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# Behavioural diversity in fishing—Towards a next generation of fishery models

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## Abstract

Despite improved knowledge and stricter regulations, numerous fish stocks remain overharvested. Previous research has shown that fisheries management may fail when the models and assessments used to inform management are based on unrealistic assumptions regarding fishers' decision-making and responses to policies. Improving the understanding of fisher behaviour requires addressing its diversity and complexity through the integration of social science knowledge into modelling. In our paper, we review and synthesize state-of-the-art research on both social science's understanding of fisher behaviour and the representation of fisher decision-making in scientific models. We then develop and experiment with an agent-based social–ecological fisheries model that formalizes three different fishing styles. Thereby we reflect on the implications of our incorporation of behavioural diversity and contrast it with the predominant assumption in fishery models: fishing practices being driven by rational profit maximizing. We envision a next generation of fisheries models and management that account for social scientific knowledge on individual and collective human behaviours. Through our agent-based model, we demonstrate how such an integration is possible and propose a scientific approach for reducing uncertainty based on human behavioural diversity in fisheries. This study serves to lay the foundations for a next generation of social–ecological fishery models that account for human behavioural diversity and social and ecological complexity that are relevant for a realistic assessment and management of fishery sustainability problems.

**KEYWORDS**
agent-based modelling, decision-making, fisher behaviour, fishing styles, literature review, social–ecological systems

## 1 | INTRODUCTION

Decades of fisheries research and management have significantly advanced the understanding and management of fisheries by, for example, focusing on the temporal and spatial dynamics of fish stocks (Botsford et al., 2008; May, Beddington, Clark, Holt, & Laws, 1979; Pikitch et al., 2004), the complexity of food webs and ecological systems (McLeod & Leslie, 2009) and the role of regulations

and economic incentives in shaping fishing practices (van Putten, Gorton, Fulton, & Thébaud, 2012). However, numerous fish stocks worldwide remain overharvested despite these advances in fisheries science and management. One important reason for the lack of progress is that fisheries management typically relies on models of human behaviour and assessments that are unable to account for social dynamics, and in particular for the diversity and adaptability of fisher behaviour (van Putten, Kulmala, et al., 2012; Wilen, Smith, Lockwood, & Botsford, 2002). Recent literature stresses how this omission is problematic: the limited understanding of the diversity of fisher behaviour may limit management interventions anticipation of fishers' response to regulation (Fulton, Smith, Smith, & van Putten, 2011; van Putten, Kulmala, et al., 2012; Salas & Gaertner, 2004). For instance, behavioural responses have been shown to play an important role in the success or failure of marine protected areas (MPAs). MPAs have swiftly become a widely used management tool based on their potential benefits to both people and planet (Chaigneau & Brown, 2016; Edgar et al., 2014). However, MPAs often fail to achieve their objectives: In the North Pacific Trawl fishery, for instance, fishers' adaptive responses to MPAs have caused a dramatic increase of prohibited bycatches of one species (Pacific Halibut (*Hippoglossus stenolepis*, Pleuronectidae) while protecting another (Red King Crab (*Paralithodes camtschaticus*, Lithodidae) (Abbott & Haynie, 2012). Furthermore, compliance with MPAs may be affected by perceptions of inequality or lack of fairness in the distribution of MPA benefits, which has led to poaching fish despite their generally positive attitudes towards the MPA and even despite receiving benefits from it (Chaigneau & Brown, 2016).

There are several reasons for why human behaviour is not represented more adequately in conventional fisheries science and management. Firstly, knowledge about human behaviour in general, and fisher behaviour in particular, is primarily held within the social (fishery) sciences and, with the exception of fisheries economics, is less visible in the fisheries literature which is dominated by natural science contributions. This lack of visibility means that many fisheries scientists, decision-makers and regulators remain unfamiliar with the contributions that social science knowledge, theories and methods can make in fisheries science and management (Heck, Stedman, & Gaden, 2015). Secondly, fisheries management is often supported by, and dependent upon, formal modelling (Hall-Arber, Pomeroy, & Conway, 2009). Such models rarely include fisher activity dynamics beyond economic considerations (van Putten, Kulmala, et al., 2012). Yet, scholars of fishery models advocate the inclusion of social science insights (Fenichel, Abbott, & Huang, 2012; Fulton et al., 2011; Girardin et al., 2017; van Putten, Kulmala, et al., 2012; Weber, Borit, & Aschan, 2019).

We answer these calls by highlighting key insights about fisher behaviour from the social sciences and by demonstrating how such insights can be modelled to support the understanding of the impact of behavioural diversity on fishery outcomes. As part of this effort, and to structure our study, we seek answers to four questions:

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1. Which social science insights are relevant for understanding fishers' behavioural diversity?
2. How are aspects of fishers' behavioural diversity represented in recent fishery models?
3. How can such insights be integrated in a fishery model? And what can we learn from the model regarding the implications of behavioural diversity for fishery sustainability and management?
4. What can we learn from this research for developing the next generation of fishery models?

This paper aims to contribute to the development and use of a new generation of fishery models that integrate social science insights to enhance our understanding of *why* and *how* fishers' behavioural diversity affects fishery sustainability and fishery management. Thus, we first review and synthesize insights from social

scientific fishery studies and evaluate whether and how recent fishery models incorporate insights on fishers' behavioural diversity (Section 2). Section 3 presents an approach for incorporating these insights into an agent-based model (ABM). The model exemplifies the formalization of human (fishers') behavioural diversity in the form of fishing styles, thus reflecting both small- and large-scale fisheries (Boonstra & Hentati-Sundberg, 2016). The ABM is then used to investigate the implication of fishers' behavioural diversity on fishery outcomes (stock, profit, satisfaction) and effectiveness of management interventions (Section 4). We conclude with a discussion of our findings' implications for the development of next-generation fishery models (Section 5).

## 2 | FISHER BEHAVIOUR IN FISHERIES SCIENCE

The point has been made often enough to almost become a platitude: human behaviour is a key uncertainty for fisheries management, because it receives too little attention in conventional fisheries science and management (Fulton et al., 2011; van Putten, Kulmala, et al., 2012). Several excellent reviews of fishery models representing both fisher or fleet behaviour and fish population dynamics have recently proved this point (Fenichel et al., 2012; Girardin et al., 2017; Hamon, Frusher, Little, Thébaud, & Punt, 2014; van Putten, Kulmala, et al., 2012). They stress the need for a more realistic inclusion of human behaviour and, in particular, the dynamics of resource users. Addressing this need crucially requires an overview of the available and relevant knowledge on human behaviour and its potential for illuminating fishery models.

In this section, we first outline key knowledge on fisher behaviour from social scientific studies as a first step towards a more realistic representation of human behaviour in fisheries modelling and management. Rather than attempting a futile exhaustive overview of all social sciences and humanities, we concentrate on literature that engages with fisher behaviour directly or provides central insight. Subsequently, we review a representative set of recent fishery models (Section 2.2) to evaluate how they consider knowledge on fisher behaviour.

### 2.1 | Understanding fisher behaviour: Contributions from social sciences

Several social science traditions highlight the importance of the *diversity and variability of fisher behaviour* (Boonstra & Hentati-Sundberg, 2016; Gustavsson, Riley, Morrissey, & Plater, 2017; Urquhart, Acott, Reed, & Courtney, 2011). With a focus on a classic distinction Boonstra, Björkvik, Haider, and Masterson (2016) between motivations (desires, aspirations, values, etc.), abilities (agency, power, perceptions, etc.) and context (interactions, institutions, social structures, social and natural environments, etc.), we present contributions from the social science literature on fishers'

behavioural diversity through a discussion of motivations, abilities, livelihoods and social interactions.

#### Motivations

In fisheries science, and especially for bioeconomic models, scholars commonly assume that fishers weigh relative costs and benefits to realize their greatest personal (economic) gain (for the theoretic statement see Becker (1986) and Clark (2006b); for applications to fisheries see Sutinen and Anderson (1985); Anderson and Lee (1986)). The central and single motive identified is thus the desire to maximize gratification and to avoid punishment. While these assumptions can be readily applied in fisheries models and may predict outcomes, they poorly represent the empirical complexity, in particular the variety of fishers' motivations leading to the decision whether to go fishing or not.

Sociological and anthropological studies of fishers' behaviour, in contrast, typically assume motivational differences. They show that fisher(s)' practices and responses do *not only* derive from a desire to (deliberately and rationally) realize their greatest personal (economic) gain, but also from a desire to conform to social norms, to uphold morality and identity, to experience esteem (or avoid shame) and solidarity and, by doing so, to maintain fishing not only as a business but also as a way of life (Hall-Arber et al., 2009). This extended spectrum of fishers' motivations implies that a singular focus on (economic) interests and deliberate decision-making is insufficient. Desires or emotions motivate behaviour through habits, intuitions and impulses that often precede or even preclude deliberate (economic) reasoning (Bourdieu, 1990; Camic, 1986; Haidt, 2001).

The importance of considering more than this single (economic) motivation can be illustrated by the question of why fishers often continue to fish despite considerable social and ecological setbacks (e.g. Daw et al., 2012). From a purely economically reasoning perspective, this outcome would be difficult to explain. Sociological or anthropological explanations often refer to fishers' desire to maintain an occupational identity and culture, meaning that for many fishers, fishing is not merely a job but rather a lifestyle through which they self-identify (van Ginkel, 2005; Gustavsson et al., 2017; Pollnac & Poggie, 2008). Continuing to fish under adverse conditions can thus be explained as an effort to uphold a preferred self-image.

