Participation in modeling social-ecological systems across scales in agriculture and forestry

Markus A. Meyer[1,*], Yue Dou[2,3], Hedwig van Delden[4,5], Thanh Thi Nguyen[6], and Melvin Lippe[7]

[1] Anhalt University of Applied Sciences, Bernburg, Germany
[2] Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, The Netherlands
[3] Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China
[4] Research Institute for Knowledge Systems, Maastricht, The Netherlands
[5] The University of Adelaide, Adelaide, Australia
[6] Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics, Organic Agricultural Sciences, University of Kassel, Witzenhausen, Germany
[7] Johann Heinrich von Thuenen Institute, Institute of Forestry, Hamburg, Germany

Abstract

Participatory approaches have gained recognition in scientific research, particularly in modeling human-environmental interactions and social-ecological systems (SES). Despite this achievement, a lack of in-depth understanding prevails to which degree, and at which scales and levels, participation takes place during the modeling cycle. Furthermore, information on the linkages between the level of the participating stakeholders and the modeling level of agents and environmental processes remains scarce. To shed light on this research gap, we conducted a systematic review including 79 relevant studies focusing on social-ecological systems within agricultural or forestry domains. Results reveal that participation was mostly carried out at lower spatial levels (local and regional) while stakeholders commonly originated from one spatial level, mainly the study area. Agent behavior was mainly simulated at a single spatial level. The number of studies modeling multi- and cross-scale levels or integrating participation was small. In rare cross-level modeling cases, local-level agents were predominately simulated as an aggregate at higher levels. We found that stakeholders most commonly participated in model parameterization and calibration, but rarely in model results communication. Participation was also relatively strong in model design, development and validation. This can be explained by the need of scientists for model input or to improve the transparency of the modeling process. To address these gaps in future studies, we recommend to model agents operating at their "real-world" level, while capturing interactions between agents across different scales, rather than (dis)aggregate agent behaviors to a single level. Furthermore, participation should go beyond fulfilling the mere scientific requirement of model development, and should be used to enhance the applicability and relevance of SES models.

Keywords

participation; modelling; scale; agriculture; forestry

1. Introduction

Stakeholder involvement and participation have been gaining increasing recognition in scientific research, particularly in models that include human-environment interactions (Pereira et al., 2020; Reid et al., 2016; Sterling et al., 2017; Voinov et al., 2016). Improved understanding of the complex and adaptive nature of social-

Correspondence:
Contact M. Meyer at markus.meyer@hs-anhalt.de

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ecological systems (SES) with different foci, such as landscape or natural resource management in agriculture or forestry, is key to addressing the most pressing threats facing the planet and society (see Fischer et al. (2015) for a research agenda). SES modeling can be viewed as a multidisciplinary approach to understand the complex interactions between social and ecological components within a system. These models can integrate insights from fields such as ecology, economics, sociology, and political science to explore how human activities and environmental dynamics influence each other over time (see Tables 1 and 2 in Schlüter et al. (2019) for an overview).

Participation has been used in different ways in modeling, ranging from a low to a high degree of participation, e.g., rapid rural appraisals or participatory decision analyses such as multi-criteria analyses focusing on decision-making processes (Arnette et al., 2010; Voinov & Bousquet, 2010). Stakeholders can play an important role in the various ways models can contribute to guiding decision processes, surfacing assumptions and disagreement, identifying unexpected second-order effects, and disseminating and increasing societal knowledge. In addition, participatory approaches, which engage stakeholders and translate their knowledge into formal scientific information have been proven useful to integrate stakeholders' insights of complex systems and to improve the modeling (Hewitt et al., 2014; Voinov et al., 2016; Vukomanovic et al., 2019). Thereby, participation may fulfill multiple functions such as joint problem framing or facilitating group processes and social learning among others (Seidl, 2015).

The work that investigated the participatory methods used in environmental and land-use dynamics modeling (Mallampalli et al., 2016; Voinov & Bousquet, 2010; Voinov et al., 2018; Voinov et al., 2016) lays a great foundation to the modeling community, however, it does not provide considerable insight on how to best address the cross-scale and -level issues emerging from stakeholder interactions when integrating them into the modeling cycle. Interactions that occur across scales are particularly complex to represent in modeling. Likewise, these interactions pose challenges for integrating stakeholder engagement at the different levels and scales. Usually, cross-scale studies consider interaction between two scales (e.g., space and time), whereas cross-level studies consider interaction between different levels at one scale. Hence, the different stages on a scale can be viewed as levels (e.g., local and regional on a spatial scale or family and society on a network scale) while scales refer to the spatial, temporal, quantitative and analytical dimensions to measure and model a particular SES of interest (Cash et al., 2006). The integration of participation in cross-scale and cross-level studies is to date however rarely implemented: there are, e.g., cross-scale/-level studies with interactions (Kozicka et al., 2022) and multi-scale/-level analyses that consider processes at multiple scales without interactions between scales and levels (Scholes et al., 2013). To model cross-scale/-level dynamics, cellular-automata models are good for local-level interactions in spatial and social scales, but may need additional rules and data to incorporate cross-level interactions (e.g., between local and regional spatial levels). Another challenge is that stakeholders often operate at different scales and levels (Fischer et al., 2015), for example, farmers may care more about yield and local livelihoods, whereas policy makers often consider broader economic and environmental targets beyond the farmers' premises at landscape scale such as agri-environmental measures from a top-down perspective (e.g., discussed in Lastra-Bravo et al. (2015)). Yet, decision-making from local communities to regional and national policies involves multiple levels of governance that may function top-down or bottom-up, or as a combination of both. How to incorporate feedback loops across scales and levels affecting actions and decision making of stakeholders in modeling activities can thus become an even more difficult modeling task to achieve.

Despite these challenges, it remains useful to consider participatory approaches for cross-scale and cross-level modeling. Cross-scale and cross-level dynamics often involve a diverse group of stakeholders with varying interests and power (e.g., for mountainous SES studies Steger et al. (2021)). Equally, engagement processes work differently at different scales and levels (Reed et al., 2018). Participatory approaches engaging with stakeholders allow diverse perspectives or belief systems to be introduced into the modeling process. This ensures a more comprehensive understanding of the SES of interest and its interrelationships; it may however also add more complexity to already complex SES models. The knowledge brought by all these stakeholders that are dominant at certain levels is however crucial for an inclusive representation of decision-making in the model, as well as for improving model validation (Salliou et al., 2017). Using participatory approaches in cross-scale and -level modeling may further incentivize stakeholders to work together and implement recommendations of the adjunct modeling exercises (Malawska et al., 2014). For example, a national-level environmental policy will not be successful if not implemented at local level, while an effective policy requires better understanding of local farm management. Likewise, models exploring cross-scale and cross-level dynamics may rely on participatory approaches for certain stages of the modeling cycle, e.g., parametrization or scenario development (see Steger et al. (2021) for a review on purposes of participation in SES modeling). This does not necessarily mean that stakeholders from these varying scales are also engaged, nor does it mean that such modeling incorporates their perspectives, norms or belief systems across scales. Who are the key stakeholders at different levels and scales, and how to best engage stakeholders and incorporate their perspectives in the modeling practices for a transparent, inclusive and accurate representation, are important for modelers to better represent the interrelationships of SES across scales.

Addressing this knowledge gap helps gain new insights into the scale and level where participation occurs, and how interactions between scales and levels are considered (see Topic 1 in Table 1). Hence, in this study, we take a step forward towards a deeper analysis of participation and modeling across scales and levels focusing on agriculture and forestry as our SES of interest. We aim to understand when participation is considered along the modeling processes, and at which scale and level (Reed et al., 2018; Voinov et al., 2018), to identify general shortcomings, but also to reveal how this may hinder or support the modeling of SES at multiple scales and across scales. Modeling scales and stakeholder perspectives may not necessarily align, i.e., mismatch and misrepresentation may exist between the stakeholders and modeling scales (especially for large-scale processes noted by Voinov et al. (2016)) (see also Topics 2 and 3 in Table 1).

Table 1: Interactions between respondents' perceived legitimacy of the planning process and the centrality of CAST in that process. Overall, more interviewees find CAST to be central and view planning as an illegitimate "paper process".

Topic	Research question
Spatial level of participation	1. How is the (dis-)aggregation of levels done in the participatory process?
Participation along the modeling process	2. At which modeling steps is participation conducted?
Scale and level in modeling focus	3. How is modeling done with agents across scales and levels?
	4. How are stakeholders' perspectives integrated at different levels and scales (e.g., spatial and temporal)?
Effective management and use of participation	5. How are participatory contributions used across scales and levels?

Beyond that, it is important to organize participation effectively for society and the modeling process because it is still unclear what society requires from the environment, how the environment feeds back on people's behavior and how different governance instruments may shape these interactions (Binder et al., 2013). The degree of participation likely varies across scales (spatial, temporal, and social), modeling approaches, and scientific disciplines. We expect a considerable variation of stakeholder involvement depending on the modeling domains and approaches regarding both the steps of the modeling process and the degree of participation (see Topic 4 in Table 1).

