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PERSPECTIVE

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How to make socio-environmental modelling more useful to support policy and management?

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Abstract

1. Dynamic process-based modelling is often proposed as a powerful tool to understand complex socio-environmental problems and to provide sustainable solutions as it allows disentangling cause and effect of human behaviour and environmental dynamics. However, the impact of such models in decision-making and to support policy-making has so far been very limited.
2. In this paper, we want to take a critical look at the reasons behind this situation and propose steps that need to be taken to change it. We investigate a number of good practice examples from fields where models have influenced policy-making and management to identify the main aspects that promote or impede the application of these models.
3. Specifically, we compare examples that differ in their extent to how explicitly they represent human behaviour as part of the model, ranging from purely environmental systems (including models for river management, honeybee colonies and animal diseases), where modelling techniques have long been established, to coupled socio-environmental systems (including models for land use, fishery management and sustainable water use).
4. We use these examples to synthesise four key factors for successful modelling for policy and management support in socio-environmental systems. They cover (a) the specific requirements caused by modelling the human dimension, (b) the importance of data availability and accessibility, (c) essential elements of the partnership between modellers and decision-makers and (d) insights related to characteristics of the decision process.
5. For each of these aspects, we give recommendations specifically to modellers, decision-makers or both to make the use of models for practice more effective. We argue that if all parties involved in the modelling and decision-making process take into account these suggestions during their collaboration, the full potential that socio-environmental modelling bears can increasingly unfold.

KEYWORDS
fishery, land use, policy support, simulation model, water management

1 | INTRODUCTION

Socio-environmental systems (SES) are characterised by a tight coupling of human and environmental dynamics (Berkes & Folke, 1998; Folke et al., 2010; Schulze et al., 2017). Both aspects need to be understood to support sustainable management of these systems (Carpenter et al., 2009; Chapin et al., 2010; Ostrom, 2009). Dynamic process-based modelling, and in particular agent-based or individual-based modelling, is often proposed as an effective approach to address such interlinked dynamics and provide solutions to pressing challenges, as it allows disentangling cause and effect of human and environmental processes (Levin et al., 2013).

Socio-environmental modelling has made many contributions in the scientific realm answering environmental issues on the sustainable management of natural resources focusing on land use/land cover change (Parker et al., 2003), agriculture (Huber et al., 2018), fishery management (Lindkvist et al., 2020) or biodiversity conservation (Drechsler, 2020). However, few SES models have had impact on decision support and policy-making (Elsawah et al., 2020; Polhill et al., 2019; Schulze et al., 2017). In contrast, models from other areas such as transportation planning, epidemiology or pesticide risk assessment have been routinely integrated into policy-making processes. Literature reviews evaluate the usefulness of models for specific fields such as conservation management (Addison et al., 2013), marine systems (Gregr & Chan, 2015), agriculture (Primdahl et al., 2010; Reidsma et al., 2018) or environmental health (Currie et al., 2018), but this work does not address how to foster the integration of socio-environmental modelling into practice.

With this paper, we aim to explore models across disciplines and topics that have already influenced policy-making and management. We look at seven good practice examples ranging from those tackling purely environmental problems that do not explicitly represent a human component as part of the model, such as the management of rivers for both fish and amphibian populations or control of animal diseases, to coupled SES models such as sustainable fisheries in Australia and water management in Jordan. Based on the evaluation of these models, we explore factors that enabled or impeded the transfer of management-oriented model results into practice. The examples have in common that they did deliver scientifically innovative insights and had an impact on policy or management decisions. Impact can range from stimulating a discussion process (e.g. raising awareness for so far neglected issues), influencing debates around a decision (e.g. laying out certain options or scenarios), to policy or management decisions being directly based on model results (see van Daalen et al. (2002) for different roles of computer models in the environmental policy cycle). Impact does not state whether the outcome of the decision was positive or negative from a given perspective. In the context of modelling for decision support and policy-making, participatory approaches for involving non-scientists in the modelling process have been suggested as an effective tool to incorporate expert knowledge not only to validate model assumptions but also to tailor policies to relevant local practices (Castella et al., 2014). Stakeholders' expertise is required in different stages of the project, ranging from defining a problem to solving conflict situations after the implementation of a measure (Pahl-Wostl, 2002). Several methods of citizen engagement have proven to be effective including interviews, focus groups, scenario workshops, citizen science and digital participation (Šucha & Sienkiewicz, 2020). In the context of modelling, various studies show the demand for stakeholder participation with a focus on participatory modelling (Voinov & Bousquet, 2010; Voinov et al., 2016) where different approaches have been reviewed (Sterling et al., 2019; Voinov et al., 2018), classified (Barreteau et al., 2017) and standardised (Gray et al., 2018; Seidl, 2015).

