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# Modeling social norms in social-ecological systems: a systematic literature review

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## Abstract

Social norms play a pivotal role in sustainability transitions by shaping human behavior and influencing responses to challenges such as climate change and natural resource management. They can facilitate or impede collective action. Although simulation models help to explore norm dynamics, modeling approaches remain scattered and lack synthesis specific to social-ecological systems. This systematic review aims to map existing computational approaches to modeling social norms within social-ecological systems, identifying trends, gaps and implications for research and policy. We conducted a systematic search of Web of Science and Scopus (search date: 15 November 2024), screened abstracts using validated large language models, and selected 153 relevant studies for analysis. Key aspects analyzed included publication trends, thematic focus, modeling methods, spatial scale, empirical data used behavioral theory incorporation and norm representation. Publications increased over 25 years, with most studies originating from Europe and North America. Two dominant themes emerged: common-pool resource management and individual consumption behavior. Agent-based and evolutionary game-theoretic models prevail, but many omit explicit behavioral theories beyond rational choice theory. Models are mostly local or regional in scale and theoretical in nature and often lack empirical data for the quantification of the social norm modeled. Norms are generally modeled on an observation base, meaning that the majority of models include norms based on what others do. Interactions between norm types and dynamic norm signaling remain under-explored. To strengthen social-ecological modeling and its policy relevance, future work should enhance geographic diversity, integrate behavioral theories more deeply and develop models that capture dynamically signaled norms in order to advance our understanding of human–environment interactions and sustainability transitions.

## 1. Introduction

With current trends such as biodiversity decline, rising global mean temperature and intensified land use, we are pushing our planet out of its safe and just boundaries (Richardson *et al* 2023, Rockström *et al* 2023). To reverse those current trends and step into a resilient, sustainable and just future, societal transformations and transitions at multiple scales are needed (e.g. Moore *et al* 2014, Olsson *et al* 2014, Abson *et al* 2017, Davelaar 2021, Woiwode *et al* 2021). One societal aspect named increasingly when discussing such social-ecological transformations are social norms (e.g. Nyborg *et al* 2016, Barnes *et al* 2017, Reyers *et al* 2018, Yamin *et al* 2019, Cialdini and Jacobson 2021).

Social Norms are powerful mechanisms that shape human behavior and can play a crucial role in understanding the success or failure of sustainability transitions (Nyborg *et al* 2016). As such,

they can act as both facilitators and barriers to change (Constantino *et al* 2022). Social Norms can incentivize pro-environmental behavior, as highlighted by Nyborg *et al* (2016), who describe how social norms can serve as 'solutions' to motivate collective action toward sustainability. However, social norms do not always support transitions. Persistent or 'sticky' norms can reinforce dominant, non-pro environmental behavior patterns, effectively cementing unsustainable practices (Efferson *et al* 2019). Thus, social norms in interplay with individual agency can take on a dual role, as both enablers and inhibitors of behavioral change.

When studying the dynamics of social-ecological systems—independent of the regarded spatial scale—social norms play an important role as they can shape human responses to major environmental changes such as climate change or influence natural resource management and the governance of common pool resources (CPRs) (Ostrom 2000, Nyborg *et al* 2016, Constantino *et al* 2022, Bechthold *et al* 2025).

One important method often used to investigate social-ecological systems are simulation models. Given the critical influence of social norms on human behavior, their formalization in such simulation models has emerged as an important research avenue already in the beginning of computational modeling efforts (e.g. Axelrod 1986, Centola *et al* 2005). However, the modeling of social norms remains fragmented, with diverse approaches scattered across different academic disciplines and application areas. There are only a few studies that aim to provide a comprehensive overview of different approaches to using computer models for simulating social norms. Gavrilets *et al* (2024) reviewed theoretical approaches to model social norms, Elsenbroich and Gilbert (2014) described models of social norms focusing on agent-based approaches, and Vahed *et al* (2024) emphasized the advantages of using computational simulations for understanding social norm dynamics. However, to the best of our knowledge, there is currently no structured and systematic overview of different approaches to modeling social norms. Here, we aim to provide such a systematic overview of social norms modeled, using different approaches, spatial scopes and themes. However, in order to narrow our focus, we specifically concentrate on the modeling of social-ecological systems. Social norm dynamics within such models are very likely comparable to dynamics within purely social modeling efforts. However, within this review we focus on social-ecological systems as this is a field in which social norms have increasingly been named as important to understand prevailing unsustainable (lock-in) dynamics and can help to understand the adoption of sustainable or behavior or resource use (Nyborg *et al* 2016).

Recently, there were more and more calls to integrate human behavioral aspects and social norms with state-of-the-art Earth systems models to advance our understanding of human–environmental intertwinedness on a planetary scale (Donges *et al* 2017, Beckage *et al* 2020, 2022, Steffen *et al* 2020, Farahbakhsh *et al* 2022, Shin *et al* 2025). Given the complexity that this interdisciplinary task entails, it is relevant to derive a structured overview of existing approaches and methods that have already been used to integrate social simulations of social norms with ecological modeling approaches.

This study aims to provide a systematic overview of existing approaches to modeling social norms within social-ecological and human–environmental systems at various spatial scales. By synthesizing dominant methods used within different subcommunities, the study will offer guidance to support future modeling efforts and foster the interdisciplinary integration of the social sciences and psychology with social-ecological modeling. Ultimately, the results of such models can inform natural resource management and support policy development across diverse human–environment contexts.

We seek to understand how norms are represented in social-ecological simulation models by mapping out commonly used modeling methods taken within this field of research. Here, we focus on modeled themes, modeling approaches, scales, connections to empirical research and theories of human behavior formalized within models. Moreover, we investigate different social norm formalizations to understand which dimensions of social norms developed in the theoretical social science literature are represented in modeling social-ecological systems. Here we distinguish between injunctive and descriptive norms, dynamically or statically signaled norms and investigate whether they were implemented endogenously or exogenously. Lastly, we investigate the related research community to understand more about the connectedness within the field.

The remainder of this paper is structured as follows: section 2 gives a short introduction into different categorizations of social norms in the social sciences literature. Section 3 introduces the methodological approach we followed for our systematic literature review of social norms in social-ecological simulation modeling. Section 4 presents the results of the analyses. These start with a descriptive overview of the reviewed entries (sections 4.1), followed by a mapping of the modeling methods used (section 4.2), their norm formalization (section 4.3), and the collaboration and co-citation analyses of the included papers (section 4.4). Section 5 discusses the results and suggests possible ways to model social norms, and section 6 concludes the paper.

## 2. Different categories of social norms

In social science research, the exploration of social norms offers insight into the mechanisms that underpin collective behaviors and societal structures. Scholars have investigated how norms emerge, evolve, and are reinforced or challenged, shedding light on their role in everything from cultural traditions to modern organizational practices (Cialdini and Goldstein 2004). This research extends across disciplines, including sociology, anthropology, psychology, and economics, emphasizing the multidimensional nature of norms and their effects on various aspects of human life (Bicchieri 2023). For this study, we followed Bicchieri's definition, which offers a nuanced framework for understanding the nature and dynamics of social norms. Generally, social norms can be defined as collectively shared beliefs about which behaviors are typical or socially approved within a group or society. They serve as a cohesive force that influences how individuals act, think, and relate to one another, often operating implicitly to maintain social order and group identity (Bicchieri 2022). Bicchieri (2005) further distinguished between two key norms:

Descriptive norms: these norms represent the observable behavior of the majority within a given reference group. They capture what people typically do and are reinforced by the perception of commonality. For example, in a community where most individuals recycle, the descriptive norm supports recycling behavior by signaling it as the standard practice.

Injunctive norms: such norms, by contrast, reflect shared beliefs about what people ought to do, based on societal approval or disapproval. These norms are underpinned by moral or ethical considerations, such as the belief that individuals should reduce their carbon footprint to mitigate climate change.