#### Abilities

Behavioural diversity can also be rooted in fishers' differentiated abilities, that is their various degrees of access to and control over economic, cultural and social capital. Social scientific studies have, for example, analysed differences in fishers' (ecological) knowledge and skills (Pálsson & Durrenberger, 1990), that is their repertoire of experiential and tacit knowledge and skills that fishers embody and which is (re)produced through their working in specific environmental and social contexts. Social scientific research conducted on this topic (see Hind (2015) for a comprehensive overview) assumes that fishers whose livelihoods directly depend on local ecosystems develop a rich and nuanced understanding of these (Johannes, Freeman, & Hamilton, 2000). Further studies document how different fishing practices and styles (re)produce various types of knowledge (e.g. Lauer & Aswani, 2018).

Moreover, studies point out how knowledge and skills—such as observing tides and weather patterns, maintaining safety at sea, finding fish, equipment handling, but also respecting other fishers, upholding norms and values related to catching fish—serve as cultural and social capital that fishers use for maintaining and developing their businesses and livelihoods (see e.g. Gustavsson et al., 2017).

### Livelihoods

Social scientific studies of fishers stress that fishing practices need to be understood in relation to fishers' livelihood diversification (Blythe, Murray, & Flaherty, 2014; Byron, 1986; Coulthard & Britton, 2015; Salmi, 2005). Fishers' livelihoods are often sustained not only through fishing but involve a portfolio of income-generating activities such as farming, trading or industrial work, or they are supported through social welfare payments or subsidies. Further, these diverse activities are not only performed by fishers but in collaboration with their family members. Reflecting such a variety constituting fisher' livelihoods in research is important because the extent of non-fishing income-generating activities influences fishing effort. On the one hand, non-fishing activities limit fishers' time available for fishing. On the other hand, revenue from non-fishing activities can be invested in developing the fishing enterprise. Alternative income sources can assist fishers in coping with periods of low fish stock levels or when fishing opportunities are limited due to, for example, policy changes.

### Social interactions

Another recurring theme in the social scientific literature on fisheries is the various ways in which fishers socially connect with one another. They, for example, simultaneously compete and collaborate (Basurto, Blanco, Nenadovic, & Vollan, 2016; van Ginkel, 2005; Löfgren, 1972; Pollnac & Poggie, 1991). This means that, on the one hand, fishers are understood as individualists trying to gain and protect (knowledge of) lucrative fishing locations (Byron, 1986). On the other hand, they are also portrayed as members of close-knit family and friendship communities in which they collaborate and share knowledge and resources (Acheson, 1981). Some scholars view the performance of these different social roles as paradoxical (McGoodwin, 1991), while others point out that they do not necessarily contradict: fishers can be collaborators within the social groups they identify with *and* be competitive towards outsiders (Acheson, 1981; Pálsson, 1994). Moreover, the literature indicates that such social dynamics can change over time. Management arrangements, for example individual transferable quota, have changed the competition between fishers from a race for fish to a race for capital and quota (Acheson, Apollonio, & Wilson, 2015) which brings us to the final aspect of social interactions. Different regimes of fisheries governance (such as state-led, market-oriented or community-based arrangements) impact fisher behaviour (Acheson, 2006; McEvoy, 1986; Ostrom, 1990). A major concern for social scientists studying marine governance is to understand how such institutions shape dependency and power relations between fishers, communities, markets, governments and marine environments (Boonstra & Österblom, 2014).

In the subsequent section, we consider the extent to which these aspects of fishers' behavioural diversity—variety of motivations; abilities; livelihoods; and social interactions—have been incorporated into fisheries models.

## 2.2 | Diversity of fisher behaviour in fishery models

To assess the inclusion of aspects of fishers' behavioural diversity in dynamic models of fisheries, we reviewed 29 recent fishery models that incorporate endogenous and dynamic fisher behaviour. The selected articles were derived from filtering 1,290 articles found in the "Scopus" database published after 1999, that is in the last 20 years. The search terms were as follows: 'fish*','natural resource', 'model'. The results were filtered to include dynamic, formal model papers that were not prescriptive, that is focusing on how fishing behaviour should be (see Appendix S1).

The review substantiates the claims that current fishery models pay too little attention to the diversity of human behaviour (Fulton et al., 2011; Hall-Arber et al., 2009), but also highlights progress in the models that do. We evaluate whether models reflect behavioural diversity, in particular a variety of motivations, abilities, livelihoods and social interactions; and if so, whether they are based on social (fishery) science insight. We selected only fishery models that explicitly considered social and ecological interactions, as well as their respective internal dynamics. Consequently, we excluded models that generate diverse behavioural outcomes without including behavioural diversity (e.g. Chakravorty & Nemoto, 2000; Metcalf, Moyle, & Gaughan, 2010), when behavioural diversity in models was produced through stochasticity in a deterministic model or when, for example, interactions with spatial and seasonal heterogeneities in the distribution of natural resources result in behavioural diversity (Gasche, Mahévas, & Marchal, 2013). Lastly, we did not restrict our selection of models in terms of their functional form (e.g. equations in bioeconomic models) or type of fishery (e.g. commercial fisheries). Within our selection, we identified two different categories of model foci.

The first category represents fishers' behaviour endogenously, that is fishers may adapt their behaviour when their own state or the state of the environment changes, and is concerned with *fishery outcomes* from fisher–fish stock interactions, that is studying the link between fishers' behaviour and its effect on the fish stock and vice versa, or with *the effect of management* on fishery outcomes. Fishing actors in these models represent individual fishers (e.g. Hunt, Arlinghaus, Lester, & Kushneriuk, 2011; Merino, Maynou, & García-Olivares, 2007), vessels, managers or company owners (e.g. Libre et al., 2015), or an aggregate dynamic fishing pressure or fleet. These models usually explore the relation between fishery outcomes and adaptive learning of fishers (Udumyan, Rouchier, & Ami, 2013); the role of social factors (e.g. performance and investment choices of others) and bounded rationality of fishers (Libre et al., 2015); the inclusion of profit maximizing fishers in a complex ecology (Wiedenmann, Wilen, Levin, Plummer, & Mangel, 2016); the

inclusion of fishers affected by both catch and non-catch related site characteristics on patterns of fishing effort and overfishing (Hunt et al., 2011); the inclusion of fishers able to switch strategies (Bischi, Lamantia, & Radi, 2013; Brede & de Vries, 2010); and the effect of fishers' ability to learn to refrain from competitive behaviour (e.g. trap cutting) and, that is, factors that facilitate emergent self-governance (Wilson, Yan, & Wilson, 2007).

Models in the second focus category investigate the *effect of management* on fishery outcomes by assessing different regulatory interventions, such as controls on catch (e.g. quotas (Gasche et al., 2013); gear-dependent quotas (Sigurðardóttir, Johansson, Margeirsson, & Viðarsson, 2014); timing to reassess or adjust quotas (e.g. van Dijk, Haijema, Hendrix, Groeneveld, & van Ierland, 2013) effort limitations (e.g. Schueller, Fayram, & Hansen, 2012); fishing bans (e.g. Soulié & Thébaud, 2006); controls on area (e.g. increase of area (Sanchirico & Wilen, 2001); closure of area (e.g. Collins, Pascoe, & Whitmarsh, 2003), seasonal closure (e.g. Metcalf et al., 2010); or the timing and duration of site closures (Gao & Hailu, 2012).

## 2.2.1 | Behavioural diversity represented in the reviewed models

We are interested in whether and how fishers' behavioural diversity is reflected in our selection of fishery models. A comparison (Table 1) shows that none of the reviewed models reflect all four aspects of behavioural diversity that we highlighted above (Section 2.1). Actors' decision-making is mostly reflected by assumptions underlying rational actor theory, that is, fishers acting as firms, maximizing their profit, such as expected utility theory or random utility theory, mainly referring to economic factors (see also van Putten, Kulmala, et al., 2012). For instance, the fishers/vessels/fleet in most models (21/29) has a single economic motive: maximizing/satisficing profit or catch. Consequently, other factors of influence are directly or indirectly economic, for example expected catch, costs of effort/travel, prices and regulations. While the behavioural focus differs slightly among models, there is little variety within the individual models. Regarding the behavioural diversity actors display, the models typically focus

on one type of behavioural choice, for example effort allocation. The selected models that do consider behavioural diversity are discussed in more detail below (see also Table 1).

Three models feature heterogeneity in *motivation*: Bastardie, Nielsen, and Miethe (2014) and Brede and de Vries (2010) vary fishers' motivations or aim in different scenarios. The scenarios have implications for the aim of fishing and the connected decisions for vessels. Bastardie et al. (2014) present a base model with random movement and fishing behaviour choices (resting, harbour or fishing ground choice). Their scenarios embed different ways to minimize fuel use, to minimize the distance to port and fishing grounds, to minimize travelling and how fishers are motivated to attain their goal. The authors demonstrate how incorporating individual (spatial) behaviour in their model leads to more realistic predictions of fisher behaviour, profits and stock size. Brede and de Vries (2010) model various scenarios with varying fishers' motivations, that is their orientation to individualistic versus community interests and to short-term versus long-time interests. Note that even though all fishers in this model maximize their interests, the object of maximization varies from optimization of own catch, team catch to community catch. Brede and de Vries (2010) demonstrate that a community-oriented long-time horizon harvesting behaviour is useful because it leads to a relief in pressure on the resource, but also to smaller fluctuations in the fish stock, thereby reducing the risk of overharvesting. They also find that an overharvested resource situation favours short-term and individualistic behaviour.