While we acknowledge both the benefits and the challenges of such transdisciplinary stakeholder engagement, this is not the focus of this paper. Instead, we concentrate specifically on the potential science–policy interface between (academic) modellers and (administrative) decision-makers. When referring to stakeholders, we therefore primarily address decision-makers who work in policy and management. Better integration of models in policy-making has been suggested with a focus on modelling for public policy (Gilbert et al., 2018), model acceptance in policy-making (Kolkman et al., 2016) and models used as decision support tools (McIntosh et al., 2007; van Delden et al., 2011; Zasada et al., 2017). Our paper contributes to this strand of literature targeting the special requirements that SES modelling bears.

The paper is structured as follows: in the next section, we present how the good practice examples were evaluated, and list the criteria used to classify them. We introduce background information about the seven models in section three. In section four, we present key principles of success or failure that we derive from the evaluation. We conclude our paper with recommendations to make modelling more relevant in policy-making and management.

2 | METHODS

2.1 | Interview framework

Based on an initial literature review and the authors' experience, we drafted a list of analytical categories which we suspected to be relevant to our problem regarding the practical impact of SES models. We arranged them according to the 'Four Ps' framework developed by Gray et al. (2018) which focuses on the purpose of the modelling endeavour, the processes of exchange between modellers and managers, details on these partnerships, and the products that emerge from this exchange, that is, the range and type of application of the model outcome in practice. This results in the following grouping of the categories:

1. Purpose: background information, relevance of outcome, driving motivation
2. Processes: group size, actors involved, data availability and accessibility
3. Partnerships: previous relationship and experience, organisation of modelling process
4. Products: building confidence and transparency, learning processes, difficulties in the project, usability of the model.

We formulated these categories as questions to compose a questionnaire for semi-structured interviews (see Supporting Information).

2.2 | Interviews

Based on the questionnaire, we conducted semi-structured interviews with seven researchers who were currently or had previously been part of modelling projects in a policy or management context. The selection was by referral through colleagues and collaboration partners and reflects a wide spectrum of models with impact in policy or management, ranging from purely environmental models that do not explicitly involve a human component to socio-environmental models coupling human and environmental processes. All interviews were digitally recorded. Prior to the interviews, informed verbal consent to be included in this research was obtained from the participants. As the study only includes expert interviews and the participants were informed about the research objectives, it does not require ethical approval according to the criteria of the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG). We assessed the respondents' narratives against our categories. This process helped us identify missing aspects as well as emerging common themes, which we added and condensed in subsequent iterations, loosely inspired by 'grounded theory' approaches (Strauss & Corbin, 1997). This led, in the end, to a set of 14 gradients that include most of our questionnaire items but also go beyond them and thus reflect a conceptual learning process by which we amended our initial assumptions.

2.3 | Gradients to describe good practice examples

The 14 gradients are again grouped according to the 'Four Ps' framework (Purpose, Processes, Partnerships, Products; Gray et al., 2018) and listed with their definitions in Table 1. For each gradient, the seven case studies are categorised as 'low', 'medium' or 'high'. The interviewees reviewed our evaluation afterwards (and sometimes suggested modifications). In the following, we present details on the classification according to the gradients.

TABLE 1 The 14 gradients used to classify the good practice examples. All gradients range from low to high

Dimension	Definition/Guiding question
Purpose	
System complexity	Number of actors, processes, interactions; range of observed real-world behaviour
Model complexity	Number of variables, processes, interactions; range of emergent model behaviour
Demand-drivenness	How important was demand by decision-makers in initiating the modelling process?
Processes	
Persons involved	Number of people involved in the modelling process
Decision-maker involvement	How far were decision-makers involved in the conceptualisation and development of the model? How participatory was the process?
Academic fields	Number of academic fields/backgrounds involved
Data availability	Availability of qualitative and quantitative data to build the model
Data accessibility	Accessibility of qualitative and quantitative data to build the model
Partnerships	
Familiarity	How familiar were project partners with one another?
Modelling experience	How experienced with/open to modelling were decision-makers?
Exchange frequency	How frequently did project partners communicate?
Continued support	How willing were modellers to continually support the model users?
Products	
Practical application	How tangible were the project outcomes (e.g. actual decision-making or even legislation vs. improving understanding and stimulating discussion)?
Ease of use	How easy was it for end users to use the model themselves?

2.3.1 | Purpose

The first three gradients (system complexity, model complexity and demand-drivenness) address the background of the modelling example and ask by whom the modelling process was initiated. **System complexity**, on the one hand, refers to the real-world system under study in terms of the number of actors involved or the diversity of processes and interactions that are important in that system. Depending on the research question, the identification of a 'system' already involves some degree of abstraction, as in most SES it is difficult to clearly delineate what elements and links to include and which ones to leave out. On the other hand, **model**

complexity indicates to what level of detail elements and mechanisms of the real-world system are represented in the model, that is, whether they are included in detail, appear in strongly simplified form or are ignored altogether. **Demand-drivenness** reflects how far the initiation of the modelling process was driven by demand from the decision-makers' side.