For this review, we classify the implemented social norms in terms of their norm origin (how is the social norm derived?) and the effect mechanism (how is the social norm applied?). Based on those aspects and the classification by Bicchieri (2005), we categorize social norms as descriptive if they are based on the actual, observable behavior of others and directly affect the probability of agents to adopt a certain behavior. Norms are classified as injunctive if they are based on approval mechanisms and/or if the social norm originates from what agents are ought to do rather than what is directly observed.

Besides this primary distinction, a growing area of research focuses on the dynamic effect of social norms: dynamically signaled norms, which emphasize how norms evolve over time (see e.g. Sparkman and Walton 2017, Mortensen *et al* 2019, Sparkman *et al* 2021) highlight behavioral trends, such as 'an increasing number of people are adopting plant-based diets', which can encourage individuals to align with perceived future behaviors. As shown in studies by Sparkman and Walton (2017), dynamically signaled norms can be particularly effective in promoting behavioral change by leveraging people's desire to adapt to emerging trends rather than conform to current standards. We use the term 'statically signaled norm' to describe the opposing approach to signaling norms, which points to the current state or status quo of a norm at a certain point in time (e.g. 'in January 2025, the majority of the German population still eats a carnivorous diet'). The terms 'static norm' or 'statically signaled norm' are not universally recognized as set terms for the opposite of dynamic or dynamically signaled norms. However, to our knowledge, no established term exists in the social science literature, so we chose 'static' or 'statically signaled' as an option used before (see Loschelder *et al* 2019, Geber *et al* 2022, Aldoh *et al* 2024).

One major difference in norm-modeling approaches is the way in which norms are included within a simulation: exogenously as external input to the simulation, or endogenously as emerging and evolving in the computer simulation. While some models are theoretical and not tied to specific domains (e.g. the Axelrod (1986) evolutionary approach to norms, or Ushchevs and Zenous (2020) network perspective), others focus on practical applications in areas such as healthcare, social-ecological systems, and sustainability science (e.g. Chen *et al* (2012) on payments for ecosystem services enrollment; Godin *et al* (2008) on healthcare professionals; Nyborg (2018) on environmental behavior).

## 3. Methods

To generate a comprehensive and consistent overview of the existing models, we followed the method of a systematic review, as this allows us to gain deeper and more systematic insight compared to what more common narrative or scoping reviews can provide. To ensure the quality of this study, we followed the latest version of the PRISMA Guidelines for systematic reviews (Page *et al* 2021).

### 3.1. Review objective

This review aims to provide a comprehensive overview of approaches used in simulation models in the field of social-ecological systems that include social norms.

As described above, the concept of social norms itself, the concepts of 'collectively shared' beliefs and the relevant 'reference group' are operationalized in diverse ways across the literature and different research communities and disciplines. For instance, some studies define a norm as the behavior exhibited by a majority of a reference group (e.g. over 50%), producing a singular, binary norm state. Others account for norm strength, where the prevalence of

a behavior (e.g. 51% versus 100%) reflects a continuous spectrum of normative influence. Similarly, the reference group may vary in scope: some approaches consider the entire population, while others focus on subsets, such as immediate neighbors within a social network. These variations illustrate the diversity with which social norms are conceptualized and operationalized, enabling the study of both discrete and continuous influences of different social groups, and underscoring the value of an open, flexible definition that accommodates different approaches in research and modeling.

To capture this richness of different approaches in the very interdisciplinary field of social-ecological systems, we aim for a rather open understanding of what a social norm can entail and include studies which model the impact of observed behavior or a representation of what agents ought to do based on societal approval. However, we exclude models that only depict learning processes (meaning that agents compare a certain outcome that results from their chosen behavior to others and adopt the most profitable behavioral option), model norms as formal institutions externally set such as laws rather than community based informal institutions, and if the norm included was clearly a personal norm, referring to what individual agents think is right and not a social norm.

Additionally, we only considered models in which social norms influence simulation dynamics either as fixed parameters provided exogenously or as variables calculated endogenously that may change over time. Studies in which norms are merely outcomes, or display variables that are considered as a simulation result without affecting prior simulation dynamics were excluded.

In short, a study was included only if the norm—whether exogenously provided or endogenously modeled—actively influenced the simulation dynamics during model runs.

Although the methodological approach of a systematic review has been used, this article cannot provide an exhaustive and complete list of all social-ecological simulation models including social norms. Given the vast number of models incorporating some kind of social norm (even without labeling them as such), we are only able to provide a relevant subset of all those models by conducting a systematic and reproducible search, as described below. Thus, the aim of this study was to understand the overall trends in this field and to identify research gaps and possible ways forward, rather than to provide an exhaustive and full list of all existing approaches in the current literature.

### 3.2. Search terms and databases

To identify publications eligible for our research objective, we used two databases: Elsevier's Scopus and Thomson Reuters' Web of Science (WoS). It is well known that not all scientific literature databases are able to cover all publications and studies. Thus, it is recommended that more than one database (Cheung and Vijayakumar 2016, Mongeon and Paul-Hus 2016). Both databases were searched using the following terms [T]:

> 'social norm*' AND (model OR simulation OR 'system dynamics')

In Scopus, these terms were used to search article titles, abstracts, and keywords. In WoS, we used these terms to search for what is called 'Topics.' This includes the title, abstract, keyword plus, and author keywords. The search terms were chosen to be comprehensive to favor the integration of too many over too few included entries. By using the three different terms for the modeling approaches, we also aimed to be inclusive. We are aware that studies might be modeling processes that we would understand as social norms, but not name them explicitly as such. Other terms used to describe social norms in the literature are, for example, peer pressure or social ostracism. Nevertheless, search terms including several of those synonyms resulted in a number of articles that were beyond the scope of this study (ca. 70 000 with the terms 'social norm*', 'social pressure,' conventions, customs, 'social ostracism,' homophily, 'peer pressure'). Thus, we choose the simple search term T for the first round of review. By doing so, we adhere to a term that is both common and neutral. However, to also respect studies that include some kind of social norms according to the definition given above but do not name them as such and state this in abstract, title, or keywords, one round of snowballing (using the method of backward and forward citation searching) was conducted. Thus, publications cited by or citing the entries found in the first round were retrieved for a second round of screening. By using this approach, we are confident that we present a meaningful sample, with which we can describe the overall trends and developments in the field.

While the search was not limited by the time of publication, it only included articles published in English. Given that this might exclude a wide field of research that is conducted in other communities, we also searched for a more language-inclusive database (SciELO) with Spanish search terms—modelo AND norma AND social. However, with these already very simple search terms, the request resulted in only 102 articles; thus, this group of articles was excluded.

Additionally, in Scopus, the search was limited to articles, conference papers and book chapters, whereas the search in WoS was limited to articles, proceedings papers, early access, and book chapters. While we included articles with the category 'early access' in the search of WoS, we did not include