Existing reviews generally address a broad thematic scope on human-environmental or SES and a rather narrow scope on models (e.g., Schulze et al. (2017) and Filatova et al. (2013) for agent-based models or Steger et al. (2021) for SES modeling). However, the broad perspective of SES makes a systematic and profound analysis challenging due to the heterogeneity of systems and disciplines. Reviews with a specific thematic scope (e.g., food systems, agricultural systems) lack a focus on the engagement of stakeholders (Huber et al., 2018; Müller et al., 2020). A review on the role of participation across modeling approaches is needed and missing for studies on agriculture and food systems in addition to systematic overviews of participatory modeling in general (Voinov et al, 2018). Comparable reviews focusing on forestry, which would include case studies such as Zupko and Rouleau (2019), have not been found. Therefore, the joint analysis of forestry and agricultural studies allows for a sufficient, but feasible number of studies and equally allows for identifying more generic patterns than focusing only on one sector or discipline (e.g., agriculture).

Against this background, we carried out a systematic review of peer-reviewed papers that combine modeling and participation within agriculture and forestry as the focus domains of SES addressing the research questions presented in Table 1. In addition, the current paper has elements of a critical review as we aim to analyze how participation is embedded in modeling, e.g., at which stage(s) to capture the degree of participatory modeling. We further compare how participation is carried out at different scales, by different models, with a focus on modeling components and processes that participatory engagement contributes to or occurs in. We then identify clusters of comparable studies that do not become immediately apparent given the relatively large number of variables coded in the reviewed papers. Findings are subsequently used to derive lessons learned and provide recommendations for future research and practice.

2. Methods

2.1 Systematic literature search

We conducted a systematic literature review based on an ISI Web of Science (WoS) and Scopus keyword search (TOPIC) (December 18, 2020) for journal articles for the following search terms: (socio-ecological* OR social-ecological* OR SES OR human-environment* OR integrat*) AND participat* AND model* AND (forest* OR agricult*). The first set of search terms (socio-ecological*, social-ecological*, SES, human-environment*) was selected to focus on SES. We added the term integrat* to capture any integrated socio-ecological systems approaches that might not have been labeled by the authors as such. As we aim to only look at studies that include participation and modeling, we included the terms 'AND participat* AND model*'. To narrow the scope based on the disciplines listed in the introduction we added the term 'AND forest* OR agricult*'. The search was limited to English, peer-reviewed journal articles with primary research, published from 2000 to 2020 (see date of the keyword search). This resulted in 634 publications in WoS and 691 in Scopus. We removed 636 duplicates. We screened the articles following the scheme in Figure 1. We included only original research articles and used review and opinion papers to frame the research of this study. Studies were only included if they met three main criteria: (1) thematically, they considered an SES perspective in agriculture and/or forestry, (2) used a qualitative, semi-quantitative or quantitative modeling approach as described by Voinov et al. (2018), and (3) used participatory approaches for at least one step of the modeling process (Voinov & Bousquet, 2010). To ensure consistent screening of abstracts and coding of studies, we harmonized the screening of abstracts and our coding in a first sample of publications by all co-authors for identification and screening. For the abstract screening and the coding, two co-authors selected the abstracts and coded the remaining papers to increase the consistency in coding (two-eye-principle). Each co-author worked in two teams for this stage, i.e., half of the abstract screening and coding with one co-author and half of it with another co-author.

2.2 Categories and criteria for the review

We aimed to analyze the degree of participation in (simulation) modeling of social-ecological land systems (agriculture and/or forestry). We classified beyond general study characteristics, mainly parameters characterizing the SES, the modeling approach, participation or analyzed scales, using Excel. Following the research questions, we designed the coding questionnaire following five sections: (1) study characteristics (e.g., country, study size, temporal and spatial resolution), (2) framework and thematic scope, (3) model characteristics, (4) participatory process, (5) degree of participatory modeling, and (6) scales of analysis as indicated in detail in the table "Classification and categorization table of coding criteria" in the Supplementary Material C.

The framework and thematic scope regarding the broader framework conceptualizing SES or human-environment interactions (e.g., Ostrom's SES framework, ecosystem services, resilience) extended Binder et al. (2013). We reviewed which social processes and environmental compartments have been studied and modeled. Equally, we were interested in the direction (e.g., social on ecological system, bidirectional) of interaction in the studies and the focus (social, ecological, or balanced). For example, more social studies might have a more detailed and thorough analysis of the social side, e.g., detailed simulation of human behavior in agent-based models (ABMs).

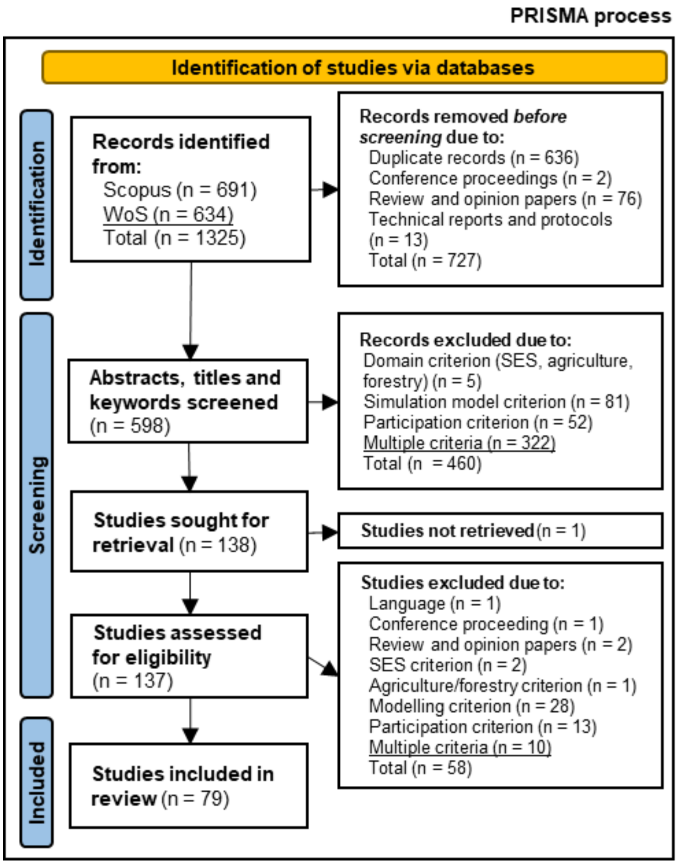

Figure 1: Selection strategy to identify relevant papers with exclusion criteria, total number of papers was identified from both Web of Science (WoS) and Scopus (Source: adapted from Systematic Reviews and Meta-Analyses (PRISMA) standards (Moher et al., 2009)).

Generally, we considered qualitative and quantitative modeling approaches as relevant models (see Voinov et al., 2018). Model characteristics were of interest for us regarding the purpose (e.g., theory testing, managing SES) and the role (e.g., analytical, forecasting and prediction) (Schlüter et al., 2019). Social learning was part of the model purpose "support governance and transformation". This category includes social learning given the potential formats and methods used for this category such as action research or supported participatory processes as mentioned by Schlüter et al. (2019). Subsequently, social learning can be viewed as a central aspect of transformation. This also fits the definition by Kelly et al. (2013) that "social learning refers to the capacity of a social network to communicate, learn from past behaviour, and perform collective action, e.g. dealing with complex technical tasks and at the same time the social relational activities (Fraternali et al., 2012; Haapasaari et al., 2012)". The purpose of a model often mirrors the aim of the research or project it was developed for (e.g., theory testing and building). The role of a model is in its (actual) use, which can be analytical, exploratory, and explanatory. Beyond the type of model (e.g., qualitative, quantitative) (Voinov et al., 2018), the type of input data for the social and ecological system as well as the way agents were included in the modeling were coded.

To capture the participatory process, we reclassified stakeholders' participation in the modeling process into five degrees from low to high. We defined stakeholders following Voinov and Bousquet (2010) as (professional) individuals representing private or public organizations, NGOs and interest groups, as well as individual citizens.

The classification of stakeholder participation was based on Arnstein's ladder of citizen participation (Arnstein, 1969). Since this seminal paper, the ladder has been adapted by various authors in the realm of participatory modeling (e.g., Basco-Carrera et al., 2017) to fit the purpose and context of the respective participatory research approach, and likewise we adapted the ladder to meet our context, focusing on those characteristics we found relevant for our review at the interface of participation and modeling, and most likely to find information on in the papers to be reviewed. In principle, the five types were exclusive to each other to summarize the purposes of participation in modeling, as outlined in Table 2.

Table 2: Participation type of the stakeholder in socio-ecological modeling research (Sources: adapted from Arnstein, 1969).

Type of participation	Definition/explanation of "participation"
Passive participation	Lowest degree of participation - scientists informing stakeholders about the model and research projects. There is no information exchange or communication between stakeholders and the scientists, rather a one- way flow of information.
Extracting information	Scientists use various means to gather information from stakeholders directly to feed into the model. Stakeholders are perceived as entities that can provide information and input to the modeling exercise upon request, however, there is no feedback process.
Participation to support the decision	Stakeholders are used to promote and articulate the chosen decisions. Their engagement in the modeling exercise is no longer restricted to solely providing input and opinions but rather demonstrating and explaining their activities and behaviors.
Interactive participation	Stakeholders' input and opinions are considered and can influence the modeling process to some degree. This degree of participation involves a two-way flow of information.
Self-organization	Highest degree of participation – stakeholders take initiatives to understand and perform in the modeling environment that researchers provide.