2.3.2 | Processes

The five gradients in this section (persons involved, decision-maker involvement, academic fields, data availability and data accessibility) relate to the organisation of the modelling process. This includes the number of **persons involved** (ranging from a single-person project to a high number of participants involved), the number of **academic fields** or backgrounds involved (from a single discipline to a highly interdisciplinary project) or the **involvement of decision-makers** in the conceptualisation and development of the model. The latter relates both to the number of decision-makers involved and to the extent of their participation in the process. **Availability of data** refers to the general abundance of qualitative and quantitative data needed to build the model. Here, the situation can be mixed, with, for example, biological data readily available and socio-economic data hard to come by. **Data accessibility** reflects that even when sufficient data bases exist, for example, within a public institution, accessibility may be low if it is difficult for modellers to obtain access to them.

2.3.3 | Partnerships

Gradients of partnerships (familiarity, modelling experience, exchange frequency and continued support) address the relations and interactions between the different project partners, especially between modellers and decision-makers. **Familiarity** indicates how well project partners already knew each other at the beginning of the modelling process. **Modelling experience** summarises how experienced decision-makers were with modelling approaches before the project. **Exchange frequency** indicates how often the project partners met or communicated during the project. This may in practice be restricted by project funding timelines, staff turnover or changing situations on the ground that make models obsolete. **Continued support** reflects the modellers' willingness and ability to provide ongoing support for model users, including beyond the official project duration.

2.3.4 | Products

The last two gradients (practical application and ease of use) relate to the end product of the modelling project: **practical application** reflects whether outcomes of the model have been relevant for decision-making or to initiate legislative changes ('high' practical application), versus stimulating discussion and generating understanding ('low' practical application). **Ease of use** reflects the complexity of the final model and how intuitive it is for the end users to utilise the model by themselves. This depends, for example, on the availability of a graphical user interface, compared to just a command line tool.

3 | GOOD PRACTICE EXAMPLES

The seven case studies we selected represent a wide range of influential modelling projects. They span different regional scales: some deal with concrete environmental questions while others attempt to understand complex socio-environmental or hydro-economic systems in their entirety. In the following paragraphs, we briefly introduce the seven projects. Additional background information is presented in Table 2.

- **FYFAM**: The Foothill Yellow-legged Frog Assessment Model (FYFAM) shows how river management affects frog breeding. It was designed to address the potential for conflicts between river management for salmon and frogs: if we provide certain conditions for the benefit of salmon, what are the impacts to frogs? Certain parts of the model (the river habitat) were borrowed from a fish model. The FYFAM model has been used to support the decision-making for river management at several sites.
- **BEEHAVE** simulates the development of a honeybee colony and its nectar and pollen foraging behaviour in different landscapes. The goal is to understand how honeybee colonies respond to multiple stressors (disease, extreme weather, beekeeping practice, insufficient forage supply and pesticides), to identify stress levels and stressor combinations that put honeybees at risk, to support risk assessment and devise mitigation measures. The model has been used by different authorities and industries to explore the effects of multiple stressors and suitable management options.
- **FarmNet-BVD** is an epidemic model. It evaluates the effectiveness of two different strategies to identify virus infections among cattle. The policy question was whether a switch to a new testing strategy would be beneficial to farmers in terms of the costs involved. This was linked to the goal of completely eradicating a cattle-related virus from the Irish cattle population. The model provided a quantitative basis for strategy comparison and influenced the decision taken by managers on a new legislation for specific testing strategies in Ireland.
- **Ecopay**: This ecological-economic model is able to simulate 15 endangered bird species, 15 endangered butterfly species and 7 rare grassland habitat types in combination with several hundred grassland conservation measures (such as different mowing and grazing regimes) in different regions in Germany and Belgium. Its objective was to identify both ecologically effective and cost-efficient payment schemes for land use measures that contribute to the conservation of endangered species and habitats in agricultural landscapes. The model systematically presents the range of

TABLE 2 Overview of the seven good practice examples that were evaluated. The models are arranged by how explicitly they represent human behaviour as part of the model, ranging from purely environmental to socio-environmental models