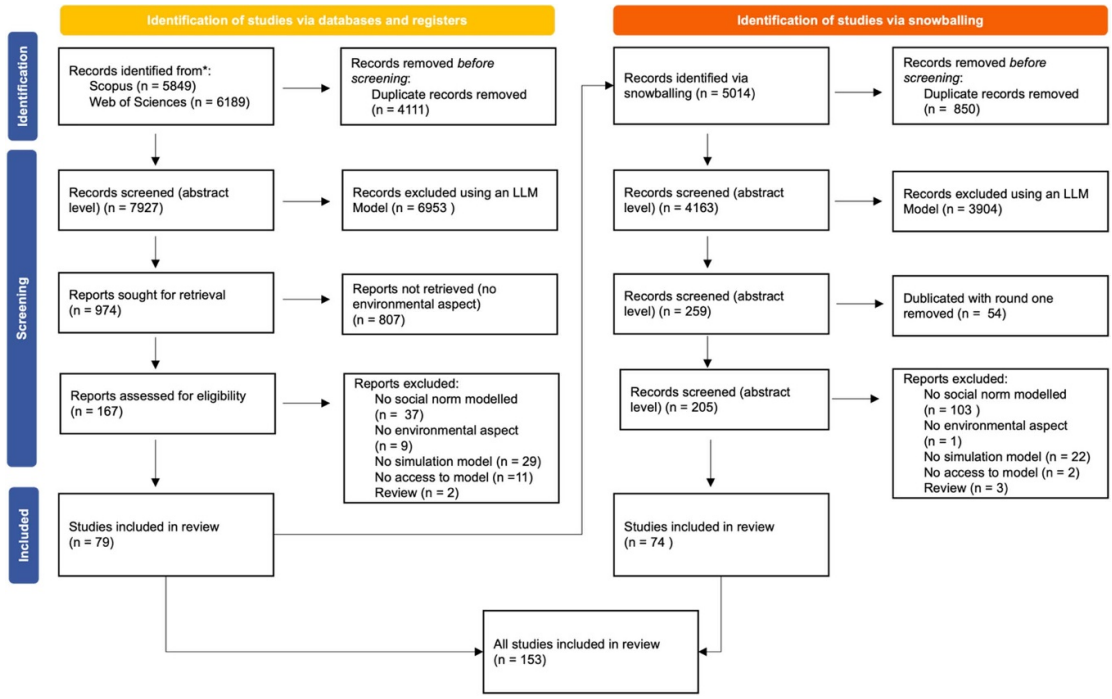


**Figure 1.** PRISMA flow diagram depicting the selection process and its different stages. The first round of review is represented on the left side while the round of snowballing is represented on the right side.

pre-prints as indicated in Scopus, as they are not automatically retrievable.

The first round was conducted on the 15th of November 2024 and resulted in 5849 entries in Scopus and 6189 in WoS (See figure 1, left side). The full screening process (described below) yielded 79 articles. The snowballing round was conducted on the 16th of January 2025 using WoS, and 5014 additional articles were retrieved (See figure 1, right side). This process yielded in additional 74 articles.

### 3.3. Publication screening and inclusion

Given that the identified articles were retrieved from two different data sources, it was expected that there would be a high number of duplicates that needed to be deleted. The Rayyan software (Ouzzani *et al* 2016) was used as it offers the possibility of automatically detecting duplicates. Using this tool, we automatically deleted duplicates with the same title or DOI. All remaining automatically detected duplicates were manually resolved. After this process, 7927 entries remained in the first round (figure 1, left side) and 4163 in the snowballing round (figure 1, right side).

Large language models (LLMs) were used to support the screening process as it was not feasible to screen all remaining articles manually. It has been shown that LLMs are very useful in supporting the abstract screening process for systematic reviews, and that they perform just as well as two independent human screeners (Dennstadt *et al* 2024, Landschaft *et al* 2024). For this study, we initially prompted LLMs with three different tasks. First, we wanted to know whether the abstract describes a paper introducing a social simulation model. Second, we wanted to know if the included model is a type of regression model. Third, we wanted to know if the abstract describes a review (all used prompts can be found in the supplementary data B). All questions were answered by the LLM with yes, no, or unclear. Only entries that describe a social simulation model, but no regression model or review, were included in the further analysis. Requests that were answered 'unclear' by the LLM were checked again by a human reviewer. To evaluate the performance of LLM, a subset of 100 randomly drawn entries was screened by two independent human researchers. The similarity of their decisions was compared with the decisions of several LLMs using several metrics (Similarly, Cohen's Kappa, PABAK and false exclusions), whereas most emphasis was given on the rate of false exclusions, as this rate should be as small as possible (all test parameters can be found in the supplementary data B). After testing different LLMs, OpenAI's ChatGPT-4o was chosen as it performed best and showed results that showed an equal similarity when comparing LLMs and humans with human reviewers.

To ensure that the chosen LLM was not 'overtrained,' a second subset of 50 articles was additionally classified by two human researchers using the same prompts as in the previous test. The results show that the LLM performs well (meaning that the LLM decisions and the decisions of the human reviewer show 100% and 98% similarity respectively, with false exclusion rates of 0% or 4%) and classifies entries with a high similarity to human researchers (similarity between the human reviewers resulted in 98% similarity and 4% false exclusions). Thus an LLM based screening approach is very likely to

yield results comparable to those of manual abstract screening by a researcher. After this process was completed, 974 entries remained in the first round and 1076 in the snowballing round (see figure 1). Since this paper focuses on modeling social norms in relation to our natural environment, the entries were further filtered for articles that explicitly mentioned such aspects. Here, ChatGPT-4o was used again, and the corresponding prompt is shown in the supplementary data B. The LLM's decisions were again evaluated by looking at a subset of 50 entries that were classified by two human researchers and were found to be very accurate (see supplemetary data B). At this stage, 167 entries remained from the first round and 759 from the snowballing round.

The articles found in the first round were screened on a full-text basis again by two independent human researchers. During this process, nine articles were excluded because they did not include an environmental aspect, 37 because they did not model social norms, 29 because they did not describe a simulation model, 11 because the authors of this study had no access to the publication or the model was described in such a superficial way that the type of social norm implementation could not be examined, and two because they were reviews. Ultimately, 79 entries were found eligible for this study and were further examined (see figure 1). In the snowballing round, the LLM was used one more time to further filter the articles such that they potentially included aspects that could be interpreted as social norms. The algorithm was again tested using two human reviews (see supplementary data B). After this round, 205 articles remained, which were again screened on a full-text basis by two independent human researchers. During this phase, one entry was removed as it did not include an environmental aspect, 103 because they did not model social norms, 22 because they did not describe a simulation model, 2 because the authors of this study had no access to the publication, and 3 because they were reviews.

A total of 153 articles were included in the analysis. During the full selection process, the LLM temperature was set to zero to ensure logical responses. The LLM was controlled via an API connection using Python3 (Python Software Foundation 2024) (following the approach introduced by Landschaft *et al* (2024)). The full code (supplementary data D) and a list of all the included articles (supplementary data A) can be found in the supplementary data.

### 3.4. Information extraction and model classifications

The included articles were categorized according to various aspects. First, we assessed the year of publication and country of origin. Because most articles are published by a team of co-authors, we use the approximation of the country of the first affiliation (if there is more than one) of the first author.

Next, we assessed the topics for each entry. Using an approach similar to thematic analysis (Braun and Clarke 2022), we clustered the different topics of the articles and attempted to assign each entry to just one category. In cases in which entries touched upon more than one of the identified categories, we chose the category emphasized the most.

Subsequently, we assessed the chosen modeling approach. Here, we distinguish five categories: agent-based models (ABMs), game theoretic models, evolutionary game theoretic models, integrated assessment models (IAMs), system dynamics, and dynamical system models. The latter category includes all articles that were based on differential and difference equations but did not include any of the other named approaches. Several of the found entries used more than one modeling approach. For example, this is common if an entry describes a coupled modeling approach. In these cases, the modeling approach used to model social norms was chosen for further analysis.

Additionally, we assessed whether the models used human behavior theories to conceptualize social norms. Here, we focus on the theories described by Van Valkengoed *et al* (2025) and Schlüter *et al* (2017) (a full list of these theories can be found in the supplementary data C) but exclude rational choice approaches as they are mentioned in nearly all articles and are thus not a good feature to distinguish differences between the analyzed publications. For further analysis, we categorized whether one or more of these theories were mentioned in the publication and, if so, whether they had been implemented explicitly in the described model.

Next, we assess the scale of the model. Here, we distinguish between local (smaller than country), regional (one country up to the world region), and global. Additionally, we included the category of 'no scale' for all models that are so generic that they are not specific to one scale.

Additionally, we assessed whether the models were context based. In this category, the following three groups were distinguished: 1. Context-driven models: a group of models built based on a specific case study or an empirical puzzle. 2. Models applied to context: more generic models are applied to one or more empirical contexts; and 3. Theoretical models: Models that are not tailored and applied to a specific case or context but are mathematical models that describe certain phenomena driven by theoretical interest. As a related category, we investigated whether the publications use empirical data sources to quantify the norm and the strength of its effect on the agent's behavior.

Finally, the definition and implementation of the social norms used in the surveyed simulation model studies were analyzed. Here, we looked for the origin of the social norm (how is the social norm derived?), and the mechanism through which the social norm is affecting the investigated behavior (how is the social

norm applied?). Regarding the first aspect, we distinguish between norms grounded in what agents see others do (observation-based) and norms grounded in what agents believe others approve or disapprove of (belief-based).