In addition to the five types of participation, we also recorded the model stages where stakeholders were involved through their participation (Table 3). These include the entire model cycle, from its scoping and conceptualization, through the parameterization and assessment, to its use and communication. Within each modeling stage (Table 3), we assessed the type of participation (Table 2), to understand if certain degrees of participation match with certain modeling stages.

Table 3: List of modeling stages and potential for stakeholders' interaction, modified from Salgado and Gilbert (2013).

Coding criterion	Type of activities carried out by stakeholders
Model scoping	The aim and purpose of the model include (or not) informing or engaging with stakeholders.
Schematic representation	System diagram, conceptual diagram or other schematic representation showing the model components and the information that flow between them.
Conceptual decisions	Whether or not stakeholders engage in adding, removing, or editing variables and relationships of the model.
Parameterization	If stakeholders' input is used to adjust the parameters of the model.
Model assessment	Stakeholders' input is used, or they were involved to assess the model results and performance.
Model use	Model results were presented or used by stakeholders.
Model communication	Any model components or results were presented and communicated to the general public other than the stakeholders involved in the modeling process.
Model results in decision process	Model results were used by decision makers or contributing to the policymaking or governance.

When referring to individual stakeholders, we classified, e.g., a study in that key informants or experts were interviewed. The term local stakeholders in this notion could refer to the participation of certain groups, e.g., male or female, young or old during focus group workshops (Lippe et al., 2011).

We recorded the scales of the modeled social phenomena and the scales of the engaged stakeholders. Finally, we identified the scales of analysis in the different studies and analyzed temporal, spatial, social, and network scales with their respective levels (Binder et al., 2013; Cash et al., 2006). We included the temporal and social scale since the aforementioned study included both as relevant for human-environment and social-ecological systems respectively. We additionally included the network scale from Cash et al. (2006) and the social scale from Binder et al. (2013) as these seemed most relevant for participatory modeling. We wanted to identify whether stakeholders from different scales and their respective levels were considered. We did not include the jurisdictional scale as it largely overlaps with the spatial scale as equally stated by Cash et al. (2006). We equally excluded the governance and management scales as both governance and management research were not in focus. We listed all levels of all scales in Supplementary Material C.

2.3 Data analysis

To understand the degree of participatory modeling, we analyzed how participation is embedded in modeling, at what component and which stage. We then compared how participation is carried out at different scales. We also recorded how participation was conducted by different models, particularly focused on the modeling components and processes that participatory engagement contributes to or occurs in. We further analyzed the clusters of studies for emerging patterns and identified potential research gaps. For this purpose, we cut the descriptive review criteria to the main keywords with the package tm (Feinerer et al., 2008) in R (R Development Core Team, 2024). We removed stop words and sparse terms (threshold: 0.9) and cut the terms to the word stems. We calculated the term frequency as inverse document frequency for the remaining major terms (c.f. Ferreira et al., 2013). The list of studies with the cleaned input data is available in the supporting information in Supplementary Material B.

We then clustered study results to identify major groups of studies, based on the following topics: model characteristics (e.g., purpose of the model, model and data type, agents), participation (categories based on Arnstein's (1969) ladder), integration of modeling and participation (e.g., participation along modeling phases), and scaling (e.g., spatial, temporal, social, network).

We conducted a multiple factor analysis to reduce dimensionality in the data with the package FactorMineR (Lê et al., 2008) in R (R Development Core Team, 2024). We applied on the factor analysis a hierarchical cluster analysis and identified the optimal number of clusters by cutting the tree at the cluster number where branches were visually longest and the relative gain of within cluster inertia change the most (Lê et al., 2008). The cluster analysis should reveal not immediately apparent categories of studies given the relatively large number of variables coded in the paper (e.g., to reveal potential differences between studies focusing on agriculture or forestry and common combinations of participation, modeling and levels of the different scales).

3. Results

3.1 Overview

3.1.1. General paper characteristics and thematic scope

We included a total of 79 papers in our review; numbers > 79 arise from multiple categories or disciplines addressed in one study. Most papers had an agricultural scope (n: 69) and primarily addressed natural resources and sustainable agricultural systems (n: 52). Papers addressing forestry (n: 35) mostly focused on the forest environment (n: 17). Less than one third of the papers (n: 25) addressed both forestry and agricultural topics. Geographically, the study regions were mostly European (n: 35) and primarily from Western Europe (n: 21). Asia (n: 14), Africa (n: 13) and the Americas (n: 15) each had a rather equal share and were less represented.

The typical temporal modeling resolution of the studies was annual and nearly all had a multiannual scope, with an emphasis for studies with a duration of less than ten years. However, multiannual studies between 10 and 50 years were equally frequent. Most studies were at landscape and regional scale, between 100 and 100,000 km² with a spatial resolution between 10 and 50 m if reported. The majority of studies did not report a resolution (see Tables S1 and S2 in the Supplementary Material A for details).

3.1.2. Model characteristics

More than 50% of the models showed bidirectional interactions between the social and the ecological systems rather than a monodirectional flow (of e.g., data, information) from one to the other (ecological to social 6.3%, social to ecological 40.2%). For example, human resource impacts on the environment (e.g., crops, timber) were, if monodirectional, much more frequent than studies on, e.g., environmental hazards affecting humans (Figure 2). We found 57.0% of the studies having an equal focus on the social and ecological system, while only a minority of the models/papers focused on the social (24.1%) or ecological system (19.0%) and placed less emphasis on the ecological or social system component respectively. Model types ranged from simplified qualitative to complex models, such as detailed quantitative and optimization models, but most (44%) were moderately complex like aggregated quantitative models. Most of the models focused on stakeholders within the study area or on affected communities rather than outside. This might be due to the high share, almost 80%, of social data from primary rather than secondary sources without spatial components.

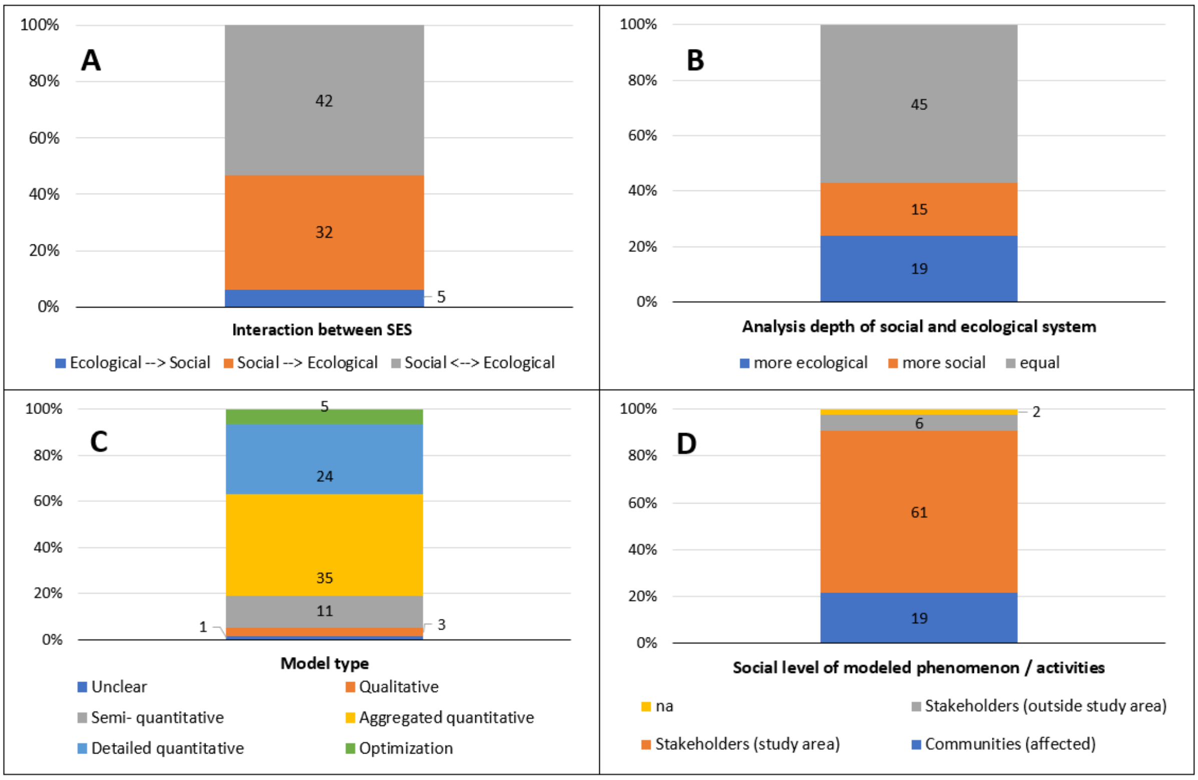

Figure 2: Descriptive statistic of model characteristics: (A) direction(s) of interaction between social and ecological systems in the model, (B) analysis depth of the model addressing the balance of social and ecological systems, (C) model type indicating the degree of detail and process quantification, and (D) social level (n: 79).

3.1.3. Typical cases of modeling SES of major land systems

We identified four typical categories of studies using a cluster analysis:

Cluster 1 (n: 12) (Table 4) contained primarily landscape- and regional-level forestry studies. These studies showed relatively weak participation apart from extracting information for exploration and explanation and used aggregated quantitative and optimization models.