Heterogeneity in *abilities* is the most common way behavioural diversity was addressed in the models reviewed. Ability reflects fisher characteristics that, for example, include how well a fisher can find or catch fish and/or is knowledgeable of when and where to fish. Heterogeneity is further commonly represented by making differentiations between fishers or vessels in terms of, for example, business strategy, ability to catch fish and the cost of fishing (Merino et al., 2007); their effect on catch, $CO_2$ impact, economic performance and job availability (Sigurðardóttir et al., 2014); or the minimum functioning crew size, maximum trip duration and speed (Pelletier et al., 2009). These models generally study the consequences of integrating heterogeneity in, for example, strategy or gear to account for behavioural response to policy. In sum, these

**TABLE 1** Models representing fishers' behavioural diversity (8/29)

| Publications | Behavioural diversity through variation of... | | | |
| --- | --- | --- | --- | --- |
| | Motivation | Ability | Livelihood | Social interaction |
| Bastardie et al. (2014) | x | | | |
| Brede and de Vries (2010) | x | | | |
| Libre et al. (2015) | x | | | |
| Manning et al. (2018) | | | x | |
| Merino et al. (2007) | | x | | |
| Pelletier et al. (2009) | | x | | |
| Sigurðardóttir et al. (2014) | | x | | |
| Wilson et al. (2007) | | | | x |

models acknowledge the importance of including empirical fisheries data and thus move beyond the standard bioeconomic models.

Only one model included variation in *livelihoods*, and only one model embedded *social interaction.* Manning, Taylor, and Wilen (2018) present a computation model in which a fishery is placed in a wider economy which facilitates multiple livelihoods other than fishing. It is a "tragedy of the commons"-model using general equilibrium modelling to explore the effect of capital restrictions in a small-scale fishery. The model highlights short-term and long-term trade-offs in resource management and demonstrates the potentially negative effects of policy interventions on labour and earnings. Wilson et al. (2007) model how social interactions influence the (development of) decision-making and behaviour of fishers. The fisher agents use information from (among others) communication with or observation of other fishers and the biophysical environment for evaluating several decision rules. The decision rules strengthen or weaken, depending on outcome performance. The model thus reflects the interplay between fleet behaviour and efficiency, and individual behaviour driven by self-interested actions.

Our review of the social scientific knowledge of fishers' behavioural diversity and of the reflection of this knowledge in contemporary fishery modelling reveals that only few models incorporate endogenous and dynamic fisher behaviour (29/1,290 or 2.2%). Of these, only 8 models (8/1,290 or 0.6%) address any aspect of *motivations*, *abilities*, *livelihoods* and *social interactions*. Moreover, none of these 8 models address all four dimensions of fishers' behavioural diversity. In the subsequent sections, we document our own efforts to construct a model accounting for the full spectrum of fishers' behavioural diversity, that is, integrate all four diversity dimensions.

## 3 | MODELLING FISHERS' BEHAVIOURAL DIVERSITY

We developed an ABM to represent the four dimensions of fishers' behavioural diversity we identified from the social science literature and to demonstrate the implications of including this diversity in fishery models for model outcomes.

Our FIsher BEhaviour model (FIBE) explicitly represents fishers' behavioural diversity as empirically observed in the (Swedish) Baltic Sea fishery, following the portrayal of fishing styles in Boonstra and Hentati-Sundberg (2016). The fishing styles are empirically grounded categories that distinguish behaviours based on fishers' practices *and* motivations (Boonstra & Hentati-Sundberg, 2016).

The fishing styles description reflects how fishers may differ in their motivation (e.g. fishing as a way of life vs. making a profit), abilities (what they know, can do and prefer, resulting in different scales/ intensity of operation—e.g. low cost, low gains vs. high cost, high gains), livelihoods (e.g. variety fisher income sources or cost reduction abilities) and social interactions (e.g. differences in how they are connected). FIBE is the first model that builds on the fishing styles and integrates the four major dimensions of fishers' behavioural diversity. The fishing styles are ideal–typical categorizations of

fishers and fishing practices. They derive from empirical evidence but have been abstracted into a typology using sociological theory. These fisher behaviour typologies enrich the understanding of and provide critical input for fisheries management (O'Farrell, Chollett, Sanchirico, & Perruso, 2019). Our model builds on this typology to incorporate fishers' behavioural diversity in a stylized way. This approach is advantageous since it produces a model simple enough for scrutinizing the causes and consequences of behavioural diversity, yet complex enough to capture important real-world aspects of this diversity (Schlüter et al., 2019). The stylized model is thus sensitive to conditions in particular contexts, but it is not specific to a particular context.

The purpose of the model is then to: (a) demonstrate a formalization of fishers' behavioural diversity based on social science insights (Section 3.1); and to (b) demonstrate the insights obtainable through using the model as a virtual laboratory for exploring the implications of this diversity when seeking to achieve sustainable fisheries (Section 4).

## 3.1 | FIsher BEhaviour model

FIsher BEhaviour model is a non-deterministic, dynamic, spatial ABM of a single species fishery and includes a multitude of heterogeneous individual fishers with fishing as their main income source. The model simulates daily decisions of individual fishers on whether and where to fish. We study the effect of their diverse fishing practices on fish stock levels, fishers' income and their level of satisfaction in pursuing their goal(s). FIBE is implemented in NetLogo 6.0.3 (Wilensky, 1999). For more model details, the model is available on COMSES (Wijermans, Schlüter, Orach, Boonstra, & Hentati-Sundberg, 2020) and described in Appendix S2, following the ODD+D protocol for documenting ABMs (Grimm et al., 2006, 2010; Müller et al., 2013), including calibration (B2 in Appendix S2) and validation (B3 in Appendix S2).

## 3.1.1 | Formalizing the biophysical environment

FIsher BEhaviour model includes the representation of a biophysical environment (the sea and the fish). The sea reflects a space with various fishing grounds that differ in their fish abundance and remoteness. It is represented as a grid (50 × 56), where each grid cell (patch) represents a fish stock. Patches are grouped into four regions which correspond to the fishing grounds of the Swedish Baltic Sea fishers from which the fishing styles typology was derived. The regions vary by distance from the home port of the fisher: region A is close to the coast; region B is further out; and regions C and D are far offshore. A patch can sustain more or less fish, reflecting spatial differences in carrying capacity. Patches with high carrying capacity are considered "hotspots." All fish populations have the same growth rate, and the fish do not move between patches. Fish population growth is represented by a standard discrete logistic growth model with

growth rate and carrying capacity (Clark, 2006a; Schaefer, 1954). Harvest levels are determined by the group of fishers.

## 3.1.2 | Formalizing fisher's behavioural diversity

The fishers in FIBE are represented by agents whose behavioural diversity is modelled according to the fishing styles. Each fisher agent reflects an individual with their own experience and interaction with the social and biophysical environment, while always being an instantiation of one of the three fishing styles: the archipelago, coastal or offshore trawler fishing styles (Table 2 details the characteristics of each fishing style).

For the representation of the fishing styles, this involved distilling and formalizing the key elements and processes of fishers' behavioural diversity (see Figure 1 and Table 2). Formalizing the fishing styles and designing the model were achieved iteratively through a series of meetings between the modellers and fishing style experts in the author team.

Based on this iterative, interactive process to formalize the fishing styles, we simplified the social and ecological context in which fishers work and elicited the key choices they make. The formal attributes of the fishers' context reflect in which region(s) the fishers typically fish; what information and knowledge they use to find fish; whether they use information of their other fishers' whereabouts; their ability to catch fish (determined by gear and skills); and their typical extent of costs/income. The specification of the choices made by the fishers reflects their behaviour, that is what drives the choices (goal or motivation); how a selection for a behaviour is made, for example maximizing versus satisficing in relation to motivation(s); and what are essential factors influencing a choice.
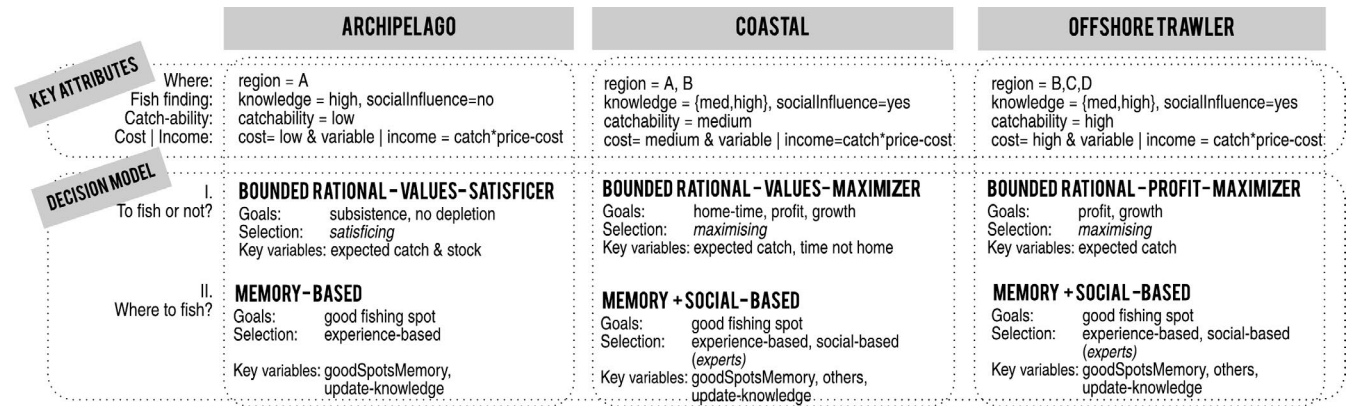
All fisher agents in the model face two main choices: (a) to fish or not to fish; and if they go, fishing (b) where to go fishing. To design these choices, a combination of empirical details and theoretical assumptions about human behaviour, preferences and choice was made, for example bounded rationality operationalized as limited memory. This is common practise as descriptive forms of knowledge are rarely specific enough for computational representation (Sawyer, 2004; Schlüter et al., 2017).