Regarding the application mechanism, we distinguish between norms applied via imitation dynamics, (expected) approval by other agents, and norms that are directly impacting the agent's intention to perform a certain behavior (intention motivation), meaning that the norm directly influences the agent's behavior intention, and the agent changes its behavior if the behavioral intention (BI) crosses a certain threshold. Based on those aspects, we can classify the implemented norms either as descriptive or injunctive (see below). Additionally, we investigated if the norm is statically signaled or dynamically signaled.

### 3.5. Collaboration and co-citation analysis

In addition to the classification of the included models, collaboration and co-citation analysis was performed using the bibliometrix package in R (Aria and Cuccurullo 2017). Here, we used meta-information regarding the articles included in the WoS.

## 4. Results

### 4.1. Publication time and origin

Overall, the number of entries found per year has increased over the past 15 years. Without applying any limit with regard to the year of publication (with Scopus including publications from 1788 and forward and WoS 1900 and forward), we found no article published before 2000, whereas 17 articles were published in 2021 (see figure 2(A)). When looking at the countries in which the articles were published (first affiliation of the first author of each entry), it is apparent that no entry was published in South America or Africa (see figure 2(B)). The majority (72 entries) were published in Europe, 45 entries were published in North America, 30 in Asia, and 6 in Oceania (all in Australia). When assessing the case studies used in publications that were context-driven or applied, we found that several studies from authors in Europe and North America used case studies from Asia and Africa, but South America remained absent in the included studies (see figure 2(C)).

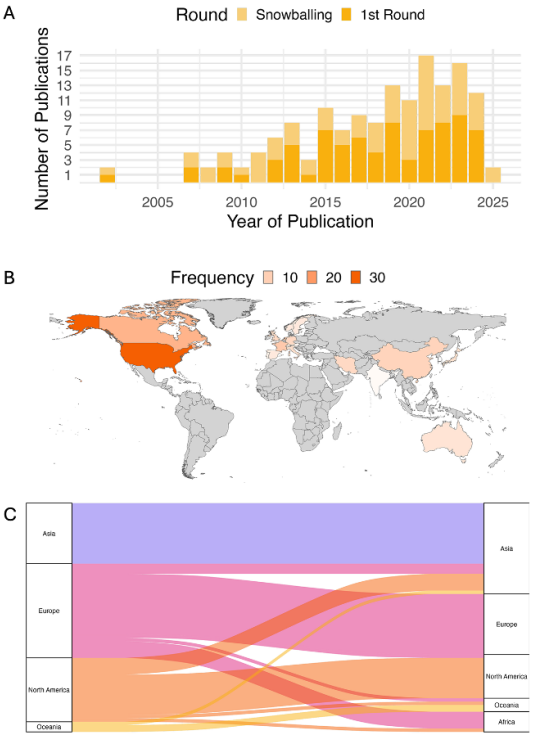


**Figure 2.** Overview of all found publications per year of publishing (A) and country of publishing (first affiliation of first author) (B). In the latter, colors indicate the different continents. (C) Overview of all publications that are using a case study (context-driven or applied), showing the continent of the origin of the study (left) and the continent on which the corresponding case study was conducted (right).

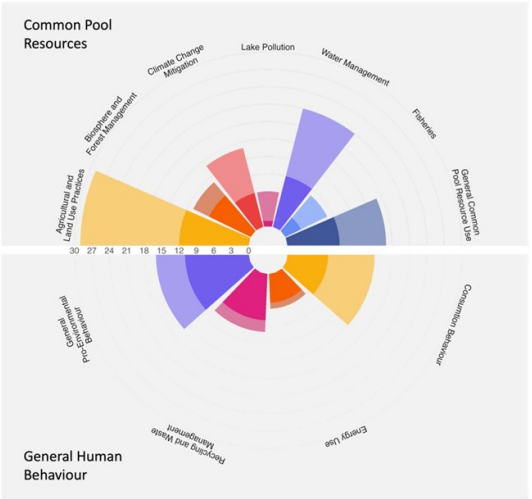


**Figure 3.** Representation of the different topics of the found publications. The two main Groups (common pool resource use and general human behavior) are further subdivided in smaller groups. The light colors identify the publications found in the first round of reviewing and the dark colors the round of snowballing.

### 4.2. Publication themes and approaches

Next, the themes of the included studies were assessed. The results are shown in figure 3. Overall, two main themes were identified, which were further differentiated. The first main theme was the use of CPRs (figure 3, upper half). Overall, 106 entries were identified for this group. Further clustering showed that most of the entries in the group were investigating the general management of CPR (21), agricultural and land use practices (29), and water management (17). While the first of these subgroups is mostly aligned with theoretical models that aim at generalizable dynamics holding true for many different CPRs, entries in the subgroups of agricultural and land-use practices, and water management are often context-driven. The four smaller subgroups in

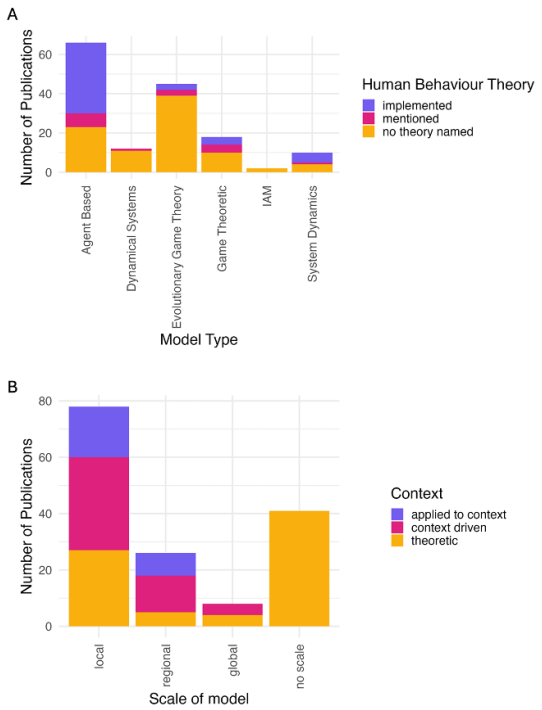


**Figure 4.** Overview of model types and human behavior theory used (A) and scale of the found models as well as their connection to context (B).

this category represent models with the topics biosphere and forest management, lake pollution, fisheries, and climate change mitigation. Interestingly, out of the small number of entries on a global scale (8) (see figure 4(B)), four were related to climate change mitigation.

The second major group of articles considered general human behavior and was subdivided into general pro-environmental behavior, a group of models that are not regarding a specific behavior but rather general sentiments or behavior; energy use; recycling and waste management; and general consumption behavior, which included dietary shifts or consumption of other products or goods.

In addition to the topics of the studies, the different model types used and the human behavior theory used were analyzed (see figure 4(A)). The most prominent modeling approach is ABM (66), followed by models using an evolutionary game theory approach (45). Game theory, dynamical systems, system dynamics, and IAMs were used less frequently (18, 12, 10, and 2, respectively).

We further investigated the use of different theories of human behavior. Here, we found that the majority (94) of entries did not explicitly refer to human behavior theory (beyond rational choice theory). However, of the studies that name a theory of human behavior (64), only 48 explicitly implement them within the described model. Here, the theory of planned behavior (TPB) is predominant (26). Other theories of human behavior include bounded rationality (18), reinforcement learning (5), theory of reasoned action (3), protection motivation theory (3), value-belief-norm theory (2), norm activation model (2), and prospect theory (1).

Moreover, theories of human behavior have mainly been used in ABMs and system dynamics models. When investigating the scale of the models included, we found that most models were either regarding a local level (77) or were so generic that they were not specific to one scale (43) (see figure 4(B)). Only eight entries were classified as global and 25 entries were found to be regional. Moreover, we investigated whether the entries were context-driven (a specific context was modeled), applied to contexts (a generic model was applied to one or more case studies in the entry), or theoretical (without any case study or specific context). While a large number of models on the local or regional scale seem to be context-driven or are applied to a context, only three models at the global scale appear to be non-theoretical. Furthermore, all the models classified as 'no scale' are theoretical in nature.