Cluster 2 (n: 20) (Table 5) contained regional-level agricultural (or partly forestry) studies with an emphasis on natural resources and sustainable agricultural systems. These studies focused on forecasting and prediction using aggregated quantitative models, partly applied for decision support as participatory element.

Cluster 3 (n: 36) (Table 6) contained landscape-level agricultural (or partly forestry) studies with an emphasis on natural resources and sustainable agricultural systems. These studies largely modeled social systems for exploration and explanation. The aggregated and detailed quantitative models aim at strong participation in decision processes.

Cluster 4 (n: 11) (Table 7) contained agricultural studies aiming at micro processes leading to macro-outcomes using primary social data. These regional- and landscape-level studies aim to manage SES for exploration and explanation using aggregated and detailed quantitative models. These models have the strongest participation of individuals along major modeling steps.

Table 4: Cluster 1: Forestry studies with a more regional-level perspective and relatively weak participation apart from extracting information for exploration and explanation using aggregated quantitative and optimization models (n: 12); missing values are unclear/NA.

Studies (Corrigan & Nieuwenhuis, 2019; Do et al., 2021; Esse et al., 2019; Garcia-Gonzalo et al., 2013; Gaydos et al., 2019; Gonzalez-Redin et al., 2016; Maness & Farrell, 2004; Marques et al., 2020; Martínez-Falero et al., 2018; Mendoza & Prabhu, 2006; Sheppard & Meitner, 2005; Sherrouse & Semmens, 2014)	
Study region(s)	Central and Western Europe (5), North America (4), Southeast Asia (2) Chile (1)
Disciplines	<u>Agriculture:</u> • No agriculture (9) • Natural Resources and Sustainable Agricultural Systems (2) • Crop Production and Protection (1) <u>Forestry:</u> • Forest Assessment, Modeling and Management (4) • Forest Environment (3) • Forest Products (2) • Forest Health (1) • Social Aspects of Forests and Forestry (1) • Forest Policy and Economics (1)
Scales	<u>Spatial:</u> • Spatial resolution: NA (8) • Size: 0.5-~40,000 km² (mean: 7,140 km²) • Levels: patches (2), landscape (5), regional (4), multiple (1) <u>Temporal:</u> • Temporal resolution (a): 1/365 – 10 (mean: 5) • Levels: weekly (1), annual (1), >annual (2) <u>Social:</u> • Levels: stakeholders (study area) (9), multiple (2), stakeholders (outside study area) (1) <u>Network:</u> • Levels: society (9), kin (1)
SES and model	• Ecosystem services • Modeled: social system as input • Social system processes: macro, micro→macro • Analysis depth: equal, more ecological • Model purpose: Managing SES • Model role: exploration and explanation • Model type: aggregated quantitative and optimization • Social data: primary, non-empirical • Ecological data: secondary, primary
Participation	• Degree of participation: largely NA, extracting information (primarily at regional level) • Modeling and participation: model scoping to model communication (participation lowest)

Table 5: Cluster 2: Regional-level (agricultural or mixed) natural resources and sustainable agricultural systems studies for forecasting and prediction using aggregated quantitative models (n: 20); missing values are unclear/NA.

Studies: (Allain et al., 2020; Bhave et al., 2014; Bhave et al., 2016; Bremer et al., 2018; Carmona et al., 2013; Chan et al., 2010; Forni et al., 2018; González-Rosell et al., 2020; Henríquez-Dole et al., 2018; Koo et al., 2019; Kotir et al., 2017; Metcalf et al., 2010; Portoghese et al., 2013; Salliou et al., 2019; Solana-Gutiérrez et al., 2017; Stigter et al., 2017; Thompson et al., 2020; Tidwell et al., 2004; van Dam et al., 2013; Wyrwoll et al., 2018)	
Study region(s)	Central and Western Europe (7), North America (4), South America (2), Africa (3), India (2), Vietnam (1), Solomon, Islands (1)
Disciplines	Agriculture: • Natural Resources and Sustainable Agricultural Systems (20) Forestry: • No forestry (12) • Forest Environment (4) • Forest Assessment, Modeling and Management (2) • Forest Products (1) • Silviculture (1)
Scales	Spatial: • Spatial resolution: NA (15) • Size: 50-~400,000 km² (mean: 42,757 km²) • Levels: landscape (5), regional (14) Temporal: • Temporal resolution (a): 1/365 – 10 (mean: 5) • Levels: monthly (1), seasonal (1), annual (6), >annual (3) Social: • Levels: stakeholders (study area) (15), communities (affected) (2), multiple (1) Network: • Levels: society (15), kin (3), family (1), trans-society (1)
SES and model	• Mixed frameworks • Modeled: social system as input • Interaction: social→ecological • Social system processes: macro, micro→macro • Analysis depth: more ecological equal • Model role: forecasting and prediction • Model type: aggregated and detailed quantitative • Social data: primary • Ecological data: secondary
Participation	• Degree of participation: participation to extract information, support decisions, and interactive (sharing tools) (regional level) • Modeling and participation: model scoping to model communication (participation 2nd lowest)

Table 6: Cluster 3: Landscape-level (Agricultural or mixed) primarily natural resources and sustainable agricultural systems studies with modeled social systems for exploration and explanation using aggregated and detailed quantitative models with strong participation for decision processes (n: 36); missing values are unclear/NA.

Studies: (Andersson et al., 2013; Barnaud et al., 2008; Berkhoff, 2008; Braasch et al., 2018; Castella et al., 2005; Delmotte et al., 2016; Delzeit et al., 2018; Dupas et al., 2015; Dupont et al., 2016; Garedew et al., 2012; Gaube et al., 2009; Giordano et al., 2007; Halbe & Adamowski, 2019; Inam et al., 2017; Kleemann et al., 2017; Koo et al., 2020; Kopainsky et al., 2015; Köstner et al., 2014; Lippe et al., 2011; Lusiana et al., 2011; Mamitimin et al., 2015; Micha et al., 2018; Mitter et al., 2014; Mongruel et al., 2011; Moraine et al., 2016; Nidumolu et al., 2016; Nidumolu et al., 2007; Pissonnier et al., 2017; Pluchinotta et al., 2018; Pope & Gimblett, 2015; Roberts et al., 2021; Ronner et al., 2018; Uthes et al., 2011; Vayssières et al., 2011; Zagaria et al., 2017; Zorrilla-Miras et al., 2018)	
Study region(s)	Central and Western Europe (18), Africa (6), Southeast Asia (4), South Asia (3), North America (3). China (1), global (1)
Disciplines	<u>Agriculture:</u> • No agriculture (1) • Natural Resources and Sustainable Agricultural Systems (22) • Agricultural Economics and Social Science (7) • Crop production and protection (5) • Animal Production and Protection (1) <u>Forestry:</u> • No forestry (25) • Forest Environment (8) • Forest Products (2) • Forest Assessment, Modeling and Management (1)
Scales	<u>Spatial:</u> • Spatial resolution: NA (23) • Size: 0.01-~41,285 km² (mean: 3,525 km²) • Levels: patches (3), landscape (16), regional (13), global (1), multiple (1) <u>Temporal:</u> • Temporal resolution (a): 1/365 – 3 (mean: 0.9) • Levels: daily (3), seasonal (5), annual (12), >annual (2) <u>Social:</u> • Levels: stakeholders (study area) (22), communities (affected) (8), multiple (4), stakeholders (outside study area) (1) <u>Network:</u> • Levels: society (21), kin (4), family (2), trans-society (1)
SES and model	• Mixed frameworks • Modeled: social system • Interaction: social→ecological • Social system processes: micro→macro, macro, micro • Analysis depth: equal, more social • Model role: exploration and explanation • Model type: aggregated and detailed quantitative • Social data: primary, primary and secondary • Ecological data: primary and secondary, secondary
Participation	• Degree of participation: participation to extract information, and interactive (sharing tools) (local level) • Modeling and participation: model scoping to model results in decision processes (participation 2nd highest), highest for model results in decision processes

Table 7: Cluster 4: Agricultural social (behavior) studies with strong participation of individuals along major modeling steps to manage SES for exploration and explanation using aggregated and detailed quantitative models (n: 11); missing values are unclear/NA.

