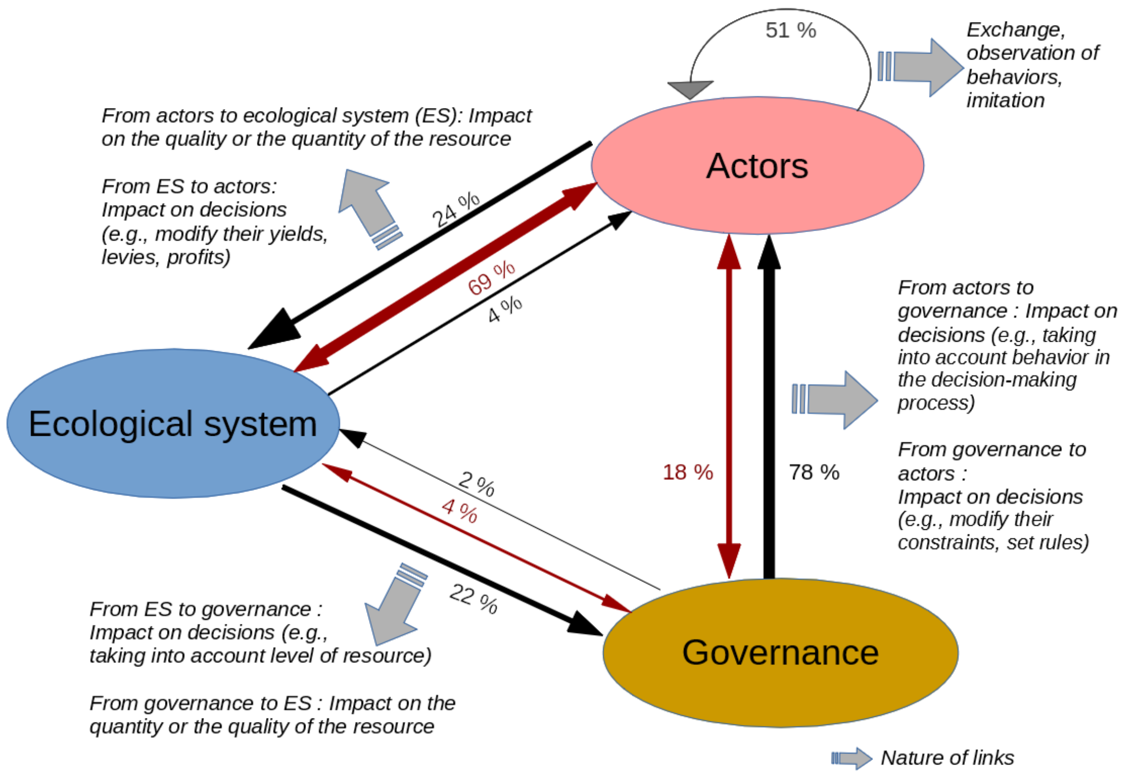
The types of governance modeling do not seem to be linked to the presence of different types of actors. We define a type of actor as a set of actors having the same possibility of actions. For example, Deng et al. (2018) described two types of actors in their models, agricultural households (farming) and factories (producing) that influence the SES. Overall, 16% of the articles included different types of actors, ranging from two to six types. Within actor types, most of the individual actors are different to each other. The differences in actor characteristics mainly concern the initial allocation of production factors and the local environmental conditions, and a minor proportion of internal characteristics such as age or family name. Often, there were also differences in decision making, mainly with different decision processes. In articles with several types of actors, there are always differences other than decision-making processes. The potential differences between types are the same as those within a type: local environmental conditions, initial allocations of factors of production, or internal factors (e.g., family name or age; see, for instance, Gaube et al. 2009). The decision-making processes of governance agents are the same as those of other agents in two-thirds of the models.

Differences in modes of governance and dynamics

The theoretical backgrounds of the conceptualization of governance processes and interactions and of actors' decision processes are different between variable-based governance models and agent-based governance models. The share of articles that mention a theoretical background is the same for both types of implementation, but neoclassical economics are more widely represented in variable-based governance models whereas institutional economics are more widely represented in agent-based governance models. Likewise, the share of theoretical and empirical bases for decision-making processes is the same for both types of implementation, but the agent-based governance models are dominated by the use of the assumption of bounded rationality whereas actors' decision-making processes in variable-based governance models are based both on rational choice theories and on bounded rationality theory.