	FYFAM	BEEHAVE	FarmNet-BVD	Ecopay	Atlantis-SE	ALUAM-AB	JWP
Degree of explicitly representing human behaviour	Environmental	→	→	→	→	→	Socio-environmental
Case study setting	River management model for one frog species	Development of honeybee colonies, foraging behaviour	Identification of virus infections among animals	Grassland species and conservation measures	Marine ecosystems and fishing	Mountain agro-pastoral systems and ecosystem services	Hydro-economic model of the Jordanian water sector
Location and spatial scale	Managed rivers of northern California; the model typically represents ~1 km length of river	England, Hertfordshire, 5 km × 5 km (can be applied to any region of same scale)	Ireland, resolution depending on geographical coordinates and cadastral maps	Saxony and Lower Saxony (Germany) and Flanders (Belgium), resolution 250 m × 250 m	SE Australia (3 million km^2)	Swiss Alps, smallest landscape unit 100 m × 100 m	Representation of whole country (Jordan)
Research question	How does frog breeding success depend on river flows, temperatures, and channel characteristics?	How do honeybee colonies respond to multiple stressors? What mitigation measures will reduce risk?	Will the introduction of a new virus monitoring approach pay off?	What land use measures are effective to conserve endangered species and grassland habitats?	Which management strategies best achieve ecosystem-based fisheries management goals?	How to manage land to foster ecosystem services supply and increase resilience to climate and socio-economic changes?	How will water policy interventions affect water-stressed countries?
Project duration	2014–2018	Since 2008, ongoing	2015–2017	2008–2018 (in several projects)	2003–2007 (ongoing, use for new questions)	2008–2020	Since 2014, ongoing
Model type	ABM	ABM + simulated age-structured model	Spatially explicit, stochastic, pseudo individual-based	Ecological-economic modelling, optimisation	ODE (ordinary differential equation) model; complex hybrid approach: 58 ecological components modelled; 26 fisheries represented	ABM	ABM
People involved	Modeller, river engineer (for modelling hydraulics) and biologists	Modellers, bee ecologists, industry	Authorities (ministry); official veterinarians; private veterinarians; subject matter scientists; modelling team; farmers' organisations	Scientists (mostly modellers), nature conservation foundation, ministry of agriculture (Saxony)	Scientists, industry representatives, managers, policymakers and economists	Empirical scientists, modellers, (local) authorities, engineers, experts from different field (land use, hydrology, natural hazards, forest, rural development)	Scientists, Jordan Ministry of Water
Key reference	Railsback et al. (2016)	Becher et al. (2014)	Thulke et al. (2018)	Mewes et al. (2017)	Fulton et al. (2014)	Grêt-Regamey et al. (2019)	Klassert et al. (2015)

alternatives, but no concrete measures were taken based on the outcomes of the model.

- **Atlantis-SE** is a fishery model representing Australia's southeast regional marine ecosystem. It covers 3 million km^2 of Australia's fisheries. The model evaluates different alternative management strategies for a complex multispecies fishery. Outcomes from the model provided information that supported change in a fishery law.
- **ALUAM-AB** is a land use model. It studies agro-pastoral systems and ecosystem services in the Swiss Alps under socio-economic and climate change. The research interest was how to make payments for ecosystem services more effective, based on biophysical factors and taking into account cooperation between land users rather than a uniform distribution scheme. Moreover, ALUAM-AB was applied to better understand which actor types and which type of collaboration are necessary to foster resilience to climate and socio-economic changes. These results were incorporated in a new agrarian policy for Switzerland.
- **JWP**: The Jordan Water Project is a coupled hydro-economic multi-agent model of the entire Jordanian water sector, allowing for an integrated analysis of short- and long-term sustainability challenges in this sector. More generally, the aim was to develop an integrated framework for the evaluation of water policy interventions in water-stressed countries, using Jordan as an example. The systematic representation of important influence factors regarding the water sector improved the awareness for socially accepted and sustainable use of water among relevant authorities in Jordan.

4 | RESULTS: OBSERVED PATTERNS IN GOOD PRACTICE EXAMPLES

Reviewing the interviews, we evaluated the good practice modelling studies along the gradients explained in Section 2. The results are graphically represented in Figure 1. As the positions on these gradients are not necessarily stable over the course of a project, we marked the dominant position.

By definition, all of the selected examples had some kind of impact with policy-making or management. However, the type of **practical application** differs, ranging from models as tools for discussion (JWP) or a systematic representation of alternatives (Ecopay) to direct influence on the decision-making of legislative or management authorities (ALUAM-AB, Atlantis-SE).

According to the answers obtained from our interviews, few factors are truly indispensable for models that have successfully been used for policy-making or management. **Exchange frequency**, **continued support** and **data availability** stand out as the factors with consistently high or high and medium ratings for all models. The majority of the aspects were mentioned as being important only in some cases and not in others. In the following, we discuss the observed patterns of all dimensions of the modelling endeavour separately to extract important factors and correlations.

In our sample, systems with a focus on environmental processes are in general less complex than systems explicitly involving a social component. These systems are also characterised by lower **model complexity**. In our good practices examples, model complexity always matches system complexity. We decided to keep both gradients in our framework because complexity mismatch may easily occur in other case studies. Similarly, the complexity of models with a social and an environmental component tends to require higher numbers of **persons involved** in the process. Due to the diverse aspects addressed, those people also have a broader range of **academic backgrounds**.

Many models were used for policy-making after modellers themselves had advocated them. Some processes were initiated on a joint proposal by decision-makers and modellers, but the case that the **demand** came solely from decision-makers was rare. In our case, only the development of FarmNet-BVD was initiated by policymakers. However, the source of original interest in the collaboration does not influence the effectiveness of the process: models initiated by modellers can also be successful in policy-making. Independently of who initiated the process, **decision-makers were involved** in model conceptualisation and development to varying degrees. Some of the projects under consideration were developed in a participatory way with considerable influence of decision-makers on the model implementation (FYFAM, Atlantis-SE and FarmNet-BVD), others were developed from an academic perspective and later applied to concrete policy-making settings (BEEHAVE, JWP). Project partners were not necessarily **familiar** with one another beforehand. Similarly, not all decision-makers were **experienced with modelling** in advance.