Studies: (Celio et al., 2014; D'Aquino et al., 2003; Delmotte et al., 2017; Gray et al., 2015; Kassa et al., 2009; Máñez Costa, 2011; Reckling et al., 2020; Roetter et al., 2007; Sandker et al., 2009; Smetschka & Gaube, 2020; Walz et al., 2007)	
Study region(s)	Central and Western Europe (5), Africa (4), Philippines (1), Guatemala (1)
Disciplines	Agriculture: • Natural Resources and Sustainable Agricultural Systems (8) • Crop production (2) • Agricultural economics and social science (1) Forestry: • No forestry (7) • Forest Environment (2) • Forest Assessment, Modeling and Management (2)
Scales	Spatial: • Spatial resolution: NA (10) • Size: 0.5-~33,000 km² (mean: 4,205 km²) • Levels: landscape (7), regional (2), multiple (2) Temporal: • Temporal resolution (a): 1/12 – 25 (mean: 4) • Levels: monthly (1), seasonal (2), annual (6) Social: • Levels: Stakeholders (study area) (8), communities (affected) (2), multiple (1) Network: • Levels: society (9), family (1)
SES and model	• SES Framework (Ostrom), Sustainable Livelihood Approach • Modeled: social and ecological system • Social system processes: micro→macro • Analysis depth: equal • Model purpose: managing SES • Model type: detailed and aggregated quantitative • Social data: primary • Ecological data: primary, all empirical
Participation	• Degree of participation: different degrees (primarily at local level) • Modeling and participation: model scoping to model use (participation highest)

3.2 Scale and level of participation

We developed an overview of the different scales and levels stakeholders operated at, followed by a summary of the spatial level where the specific purpose of participation is more likely to occur. Figure 3 shows that most of the papers (n: 49) involved regional stakeholders with a regional perspective (e.g., regionally active politician or watershed manager), followed by local stakeholders (36), individual stakeholders (9), national stakeholders (6) and supra-national stakeholders (1). There were 55 papers that included stakeholders from one spatial level and 20 papers that included stakeholders from multiple levels. Across the 20 papers that involved stakeholders operating at different levels, all involved local stakeholders, 16 involved regional stakeholders, six involved individual stakeholders and four involved national stakeholders. The others did not report the spatial level of stakeholders. Figure S1 in Supplementary Material A shows for these 20 papers, the number of levels stakeholders that were included per paper: there were 15 papers that included stakeholders from two levels (mostly regional and local), four papers that included stakeholders from three levels (all local, regional, and national) and only one paper with involvement of stakeholders from four levels (individual, local, regional, national).

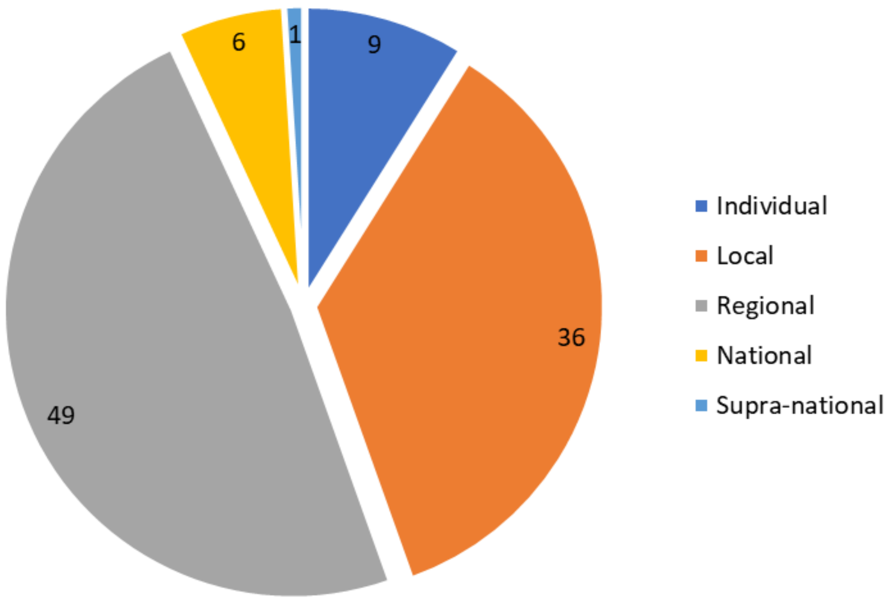

Figure 3: Number of studies including stakeholders from a specific spatial level (n: 79).

For the reviewed 79 cases, participation happened mostly when scientists needed to extract information for the model (n: 74); this was also supported by participation during modeling stages with almost 80% of the reviewed models having participation in parameterization (see section 3.2). Most stakeholders participating in the modeling could be attributed to the regional (n: 35) and local level (n: 22) if extracting information is the focus (Table 8). On the contrary, only three cases had passive participation, where the purpose of the model was to inform stakeholders. Participation at supra-national levels appeared least frequent (n: 2), followed by participation at national levels (n: 4).

Table 8: Type of participation and spatial levels at which stakeholders operate. Papers can include stakeholders operating at different levels.

	Type of participation				
Spatial levels of modeling	Passive	Extracting information	Support decision	Interactive participation	Self-organized
1.Individual	1	4	1	3	1
2. Local	1	22	9	11	4
3. Regional	1	35	12	10	0
4. National	0	2	1	1	0
5. Supra-national	0	1	0	1	0
10. Multiple	0	10	3	5	0
Not applicable	76	3	48	45	71
Unclear	0	2	5	3	3

Figure 4 summarizes the most common spatial levels at which the participation activities take place. Within these 41 studies, 38 studies have more than one participation activity conducted with stakeholders from the same spatial levels. For example, the modeling process may engage two participation activities: extracting information for the purpose of model parameterization and participation to support decision. If both activities are with local stakeholders, then we considered it a level match. However, if the former is with local stakeholders and the latter is with stakeholders from a regional level, we consider it a mismatch.

When more than one participation activity took place within the same model study, most of them focus on either local (n: 12) or regional (n: 14) levels. For example, in the reviewed paper of Mitter et al. (2014), the model scope was to assess soil water erosion in Austria and to use stakeholder participation for three purposes: stakeholders including farmers, agricultural extension specialists, policy makers from the region helped scientists to identify highly erosion-prone areas or climate parameters (extracting information for scientists);

stakeholders were also invited to review and reflect on the modeled adaptation results for the region (support decision-making); the reflection was carried out as a group feedback workshop, where stakeholders discussed and exchanged their opinion of adaptation options for the region with each other and with scientists (interactive participation). However, compared to the popularity of multiple participatory activities at local and regional levels, only one study conducts multiple participatory activities solely at national level and one other study at supernational level. When a participatory activity involved stakeholders from multiple levels, the same level distribution was maintained across other participatory activities within the study. In general, if a model has more than one participatory process, participation mostly happened at the same level.

We further compared the spatial levels of modeled phenomena (e.g., forest parcel dynamics) with the spatial levels at which information was gathered from stakeholders for modeling use (e.g., collecting forest management strategies from a national park agency) . Among the 79 papers, 41 aligned these levels. Within the 41, 16 studies focused on the landscape/local level, 23 on the regional level, and two incorporated both. In the remaining cases, after excluding unclear and unavailable data, most mismatches occurred at the local and regional levels, meaning that while the modeled phenomenon is at one level (e.g., local), stakeholder information was gathered at another (e.g., regional), or vice versa. Only two models investigated patch scale phenomena and the level of participation was regional or local.

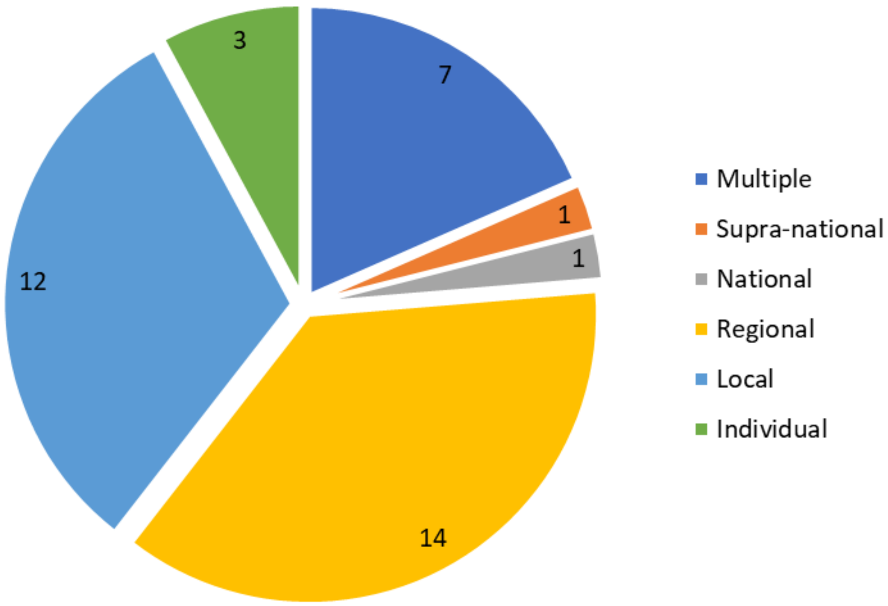

Figure 4: Number of reviewed studies with more than one participatory activity at the same spatial levels (total n: 38).

3.3 Participation along the modeling process

For each of the modeling stages, we analyzed the extent to which models were co-developed with or affected by stakeholders through participatory activities (Figure 5). As expected, stakeholder input was most widely found in the parameterization of the models (62 out of 78, 79%), either by extracting information through questionnaires or interviews or by discussing parameter settings in a workshop. A substantial number of studies involved stakeholders in the conceptual phases of model development, either in conceptual decisions regarding the model and its application (54 out of 79, 68%) or the schematic representation of the model linkages and their flows (48 out of 79, 61%). Most studies involved stakeholders in the assessment of the models' behavior or its results (47 out of 78, 60%), while in 42% (33 out of 79) of the papers stakeholders were involved in model scoping, often by defining the problem context.

When the focus switches to the actual use of the model and the use of results in practice, we found fewer papers with evidence of any of these activities being done in a participatory manner. Among the 24% of the papers that still mentioned the involvement of stakeholders in the use of the model, only 10% reported on the involvement of stakeholders in the use of the model results in decision-making and even less (7%) reported on stakeholder involvement in model communication. Especially regarding the latter two categories, it was often unclear from the papers if these activities have not taken place at all, or if they were carried out, but without the involvement of stakeholders.