Informal and formal institutions are rarely represented in both types of implementation. However, differences are noted in terms of governance modes and policy instruments. In agent-based governance models, there are only state-based modes of governance: 36% of models implemented command-and-control instruments, 45% economic instruments, and 27% information. In variable-based governance models, other modes of governance are represented: market-based or community and private-social partnerships. They account for 25% of the models. Economic instruments are the more widely represented form at 62%, followed by command-and-control instruments at 44%. Information is represented in only 15% of the articles. Thus, although a larger range of governance modes is represented in variable-based governance models, the focus is more on economic instruments and less on information instruments compared with agent-based governance models.

Fig. 3. Types of links between sub-systems (percentage of articles).



The interactions between governance and other systems can provide a better understanding of the emerging dynamics of the model. When governance is represented as a variable, interactions are bidirectional with the actors in 15% of the models but they are never bidirectional with the ecological system. On the other hand, when governance is represented by an agent, interactions are bidirectional with the actors in 36% of the models and with the ecological system in 18% of the models. For instance, in the work of Holzhauer et al. (2019), the institutional agents' decision-making preferences are guided by public support from actors and actors receive subsidies from them.

The theories used for agent-based governance models are further away from neoclassical theories, for conceptualizing both governance and actors' decision making. This may indicate a willingness on the part of the authors to get closer to reality. The three policy instruments are represented in a more homogeneous way. Moreover, the greater presence of bidirectional links may suggest a desire for more complexity. However, these results are nuanced by the fact that the implementation of actors is similar between the two types of implementation. The presence of a typology of agents is the same in both implementations, the decision-making processes are the same as are the decision factors. Furthermore, formal and informal institutions are represented only in the variable-based governance models.

Governance and interactions in social-ecological agent-based models

Interactions in SES have several implications for the sustainability and management of these systems (Folke et al. 2010). Governance influences interactions between actors and the ecological system and is in turn influenced by the changes occurring in the actors' and ecological systems. Links can be unidirectional or bidirectional (see Fig. 3).

Governance systems affect the decisions of the actors in all but two articles, by incentivizing or constraining actors in terms of possible actions. For example, in the work of Cenek and Franklin (2017), governance takes the form of a regulatory instrument that determines fishing dates considered by agents to decide on whether to fish or not. Governance can also take the form of an economic instrument and can modify the economic context by giving subsidies (e.g., Van Schmidt et al. 2019) or by collecting taxes (e.g., Gross et al. 2006). In three-quarters of the models, the link between governance and actors is a unilateral one: from governance to actors. In other papers, the link is bilateral, i.e., actors also influence governance. For example, in the study by Guzy et al. (2008), actors rank the policies proposed by the agent of governance. Then, the agent of governance has to choose the policy to implement according to these ranks, among others. In two articles, governance interacts only with the ecological system (Charnley et al. 2017, Gonzalez-Redin et al. 2020). In these articles, governance is represented by an agent that manages its own parcels of land.

Actors may also affect governance because of interactions between agents that may have unexpected effects on governance. In two-thirds of the articles, agents have interactions with other actor agents. The interactions between agents can be direct or indirect. We define direct links as interactions occurring in the system of actors. Indirect links represent interactions through other systems. In 51% of the reviewed articles, interactions between actors are direct interactions such as the observation of behaviors, for example, the fishing effort of other fishers included in the calculation of profit (Tilman et al. 2018) or the imitation of strategies between actors (Müller-Hansen et al. 2017). Indirect interactions, present in one-third of the articles, occur through the ecosystem, for example, the use of a collective pasture leading to decreased availability of grass for others (Miyasaka et al. 2017). In works with different types of agents, inter-type interactions are present in two-thirds of the articles. For example, interactions could be the sharing of information on whale locations (Parott et al. 2011) or the exchange of biogas (Verhoog et al. 2016).

In 70% of models, there is no link between the ecological system and the governance system. One-quarter of the models have a link from the ecological system to governance. This is the case when ecological factors are considered in the calculation of variables for governance or in the decision-making process of a governance agent. For example, in the work of Gross et al. (2006), subsidies depend on droughts. In two articles, the links are bidirectional (Charnley et al. 2017, Gonzalez-Redin et al. 2019). In only one case, the link is from governance to the ecological system: a case in which governance acts directly on the forest (cutting; Dupont et al. 2016). The lack of links between governance and the ecological system can be explained by the fact that the actions of governance on the ecological system are mainly through agents. In fact, if we consider the social system as a whole composed of governance and actors, 80% of interactions are bidirectional, 16% are from the social system to the ecological system, and 4% are from the ecological system to the social system.