This pattern is also mirrored when looking at the empirical data used to quantify the social norm and its relative impact on the agent's behavior. Finding adequate data to quantify social norms is named as a major difficulty in modeling human behavioral aspects (e.g. Ali *et al* 2015, Grabowski *et al* 2019, Aghaie *et al* 2020). Thus, the vast majority of the included studies do not use any empirical data to quantify the social norm or the strength of its impact. In many cases they estimate a reasonable value or conduct a local sensitivity analysis to quantify the influence of the social norm term. Nevertheless, many studies overcome this difficulty using different empirical approaches. The most common way is to use survey or administrative data to derive the initial fraction of a certain behavior. Oftentimes, this data is provided by other studies or official agencies (see e.g. Kniveton *et al* 2011, Abbott *et al* 2013). Other studies conduct their own customized survey to obtain the initial fraction of a certain behavior (e.g. Van Duinen *et al* 2016, Taghikhah *et al* 2020), belief-based social norms (e.g. Harik *et al* 2023) or the weight factor of the norm (e.g. Tong *et al* 2023). Another way to derive the needed data are behavior experiments as conducted by Konc *et al* (2021) and Tverskoi *et al* (2023) or qualitative interviews and expert judgements and for example conducted by Bhalla *et al* (2024) and Farhadi *et al* (2016). Lastly, several studies take a top–down approach and calibrate needed values so that the overall model follows dynamics that match empirical observations of other variables (e.g. Lin *et al* 2022).

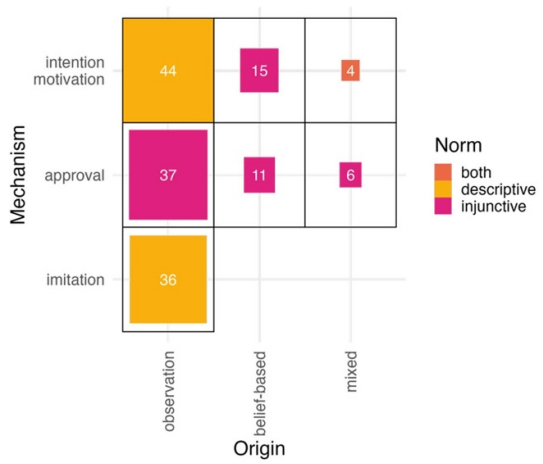


**Figure 5.** Overview of all the norm types modeled. The colors depict the norm type (injunctive, descriptive or both) and the size of the squares represent the absolute frequency of the norm combinations (mechanism and origin) modeled.

### 4.3. Types of norms modeled

Finally, we analyzed the social norms implemented in different models. Figure 5 depicts the frequency of combinations of different norm origins (observation-based, belief-based, or mixed (meaning observation-based and belief-based norms are modeled)) and mechanism type (imitation, approval, intention motivation or mixed). Moreover, those combinations were then classified as injunctive, descriptive or again both. Overall, descriptive norms were used in 84 cases, whereas injunctive norms were somewhat less frequent in 73 cases. During the process of screening publications, we found only one model (Álvarez-Antelo *et al* 2025) using dynamically signaled norms.

Using this classification, we can detect typical ways of modeling social norms: descriptive norms with the type **observation-based/imitation** normally follow either social contagion dynamics, spreading over pre-defined networks (e.g. Kapeller *et al* 2021) or follow a replicator dynamic with social impacts determined by majority behavior. Here the pay-off functions ($\pi$) of two groups ($A$ and $B$) are determined by an independent utility ($U$) and the fraction of agents ($x$) performing a certain behavior:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)\left[(U_A - U_B) + c(2x-1)\right]$$
$$\pi_A(x) = U_A + cx$$
$$\pi_B(x) = U_B + c(1-x)$$

With $c$ as the weight for the social norm. Examples of this formalization can be found in Bauch *et al* (2016), Bury *et al* (2019) and Deb *et al* (2023).

Descriptive norms of the type **observation-based/intention motivation** are also based on observed behavior, but other than depicted in the replicator dynamics above, the norm does not necessarily depict the majority behavior. In these models, the normative behavior (e.g. recycling) is often set and the strength of the norm is determined by the fraction ($N_B$) of all agents ($N$) performing the behavior. However, some of those model approaches integrate a threshold ($t$) for this norm to become effective and impact the BI of the agent. A typical implementation of this type is:

$$\mathrm{BI} = \begin{cases} A + \omega\frac{N_B}{N}, \frac{N_B}{N} \geqslant t \\ A, \frac{N_B}{N} < t \end{cases}$$

where $A$ depicts influences of other aspects (beside the social norm) on the agent's BI. Models using this approach are for example Abebe *et al* (2020) and James and Rosenberg (2022).

Injunctive norms of the type **belief-based/intention motivation** follow a similar approach, however, here the norm is not derived based on observed behavior but set in a different way. Beckage *et al* (2018) for example sets a static value as the social norm that does not change over the course of the model run and Chen *et al* (2012) combine the observed norm with a random norm and the knowledge of this derived norm. Models following this mechanism of intention motivation often use the TPB to motivate their approach.

Injunctive norms of the type **belief-based/approval** mainly follow dynamics similar to observation-based/imitation norms. However, here the agents' pay-off is not determined by the observed majority, but by a distinct sanction term ($n$):

$$\frac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)\left[(U_A - U_B) + 2n\right]$$
$$\pi_A(n) = U_A + n$$
$$\pi_B(n) = U_B - n.$$

Thus, agents are rewarded (or punished) if they (or do not) follow the norm. Again, within this model type, the normative behavior is externally set, and the agents expect a reward or punishment for not following it. Applications of those norms are for example found in Sarkar (2023) and Song *et al* (2012).

Lastly, the injunctive norm of the type **observation-based/approval** has been formalized in three main ways. The first two also utilize replication dynamics, however, the approval term is differently defined than above. In one version of this type, the cost or reward connected to the social norm is only applied to one behavior ($f(x)$), e.g. defecting:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)\left[(U_A - U_B) + f(x)\right]$$
$$\pi_A(x) = U_A$$
$$\pi_B(x) = U_B - f(x).$$

Thus, an agent not following the norm expects to be punished, while agents following the norm are not affected. This is for example implemented in Sigdel *et al* (2019), Sugiarto *et al* (2015) and Furuzono *et al* (2013).

Another version of this norm type incorporates punishers as agents. The agents here respond to the anticipated punishment based on the number of punishers ($z$) in the model:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)\left[(U_A - U_B) + 2z\right]$$
$$\pi_A(z) = U_A + z$$
$$\pi_B(z) = U_B - z.$$

This type can for example be found in Shahi and Kant (2007), Atzenhoffer (2012) and Couto *et al* (2020). The last common way of formalizing this norm type is via the difference in behavior between an agent ($\alpha$) and the mean of all agents ($\overline{\alpha}$). Here, agents are rewarded if they, for example, fish less than the mean population and punished if they fish more:

$$\pi(\alpha) = U + c(\alpha - \overline{\alpha}).$$

Examples of this implementation can be found in Abbott *et al* (2013), Bhalla *et al* (2024) and Charlier and Kirakozian (2020).

While the vast majority of models implement one of the named model types, some models include an intention motivation mechanism combined with both, an observation- and a belief-based norm (see Ceschi *et al* 2015, 2021; Guo *et al* 2016). Ceschi *et al* (2021), for example, uses the TPB to model the impact of the norm, but includes both a peer influence term based on the observed recycling levels of others and a belief-based norm, modeled as a 'moral obligation', externally set in the model.

Another way to combine those types is to also have both an observation- and belief-based norm, but apply them via the mechanism of approval (see Haab and McConnell 2002, Coutts *et al* 2013, Furuzono *et al* 2013, Le Coent *et al* 2021, Franceschetti *et al* 2023, Tverskoi *et al* 2023). Furuzono *et al* (2013) for example integrate both an observation-based norm as social pressure from a large fraction of cooperators, and a belief-based norm based on the ecological state of a resource stock. However, both aspects only directly impact the pay-off of non-cooperators, indicating an approval based norm mechanism. Only very few models combine several pathways with several norm origins (Haab and McConnell 2002, Santos *et al* 2021, Armstrong *et al* 2024).