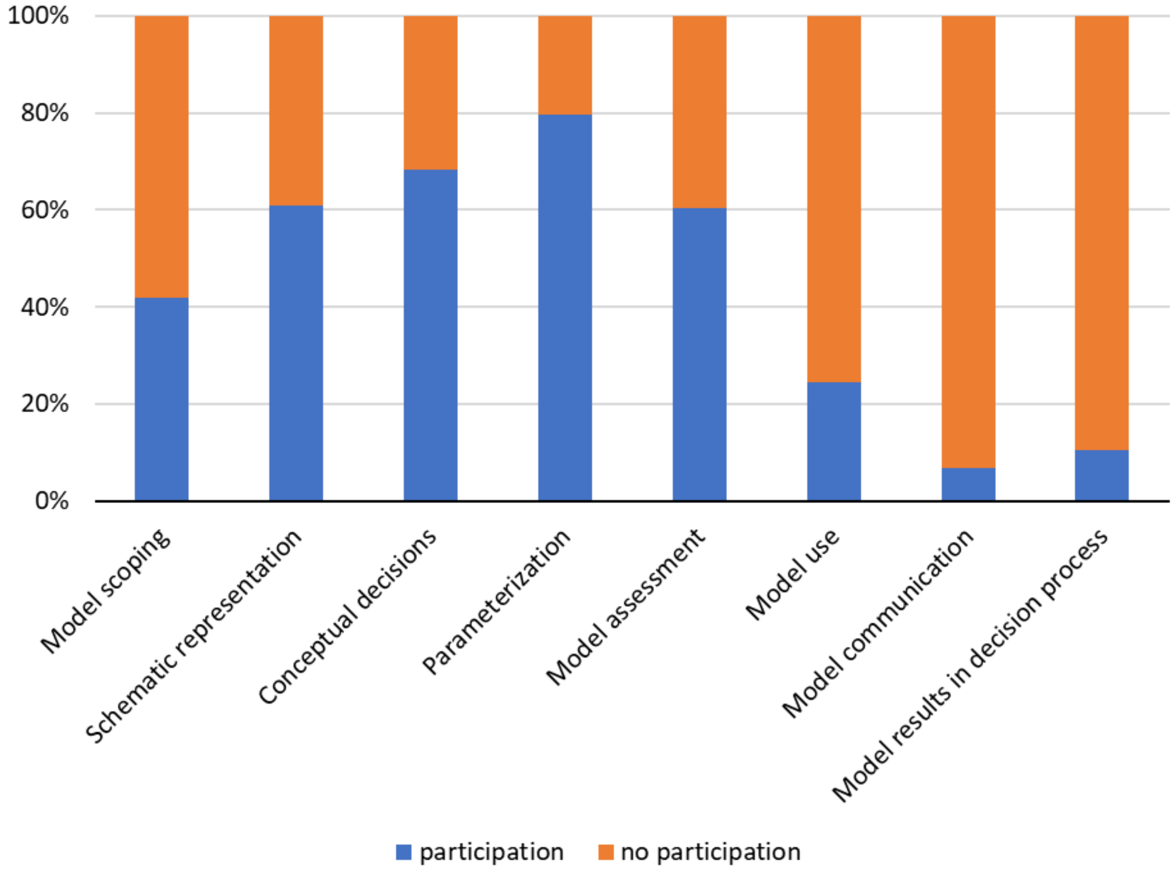

Figure 5: Percentage of reviewed papers have participation of stakeholders at different stages of the modeling process (n: 79); no participation include studies with unclear status of participation.

Figure S2 in Supplementary Material A further shows that most of the reviewed papers included participatory activities in two to five modeling stages, while there was no study that included participation in all (eight) modeling stages. The four studies that included participation in seven stages missed the stage of model scoping, model use, model communication, or model results in decision processes, as part of the participatory activities. Combining this information with that from Figure 2, we concluded that it is more likely that studies include participation in several stages of the model application and calibration (i.e., schematic representation, conceptual decisions, parameterization, and model assessment) while stakeholder involvement happened to a much lesser extent in model use, communication or in using model results in a decision process.

3.4 Scale and level in modeling focus

We assessed if and at what spatial levels agent behavior was included in the models presented in the 79 papers. Whenever a paper included an agent or agent behavior as a model variable, we assessed if this behavior was modeled at individual, local, regional, national, supra-national or multiple levels and if the agent modeled was a local, regional, national, or supra-national actor respectively.

Out of the 79 papers, we found 48 cases (61%) that included modeling of agent behavior in some form, while in 31 papers modeling of agents and their behavior was not included. From the 48 papers with modeled agents, 10 simulated agent-behavior at an individual level using an ABM, 10 simulate agent behavior at a local level (grid or patches) using approaches such as Cellular automata where the agent types and their behavior were aggregated, but the impacts were presented locally (e.g., a land use change model that simulated the allocation of residential, agricultural and forestry land at a high spatial resolution using simple behavior rules), and 28 models simulated agents and their behavior at regional level and also presented impacts of their actions regionally. This latter group included mostly Bayesian Belief Network (BBN) and system dynamics approaches. The study of Celio et al. (2014) is a special case as it uses a BBN with a spatially explicit component and hence it was marked as a paper that simulated behavior at local level. None of the papers simulated agent behavior at multiple levels and or cross-level. When agents from different levels were included, they were aggregated or disaggregated to be included at the selected modeling level.

When reviewing the types of actors that were considered as modeling agents, almost all considered studies relied on agent-based modeling to simulate the behavior. 47 out of 48 studies considered local actors (n: 30) or local and regional actors (n: 17) such as farmers or households (Table 9). A substantial number of models simulated also the behavior of regional/national actors (n: 18), where the distinction between regional or national actors was not always clear. In all reviewed cases, however, it was intended to represent (the behavior of) a certain organization, e.g., municipality, regional administration, NGO, water company or farmer association in the modeling. We did not find any paper that simulated supra-national actors (e.g., international governmental bodies, private companies, or institutions such as the EU commission or UN) as agents and in conjunction with participatory processes. Most of the models that included regional actors also included local actors (n: 17). Most of these models operated at regional level and included local actors (often farmers) in an aggregate form, e.g., X% of the farmers does A, while Y% of the farmers does B.

Combining the above information (Figure S3, Table 7 and Table 9), out of the 47 studies that modeled the behavior of local agents, only 20 modeled this behavior at individual or local level, while in 27 studies their behavior was included in an aggregate form in the regional level modeling. There was only one study that modeled the behavior of regional agents at the regional level. For those studies that modeled the behavior of local and regional stakeholders in combination, all except one modeled the social behavior at regional level, too. From the studies that only focused on modeling the behavior of local agents, 11 out of 30 reviewed studies revealed to model agent behavior at regional level. From the 18 studies that modeled behavior of regional actors, 17 used a regional-level modeling approach (Table 9). 11 used local actors for regional-level modeling. In only one study, behavior of regional actors was modeled at local level. In this particular approach, a cellular automata model is used to simulate the behavior of local and regional agents (Thompson et al., 2020).

Table 9: Matrix on the (mis)match of agent levels with spatial modeling levels at which social behavior is simulated (n: 79).

Modeling level	Local agents	Regional agents	Local and regional agents	Total
Individual	10	-	-	10
Local	9	-	1	10
Regional	11	1	16	28
Total	30	1	17	48

Although most papers conceptually focused on modeling and participation at multiple levels, most reviewed studies focused on a specific level and included models operating only at a single level. In the latter case, information from other level(s) was either included in a (dis)aggregated form that matched the selected modeling level or as external drivers.

From the reviewed papers, there are four exceptions worth mentioning that have attempted to model at and across different levels. Roetter et al. (2007) presented a dual-level analysis, in which farm household and regional linear programming models were run independently and results from the individual models were compared afterwards. Marques et al. (2020) followed a similar approach, in which they also developed and applied linear programming models for two different levels (entire landscape, named the 'upper level' and three sub-areas together composing the entire landscape, named the 'lower level') and in addition fed information from the upper-level modeling into the lower-level models. Results from the modeling at both levels were subsequently discussed in a stakeholder workshop in which stakeholders decided on the most appropriate solution. Gaube et al. (2009) integrated an ABM for simulating farmer behavior with a carbon and nitrogen stock and flow model using a land-use component as linking element. In this model, the impacts of farmer behavior on carbon and nitrogen stocks and flows were analyzed. There was no feedback from the stocks and flows model to the ABM. Walz et al. (2007) combined information from three models, i.e., a land-use allocation model, a regional input-output model and a resource flux model. These models ran in parallel, all using information from a local agricultural model. The approach integrated numerical modeling, scenario analysis and participatory components analyzing changes in agricultural landscapes. Local stakeholders were invited to participate to improve regional scenarios and to ensure their relevance and acceptance amongst the local population. Communication of scenario results was considered as further interface between numerical modeling and local actors' knowledge in the participatory process.

We did not find any papers that model social behavior of actors operating at different levels in their real world setting and being simulated at different levels in the model. Inclusion of agents operating at different levels does happen. In most of those cases, local agents were incorporated in the regional-level modeling.