Our interviews suggest the **exchange frequency** as the most critical aspect during the whole process. Meeting on a regular basis to discuss model results and project development ensures a stable ground for project impact. For all our examples, it was furthermore guaranteed that the model developers **continued the support** at the end of the project duration such that some of the models could be adapted to new situations with similar research questions (Ecopay, FarmNet-BVD). Besides reusing the same model in follow-up projects, continuing the application of models in policy-making can also be facilitated when decision-makers can apply the models to specific questions, potentially also different to the original one, independent of the modellers. Only two models in our sample (FYFAM, BEEHAVE) are designed in a way that policymakers can use them completely on their own. In other models, policymakers design new scenarios or evaluation options in direct collaboration with modellers (Ecopay, ALUAM-AB, JWP). One factor that simplifies the **ease of use of models** by non-modellers is the creation of an intuitively designed graphical interface. Furthermore, training provided by modellers can encourage decision-makers to work with the models on their own. Here, the application of a programming language with low complexity (e.g. NetLogo) might be beneficial.

Another key aspect across all selected studies which allowed them to be good practice examples is the **availability and**

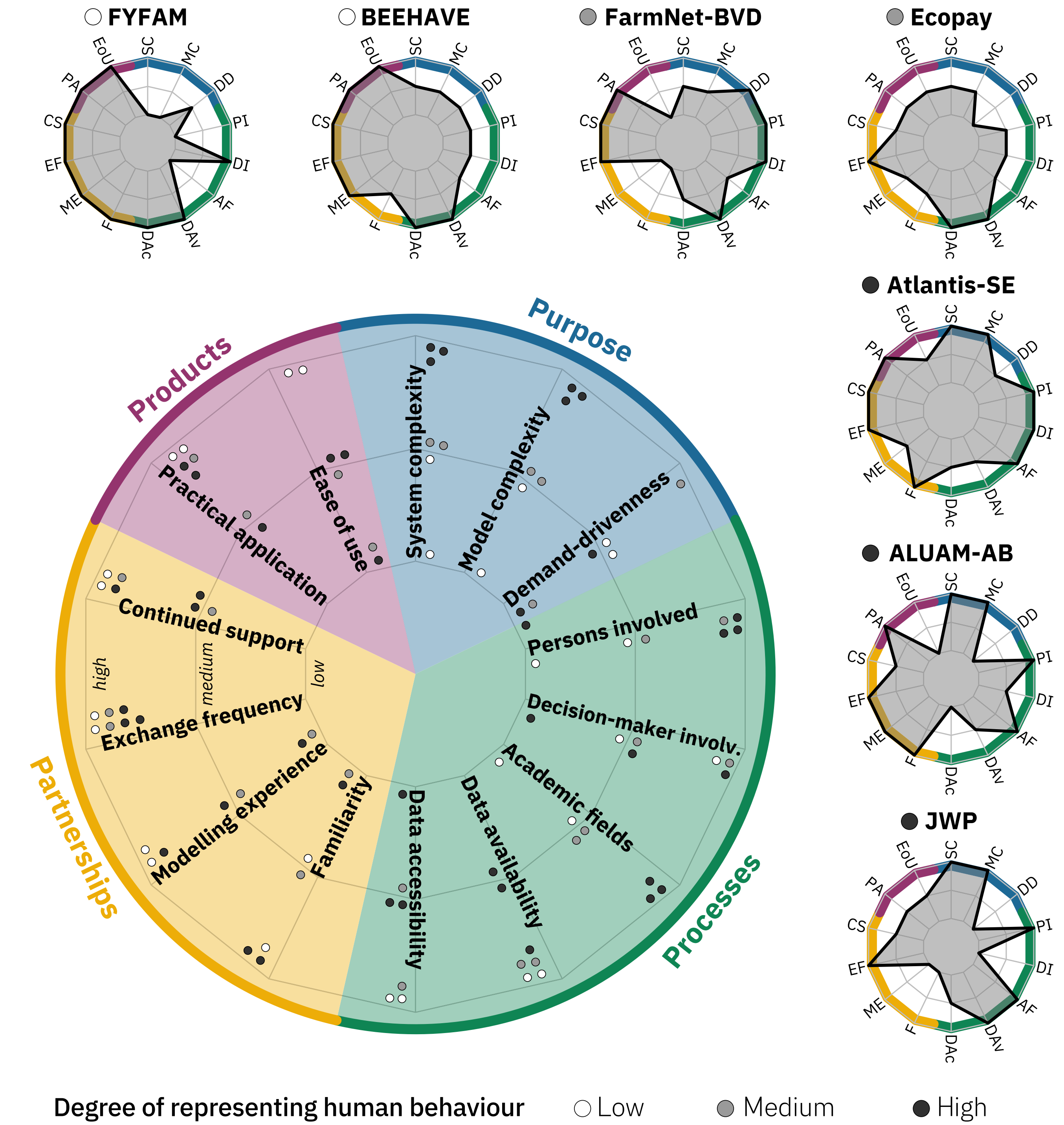

FIGURE 1 Classification of the good practice examples along the 14 gradients. The large panel shows the number of studies classified as low, medium or high for each gradient. The outer radar charts show the classification of the individual models. Abbreviations correspond to the gradient named at the respective circular position on the large panel. The outer charts are arranged according to their degree of explicitly representing human behaviour as part of the model, ranging from purely environmental to socio-environmental models. For better visualisation in the larger panel, we divided this continuous gradient in three distinct groups with similar degree of human behaviour and use different colours in the large panel to represent the classification of the models with low (white), medium (grey) and high (black) level of human behaviour

accessibility of data. Calibrating and validating models to existing data at the required resolution is essential to make policy or management decisions drawn from the models as precise and reliable as possible. Although all interview partners confirmed that their models had excellent or appropriate data available, two also mentioned that data accessibility can be an issue, for example, due to European data sharing regulations (FarmNet-BVD, ALUAM-AB).

5 | DISCUSSION: SPECIFIC RECOMMENDATIONS FOR SES MODELLING

From the seven interviews and our general experience in the field, which also includes modelling endeavours that were not seen as having achieved an impact in the sense used here, we conclude that there are four key factors for 'successful' models. These factors refer to what was mentioned as important by all our interviewees (data availability, exchange frequency and continued support) but also go beyond that. Once more structured around the 'Four Ps' framework, we discuss the importance of modelling the human dimension (purpose); data availability and accessibility (processes); collaboration, trust and acceptance (partnerships); and decision processes (products). We give recommendations for each of these factors on how to overcome difficulties that arise when modelling for policy and management support. Some parts of the discussion are transferable to other domains, but as most of the aspects are more difficult to address for socio-environmental models compared to models with a focus on environmental processes, the four key factors may explain why models have found comparatively little use in policy or management advice in this field in particular.