Figures 2 and 3 show the formalization of both choices for each fishing style in decision trees. For the first choice, "to fish or not to fish," the reasoning that motivates the choice differs between fishing styles:

1. A *trawler fisher* agent only goes fishing if it expects an economic return: the expected catch should at least cover the operating costs for the trawler fisher agent to decide to go out and fish. At sea, it bases its catch expectation on the fish it can perceive nearby (e.g. using sonar technology in the real-world).
2. A *coastal fisher* agent decides to go fishing when the trade-off between expected profit and time not spent at home is not too big: if a coastal fisher agent has satisfied its preference for staying at home and expects a profit, it will go out and fish. Coastal fisher agents stay at home when staying home preference is not satisfied or when they do not expect a profit.
3. An *archipelago fisher* agent goes out to fish when it needs to, that is when it has not caught enough in the previous week or if it has negative financial capital. In addition, if the archipelago fisher

**TABLE 2** Description of the three fishing styles that are modelled in FIsher BEhaviour model

| Fishing style | Description |
|---|---|
| Archipelago | General: Swedish Baltic archipelago fishing is a very particular and traditional style of fishing, requiring substantial investments in learning and in material resources<br>Practice: Fishers localize fish close to harbours with passive gear. Traditionally (50–80 years ago), they target a broad portfolio of freshwater and coastal species. Recently, this has become increasingly restricted due to management regulations and loss of infrastructure<br>Motivation: Fishers emphasize the importance of being able to catch multiple species and being self-reliant, that is avoid becoming too dependent on banks for investments |
| Coastal | General: This style represents the dominant type of fishery in the Baltic Sea. It forms an intermediate between the other two styles in terms of scale of operation and motivation<br>Practice: Fishers combine passive and active gear and fish in coastal areas. Atlantic herring (*Clupea harengus*, Clupeidae), Atlantic cod (*Gadus morhua*, Gadidae) and Atlantic salmon (*Salmo salar*, Salmonidae) are the dominant species targeted in this style. Of these three species, cod is currently the dominant target species since fishing herring with passive gears is not profitable and offshore salmon fishing is prohibited<br>Motivation: Similar to the archipelago style, but with a blend of entrepreneurial spirit (see description of offshore trawling style). Fishers also emphasize the importance of being able to catch multiple species and being self-reliant, that is avoid becoming too dependent on banks for investments |
| Offshore trawling | General: This fishing style represents specialized fishing using trawler ships (both pair and single trawls) with modern fish-finding and fish-processing technology<br>Practice: Fishers have mobile gear (trawling) used on large vessels (often larger than 20 m). The target species are Atlantic cod, sprat (*Sprattus sprattus*, Clupeidae) and Atlantic herring (*Clupea harengus*, Clupeidae)<br>Motivation: Fishers have a strong entrepreneurial spirit in fishing. They are competitive, seize opportunities, invest and are willing to take risk when there is a profit to be made |

| | ARCHIPELAGO | COASTAL | OFFSHORE TRAWLER |
|---|---|---|---|
| **KEY ATTRIBUTES** Where: Fish finding: Catch-ability: Cost \| Income: | region = A knowledge = high, socialInfluence=no catchability = low cost= low & variable \| income = catch*price-cost | region = A, B knowledge = {med,high}, socialInfluence=yes catchability = medium cost= medium & variable \| income=catch*price-cost | region = B,C,D knowledge = {med,high}, socialInfluence=yes catchability = high cost= high & variable \| income = catch*price-cost |
| **DECISION MODEL** I. To fish or not? | **BOUNDED RATIONAL – VALUES–SATISFICER** Goals:　subsistence, no depletion Selection:　*satisficing* Key variables: expected catch & stock | **BOUNDED RATIONAL – VALUES–MAXIMIZER** Goals:　home-time, profit, growth Selection:　*maximising* Key variables: expected catch, time not home | **BOUNDED RATIONAL – PROFIT–MAXIMIZER** Goals:　profit, growth Selection:　*maximising* Key variables: expected catch |
| II. Where to fish? | **MEMORY–BASED** Goals:　good fishing spot Selection:　experience-based Key variables: goodSpotsMemory, update-knowledge | **MEMORY + SOCIAL–BASED** Goals:　good fishing spot Selection:　experience-based, social-based (*experts*) Key variables: goodSpotsMemory, others, update-knowledge | **MEMORY + SOCIAL –BASED** Goals:　good fishing spot Selection:　experience-based, social-based (*experts*) Key variables: goodSpotsMemory, others, update-knowledge |

**FIGURE 1** Conceptual representation of the fishing styles with key attributes and decision models. Note that bounded rationality is formalized by agents not being able to anticipate the probabilities and consequences of their actions (for all styles)

thinks fish is scarce, it can decide against fishing and instead reduce living expenses.

While the trawler fisher agents' fishing activities are independent of the weather, both the archipelago and coastal fishers do not go out to fish when the (stochastically determined) weather is bad. We connected the reasoning underpinning each fishing style to the way the behaviour selection process works, that is *maximizing* OR *satisficing* to meet the goal(s) of the fisher agents. Maximizing gain is the rationale for the trawler fisher agents, a trade-off between maximizing gain and home time drives the coastal fisher agents, and satisficing gain and conserving the stock are the goals of the archipelago fisher agents.

The second choice—"where to fish?"—is influenced by the location within its reach at which a fisher agent expects the fish. Fisher agents use their memory of good spots to decide where to go. In addition, both *trawler* and *coastal* fisher agents use the other fishers' whereabouts to inform their target location choice. The functional representation of the fishing location choice is rule-based (heuristic): the fisher's decision will either be informed by its own past experience (memory of good spots) or by what others do (social influence).

# 4 | EXPLORING THE ROLE OF FISHERS' BEHAVIOURAL DIVERSITY

To illustrate the kinds of insights obtainable from a model that reflects fishers' behavioural diversity, this section highlights two kinds: firstly, system-level understanding—which is the more traditional use of models—to present emergent patterns of each fishing style at the system level (the sustainability of a fishery) and secondly, an understanding that stems from connecting system-level outcomes to the underlying mechanisms (how the actions and interactions of individual fishers bring about the system-level outcomes) to explain the emergence of system-level patterns.

Table 3 outlines the simulation experiments designed to explore (a) the effect of each fishing style (archipelago, coastal, offshore

trawler) on fishery outcomes and (b) the effect of a fuel subsidy on a fishery characterized by the three fishing styles. Each subexperiment includes only one of the three fishing styles. We have not (yet) combined all fishing styles within a single experiment in order to facilitate an analysis of the mechanisms that lead to the different outcomes in fisheries caused by a single fishing style.

We compare the outcomes of our simulation experiments to the theoretical benchmark of a regulated fishery in which the number of fishers is restricted through, for example, licences to a level where their aggregate harvest corresponds to maximum sustainable yield (MSY). MSY is a biological measure that indicates the stock size at which the reproductive rate of the population and hence the harvestable surplus is highest. It is a key indicator used in contemporary fishery management, despite some critique (e.g. Hilborn, 2004; Larkin, 1977). We call this benchmark "theoretical optimum management."

For the benchmark calculations, we use a single fish stock and assume that fishers follow an optimum fishing strategy, as commonly assumed in bioeconomic fishery models. We calculate the benchmark MSY profit as the total profit that can be made in this fishery assuming fishing style-specific costs. This benchmark serves to assess the relative differences in fishery outcomes among the different fishing styles. We assess three types of fishery outcomes: the fish stock size (ecological), the profit (economic) and fishers' goal satisfaction (social). The first two are assessed relative to the stock size and profit of the theoretical optimum management benchmark. Both the experimental design and benchmark are described in more detail in Appendix B4 in Appendix S2.

## 4.1 | System-level understanding

### 4.1.1 | Experiment 1: Effect of fisher behavioural diversity on fishery sustainability

This experiment demonstrates that the behavioural assumptions underpinning the different fishing styles have a strong effect on fish stock levels, profits and fisher satisfaction (Figure 4). The fishery
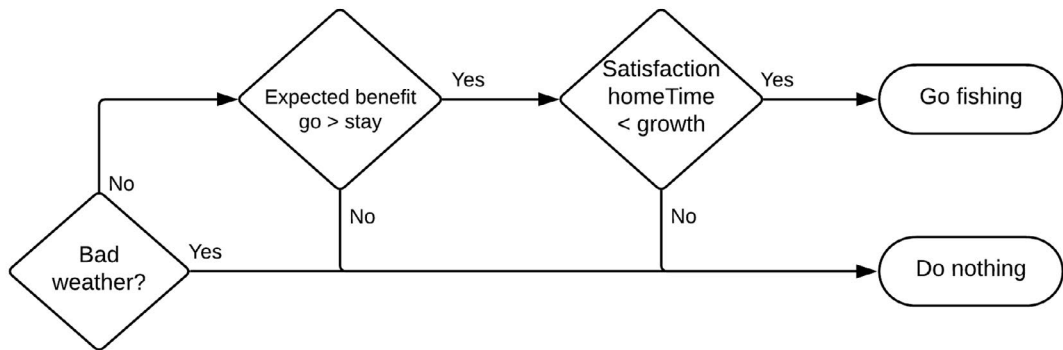
**Trawler**
*Bounded rational-profit-maximizer*
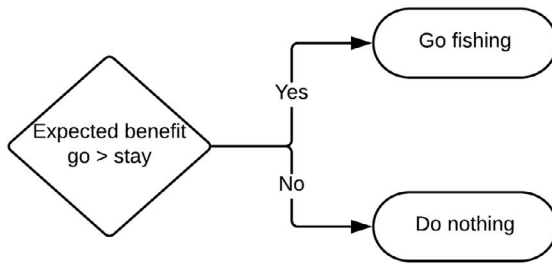