In all the articles reviewed except one, there is a link between the actors and the ecological system. The exception is the article by Gonzalez-Redin et al. (2019), in which there are no actor agents but only governance agents. These agents represented governance forces driving the development of land for sugarcane production, the creation of new protected areas, and the restoration and maintenance of semi-natural areas, in which actors as farmers were implicitly included. In 69% of cases, it is a bidirectional link. It is often the case in articles modeling productive activities such as fisheries and agriculture (e.g., Bitterman and Bennett 2016, Cenek and Franklin 2017) that the actors are influenced by the level of resources or past yields and their actions affect the level of resources or future yields (e.g., Caillault et al. 2013). Among the articles describing a unidirectional link, one-quarter of the articles include links from the ecological system to actors. These links can take different forms: the ecological system directly influences the actors by modifying their outcomes (yields, profits) or decisions (e.g., Chion et al. 2013); the ecological system is considered in the decision-making process and thus influences behavior. The second unidirectional link, from actors to the ecological system, is present in three-quarters of the articles involving unidirectional links. The actors influence the quality or quantity of resources in the ecological system.

DISCUSSION

Highlights and limitations

Our results show that half of the models have a theoretical background about conceptualization governance processes and interactions. A little less than two-thirds of these models are grounded in neoclassical economics in which environmental and natural resource management problems are approached from the perspective of market dysfunction. State intervention is the mode of governance mostly represented in the models (see Fig. 2). Among the policy instruments, command-and-control and economic instruments are mostly represented. Informal and formal institutions, self-governance, or market-based modes of governance are also modeled but remain marginal. Market-based modes of governance are probably rarely represented because the challenges in SES are often issues that are not resolved by the market and therefore require public interventions.

In terms of implementation, governance as a variable is preferred to that as an agent. Governance is often represented as a test of the value of variables in different scenarios and therefore does not require representation with an agent. In variable-based governance models, there is a greater diversity of modes of governance represented even though command-and-control and economic instruments are the most widely represented. Agent-based governance models are more frequently based on institutional theories and represent instruments of information. These models present more interactions between governance and ecological systems or actors than variable-based governance models. Bidirectional links are found in approximately one-fifth of all models. For the others, governance acts mainly on the ecological system through the actors by impacting their decisions. The links are between the agents that interact with each other and between the ecological system and the agents. Actors impact the ecological system (in terms of quantity or quality) and in turn are influenced by it in their decisions.

This review has shown the potential of ABM to analyze governance in SES. Until now, ABM have been mostly used to analyze or compare theories (Janssen and Baggio 2017), to examine empirical case studies (Matthews et al. 2007), and to predict the evolution of SES (Grimm and Railsback 2005) but rarely to develop a new theory for analyzing SES. Future research could consider the use of ABM to develop theories of SES, to improve our understanding and management of complex systems (Lorsheid et al. 2019), to explore land use changes (O'Sullivan et al. 2016), or to analyze social-ecological phenomena (Schlüter et al. 2019). However, the use of ABM also exhibits some drawbacks. With regard to SES complexity, it can be difficult for models to both represent a range of governance dynamics and use sound simplifications to do so without undue complexity. Then, because ABM represent agents with their own individual properties, the number of parameters can be high and the model difficult to calculate (Gotts et al. 2019). Moreover, models are often either highly conceptual or very case specific (Schill et al. 2019). Furthermore, ABM may lack transparency, which makes it difficult to determine the influence exerted on the system by a part of the system or by a specific parameter (Gotts et al. 2019). Introducing governance underlines these issues. Indeed, adding dynamics and new processes with governance contributes toward complicating the model and increasing the number of parameters and the ensuing problems associated with this.