Although a substantial number of papers included stakeholders from different levels in workshops or interviews, generally no specific attention was given to these levels and the differences that might result from this. However, in Köstner et al. (2014) participation took place at two different levels. One supra-regional workshop was organized where stakeholders focused on a 20-40-year time horizon, while two regional workshops were organized with a 10-20-year time horizon. Although the authors conceptually distinguished between local and regional level, the actual modeling was carried out at local level with regional constraints.

4. Discussion

Generally, we were able to identify four major groups of studies using a cluster analysis to gain an overview and to condense the informational gain. The most dominant cluster (cluster 3, Table 6) refers to agriculture-oriented landscape level studies modeling social processes (aggregated and disaggregated) for exploration and explanation to manage natural resources for decision-making. Regional-level models focusing on agriculture (cluster 2, Table 5) were more quantitatively aggregated (beyond individual agents) and developed for forecasting and prediction in decision support. Less prominent were agricultural social (behavior) studies (cluster 4, Table 7) with a very strong participation of individuals along major modeling steps for exploration and explanation using both detailed quantitative or aggregated approaches to capture agents. Forestry dominated studies (cluster 1, Table 4) were weak in participation and emphasized more strongly on optimization and refer to aggregated quantitative modeling. Participation has just recently been taken up in forest modeling studies (e.g., Fouqueray et al., 2022), although forest systems were usually represented in land-use/land-cover change modeling (e.g., Dietz et al., 2023; Lippe et al., 2022), or in some cases also including participatory co-design approaches (Lippe et al., 2017).

4.1 Participatory modeling across scales and levels – status quo

In the following paragraph, we will address our research questions and discuss potential implications and lessons learned:

1) *Spatial level of participation: How is the (dis-)aggregation of levels done in the participatory process?*

Three types of participatory activities were reported: surveys, interviews and workshops, in line with other reviews on participatory research on SES (e.g., Thorn et al., 2020). Surveys and interviews were in most cases carried out with stakeholders operating at the local level, such as farmers or households, with extracting information as the main purpose for the interaction. Workshops were often organized to discuss topics relevant at the landscape or regional level, involving a broader range of stakeholders operating at various levels with local and regional levels being most common, e.g., local farmers or households, forest managers, farm advisors, municipality or regional representatives, NGO representatives, etc. A large majority of the papers included stakeholders operating at one spatial level, with the local and the regional level being the prevalent levels of interest, which is in line with Steger et al. (2021). Studies that included stakeholders operating at different levels can be split into two groups. The first group of papers included all stakeholders in the same workshop or workshop series, often combining the local and regional level. Having local and regional stakeholders in one workshop, one could argue that this is cross-level participation. However, there were no specific events organized for stakeholders operating at these different levels nor did we find evidence that the role of the workshop participants differed based on the spatial level they operate at. We found one exception where workshops were designed at two different levels (Köstner et al., 2014) aiming to obtain different information by focusing on those different levels and cross-level (and cross-scale) participation was conducted. The second group of papers involved stakeholders from different levels for different types of participation, e.g., questionnaires for extracting information from local farmers and a workshop (series) for involving regional stakeholders to discuss topics relevant at landscape/regional level.

2) *At which modeling stages is participation done?*

As expected, stakeholder engagement is mostly found for the purpose of both model parameterization and calibration. A vast majority of the reviewed papers reported on stakeholder involvement for the model parameterization only, either by extracting information through questionnaires or interviews or by discussing parameter settings during a workshop. This shows the ongoing trend and strengthened participation beyond traditional modeling with participation in initial and final modeling stages (Fulton et al., 2015). However, participatory modeling is not well reached during the entire modeling process as discussed by Fulton et al. (2015). An exception might refer to companion modeling approaches which aim to use ABM in conjunction with serious games for collective decision processes (https://www.commod.org/en).

Most of the reviewed studies involved stakeholders in the schematic representation, the conceptual decisions and/or the assessment of the model's behavior or its results. The more we turned the focus to the actual use of the model and the use of results in practice, the fewer papers we found evidence that these activities are carried out in a participatory manner. Since learning for stakeholders and modelers is crucial during model use (Sterling et al., 2019) and to empower stakeholders (Gray et al., 2018), it would be beneficial for future work to put more emphasis on this.

We found that it is common to include stakeholder participation in several stages, with most of the papers involving stakeholders in three to four out of the eight listed phases. Agricultural social behavior studies (cluster 4) and landscape-level (agricultural or mixed) studies on primarily natural resources and sustainable agricultural systems with modeled social systems primarily involved more than the three to four stages of participation. Forestry studies (cluster 1) and regional-scale agricultural studies aiming at sustainable resource management (cluster 2) mainly limited their focus to the three to four stages which is in line with Maeda et al. (2021).

3) *How is modeling done with agents across levels?*

We have looked at two aspects of this question: a) who is being modeled (e.g., farmer, household, municipality, water corporation, company) and at what spatial level does this actor operate (local, regional, (supra)national), and b) how is this agent represented in the model and at what level is the agent and its behavior incorporated in modeling?

From the 79 reviewed studies, we found that 17 reported on actors operating at different levels, while the relevant behavioral modeling was done in all cases at a specific level only and not at the respective levels actors operated at in reality. In cases where behavior of actors operating at different levels (local and regional/national) was included, the local agents were generally included in an aggregate form in the regional-level modeling. However, we also found an example of regional/national actor behavior being included in the local-level modeling. Therefore, we agree with Steger et al. (2021) who call for higher diversity of actors in participatory modeling of SES to enhance the likeliness for decision support. Reasons for modeling at a single level may refer to the complexity of the modeling at and across levels together with the lack of availability of modeling frameworks allowing for multi- and cross-level modeling of social behavior. Equally, the simulation of individual behavior is largely limited to agricultural behavior (cluster 4) and landscape-level studies (cluster 3). Recent software developments for asynchronous, many-tasks modeling in the ABM community, e.g., Jong et al. (2021); Jong et al. (2022) and De Jong and Schmitz (2021) may be a solution to close this gap. To better understand the impact of behavior of agents operating at different levels (e.g., farmer, advisory service, regional government, NGO), a hierarchical approach for different agents would be preferred. A hierarchical approach is in line with the integrated modeling community, which proposes to integrate across disciplines and scales, both conceptually and technically (Elsawah et al., 2019; van Delden, Seppelt, et al., 2011).

Multi-level modeling of agents with stakeholder participation is absent in the reviewed studies. This however does not necessarily mean that studies on multi-level modeling of agents do not exist, but may rather point to the fact that they cannot be identified straightforwardly with a systematic review approach as done here. Agents operating at different spatial levels are often combined in one model. Such an approach requires aggregation or disaggregation to one spatial modeling level. For example, local agents need to be aggregated for their behavior to be modeled at regional level, or behavior of regional agents needs to be downscaled for inclusion in local models.

4) *How do we integrate stakeholders' perspectives at different levels and scales (spatial and temporal)?*

Most of the modeling processes did not include stakeholders from different levels. For the models that engaged stakeholders from different levels, workshops were often used to facilitate the conversation between the different stakeholders. Sometimes, interviews and surveys were used to collect individual perspectives, which were used for different components of the model. For example, surveys can be used to better understand individual behavior, such as identifying adaptation among farmers (see also e.g., Eitzinger et al., 2018), while workshops with a broad range of stakeholders across different levels were more suited for co-developing long-term scenarios. This aligns with findings from other disciplines such as scenario studies in the field of disaster risk reduction (Riddell et al., 2019) and regional development (e.g., Kok & van Delden, 2009; van Delden & Hagen-Zanker, 2009) as well scenario planning of SES (Thorn et al., 2020).

5) *How can we use participatory contributions across scales and levels?*

We found that there is no apparent relationship between the level of participation and model complexity which may hint that there is a limit to what researchers feel comfortable to work with. Although it could also mean that the multi-level modeling of agents is still rather novel, and hence, we might see these types of models with participation more occurring in the next couple of years.

Moreover, SES models' complexity is not decisive for their success (Steger et al., 2021). We have still 31 of 79 cases without modeled agents and 28 of 79 consist of agents at regional level; only 10 of 79 cases address the local and similarly the individual level (Figure S3). We further did not find a clear pattern on the relationship between model input and the level of participation. Across the clusters with different degrees of participation, primary social data was consistently used. That also means that participation does not always aim to capture social behavior but rather focusses on using participation to generate model inputs. Most cases were reported as surveys or workshops for the study area, i.e., most models were rather site specific than generic. Interestingly, there was no ABM approach in forestry, but rather optimization and aggregated models with ecosystem services that often-mentioned forestry. The involved stakeholders could be mostly attributed to the study area (Figure 5) rather than represented persons outside of the area of interest, which may explain the recognized limitation for upscaling stakeholder interactions in most of the studied papers and models. Using semi-structured questionnaires for example could increase the integration of stakeholders in the modeling process and vice versa, e.g., by emphasizing personal relationship to motivate stakeholders to participate (Ferguson et al., 2017). Moreover, Citizen Science approaches (e.g., stakeholder-driven model development) and a stronger appraisal of participatory approaches (e.g., ready-made tools for decision support or financial compensation) could also be an option to strengthen participation in model development especially from a stakeholder's perspective (Gray et al., 2017).