Perceptions:

Expected benefit (go) = (expected catch * price) - expected-cost
Expected cost (go)    = existence (+ travel + equipment)

Expected catch        { = catchability *at the beginning of the season*
                        = max (past catch * of each region) *rest of the time*

Expected benefit (stay) = expected-cost
Expected cost (stay)    = existence

**Coastal**
*Bounded rational-values-maximizer*



Perceptions:

Expected benefit (go) = (expected catch * price) - expected-cost
Expected cost (go)    = existence (+ travel + equipment)

Expected catch        { = catchability *at the beginning of the season*
                        = max (past catch of each region) *rest of the time*

Expected benefit (stay) = expected-cost
Expected cost (stay)    = existence

Need satisfaction:

Home-time   = f(time-away-from-home)
Profit growth = f(capital (t-1,t0))

**Archipelago**
*Bounded rational-values-satisficer*
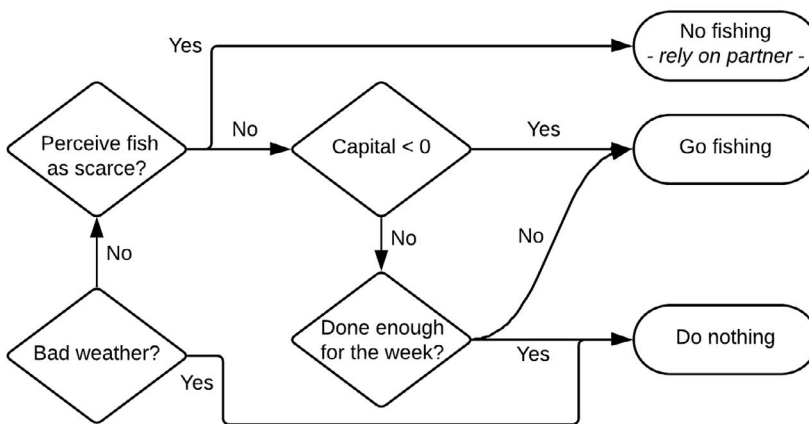


Perceptions:

Fish scarcity { Scarce: lowCatchCount > 75% #goodspots in memory AND no catch for a year
                Not scarce  beginning of the season or lowCatchCount < 75%

Done enough? { Profit-current-week > cost-5day-workweek

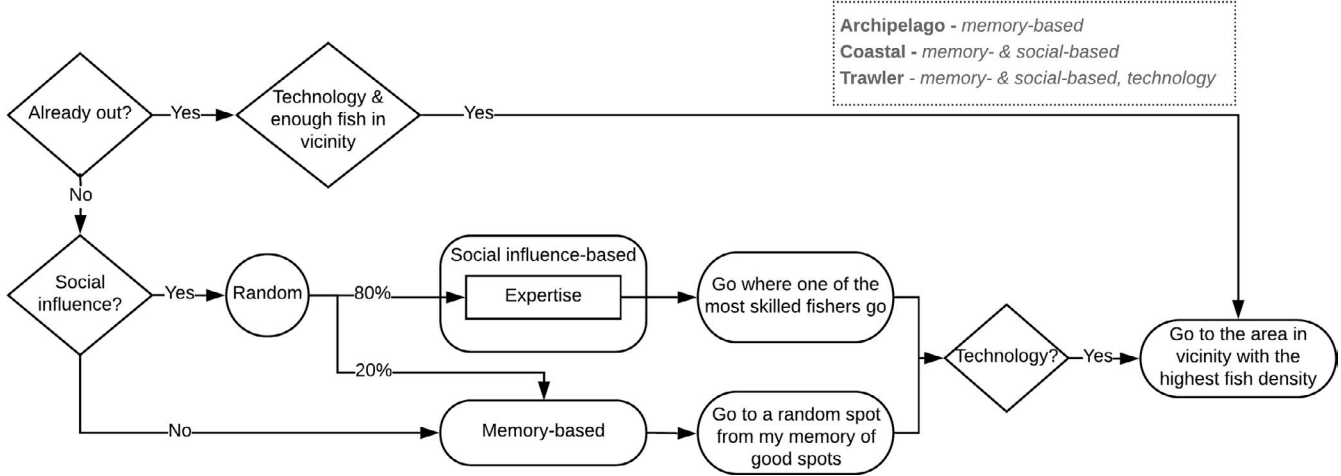**FIGURE 2**  Decision trees for the choice whether to go fishing for each fishing style

> **Archipelago** - *memory-based*
> **Coastal** - *memory- & social-based*
> **Trawler** - *memory- & social-based, technology*

**FIGURE 3**  Decision tree for the choice where to fish, integrating the fishing styles

**TABLE 3**  Design of experiments to illustrate the different understandings of behavioural diversity with the FIsher BEhaviour model

| | | Fishing style | Policy | Outcome variables |
|---|---|---|---|---|
| System level | Experiment 1 | {Trawler, Coastal, Archipelago} | Off | Stock |
| | Experiment 2 | {Trawler, Coastal, Archipelago} | On | Profit |
| | | | | Satisfaction |
| Multilevel | Experiment 1 | Zoom-in: Coastal—why not fishing? | Off | reasonsNotFishing (weather, profitExpect, homeTime) ratioAtGoodSpot |
| | Experiment 2 | Zoom-in: Trawler | On | Stock |
| | | | | Profit |
| | | | | Satisfaction |
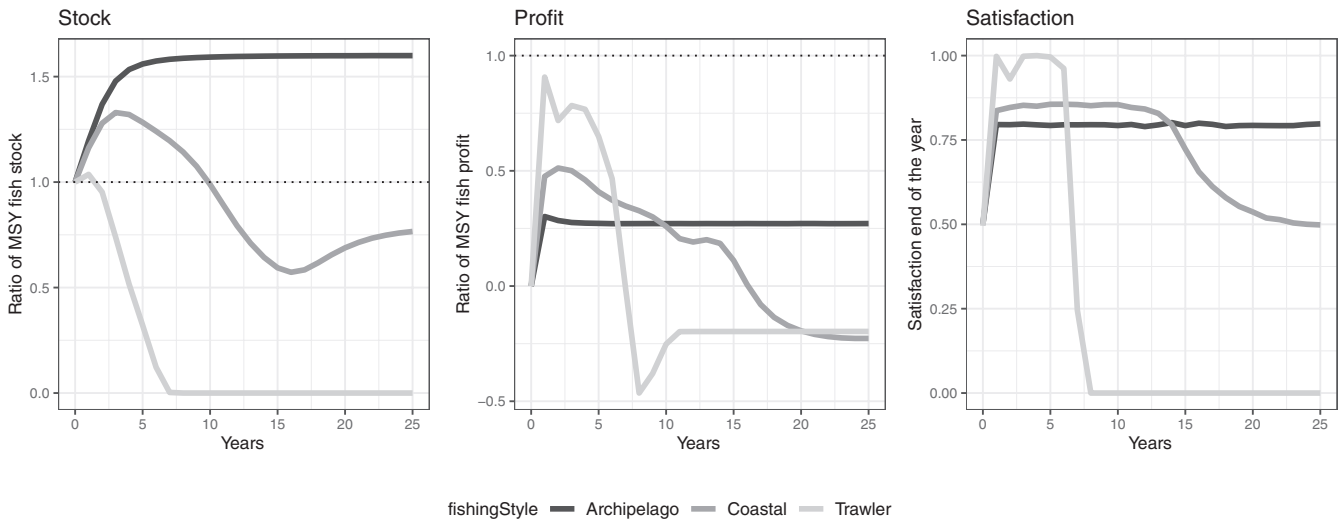


**FIGURE 4**  The effect of diverse fisheries on the stock, economic profit and fishers' satisfaction. Each line (in each graph) represents the mean outcome for one fishing style (see legend) over 1,000 repetitions of the simulation experiments. Benchmark scenario: the thin dotted line in stock and profit graph. Note: In these experiments, there is no interaction between fishing styles agents, that is they do not compete for the same resources

outcomes of the formalized archipelago, coastal and trawler fishing styles differ significantly from the benchmark of theoretical optimal management (the dotted line at 1.0 on the y-axis, Figure 4).

Of the formalized fishing styles, the archipelago fisher agents under-exploit, while the coastal and trawler fisher agents overexploit and deplete the fish stock (albeit at different speeds). Differences

in exploitation rates and speed are due to differences in fishers' adaptive decision-making. Some are affected by weather (archipelago and coastal) or are sensitive to their perception of fish stock conditions (archipelago). Also, motivation heterogeneity influences whether fishers go fishing: seeking to spend time at home as well as make a profit (coastal) or whether profits can be made (trawler), see Section 4.2 for details.

The comparison of these outcomes with the benchmark outcomes reveals how coastal fisher agents' behaviour results in stock levels approximating the benchmark stock level. This finding is somewhat surprising given that the formal assumptions regarding the behaviour of the trawler fisher agents most closely reflect the benchmark rationale, that is maximizing profit. Over time, only the archipelago agents sustain the fish stock, with low, but stable profits and reasonable levels of satisfaction.