This review is limited to the set of articles that describe models self-identified by their authors as applied to a social-ecological system, socio-ecological system, or socio-ecosystem in the title/

abstract/keywords. Although the concept of social-ecological systems lacks a common definition (Herrero-Jáuregui et al. 2018, Colding and Barthel 2019), other concepts describe systems including humans and nature as coupled human and natural systems (e.g., Kline et al. 2017), earth systems (e.g., Müller-Hansen et al. 2017), or ecological-economic systems (e.g., Gao and Hailu 2018). Moreover, other fields of research focus on the same type of SES that we identified such as the energy-water-food nexus systems (Namany et al. 2019), land use and cover changes (Parker et al. 2002), natural resource management (Loomis et al. 2008), or agricultural systems (Kremmydas et al. 2018). The choice of search commands may have implications in terms of the type of SES involved. For example, the inclusion of the term "coupled human and nature" (CHAN) would probably have led to the selection of more articles dealing with land use and land-cover change because these are areas that characterize research related to CHAN systems (An 2012). The tightening of our review based on these keywords allowed us to focus on the research conducted by the community of authors referring to the concept of SES.

Finally, our review of the literature was constrained by the heterogeneous descriptions of the models in the reviewed papers. In some cases, supplementary material is provided or the description of the model follows the ODD (Overview, Design concepts, and Details, or ODD+Decision) protocol (Grimm et al. 2010, Müller et al. 2013), although in other cases, models lack precision. The use of a common protocol for the description of models would certainly be very useful in limiting biases in the comparative analysis of models.

Perspectives

Although a diversity of theories that conceptualize governance processes and interactions exist, many articles do not explicitly refer to theories in model building. This diversity is, for instance, highlighted by Cox et al. (2016), who identified, in a database of over 117 SES studies, more than 60 different theories across various fields such as geography, economics, ecology, biology, and politics. Moreover, among the articles that refer to a theory, there is very little diversity in the theories implemented in SES ABM, which are mainly based on the neoclassical economics approach. Beyond the neoclassical economics field, theories are less modeled, even though they are recognized to be relevant for the analysis of SES. For example, the theory of collective action by Ostrom (2003) describing how structural variables affect the levels of cooperation is cited only once (Wang et al. 2013). Another part of the literature that is of relevance in this field is ecological economics. This transdisciplinary field of research was promoted by Georgescu-Roegen (Missemer 2013), who worked on the coevolution and interdependencies of human economics and natural ecosystems. He proposed new theories in the management of relationships between humans and the environment. Management theories in this field are mostly formalized. Thus, it could be very interesting to consider them when modelling governance in SES ABM.

The lack of diversity applies not only to the theories but also to the modes of governance. Other dimensions of governance have not been modeled yet in social-ecological ABM that include governance despite being identified as key for the sustainable management of SES, for instance, adaptive management and polycentric governance. The concept of adaptive management has emerged from the adaptive management framework that appeared in the 1970s (Holling 1978, Walters and Holling 1990) and then developed within the framework of SES (Berkes and Folke 1998, Folke et al. 2005). More recently, adaptive management has been defined as "a systematic process for improving management policies and practices by learning from the outcomes of management strategies that have already been implemented" (Pahl-Wostl et al. 2007). Although interest in this approach has been growing steadily since its inception, it is not implemented in any of the models reviewed here. However, ABM are well suited to the implementation of adaptive governance because of their ability to represent learning processes at different scales, notably at the level of governance agents (e.g., Klos and Nooteboom 1997, Scheffran 2016, Macq et al. 2017). This is also the case for polycentric governance, a concept that was first introduced by Ostrom et al. (1961). Polycentricity characterizes a governance system in which governing authorities at multiple scales interact to make and enforce rules (Ostrom 2010, Biggs et al. 2015, Mathias et al. 2017). According to Carlisle and Gruby (2019), a growing interest in polycentricity on the part of commons scholars is evident in the number of articles and books that consider the advantages of polycentric governance for sustaining natural resources (e.g., Blomquist and Schlager 2005, Andersson and Ostrom 2008, Pahl-Wostl and Knieper 2014). The advantage of ABM in describing polycentricity is that they can describe horizontal and vertical linkages in fine detail and highlight the potential emergence of sustainable system dynamics. Nevertheless, none of the models reviewed integrates this dimension of governance, probably because of the difficulties in translating these concepts into equations. In fact, it remains a challenge to implement this type of governance in ABM: these approaches are less formalized and can use large-scale variables (from more complex decision-making process because of the adaptation and learning process or from embedded levels of governance) that compound difficulties in implementation. Nevertheless, some authors already modeled these dimensions of governance in other types of modeling (as ordinary differential equations) that can be inspiring for our topic (e.g., Mathias et al. 2017, Ahlering et al. 2020). The use of conceptual models and stylized models or the distinction between different cycles of adaptation could be approaches to follow in ABM. A better consideration of the various characteristics of governance would be advantageous to improve the relevance of ABM to the analysis of SES.