5.1 | Purpose: Human dimension

The **human dimension**, the 'socio-' in socio-environmental systems, adds levels of complexity as humans, more vehemently than other species, continually innovate and adapt their practices while negotiating their interests. This sometimes leads to what has been called 'wicked problems' (Churchman, 1967; Davis et al., 2018)—problems that involve a host of stakeholders with conflicting interests, and for which no simple or optimal solutions exist. Such a situation occurred, for example, when discussing effects of strategies to prevent new infections during the coronavirus pandemic (Squazzoni et al., 2020). Here, models can be particularly useful in providing a forum for discussion by revealing the interests and assumptions of the different parties involved, creating a space to take new perspectives and, thus, have the potential to stimulate a change in lines of thinking. With respect to our good practice examples, such an approach was employed in the JWP example that aimed at a long-term sustainability perspective—a view the involved ministry had not taken before. However, as structures and dynamics that involve humans are difficult to formalise in model terms (Schlüter et al., 2017), their inclusion in a model may drastically increase the complexity of model dynamics as well as the uncertainty around model results (Squazzoni et al., 2014).

Recommendations: We encourage the use of models as discussion tools to bring different perspectives of stakeholders together—a process that is also referred to as social learning (Edmonds et al., 2019; Schlüter et al., 2019). Furthermore, we recommend that modellers and decision-makers acknowledge that the understanding of complex socio-environmental systems depends to a large extent on a sound representation of human decision-making. The need for rapid answers must therefore not lead to models being overly simplified (Squazzoni et al., 2020). The trade-off between the expectation of quick responses and precise projections of the future, which can only be achieved by a detailed implementation of human behaviour, should rather be resolved by clearly communicating the purpose of a model (Grimm et al., 2020).

5.2 | Processes: Data availability and accessibility

The seemingly obvious assumption that it is generally more difficult to obtain reliable **data** on socio-environmental problems compared to purely environmental ones, once again due to the complexity added by the human factor, was not fully confirmed by our good practice examples. In the cases of JWP and Atlantis-SE, socio-environmental data were relatively abundant and accessible. In contrast, accessing existing databases was an issue in two of our examples, as mentioned above. Since these difficulties arose in both the socio-economic and the ecological context, this factor appears to be context-specific rather than systematic. In the case of the BEEHAVE model, the interview partner indicated that industry partners had easier access to data; however, most of these data were subject to company confidentiality regulations and would therefore not be available for other projects to use.

Recommendations: As we have observed for our good practice examples that data availability was a key aspect for impactful models, we highly encourage coordinated and harmonised data collection not only of ecological but also of socio-economic data. Examples for this are endeavours such as Long-Term Socio-Ecological Research (LTSER) platforms, where socio-ecological data collection is organised across the world (Dick et al., 2018). These systematic efforts come along with transparent rules for data accessibility which are crucial for impactful modelling projects.