### 4.1.2 | Experiment 2: Effect of a policy intervention on fishery sustainability

To explore the effect of a policy intervention for the different fishing styles, we performed the same experiment as above but introduced a fuel subsidy which reduces travel costs for all three fisher styles. The fuel subsidy has no or only a detrimental effect on the resource stock (see Figure 5). The policy affects fishers' profit, but the resource stock gains no observable benefit. The policy actually proves detrimental for the fish stock for the coastal fishing style agents. The financial support delays coastal fishers' realization that they have to reduce their catch. The fuel subsidy thus appears to enable coastal fishers to catch more while being in a more resource-scarce situation, resulting in increased overexploitation. Interestingly, even though the profit is higher due to the policy intervention, the coastal fishers are less satisfied. The choice to fish (or not) by both the *archipelago* and *trawler* fisher agents is not

affected, that is they do not go out less or more frequently and they merely have more profits when catches are large enough.

### 4.2 | Multilevel understanding

In these experiments, we analysed system-level patterns (stock size, profit and satisfaction) and highlighted differences between the fishing styles (trawler, coastal and archipelago). Some results may appear intuitive, but others leave questions that require closer inspection. For instance, the first experimental results for the archipelago and trawlers can be explained following by their decision-making formalization (recall Section 3.1), while the results for the coastal fishery that was partially bouncing back invite closer inspection. Similarly, the second experiment did not produce the expected effect of trawler fishers' fishing longer due to a subsidy. Even though we know all variables and their relations in the model, the amount of relations and their interplay over time leads to unforeseeable results. In this section, we thus dig deeper into the "why" and "how" of the experimental results to deepen our understanding of fishers' behavioural diversity.

Experiment 1 (Section 4.1.1) revealed outcomes resulting from the different formalized fishing styles. The *outcomes for the archipelago fishery* can be explained by the way its decision-making is characterized and how the interaction within a social–ecological environment plays out over time. An archipelago fisher agent is motivated to satisfy the needs to sustain itself as a fisher. The behaviour shown in the results reflect archipelago fishers in a situation where enough fish is available for all of them to satisfy their needs. Consequently, they fish until they are satisfied and then stop. Overall, most archipelago fishers are satisfied, creating a stable situation where a proportion of the archipelago fisher agents is satisfied and stays at home and a proportion goes out to fish, not being satisfied yet.
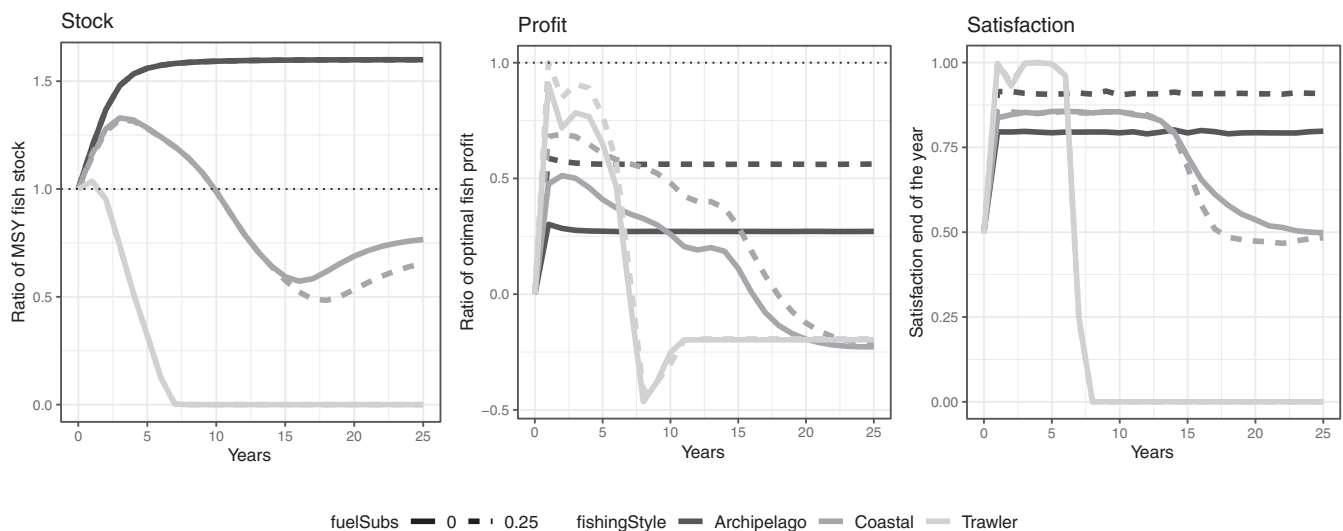


**FIGURE 5** The effect of a fuel subsidy policy in fisheries with different fishing styles on fish stock, fisher profits and fisher satisfaction. The line types reflect the no subsidy (straight line) versus subsidy (thick dotted line) manipulation for each fishing style (line colour). Each line shows the mean results for each simulation scenario with 1,000 repetitions of the simulation experiments

Likewise, the outcomes for the trawler fishery can be understood by looking at the way its decision-making is characterized, in particular the motivation that underpins the behaviour of *trawler* fisher agents in relation to the social–ecological dynamics. A trawler fisher agent is motivated to maximize profits which drive the trawler fisher agents to go out and fish as much as possible for as long as they expect a profit. The model shows how under these assumptions the trawler fisher agents depletes the fish stock faster than they perceive signals from the declining fish stock. They are thus unable to respond in time and reduce fishing. Their delayed response to catch fluctuations is due to not having full information, that is bounded rationality. Their behavioural choice is based on past experiences of having found fish and earning a profit. A few days of bad catches do not immediately change this expectation, which explains their tendency to overfish.

For the coastal fishery outcomes, we ran some additional experiments to better understand the results. When following the reasoning of the decision-making type, a coastal fisher agent is similar to a trawler, with one major difference which is that they value other things than merely profit maximization: they also value spending time at home. When looking at the social–ecological situation, the coastal fisher agents find themselves in a different situation than the trawlers: they notice that they are overfishing (i.e. decrease in profit and satisfaction) and adapted their behaviour. Since the overfishing was not as extreme (or fast) they could avert a fish stock collapse. But questions remain: for example, why do their catches reduce? Do they go out fishing less often? Or do they not find the fish? To answer these questions, we examined individual fisher agent behaviour more closely.

A *coastal fisher* agent may not fish for several reasons: bad weather, no expectation of profits or wanting to spend time at home. Figure 6 (left) shows the reasons for *coastal* fisher agents not to go fishing over time. The main reason for not fishing is "spending time at home," varying between 10% and 20%. However, after approx. 15 years this need reduces and not expecting profits becomes the dominant reason for not going fishing and an increasing number of fishers stops fishing

every year. If a coast fisher does not expect profits from a fishing trip, it will not go fishing. The expectations profits depend on the catch fisher agents had in the past. If a fisher had many instances of bad catches over time, the overall expectations of catch and profit will reduce to a point that the coastal fisher considers fishing as not profitable anymore and will stop fishing for the remainder of the year. As over time the fish stock decreases, for an increasing number of fishing trips, the visited spots are not good fishing spots anymore, see Figure 6 (right). Even though there still are some spots with fish in both regions (A and B) accessible by the coastal fisher, see Figure 7, this is not visible, and the series of bad catches signals resource scarcity and results in a drastic reduction in fishing (See Appendix S2—Figure B1c and Movie B1 for examples of this fishing activity in space).

Experiment 2 (Section 4.1.2) The effect of a fuel subsidy as a policy intervention was explored. It only affected the simulation runs with *coastal* fisher agents, wherein the subsidy triggered the fisher agents to fish more and consequently reduce the fish stock. Surprisingly, we did not observe the same outcome in the simulation runs with the trawler fisher agents. We expected the subsidy to lower their costs and thus allow the trawler fishers to fish for longer periods, just like the *coastal* fisher agents. For the simulation runs with *archipelago* agents, we expected them to fish less, resulting in a higher fish stock, at the stable profit and satisfaction levels. So, why did the fuel subsidy not influence the trawler and archipelago fishers? We explore this by exaggerating the fuel subsidy.

Figure 8 shows the results of experiments to test the intuition that the subsidy reduces the cost and increases (expected) profits. It shows that our expectation holds for the *archipelago* fishers. The introduction of a fuel subsidy lowers their costs, which means they need to catch less fish to be satisfied, resulting in higher fish stock levels. The subsidy thus helped to keep profits at the same level (compared to the pre-intervention situation), but with higher levels of fisher agent satisfaction and a higher fish stock.