In the models reviewed, many authors proposed ad hoc implementations of the governance or actors' decision-making processes without any reference to theories, based on the case study at stake, or serving only the situation they seek to analyze. When processes are based on theories, they are mostly based on the assumptions of rational choice or bounded rationality. In some of these models, actors have no direct interactions with each other and their decision-making process is only influenced by financial factors. Thus, the system represented is closer to an economic system than a social system. This finding does not apply only to social-ecological ABM that integrate governance, but to all social-ecological ABM (Schulze et al. 2017). There is a large difference between the diversity of decision theories developed in social sciences and the diversity of theories used in agent-based modeling of SES. However, the human decision-making submodels are key elements, and therefore a representation of human decision making suited to the purpose of the model is a prerequisite for models integrating governance (Schulze et al. 2017). Schlüter et al. (2017) have identified the multiple challenges of the implementation of alternative theories of human behavior and decision making: (1) going beyond the difficulties because of multidisciplinary collaboration; (2) improving knowledge about the theories that are useful and usable in SES contexts; and (3) operationalizing the theories. Decision-making models associated with theories that conceptualize governance processes and interactions should be improved and enriched by other decision theories to be closer to the real world. For example, one of the well-known theories in decision making is used only once in the models reviewed: the theory of planned behavior. This theory, and the theory from which it originated, the theory of reasoned action, have proven their usefulness and capacity to reproduce behavior, especially in the field of environmental governance and management. Scalco et al. (2018) concluded that the theory of planned behavior and its use in ABM can certainly offer a useful model of deliberative decision-making processes for virtual agents. This theory is particularly relevant in terms of natural resource management because of its ability to consider different factors (Grilli and Notaro 2019, Si et al. 2019). Indeed, it could be a useful theory for analysing SES because of its capacity to include different elements from the ecological system (e.g., the role of the perception of the environment in actors' attitude), from the governance system (e.g., modifying the attitude or the perceived behavioral control), or from the others (e.g., included in the subjective norm). When addressing governance issues, other specific elements of decision making are important such as the perception, the evaluation (Schlüter et al. 2017), or the learning approach, shown, for instance, in triple-loop learning approaches (Argyris and Schön 1978). Indeed, integrating learning processes in governance in the context of increasing uncertainty due to climate change is important because it permits an adaptive response of the system (Palh-Wostl 2009). Nevertheless, the implementation of such psychological and cognitive processes and theories remains challenging. For instance, as shown by Muelder and Filatova (2018), the use of the same decisional theory with similar data can lead to different simulation outcomes. The authors highlight methodological recommendations to enhance the reliability of ABM in the implementation of these theories: improvement of transparency on implementation and systematic tests, consultation with psychology scholars to resolve ambiguities of theories, use of a recursive process to collect micro-level data on behavior, and use of a standardized and modular approach (Muelder and Filatova 2018).

CONCLUSION

In this review, we examined the ABM literature on governance in SES to: (1) provide a detailed overview of the conceptualization and implementation of governance and (2) highlight the critical aspects and challenges for future research on governance in social-ecological ABM. First, a significant share of articles does not refer to theories that conceptualize governance processes and interactions. Few theories are implemented in the literature, especially in the field of collective action led by Ostrom, despite the fact that their relevance to SES analysis has been proved. Therefore, it may be important to also use these theories in social-ecological ABM. Furthermore, the decision-making processes intertwined with governance are often described in a limited way and make little use of the diverse theories of decision making, although these are crucial for the outcomes of governance. The effect of the choice of decision-making process on governance should therefore not be overlooked and care must be taken to ensure that these choices are well informed. Moreover, institutions (formal and informal), as well as market-based and community-based modes of governance could be more widely represented in models, and, for further research perspectives, other dimensions of governance such as polycentric or adaptive governance could be examined. Finally, the representation of governance as an agent could help us move toward a greater diversity in the representation of governance and to a better implementation of the dynamics of the models linked to the governance of SES.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/12440

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Data Availability:

Data/code sharing is not applicable to this article because no new data/code were created or analyzed in this study.