In cases with more than one social norm type, the norm can be conflicting and thus have different effects on an agent's decision. In all but one of those models the different norms are simply added together. Some models include weighting factors in order to reflect that one norm might be stronger than the other but many also simply sum them, giving them a similar weight. Only Harik *et al* (2023) take a different approach. Here, the authors conducted a questionnaire to acquire the value of the belief-based norm and then multiply it with the observation-based norm, proposing that the norms are amplifying each other rather than just being a sum.

Within the group of models with observation-based norms, the reference groups differed substantially. In some models, the norm is based on a global observation, meaning that the norm reflects the behavior of all agents within the model (see e.g. Furuzono *et al* 2013). Other models (see e.g. Menard *et al* 2021) define norms with respect to a specific peer group, while still others only refer to an agent's direct neighborhood (e.g. Pedehour and Richefort 2022).

### 4.4. Collaboration and co-citation analysis

The collaboration analysis (see figure 6(A)) depicts the collaboration of authors from different research institutes regarding the included studies. The different nodes in figure 6(A) represent different research institutions and the links between them represent publications in which authors from different institutions worked together. The analysis revealed a large number of smaller hubs or clusters of different institutions. However, these clusters appeared to be highly disconnected from each other. The co-citation analysis (see figure 6(B)) also revealed different topic hubs. However, they seem to be better connected. Overall, the analysis shows four main hubs that seem to structure the overall field. First, the topic CPR governance, dominated by publications citing Elinor Ostrom (e.g. Ostrom 1994, 2000) seems to be a central cluster of research in this field. This cluster is strongly connected to the second cluster in theoretical social norms research and the third cluster in game-theoretic approaches and cooperation.

The second cluster is dominated by research by Karine Nyborg (e.g. Nyborg *et al* 2006, Nyborg *et al* 2016) and is only very weakly linked to the third cluster of game-theoretic approaches and cooperation. This third cluster is not dominated by a single author but seems to be a less centralized sub-network with authors such as Hofbauer (e.g. Hofbauer and Sigmund 2003) and Scheffer (e.g. Scheffer *et al* 2001). The last and fourth cluster of the TPB & ABMs are formed around Icek Ajzen, the developer of the TPB (Ajzen 1991). Compared to clusters two and three it has fewer links to the first cluster on CPR governance but is better linked to the social norms cluster (two) and the cluster of game theory and cooperation (three).

## 5. Discussion

### 5.1. Publication time and origin

The descriptive analysis of the entries showed that the number of studies increased significantly over

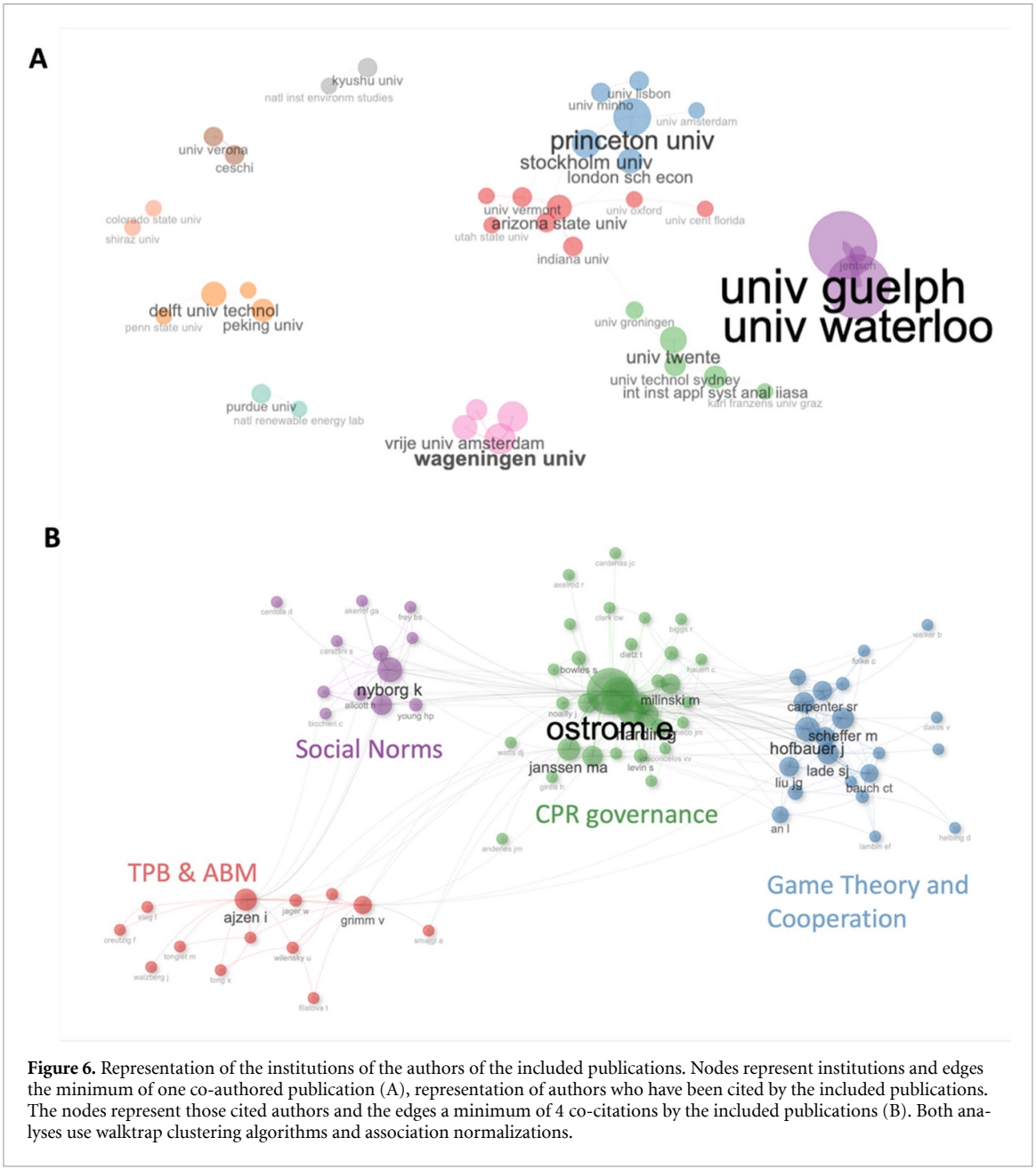


**Figure 6.** Representation of the institutions of the authors of the included publications. Nodes represent institutions and edges the minimum of one co-authored publication (A), representation of authors who have been cited by the included publications. The nodes represent those cited authors and the edges a minimum of 4 co-citations by the included publications (B). Both analyses use walktrap clustering algorithms and association normalizations.

the last 25 years. This might indicate a growing interest in the simulation modeling of social norms in a socio-environmental context. However, given that the number of publications per year in the area of simulation models increased with a similar slope (according to a search in Scopus for 'simulation model*' on the 18th of December 2024), modeling social norms specifically is possibly of consistent interest when it comes to simulation models more generally.

An analysis of the countries of origin showed that most entries were published in Europe, followed by North America. In Asia, the vast majority of included publications included articles originating from China, Iran and Japan. No entries were published in South America or Africa. While this might mirror the general dominance of publications from Europe, North America, and Asia (see e.g. Collyer 2018), it is rather problematic as this means that perspectives from Africa and South America are underrepresented in this field of research. Given that all models must make assumptions and can only represent parts of the real world, the situatedness of the authors is highly influential in modeling studies (Klein *et al* 2024). When analyzing the continents on which the case studies were conducted, the picture shifted slightly. Some studies published in Europe or North America used case studies in Asia and Africa, while all publications with origins in Asia also used case studies on the same continent. However, none of the studies described a case study conducted in South America. Thus, perspectives from this continent seem to be completely missing in this field of research. For further research, it may be crucial to include more diverse perspectives and case studies. The entry topics, however, were equally distributed

over the continents of origin, so no clear trend could be found.