For the simulation runs with *trawler* fisher agents, the introduction of a fuel subsidy had little effect because fish stock decline
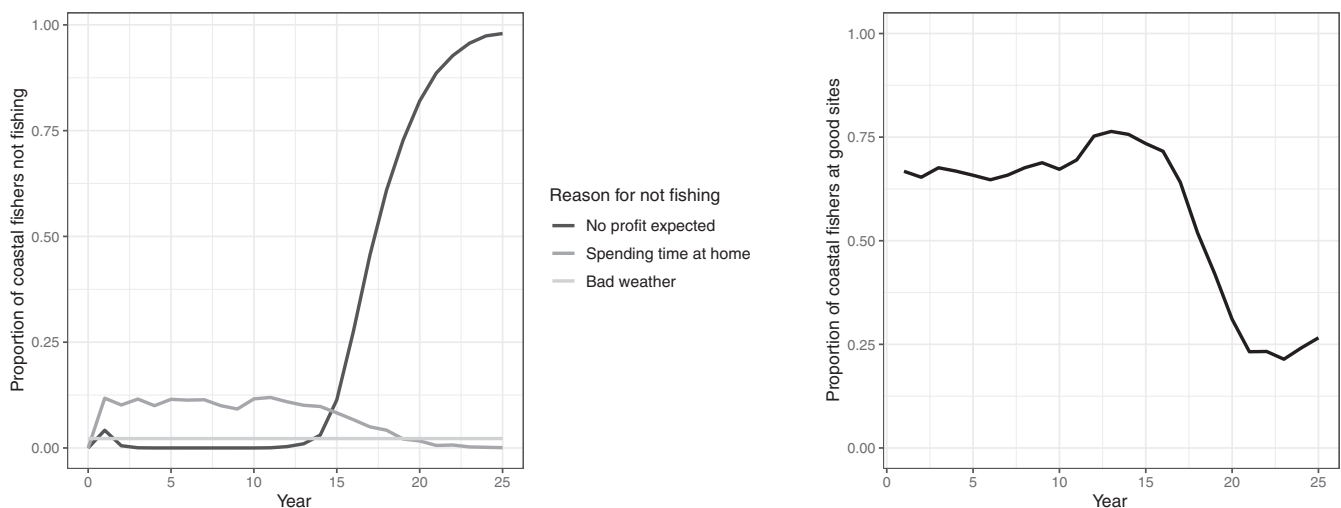


**FIGURE 6** Reflect the reasons for *coastal fisher* agents to not go fishing during the simulation experiments (left) and the ability of the *coastal fishers* to find the good spots for fishing (right). Each line represents the mean of 1,000 repetitions of the coastal fishery simulation
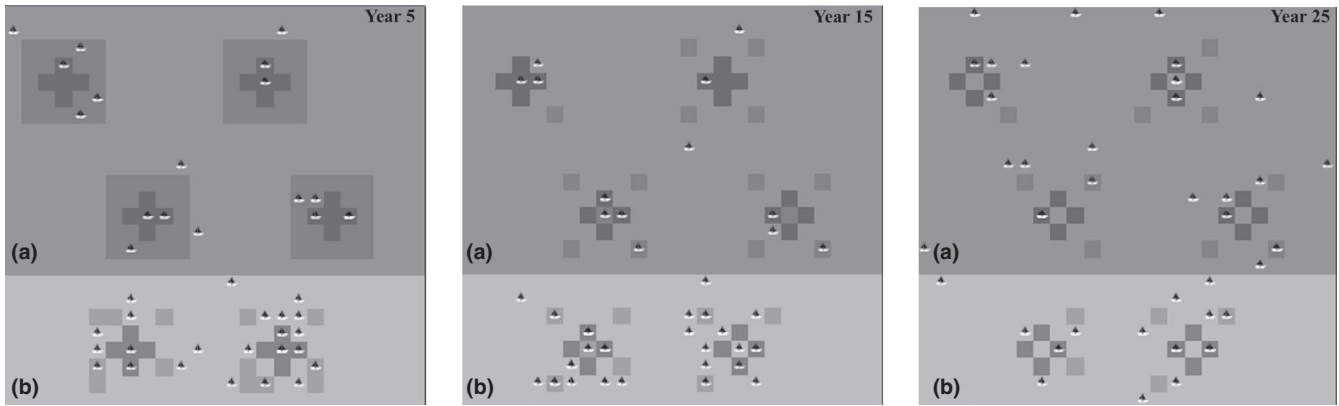
**FIGURE 7** Fish stock in space in a coastal fishery (region a [light grey] and b [dark grey]) at year: 5, 15 and 25. The darker the fishing sites, the more fish there is and vice versa
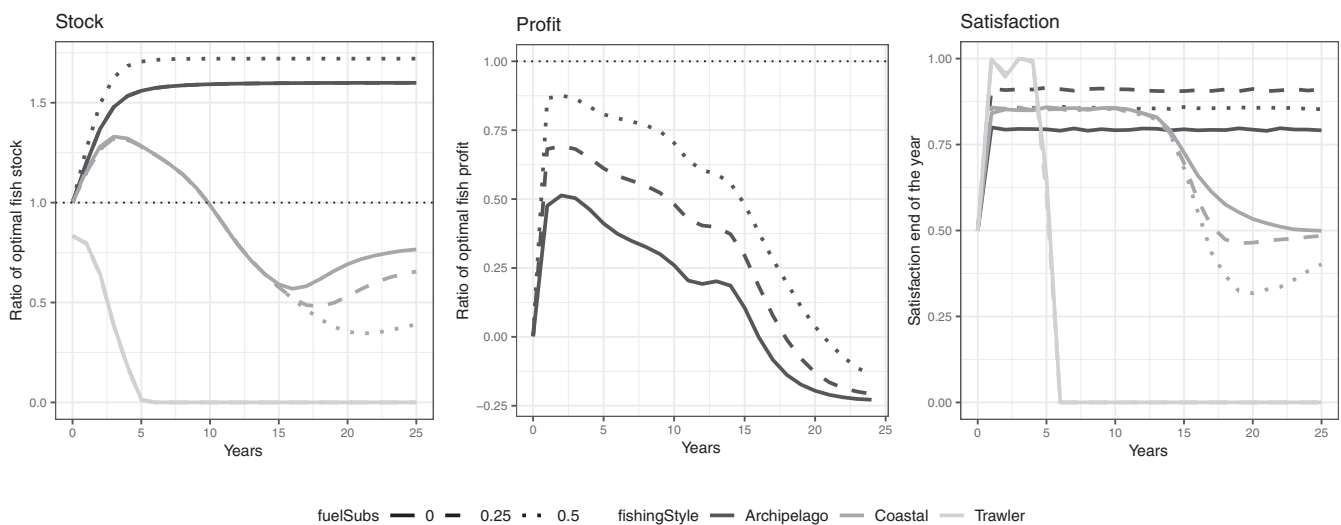


**FIGURE 8** The effect of different fuel subsidy policy levels (line types) in fisheries with diverse behaviour on the stock, profit and fisher satisfaction

occurred so rapidly that the fuel subsidy only caused the trawler to go out more for a very short time. In the beginning, trawlers have high catches and high profits. Thus, they have no reason to expect lower catches and fish less. The subsidy then merely increases their profits (see Figure 8). The decline in profit resulting from lower catches, however, occurs so rapidly that the influence goes unnoticed. The subsidy amount cannot compensate for the bad catches because they are so low that costs are increasing too much. This demonstrates how the effect of a fuel subsidy depends on the situation of the fishers. The combination of the resource being (perceived to be) scarce, speed in which overexploitation takes place and the ability to actually catch more fish explains the limited influence of a fuel subsidy for the trawler fisher agents.

## 5 | DISCUSSION AND CONCLUSION

In this paper, we present a way for integrating social scientific knowledge about individual and collective human behaviours into

the modelling and management of fisheries. We demonstrate, using agent-based modelling, how such an integration is possible, and we thereby propose a scientific approach for reducing the uncertainty arising from human behaviour in fisheries. This approach lays the foundations for a next generation of social–ecological fishery models that account for aspects of human behavioural, social and ecological complexities that are purposive for a realistic assessment of a fishery sustainability problem.

### 5.1 | From acknowledging towards understanding

Scholars of fisheries science have taken an important first step in acknowledging the uncertainty they experience when making assumptions regarding fisher behaviour and social and ecological change in marine environments more generally. There exist fishery models that account for human behaviour more realistically (see Section 2.2). Yet, most of these models are based on expected utility maximization and focus on factors such as a fleet's ability to change

strategies (van Putten, Gorton, et al., 2012) or on factors affecting fishing efforts, such as vessel or gear type. Only few models go beyond expected utility maximization and consider, for example, social norms or resistance to exit by relying on empirical data (Libre et al., 2015). We found no models that explicitly incorporate insights from social science theories of human behaviour. Altogether, this indicates a broad recognition of the need for more realistic representations and thus assessments across fields.

## 5.2 | Towards a next generation of social–ecological fishery models

We envision the next generation of fishery models to account for and enhance our understanding of the importance of the dynamics (and diversity) of human behaviour for the development and management of sustainable fisheries (Weber et al., 2019). These new models will be built on knowledge of human behavioural as well as biological and ecological complexities that is available from across the sciences. This knowledge will then be operationalized and contrasted against empirical findings or alternative models of similar fisheries.

Fisheries research and management benefits from a diversity of models that allow for studying and assessing fisheries (Nielsen et al., 2018; Weber et al., 2019). This diversity of model types is ultimately needed to advance the development of next-generation social–ecological fishery models. However, we see an important and specific role for ABMs in this development (Fulton et al., 2011; Lindkvist et al., 2020; van Putten, Kulmala, et al., 2012; Schill et al., 2019). Their main advantage is that ABMs allow for incorporating empirical or theoretical social science insight. It is their very nature to include both the microlevel (agents and their interactions) and the system or aggregate (macro) level (patterns) we aim to understand, such as overfishing. The necessity to specify agent characteristics and agent interactions in a social and ecological contexts over time allows for the incorporation of social science insights that may reside on microlevel, macrolevel or both level. Agent-based modelling is presently the only modelling approach able to reflect heterogeneous agents and their behavioural diversity over time (Conte & Paolucci, 2014). In terms of process, they allow for making existing knowledge accessible and integrable and stimulate theory development. ABMs require the modellers to be explicit about their assumptions regarding human decision-making and behaviour, including the motivations, goals, social and ecological contexts that influence fishers' choices and the processes by which fishers make decisions in response to changes in their social or ecological environments. Once a model has been built based on the best available understanding of human decision-making, systematic analysis of model outcomes and underlying mechanisms (as e.g. in Section 4) generates understanding of *why* and *how* certain outcomes of these complex fishery systems occur. This ability to connect the micro- and the macrolevels is an essential feature for enabling the development of testable explanations and exploration of scenarios that go beyond the scope of known situations. Moreover, the adoption of social science insight

for other types of modelling may become easier once they have been formalized and tested in ABMs. Agent-based modelling can thus provide a stepping stone for formalizing alternative behavioural models for application in other model types, such as mathematical models.