4.2 Implications and lessons learned

When designing a model-based solution to an environmental problem, participation in modeling SES offers the opportunity to consider stakeholders' interests, knowledge, and values and to incorporate stakeholders in the modeling process (MacLeod & Nagatsu, 2023). This requires finding the right balance between model complexity, available data and technology, and stakeholder needs (see van Delden, van Vliet, et al., 2011; Steger et al., 2021). Challenges on the technical side may arise in terms of model availability and development, as well as software maintenance. For example, SES models are often developed for a certain project or application purpose without having a long-term development and software maintenance strategy in mind. This bears the risk that model reusability is limited; models are likely less robust or lack certain details that are important to represent the context of the SES of interest; in particular, representing agents at their relevant scale, taking cross-scale dynamics and feedbacks is difficult to consider, although crucial to understand major systemic changes (Vervoort et al., 2012). Likewise, relevance and value of participation across all levels must be carefully assessed before embarking on a participatory modeling journey as extensively discussed by Jordan et al. (2018).

On the one hand, it appears to be a form of basic democracy to involve stakeholders as much as possible in all stages of modeling (Fulton et al., 2015; Steger et al., 2021); on the other hand, one (usually the modeler) has to be realistic in terms of model design and simulations goals, the stakeholder capacity and capability to co-design and co-use a model, as well as the desired application needs (Voinov et al., 2018). The latter one would be especially important when aiming to support decision processes and policy making.

From the reviewed studies, we learned that model applications mostly served certain study purposes or project objectives and were not necessarily designed for long-term use. A potential solution to support long-term use could be providing funding opportunities that are specifically steered to software development and model design stages, potentially with the further aim to develop prototypes or pilots. While this is an important implication of our study, it appears to be of minor relevance in current funding schemes, e.g., Horizon Europe in the European Union as well as most organizations involved in (applied) research; the latter either by not having a (long-term) product focus or not rewarding technical activities, such as facilitation, data science or software development in the same way as scientific activities (see van Delden, Seppelt, et al. (2011) for a plea for development of products and tools for long-term use).

From the reviewed studies, we see that more transparency and better documentation of the modeling process and the related stakeholder involvement is required. Hence, we deem it of particular importance to clearly explain ‘when, how and why’ stakeholder participation was considered at the selected scales and to further describe the underlying rationale of the related modeling and stakeholder processes at, and across scales and levels. Although this is somehow common sense for a peer-reviewed study, it was in many cases not a straightforward task to identify these issues, and often required us to conduct several iterations to retrieve the necessary information for the needs of the systematic review. For example, we often missed information on model use or communication that may happen post-publication of the respective articles. However, we do not call for developing new guidelines or protocols; Ayllón et al. (2021), Troost et al. (2023), and Grimm et al. (2020) provide good examples in how to coherently document modeling processes. But we call for better documentation and transparency of explaining the link of model application and stakeholder participation and how this influenced certain modeling decisions. A good practice example in doing so refers to the ‘CoMSES Net, the Network for Computational Modeling in Social and Ecological Sciences’ (https://www.comses.net/) which provides a large and growing open access repository of model codes and algorithms. It currently maintains a curated database of over 7600 publications of agent-based and individual based models with additional metadata on availability of code and bibliometric information, including a DOI provided by CoMSES for an uploaded code snippet or algorithm. We propose to amend the aforementioned guidelines as well as CoMSES to better document how cross-scale dynamics and feedbacks are modeled and how and why stakeholder participation is considered at the different scales and levels of simulation. Troost et al. (2023) for example provide a good example of how to conduct such an exercise for ABM and similar concepts could be also developed for system dynamics models or CA.

Beyond, other scales than temporal and spatial, e.g., thematic (see e.g., van Delden, van Vliet, et al., 2011; García-Álvarez et al., 2019), organizational (Dressler et al., 2022) and networks (Cash et al., 2006) could provide further insights and patterns in SES modeling and thereby especially improve the quality of social aspects in SES modeling.

Finally, we also see an imbalance in the application of SES modeling for agricultural and forestry systems as most of our reviewed studies focused on agricultural applications. Potential reasons for this could be the different nature of the sectors as farming is often done by individuals or communities in many parts of the world and hence can be relatively easily represented as agents in a model application. On the contrary, forest land is more often state property, managed by state-owned enterprises or government agencies as well as involves larger property sized (FAO, 2020). Subsequently, it would require modeling approaches to represent such institutional entities and their internal decision processes, which is not an easy task as, e.g., shown by Holzhauer et al. (2019). The systematic review, however, cannot fully answer the underlying rationale of this, and hence, we only want to point to this as a relevant gap for further studies in the field of SES modeling (e.g., Steger et al. (2021) for mountainous regions).

4.3 Limitations of the methodology

We built this systematic review on a keyword search in WoS and Scopus using the keywords given by the respective authors to retrieve the respective studies. Using the given keywords should reflect best the central theme aimed at by the authors. Using, e.g., the abstract for such search would have made the number of abstracts for screening unmanageable as equally stated by Seidl (2015), who propose a comparable approach for the application of search terms that resulted in a largely bigger number of ineligible papers that do not match the thematic core of this review: participatory modeling of social-ecological systems in forestry and agriculture as their central theme.

Even if individual studies could be missed due to a mismatch in keywords, we expect that we still obtained a largely representative sample of studies relying on the authors judgment in keyword choices. An alternative approach would have been to take a random sample of the abstracts suitable for review to make the number of abstracts manageable. However, this approach would ignore the informational value of the keyword selection of the authors.

5. Conclusions

Participation is still largely seen as data provider and conceptual consultation for modeling approaches: stakeholders are mostly involved in parameterization and calibration and even in the design, development, and validation of models. Our study reveals that stakeholders' benefits from participatory processes are largely missing in the analyzed publications. The benefit mostly stays on the modelers' side on information for parametrization and calibration while stakeholders often miss information on model outcome and are rarely considered to use the model outcome for decision-making processes. The latter may either not happen in general, or is not published given that the transfer is happening at a post-publication stage.

Multi-level participatory modeling in general is scarce in the context of SES modeling and the analyzed domains of agriculture and forestry. The use of participation in forestry-related model studies is still limited and might be explained by the strongly influenced top-down level of stakeholder engagement in this sector in general. We further found that cross-level and cross-scale interactions are insufficiently addressed in modeling social behavior and research is often limited by mainly including local agents (either in individual or local level models such as ABMs or CA models, or in an aggregate form in regional models or qualitive approaches using expert workshops for example), while regional-level agents are more scarce and national-and supra-national level agents often missing. Moreover, the combination of different scales (e.g., temporal, spatial, thematic, social) and levels is especially lacking and might be a first pathway for multi-scale modeling in future research.

The review has resulted in a set of key gaps for which we recommend further research and consideration by the modeling community:

- We suggest a stronger focus on the conceptualization of studies involving participation and SES modeling across scales. Due to the complex nature of these studies, it is especially important to develop a framework for the entire process in line with the objectives of the study. Such a framework will help to delineate the various scales and their interactions, and will structure the participation alongside the modeling activities. It will facilitate deciding for what activities and what purpose participation is included and how the scale the stakeholders operate at matches with those included in the modeling.
- A better documentation of the considered levels and scales of participation as well as related modeling appears necessary to make participatory modeling more transparent and reproducible. The reviewed studies showed a considerable challenge identifying the actual scale of participation as well as the considered levels of stakeholder interaction. The integrative nature of SES modeling makes this especially relevant given its focus on interactions. We do not call for developing new guidelines or protocols but for better documentation and transparency of explaining the link of model application and stakeholder participation (when, how and why). This should include the underlying rationale why certain study decisions were made, and how this influenced the considered modeling approach.
- Although it appears to be a form of basic democracy to involve stakeholders as much as possible in all stages of modeling, one must be realistic in terms of model design and purpose of the modeling, as well as the desired stakeholder involvement. Hence, relevance and value of participation across all levels

and scales, and in conjunction with its desired application needs (e.g., support management decisions or policy design) should be carefully assessed before embarking on a participatory modeling journey. This assessment should include the use of participation for model needs (model inputs, validation) but also extend it towards stakeholder needs (model use and use and communication of results in practice). Here, for example, Citizen Science could be of use, as it goes beyond classical participatory appraisals due to its stronger focus on collective learning and engaging in socio-political processes.

- While new software applications are becoming available, there seems to be persistent reservation in the scientific community to invest in conceptually sound multi- and cross-scale SES modeling approaches. But the continued use of existing modeling concepts may not be of help anymore, as they are likely less robust for such kind of SES modeling or lack certain details that are important to represent the context of the SES and its agents under investigation. This calls for developing new design concepts of multi- and cross-scale modeling, where agents operate at their 'real-world' level with interactions between the agents at different scales and levels. This equally calls for multi-level participation to better represent the role of actors at, e.g., local and national level as well as their interactions. These new concepts should also allow for including a broader range of scales, such as thematic, network and social scales.

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Supplementary Material

Supplementary Material A, containing Figures S1 to S3 and Tables S1 and S2 can be found online at: https://sesmo.org/article/view/18614/18248. Supplementary Material B presents the 79 coded and analyzed studies following PRISMA outlined in Figure1 and is available at: https://sesmo.org/article/view/18614/18249. Supplementary Material C outlines the coding criteria and levels used to categorize and evaluate the reviewed studies and is available at: https://sesmo.org/article/view/18614/18250.

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