Overall, the thematic analysis of the entries' topics highlighted that most entries were researching some type of CPR management with most entries focusing on food production. This includes all articles in the subgroup of agriculture and land use practices but also most articles in the subgroups of water and general CPR management. Surprisingly, most of these publications focused on terrestrial CPRs and only a very small number of entries emphasized fisheries. Interestingly, the actors represented in these models are mostly individual resource users or farmers; only a few models represent companies or actors on a higher level of social organization, such as governmental actors or decision-makers. Overall, the models show less emphasis on the general topic of climate change mitigation than one would possibly expect, and models that focus on climate change mitigation are rather generic. The second group of entries focuses on general aspects of human behavior. The predominant topic is the consumption of goods in all the subgroups. When examining the actors represented in these models, most focus on individual or household consumers.

### 5.2. Publication themes and modeling approaches

The two most dominant modeling approaches are ABMs and evolutionary game-theoretic approaches. Interestingly, the number of system dynamics models among the identified entries was rather small. Nevertheless, this may reflect that modelers in this community do not explicitly use the term 'social norms' when modeling the concept. Moreover, this approach is usually used to model aggregated dynamics; thus, modeling social norms might be more challenging using this approach. Therefore, this approach may be chosen less frequently when explicitly attempting to model social norms. The combined analysis of the modeling approach and the use of human behavior theories has revealed that models in the categories of ABMs and system dynamics are more likely to integrate such theories (beyond rational choice) as compared to the other modeling approaches. This could indicate that modeling communities using these approaches are more closely connected to communities in social sciences and environmental psychology. This also aligns with the results of co-citation analysis.

The overall lack of use of human behavior theories, as well as the predominant use of TBP, could indicate a large gap between the social simulation community and experts in environmental psychology, as also proposed by others (e.g. Van Valkengoed *et al* 2025). Further research should aim to close this gap and include more interdisciplinary cooperation in the research process. However, this analysis should be handled with care, as it is quite possible that other entries also used human behavior theories but did not name them explicitly. Moreover, we found high heterogeneity in the implementation of theories of human behavior. For example, some models use descriptive norms (see, e.g. Niamir *et al* (2024), who consider descriptive norms of neighbors' energy-related actions), while others implement injunctive norms (see, e.g. Tong *et al* 2023), representing the injunctive norm 'my family and friends think I should recycle') as the social norm described in the TPB.

An analysis of the scale of the entries reveals that most models are situated on a local scale. At this scale, the majority of models are context-driven, or at least applied to a context. When examining the different modeling approaches, the results show that most context-driven models use the ABM approach. This indicates a strong link or overlap between ABM modelers and an empirical research community that seems to be weaker than other modeling approaches. This is also reflected when looking at the models using empirical data to quantify the social norm. The use of empirical data is much more common in models using an ABM approach. In addition to context-driven models, a significant number of models were classified with no explicit scale and thus as theoretical. The fact that around half of the overall entries found have been classified as theoretical and more than half lack quantitative empirical data for the modeled norms, shows that this field of study has so far focused on conceptual and theoretical models that typically do not rely on empirical data. This is possibly due to the lack of empirical data on social norms (e.g. Beckage *et al* 2022). From an empirical perspective, the concept of social norms is challenging to operationalize; thus, the generation of reliable data for models in this field remains a challenge. This may also explain why the number of models remains small on a global scale. Thus, future research should aim to generate and integrate the relevant empirical data.

### 5.3. Modeling different types of norms

Regarding the question of how norms are included in models of social-ecological dynamics, one critical design consideration is whether norms are modeled based on observed behavior or what agents believe they ought to do. This review shows that the vast majority takes the approach of modeling observation-based norms and derives those norms endogenously from model dynamics. However, those models that choose a different approach and integrate a belief-based norm only derive the norm endogenously in the minority of the included cases. Choosing to model endogenously derived observation-based norms instead of providing them as exogenous inputs could be the preferred approach because of its intuitive alignment with many modeling approaches, such as ABMs, dynamical system models, and system dynamics models. However, an explicit discussion of this design choice is often absent in the literature.

Occasionally, belief-based norms are modeled as outcomes that emerge from the behavior simulated, rather than being defined as explicit components of the system. During our screening process, we identified several studies that took a sophisticated approach to modeling belief-based norms endogenously. However, most of these lacked a clear feedback mechanism whereby the emergent norms influenced future simulation behavior. As the modeled norms did not affect the system dynamics, we excluded these studies from our analysis. Nevertheless, these approaches demonstrate the potential of endogenously modeled belief-based norms in capturing complex social behaviors and understanding normative influence. Future research could benefit from incorporating feedback loops where emergent belief-based norms actively influence ongoing simulation processes. This would provide a more comprehensive representation of injunctive norms.

The mechanisms used to model the norms are well distributed between the three options (imitation, approval and intention motivation) distinguished in this review and there are many different formalizations implemented, reflecting a high diversity of different strategies. The majority of the models following the intention motivation approach also explicitly implement a behavioral theory, mainly the TPB, which clearly expresses the mechanism of norms impacting BIs.

Generally, the different norm types and related norm formalizations show very different understandings of how norms are derived and how they influence the agent's behavior. The different groups of norms described here all follow distinctive dynamics and can capture diverse societal processes which result in deviating roles and effects of the social norm modeled. Our results show clearly that even publications that can be classified as injunctive or descriptive might use very different formalizations, resulting in different dynamics: Following the approach of modeling a descriptive norm with the observation-based/imitation mechanism for example, allows the norm to change qualitatively, meaning that depending on the majority behavior it can be the social norm to perform a certain behavior but it can also be the social norm not to perform the behavior. Thus, the social norm can switch and can create certain lock-in situations in which the social norm solely reinforces the dominant behavior. However, when representing the descriptive norm in a typical observation-based/intention-motivation implementation, the norm is set qualitatively and only its strength can vary within the model run. This formalization does not represent similar lock-in situations. Thus, when conceptualizing a model including social norms, it is not enough to define which kind of social norm should be represented, but also the formalization mechanism should be carefully chosen to fit the context. Similar considerations have been presented by Muelder and Filatova (2018). The authors have shown that using the same theoretical foundation (e.g. the TPB) can still end in very different formalizations and thus model outcomes and dynamics. Therefore, researchers should carefully reflect which theoretical foundation, but also which formalization approach fits their research case and choose the modeling approach accordingly. The accuracy of the approach should outplay the simplicity of implementation. A notable limitation of the existing models of social norms is the predominant focus on a single type of norm. Few studies have investigated the interplay between different types of norms. This could be especially relevant for research fields such as sustainability transitions, where the relative importance of distinct norm types may vary during the transition process. Exploring the interaction of multiple norm types within simulations represents a promising research frontier, as it could elucidate the combined influence of normative pressures on behavior and system change (Bechthold *et al* 2025).

Moreover, most of the few models found that integrate both, an observation-based and belief-based norm just calculate the sum of both to affect the agent's behavior. Only one study proposes that the two kinds of norms could amplify each other, suggesting that they could be more than just the sum of the two. This opens up an interesting research avenue on the interaction of different, possibly conflicting norms and how to depict this within modeling efforts.

In the literature, it has been discussed that an agent's perception of what others think might differ from what they are actually thinking (see e.g. Sparkman *et al* 2022, Gavrilets *et al* 2024). This idea of 'pluralistic ignorance' could also have strong implications on the modeling of social norms, as agents might be uncertain about what the prevailing social norm is. However, the majority of the models included assume the agents to have perfect knowledge of the social norm, and the question of whether an individual's perception of the social norm can deviate from e.g., the observed behavior, is rarely addressed in the found modeling approaches. However, there are approaches that are able to capture this nuance. Chen *et al* (2012) for example depict this dynamic by multiplying the 'objective' social norm with a knowledge factor that represents the agent's knowledge on the social norm and add a random factor to it, shifting the perceived social norm away from the actual observable norm, if the knowledge factor is low. Nevertheless, approaches like these are very rare and further work on capturing those nuances in norm perception is needed, possibly drawing from game-theoretic approaches that already strongly discuss the possibility of imperfect knowledge.