Based on our experience with FIBE, we highlight three aspects that scholars or managers of fisheries seeking to construct such new models should consider:

1. Carefully *consider how to represent fisher behaviour* and how to account for behavioural diversity in a particular context, considering the best available social science knowledge and data. We have highlighted four dimensions of behavioural diversity, that is motivations, abilities, livelihoods and social interaction. These are important starting points for efforts to develop such new models.
2. *Make use of multiple knowledge and data sources* including quantitative and qualitative empirical data, expert knowledge, frameworks and theory to make informed choices about how to model fisher behaviour. In FIBE, we combined the empirically based typology of the fishing styles with theoretical considerations to develop three archetypical fisher agents: the archipelago, the coastal and the trawler fishers.
3. *Use models to assess uncertainties* resulting from the possible range of motivations and behaviours present in a particular study when evaluating sustainability or policy outcomes. Through the simulation of fishing styles in an ABM, for instance, we demonstrated how the fishing styles impact the sustainability of a fishery differently and also how policy interventions have different effects depending on the diversity in fishers' behaviour.

The development of a new generation of fishery models is, however, not without challenges. Firstly, finding relevant knowledge and data on human behaviour and formalizing it can be challenging given the fragmentation and often little formalized nature of social science insight. Literature synthesizing knowledge from social science or related fields such as psychology such as the one provided herein, but also frameworks for modelling human behaviour (Schlüter et al., 2017), can help identify and organize relevant theories and empirical knowledge. Secondly, developing these models in collaborative processes is time-consuming and finding the adequate level of complexity that allows for rigorous model analysis while accounting for important real-world structures and processes is difficult. Our behavioural typology in the form of empirically derived fishing styles combined with behavioural theories demonstrates a way towards how reality can be represented more comprehensively without being overly complex. If these challenges are overcome, such new models provide enormous potential for enhanced fisheries research and management.

## 5.3 | New opportunities and roles of next-generation fishery models

These new models and the collaborative processes of their development can help address challenges of fisheries research and

management in novel ways by (a) supporting a *process of integrating knowledge* across social and natural fishery sciences, (b) enabling the *assessment of consequences of behavioural uncertainty* and (c) serving as a means to identify underlying causal mechanisms that can provide *entry points for governance*.

### Models as tools for integrating and contrasting knowledge about human behaviour

To create FIBE, we employed a joint development process, involving empirical scientists and modellers. The many conversations and iterations on the fishing styles and "bringing them alive" as agents exposed knowledge about context, style specifics and understanding beyond the written descriptions that reside between the lines of any conceptual/theoretical description of human behaviour. Moreover, it allowed us to tackle the inevitable conceptual gaps and logical inconsistencies encountered when formalizing theory (Sawyer, 2004). This process not only enabled making social science knowledge more accessible, it enables us to integrate these existing findings. At the same time, the process of developing FIBE, particularly the need for precision and reflection on key assumptions regarding human behaviour when implementing the fishing styles, stimulated critical thinking, raised awareness of simplifications, showed existing knowledge gaps and improved the validity of decisions on system boundary conditions.

Apart from answering research questions with FIBE, we also explored other assumptions and theories to compare and contrast their effect on the outcomes. We tested, for instance, two ways for trawler and coastal fishers to be sensitive to the social information for decide where to fish: we formalized a "go where most others go" and "go where a (perceived) skilled fisher colleague is going." Although for this paper this exercise remained part of the sensitivity analysis, one might also implement competing explanations, observations or theories and explore their consequences.

In sum, model development and application can support a process in fishery management and research to bridge between social and ecological fishery science and can help improve the accessibility of behavioural insight for fishery research and management. Modelling can serve as a central binding element and guide the process of integration between different fields, where the model becomes a common product, purpose, language and tool for mutual understanding.

### Models for assessing the consequences of behavioural uncertainty

In FIBE, we represented the formalized fishing styles and thereby presented a way to integrate social (fishery) science knowledge that reflects diversity of fisher behaviour in motivation, ability, livelihood and social interactions. This model demonstrated several implications of incorporating behavioural diversity. Firstly, we compared FIBE's outcomes against a theoretical optimal management benchmark and showed that none of the empirically based implementations of fishing behaviours approximates traditional optimal management, not even the trawler which can be considered the conceptually closest. Secondly, we demonstrated the interaction with a policy intervention, that is a fuel subsidy. The model revealed

different ways in which policy can affect behaviour. Surprisingly, the subsidy mainly affected the coastal fishers; we had instead expected the trawler to fish earlier and longer. More investigation showed how this subsidy made each trip more profitable, but did not affect the choice whether to fish or not because the signal from the resource emerged too late for reversing overexploitation properly. Lastly, we demonstrated how these differences within a spatial fishery can be explained by connecting the agents and their interactions in their environment with the system-level outcomes. This leads to models that allow for connecting models, theories and insight of human behaviour to system consequences, like Beckage et. al. (2018) do for climate change projections, and allow for exploring the response to and effect of policy options (Pelletier et al., 2009; Sigurðardóttir et al., 2014).

Knowing the range of possible outcomes given different assumptions regarding fisher behaviour can help reduce uncertainty based on the complexity of human behaviour. Although not directly suitable for policy design in the conventional way, the implementation of different decision-making models provides a powerful approach for analysing the consequences of policy for fishery outcomes and policy effectiveness, thus complementing and broadening the traditional use of models.

### Models for identifying causal mechanisms as entry points for governance

Fisheries are complex adaptive social–ecological systems, that are their intertwined dynamics of the social and the ecological system, their continuous interaction and influence on each other over time must not be neglected when seeking to understand why policies fail, overfishing occurs etc. We envision the next generation of fisheries models to not only help assess the implications of behavioural diversity and policy outcomes, but also to support analyses of underlying complex causal mechanisms that brought about certain outcomes (Biesbroek, Dupuis, & Wellstead, 2017; Schlüter et al., 2019).

Agent-based models such as FIBE lend themselves for opening the black box of human behaviour and investigating how certain outcomes or patterns came about. This is achieved through systematic experimentation with the model where certain processes are, for example, turned on/off, different behavioural models are tested or environmental or social contexts are changed. The analysis of model results then involves tracing the underlying processes leading to aggregate outcomes, such as overfishing. This process facilitates uncovering the different mechanisms that cause a certain outcome and to trace it back to the specifics of the different decision-making processes and their interaction within the fishery. With FIBE, we explored several *why* questions underlying the overall patterns (Section 4.2). For instance, we traced the reasons for not fishing to understand more why and at which moment the coastal fishers decide not go fishing, which could be either motivational (wish to be home was bigger than making profits), situation-based (bad weather) or experience-based (not expecting a profit).

The identified causal mechanisms may serve as anchor points for policies or interventions. They can help develop policy measures

that are sensitive to the underlying processes and contextual aspects that give rise to fisher behaviour. Gaining a deeper understanding of *why* and *how* management measures such as a regulation are not effective is particularly relevant for managing complex systems such as fisheries. It may also point to measures that do not target individual fishers' behaviour, but rather influence social structures or other contextual conditions. Using models to unravel the causes of emergent outcomes is currently not a common use of models in management, but they can be of great importance when developing complexity-informed management and governance approaches. For instance, our model has shown that the different types of behaviour generate different ecological, economic and psychological outcomes, as well as similar outcomes for different reasons. Both nuances are important when designing and implementing policy since the same policy can lead to different outcomes for the fishery and the fishers, or it may result in the same outcome but through different underlying mechanisms, with potential side-effects.

## 5.4 | Conclusion

We aimed to answer the calls to better account for human behavioural diversity in fisheries and provide support for others to do so. In this study, we took the next step by synthesizing knowledge from social (fishery) science and applying it to an exemplified fishery model. Social (fishery) science provides valuable insight into human behaviour and its underlying mechanisms and processes that are important in fishery contexts. While some fishery models are developing ways to include more realistic representations, most, however, lack in their approach to incorporate aspects of human behavioural diversity for understanding their implications for fishery outcomes. This, would, however, ultimately help reduce and assess uncertainty as is required for advancing our scientific understanding of social–ecological fishery systems. It would enable us to identify effective entry points for fishery management and thus improve overall management effectiveness with regard to sustainability of both the social and ecological systems. Our approach and findings highlight a promising avenue for reducing and assessing uncertainty based on human behavioural diversity by specifying, including and analysing its consequences through the use of agent-based modelling in fisheries (and beyond).

## DATA AVAILABILITY STATEMENT

The FIBE model is available on COMSES (https://www.comses.net/) allowing for the reproduction of all the findings of this study (Wijermans et al., 2020) https://www.comses.net/codebases/4d9cfac5-7331-4a03-9d83-ab06cbedc143/releases/1.0.0/. The simulation data, the r-scripts for analysis and summarized information from the literature review that support the findings are available from the corresponding author upon reasonable request.

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## SUPPORTING INFORMATION

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