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Appendix 1

List of articles reviewed

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Appendix 2

Detailed questionnaire

Overview

Purpose	Phenomena addressed
Software	
Type of SES	
Type of dynamics of the ecological system	

I. Questions concerning Governance

Questions	**Responses**
To which theoretical governance framework does the article refer?	
How is governance represented in the model?	Agent-based modelling Variable-based modelling
Questions following if variable-based modelling	
How is governance implemented?	Informal institutions Formal institutions Modes of governance → Market-based → Private-social partnerships → Community-based → Co-management → Public-private partnerships → State-based: Information/Command-and-control/Economic instruments
Does governance change over time?	Yes → and it is exogenous → and it is endogenous No
The objectives of governance are to...	Agents Ecological system Both Other
To achieve its objectives, it takes into account factors....	Agents Ecological system Both Other
It acts on (process)....	Agents Ecological system Both Other

Questions following if agent-based modelling	
How is governance implemented?	Informal institutions Formal institutions Modes of governance → Market-based → Private-social partnerships → Community-based → Co-management → Publi-private partnerships → State-based: Information/Command-and-control/Economic instruments
How is construct the decision-making process ?	Rational choice Socio-psychological theories Bounded rationality Participatory modelling From primary data From secondary data
What are the objectives of agent ?	Economic Ecological Social Risk management Preserve the spatial characteristics of the environment Other
Which factors are involved in decision ?	Financial Human infrastructure Ecological system resource The others individually The others collectively Risk Other
Where do the data for decision making parameters come from?	Literature Survey Assumed
Decision-making algorithm	Optimization Other (Threshold; Heuristics; Probabilistic after calculation; Calculation and better choice) Utility function
Memory ?	Yes/No
Learning ?	Yes/No
Are there interactions between governance agent(s) and individual agents?	Yes/No
What type(s) of interactions are there between the governance agent(s) and other agents?	No Exchange Behavioural observations Environmental observations Observation of characteristics Through the ecosystem

II. Questions concerning actors

We define a type of agents as a set of agents having the same possibility of actions.

Dimension	**Questions**	**Responses**
Agent diversity	Are they different types of actors?	Yes/No
	Number of types of agents	
	What are the difference between agents inter-types?	No difference Local environmental conditions Allocation of factors of production Internal ("intangible factors" such as surname, knowledge) Same decision process but different decision parameters Different decision-making processes
	Are there interactions between agents inter-types?	Yes/No
	What type(s) of interactions are they inter-types?	No Exchange Behavioural observations Environmental observations Observation of characteristics Through the ecosystem
	How are inter-types social interactions structured?	No network Random → Uniform Based on characteristics → Geographical → Other Complete network
	Is it possible to change of types ?	Yes No
	Following questions are repeating for each types	
General	How is construct the decision-making process ?	From a theory → Rational choice → Socio-psychological theories → Bounded rationality → Other, specify Empirically → Participatory modelling → From primary data → From secondary data
	Abstraction level	Aggregation
	What are the objectives of agent ?	Economic Ecological Social Risk management

		Preserve the spatial characteristics of the environment Other
Algorithm	Which factors are involved in decision ?	Financial Human infrastructure Ecological system resource The others individually The others collectively Risk Other
	Where do the data for decision making parameters come from?	Literature Survey Assumed
	Decision-making algorithm	Optimization Other (Threshold; Heuristics; Probabilistic after calculation; Calculation and better choice) Utility function
Various aspects of agent decision making	Memory ?	Yes/No
	Learning ?	Yes/No
Diversity intra-types	What are the difference between agents intra-types?	No difference Local environmental conditions Allocation of factors of production Internal ("intangible factors" such as surname, knowledge) Same decision process but different decision parameters Different decision-making processes
Interactions intra-types	Type of interactions intra-types	No Exchange Behavioural observations Environmental observations Observation of characteristics Through the ecosystem
	How are intra-types social interactions structured?	No network Random → Uniform Based on characteristics → Geographical → Other Complete network

III. Questions concerning links between systems

Questions	Responses
In wich direction are the links between the ecological system (ES) and the governance system (GS) ?	ES → GS GS → ES ES ↔ GS No link
What are the nature of these links ?	
In wich direction are the links between the ecological system (ES) and actors (A) ?	ES → A A → ES ES ↔ A No link
What are the nature of these links ?	
In wich direction are the links between actors (A) and the governance system (GS) ?	A → GS GS → A A ↔ GS No link
What are the nature of these links ?	