5.3 | Partnerships: Collaboration, trust and acceptance

With exchange frequency and continued support, two aspects of the partnership between modellers and decision-makers stood out as being important in all our case studies. This suggests that the **collaborative process** is critical to an impactful modelling endeavour. Strong exchange can help to prevent false expectations of decision-makers concerning the power of models (Kolkman et al., 2016). In the Ecopay project, there were diverging expectations between scientists on the one hand (long-term project, transferable models) and decision-makers on the other (concrete measures). Providing enough time to understand the perspectives of other disciplines and to find a common language was seen as crucial. In the JWP project, for example, a series of four 2-week workshops was organised to foster understanding of the model. However, a large heterogeneity in the group of stakeholders and disciplines involved made it difficult to find the appropriate speed for workshop discussions. Continuous communication ensures the understanding of decision-makers concerning limitations and uncertainty of models and prevents turning models into black boxes (Gilbert et al., 2018). Due to a broader range of backgrounds of people involved in the process, all these factors seem to be more pronounced in socio-environmental than in purely environmental contexts (see Kline et al., 2017 for their experience in a project investigating forest wildfires, Squazzoni et al., 2020 for the importance of interdisciplinary research on the coronavirus pandemic).

When the involved parties are not familiar with one another in advance, project partners need to be aware that creating **trust** between collaborators needs time, which has to be included in planning the process (see also Briggs (2006) for the difficulties of integrating science and policy on natural resources in general). The establishment of mutual reliance in the project team was often, but not always, related to a specific 'eye-opener' or breakthrough moment which advanced the shared understanding of different stakeholder groups, led to bonding between them, and created strong confidence in the project's usefulness. In our case studies, methods that induced breakthrough moments included the use of graphical representations, games and simulation runs based on past conditions showing that the model was able to represent the recent past correctly (Atlantis-SE). During workshops in the FarmNet-BVD project, it proved helpful to explore contradictions in the assumptions of decision-makers to open up the debate about alternatives. Conventional methods of trust-building are equally important in successful projects; these can consist in benchmarking with existing models, or having an independent peer review of project-related documents and models (Atlantis-SE, BEEHAVE). In the case of BEEHAVE, such a peer review of the formerly used model of the EFSA (European Food Safety Authority) and the BEEHAVE model assured the quality of the model and finally led to the replacement of the original model with BEEHAVE. The establishment of such instances of quality control may also foster the acceptance of models in policy-making and management support. These can range from simple model code review (e.g. as offered by CoMSES Net) to the examination of complete modelling assessments (e.g. as done by the Regulatory Scrutiny Board of the European Commission).

It is not essential that decision-makers are experienced with modelling in advance. However, openness for such an approach and knowledge of similar methods such as statistical models simplifies communication and collaboration. In general, standard economic models appear to be more broadly **accepted** in policy and management support than SES models, which is partly a matter of traditions that have been established for longer, but also of many policymakers having a background in economics rather than the interdisciplinary training that is often helpful for SES analysis. We generally observe that the acceptance and use of SES modelling has actually been steadily spreading, from research to industry and on to public authorities—but it takes time. Mixed institutions that involve industry, researchers and policymakers might facilitate this process.

Recommendations: First, with respect to collaboration, we highly encourage all parties involved to make their expectations explicit at the beginning, especially concerning the outcomes of the policy-making process. To achieve successful exchange, we furthermore underline that finding a common language is crucial to combine expertise from a wide range of disciplines.

Second, to foster the understanding of models and facilitate trust in them, we encourage modellers to promote the emergence of 'eye-opener' moments using various tools of visualisation. Additionally, modellers can contribute to confidence in model results through benchmarking, independent peer review or by including quality control in the project structure (Houweling et al., 2015). Transparent handling of model code through open-source development and sharing of models on public repositories (GitHub, CoMSES Net, etc.) helps to foster this.

Third, as in the quote famously attributed to Henry Ford that states that if one had asked people what they wanted, they would have said faster horses but not cars, decision-makers may simply not be aware of the benefits and feasibility of state-of-the-art modelling approaches. To reach acceptance of models, modellers should therefore disseminate information to decision-makers, promote exchange between modellers and decision-makers, be ready to teach modelling skills, and engage in the organisation of workshops that attract both sides. Large institutions and authorities can contribute to this exchange by employing modelling experts for consulting, evaluation and assistance.

5.4 | Products: Decision process

Research objects in SES models tend to be more contested than those mapped by purely environmental models since they touch the interests of a broader set of stakeholders who may have diverging opinions. In contrast, resource management decisions such as in the FYFAM model—frogs versus salmon—are often less politically debated. Favouring one species over the other cannot easily be characterised as 'progressive' or 'conservative' political positions, for instance. Gotts et al. (2019) accordingly speak of SES as 'contested systems'. Furthermore, a chain of institutions with diverging time horizons are involved in the policy cycle. To ensure that an SES model can have true impact, it is hence important (and at the same time challenging) to include those decision-makers who actually have the power and legitimacy to implement model findings. In the FarmNet-BVD model, for example, having both the ministry and farmers on board facilitated the uptake of model outcomes in new legislation in Ireland as the two implementing forces were able to discuss details during the model development phase. In ALUAM-AB, one of the key researchers later on became an influential person in the policy sector. On the other hand, for Atlantis-SE, it was reported that the absence of a competent 'policy champion' that modellers could turn to slowed down the policy-making process.