Even though there has been growing interest in the study of dynamically signaled norms, we could only find one model (Álvarez-Antelo *et al* 2025) using dynamically signaled norms within our

analysis. This seems to be a great shortcoming of this field of research, as comparative studies demonstrate that dynamically signaled norms, which signal trends in normative behavior, exert a greater influence on behavior than statically signaled norms, particularly during the early stages of behavioral adoption (Sparkman and Walton 2017). While statically signaled norms reinforce existing behavioral patterns, dynamically signaled norms provide critical signals to early adopters about emerging trends, encouraging adoption even when prevailing statically signaled norms remain entrenched (Sparkman *et al* 2021). From a modeling perspective, incorporating dynamically signaled norms does not pose significant technical challenges. For example, in descriptive norm models, the current behavioral prevalence within the population (statically signaled norm) could easily be replaced by the rate of behavioral change (dynamically signaled norm), or they could be utilized simultaneously.

Regarding the social-cultural dimensions of social norms, it is well established that social norms differ across regions and cultures (Gelfand *et al* 2011, Eriksson *et al* 2021). Thus, one could expect that the norm type modelled might vary depending on where the model originated or the region of the used case. However, the distinctions made in established frameworks (see e.g. Gelfand *et al* 2011, Thomson *et al* 2018, Eriksson *et al* 2021) pertain to norm strength and enforcing rather than differences between injunctive and descriptive norms. When looking at the included models with a global scale we could only find one study that reflects those cultural differences of norm strength within the presented model (Pettifor *et al* 2017). One reason for the lack of cultural diversity is the global aggregated nature of the majority of those models. However, for instance, Eker *et al* (2019) address this issue and acknowledge that implemented cultural differences across the world might impact the model results. Thus, integrating cultural diversity and related norm differences would be an advancement to current modeling efforts.

Another critical frontier for this field lies in establishing a shared and standardized terminology. While terms such as 'dynamic' or 'dynamically signaled norm' have become increasingly common in the social science literature (Çoker *et al* 2022, Caso *et al* 2024, Gelfand *et al* 2024, Otten *et al* 2024), there remains no broadly accepted counterpart for describing non-dynamically signaled norms. The terms 'static' or 'statically signaled norm' are not yet established standards but rather reflect recent attempts within the research community to introduce a counterpart to dynamically signaled norms (e.g., Loschelder *et al* 2019, Aldoh *et al* 2024). The development of a standardized vocabulary would help foster conceptual clarity and greater comparability across modeling studies of social norms.

### 5.4. Collaboration and co-citation analysis

The collaboration analysis reveals that there are a large number of institutions and hubs in the field of modeling social norms. Nevertheless, the analysis also shows that the field is rather fragmented, with different hubs working independently.

Overall, the co-citation analysis supports the strong connection between the field of social simulation models of social norms and the governance of CPRs. While this was found to be the main thematic field within the retrieved publications, it was also one of the main clusters found in the co-citation analysis. Interestingly, the cluster of social norms is not central to the network, and other clusters are only weakly linked to this cluster, showing that the articles found in this review often do not connect their fields (e.g. game theory and cooperation) with the general scholarship of social norms. Overall, the analysis indicated that the field can be described as fragmented as opposed to one well-connected research hub.

### 5.5. Limitations

Although this study was conducted with great care and using state-of-the-art methods, the approach of a systematic review can only limit a selection bias that might be dominant in other types of reviews. Moreover, the issue of publication bias cannot be accounted for. Moreover, even though we aim to make this review as comprehensive as possible, we acknowledge that we are not able to find all social-ecological models that implement social norms according to the definition used in this review. Nevertheless, we assume that the sample found and studied provides a comprehensive overview of the approaches used to model social norms in the current literature on social-ecological systems.

## 6. Conclusions

This study provides a systematic overview of how social norms are represented in social-ecological models on different scales. In total, 153 relevant entries were identified. Generally, this field appears to be dominated by publications from Europe and North America, with a lack of studies originating from Africa and South America. When looking at the topics of the identified articles, two main clusters were found: management of common-pool resources and general human behavior, which mainly focused on individual consumption patterns. Regarding general modeling approaches, most entries used ABMs, followed by evolutionary game-theoretic approaches. Less than half of the included studies explicitly mentioned the use of human behavior theories beyond rational choice approaches. Of these models, the majority use the well-known TPB or the concept of bounded rationality to integrate social norm dynamics which highlights the current lack of diverse

approaches from environmental psychology implemented in social simulation models. This is also underlined by the co-citation and collaboration analysis, which revealed that the field remains rather fragmented and suggests it could benefit from more interdisciplinary collaboration.

Most of the found entries described models at the local or regional level, revealing a gap in models aimed at representing processes up to a global scale. Regarding the models' relation to the context, we found that most models could be classified as theoretical, indicating a gap between theoretical considerations and empirical knowledge.

With regard to the types of social norms modeled we found that models that can be described as injunctive or descriptive, respectively, differ very much in their formalization, which makes it necessary to distinguish them at an even more detailed level, e.g. by looking at the norm origin and mechanism. Clear patterns emerge when this is done: the vast majority of the included approaches use an observation-based origin of norms, meaning that social norms are derived endogenously. Belief-based norms are less frequent and are mostly represented exogenously. We hypothesize that this difference in the representation of observation-based and belief-based norms stems from technical considerations: modeling observation-based norms as endogenous parts of the model dynamics is a technically feasible and intuitive approach for many modeling styles found in this review, such as agent-based and system dynamics models. However, the underrepresentation of endogenously modeled belief-based norms points to the technical implementation challenges of representing the emergence and development of this norm type within model dynamics. While approaches for representing belief-based norms endogenously exist, many solely represent the emergence of belief-based norms as a model simulation output. Without considering feedback mechanisms back to the model, belief-based norms are an emergent property rather than integral components of the system dynamics. Regarding the effect mechanism of the norm, we found that all three categories (imitation, approval, intention motivation), are well represented in the sample, indicating that all three approaches are very common. Additionally, the interaction of multiple norm types within a single model has rarely been examined, despite evidence suggesting that their interplay could offer a richer understanding of normative dynamics across various stages of behavioral adoption. Moreover, the analyses show that, overall, there is limited exploration of dynamically signaled norms in the literature and models very rarely differentiate between a perceived social norm and an objectively observable social norm, assuming the agent to have full knowledge of what others do.

This systematic review is a valuable resource for interdisciplinary efforts to model social norms in social-ecological systems. Our analyses reveal that the research community is somewhat fragmented, with distinct sub-communities favoring particular modeling approaches. Researchers seeking to model social norms would benefit from adopting methods that go beyond those commonly employed within their own subfield. Furthermore, due to the wide range of theories of human behavior and types of social norms, it is essential to carefully identify the specific norm to be modeled and adapt the design principles of the model to fit the particular context.

Finally, several directions for further research are suggested based on the findings of this review: There is a need for greater geographical representation in terms of both the origin of the article and the region of the case study. This is of high importance as the geographic bias currently dominant is likely to create biased results and miss important perspectives. Moreover, stronger interdisciplinary collaboration would enhance the integration of human behavior theories from the field of (environmental) psychology as well as empirical data to overcome the dominance of solely theoretical models and add more behavioral realism. Furthermore, these frontiers enclose the development of modeling approaches that endogenously represent belief-based norms, the inclusion of dynamically signaled (as opposed to statically signaled) norms, the interplay and feedback dynamics of multiple norm types, the inclusion of agents acting on different levels of society and cultural differences affecting social norms in global model approaches. Further research on these pathways provides an opportunity to better understand the interplay of natural and social dynamics that can foster the social-ecological transformations needed to bring us back into a safe and just operating space.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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## Declarations

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Research data supporting this publication is available in the supplemenatry data.

## Conflict of interest

The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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