In general, only if model assumptions and rules are well-grounded and fitting to purpose and context, their outcomes will be able to support wise policy-making and management and should be included in the decision-making process. This can be especially harmful when models are not properly adapted to a context different to the one they were originally developed for (Squazzoni et al., 2020) or when they are still widely used in consultancy but not updated to standard practices (Railsback, 2016). One of the rare documented examples of negative impact of models can be found in the context of the 2001 outbreak of foot-and-mouth disease in the United Kingdom where misguided interpretation of mathematical model results led to the slaughtering of a large number of animals, which was later considered to have been unnecessary (Kitching et al., 2006). The modelling endeavour may, moreover, be captured by decision-makers to one-sidedly support their previously held convictions and shut down rather than open up discussions of policy or management alternatives (Squazzoni et al., 2020). Modellers thereby inevitably have to take on the role of translators for the model results, as only this allows a sound understanding by decision-makers which needs to be the basis to use the model in any decision process (Gilbert et al., 2018). Explicitly communicating assumptions in the model conceptualisation and uncertainties in the model output is particularly important for an effective incorporation of the results in the decision-making process (Brugnach et al., 2007; Davis et al., 2018; Gregr & Chan, 2015). But even if the cooperation process is carefully framed, modellers need to be aware that policy advice is simply not always desired (Squazzoni et al., 2020) as for some problems there is only a small 'window of opportunity' (Kingdon, 1984) where policymakers are open to tackle a problem and need advice that could then be provided by models.

Recommendations: We underline that model users (including from the decision-makers' side) should have a profound understanding of the model and only apply it in cases where model assumptions are suitable. In the end, the consequences of decisions may reach well beyond the original scope of any single research question and model. In this regard, due to higher complexity, modellers are even more obliged to apply good modelling practices (Schmolke et al., 2010; Schulze et al., 2017) to SES models. Furthermore, policymakers are highly encouraged to provide a 'policy champion' or 'knowledge broker' as interface person to modellers. Ideally, this should be someone open to modelling approaches and at an influential position in the decision-making process who is able to mediate between both parties.

6 | CONCLUSION

By evaluating seven good practice examples, we show that leverage points for increasing the impact of socio-environmental models in policy-making or management are manifold. While our paper focuses on the transfer of knowledge generated by models to the actual decision-making process and therefore mainly refers to the community of modellers and to decision-makers, many of the aspects we highlight, especially those referring to model development, will also apply to situations where a broader range of stakeholders is involved, such as during participatory modelling (Castella et al., 2014; Reid et al., 2016).

We conclude that the main reason currently inhibiting a wider use of socio-environmental models in policy-making or management is their higher complexity compared to purely environmental models that arises from explicitly incorporating the human dimension. Adding levels of behaviour results in more difficult models. These additional aspects also impede simple solutions for policy-making and management. This is reinforced by the fact that addressing both the social and the environmental dimension adequately in models requires involvement of people from different backgrounds. Their potentially contested positions make consensus building and thus decision-making for policies more challenging. In contrast to other problems, where decision-makers rely on the judgement of experts to assess the importance of influencing factors that should be integrated into models, human behaviour is more tangible for many of the actors involved so that more concrete expectations are placed on the representation of processes in models. This can easily threaten the acceptance of models when not all of the desired factors can be addressed. Furthermore, data accessibility, a crucial aspect of impactful modelling projects, is more difficult due to privacy issues.

All these factors pinpoint the importance of using models for SES problems on the one hand to provide a common ground for exchange and on the other hand to allow disentangling cause and effect of human and environmental processes. The same factors, however, urge to respect fundamental aspects of science–practice interactions, such as clear communication of expectations and results or building trust. Even though any model can depict only a part of reality, this issue is, more than in other disciplines, pertinent to the inclusion of human behaviour, as some patterns will never be reproducible in model rules due to the inherent complexity of decision-making. Nevertheless, modellers and decision-makers should continue to embark on common projects and learn from successful examples to increasingly unfold the full potential that socio-environmental modelling bears. We have synthesised recommendations for dealing with common difficulties that may arise during the process of modelling for policy or management support, which are addressed to modellers, decision-makers or both. If all parties involved in the modelling and decision-making process take into account our suggestions during their collaboration, socio-environmental modelling will hopefully no longer be largely limited to contributions to the scientific debate, but will be able to be effectively integrated into supporting decisions for policy-making and management.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

M.W., G.D., D.K. and B.M. conceived the ideas and designed the interview questionnaire; M.W., G.D. and B.M. conducted the interviews; H.-H.T. and A.G.-R. were part of the interviewed group of experts; M.W., G.D., D.K. and B.M. analysed the interviews; G.D. created the figure; M.W. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

No data were generated during the course of this study, aside from that presented herein.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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