THE PARTICIPATORY POTENTIAL OF FUZZY COGNITIVE MAPPING IN THE CONTEXT OF HARMFUL ALGAL BLOOMS IN PERU

Master Thesis

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Abstract

The involvement of non-academic actors in research has become a key characteristic of sustainability studies. As part of this trend, modellers increasingly turn to *Participatory Modelling* (PM) to incorporate stakeholders' knowledge, perceptions, norms, and values in the development of formalized, shared representations of social-ecological systems. While stakeholder participation has been shown to have many advantages, its limits are not adequately discussed in the contemporary PM literature. In particular, there is a lack of engagement with insights from fields that have a long participatory research tradition, such as development studies. To address this gap, the thesis employs Fuzzy Cognitive Mapping (FCM), a widely employed form of PM, in a case study in Peru, aiming to map the socio-ecological drivers, impacts, and related adaptation strategies in the context of Harmful Algal Blooms involving diverse groups of local stakeholders. Subsequently, the thesis critically reflects on the participatory knowledge production process, drawing on sociology and development studies literature. By identifying and discussing the limitations of the participatory approach within this specific case study, the thesis aims to contribute to the development of best practices specific to FCM.

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Acronyms

ENSO	El Niño Southern Oscillation (ENSO)
FCM	Fuzzy Cognitive Mapping
HABs	Harmful Algal Blooms
IMARPE	Institute of the Sea Peru (Instituto del Mar Peruano)
LA	Local Authorities
LE	Local Scientific Experts
LSM	Large-Scale Mariculture
PM	Participatory Modelling
SANIPES	National Agency for Fisheries Health
SSF	Small-Scale Fisheries
SSM	Small-Scale Mariculture

1 The Participatory Potential of Fuzzy Cognitive Mapping

Participation has become a core tenet of sustainability science (Musch & von Streit, 2020, p. 55; Reed, 2008, p. 2418). Researchers argue that all forms of knowledge and diverse methods must be mobilized to address complex problems such as biodiversity loss, the energy transition, and climate change (Bennett, 2016; Berkes et al., 2000; Kates et al., 2001; Limoges et al., 1994). In the spirit of Karl Polanyi, the German Advisory Board on Global Change (WBGU) has even called for a new *Great Transformation*, where researchers closely collaborate with civil society and decision-makers to address the sustainability challenges of our time (WBGU, 2011, p. 68). While its supporters argue that participation produces more context-sensitive, socially-robust findings, its growing influence has encouraged critical scholars to warn of an "imperative for collaboration" (Knecht, 2017), an "illusion of inclusion" (Few et al., 2007), and even "tyranny of participation" (Cooke & Kothari, 2001).

Moreover, participation is increasingly advocated within the natural- and applied sciences that pragmatically use quantitative methods and modelling approaches to address societal problems as part of the shift towards 'post-normal sciences' (Király et al., 2016, pp. 1–2; Lang et al., 2012, p. 27). This trend has led to a boom in *Participatory Modelling* (PM) – the stakeholders' involvement in developing system models as shared and formalized representations of reality (Voinov et al., 2016, p. 1, 2018, p. 196). Within the PM literature, Fuzzy Cognitive Maps (FCM) emerged as a popular method to build causal maps with participants, connecting quantitative analysis with qualitative storylines to represent how different actors perceive a given phenomenon (Barbrook-Johnson & Penn, 2022, p. 80; Jetter & Kok, 2014, p. 45). Many of these FCM papers present participation and the integration of local knowledge as "new ways of knowledge production" (Lang et al., 2012, p. 25). Nevertheless, participation is neither a new discourse nor a newfound practice (Cooke & Kothari, 2001; Cornwall, 2006, p. 63; Mohan & Stokke, 2000). Instead, Cornwall (2006) argues that the concept has repeatedly been reinvented through shifts in language without necessarily being accompanied by new ways of thinking and doing (pp. 78–79). This tendency towards reinvention is illustrated by some of the buzzwords in development and sustainability research that emerged over the past decades, including *stakeholder participation*, *perception-based research*, *community research*, *Participatory Rural Appraisal*, *Collaboration*, *Co-Design*, *Citizen Science*, *Participatory Action Research* or *Participatory Modelling*.

The reinvention of participation has posed several problems. Firstly, it has created conceptual ambiguity since participation is "used to evoke - and to signify - almost anything that involves people" (Cohen & Uphoff, 1980; Cornwall, 2008, p. 269). Consequently, determining whether a process is genuinely participatory has been challenging. Secondly, the tendency to redefine or reinterpret participation has hindered learning from past research failures and engaging in critical reflection (Cornwall, 2006, p. 64; Norström et al., 2020, pp. 182–183). Finally, academic fields that newly engage with participation tend to focus on methodological and practical issues, such as the “applicability and appropriateness of the techniques and tools” (Cooke & Kothari, 2001, p. 6). As a result, the underlying problems related to participation as a research paradigm are frequently disregarded (pp. 5-6). Therefore, Hickey and Mohan (2005) advocate for a post-participation consensus that encourages researchers to learn from previous mistakes and identify improved practices to move forward (as cited in Reed, 2008, p. 2418).

These three problems associated with participatory research also apply to the literature on FCM. While FCM research reflects on methodological and processual issues such as transparency (Olazabal, Neumann, et al., 2018), modelling techniques (Aminpour et al., 2021; Felix et al., 2019; Papageorgiou & Salmeron, 2013) and knowledge elicitation (Jetter & Kok, 2014), the participatory aspects are often presented optimistically, without assessing whether they fulfilled their promises (Tsouvalis & Waterton, 2012; Voinov et al., 2016, p. 212). For instance, there are few critical discussions of epistemological challenges or power issues related to the combination of modelling and participation (for exceptions, see Denney et al., 2018; Jordan et al., 2018; Maru et al., 2009). Consequently, Voinov et al. (2016) have called for more research on the participatory dimension of existing PM methods (p. 198). Furthermore, papers on PM rarely incorporate insights from other disciplines, such as development studies, that have a long history of research utilizing participatory methods (Chambers, 1983, 1994; Mohan, 2014). With this thesis, I aim to address this gap and discuss the participatory potential of FCM by focusing not only on processual and methodological problems but also on the “theoretical, political, and conceptual limitations of participation” (Cooke & Kothari, 2001, p. 5). I do so by linking sociology, development, and sustainability studies research on participation to the FCM literature. The discussion will beginn with the following research question: *What are the limitations of FCM as a form of participatory knowledge production in sustainability science?*

Building and Deconstructing a Case Study of Harmful Algal Blooms in Peru

Instead of only deconstructing the modelling tool of FCM from a critical distance, I engage in what Niewöhner (2019) describes as the first step of interdisciplinary 'situated modelling': I actively participate in pragmatic FCM modelling as a social scientist. Subsequently, I built a critical discussion on this experience. The aim is to encourage social scientists to take responsibility for modelling reality and modellers to reflect more critically on the social and political dimensions of the process (pp. 47-48).

Following this idea, I conducted an exploratory FCM case study based on the guidelines of previous FCM studies (Furman et al., 2021; Olazabal, Neumann et al., 2018; Özesmi & Özesmi, 2004; Singh et al., 2019). The case study analysed the drivers and socio-economic impacts of Harmful Algal Blooms (HAB) in Peru as perceived by local stakeholders. Additionally, it evaluated the capacity of Peru's scallop mariculture sector to adapt to the phenomenon. Previous research in Peru has identified the oceanographic drivers of HABs, identified potentially toxic species and their distribution and abundance, and linked them to deoxygenation events (Cuellar-Martinez et al., 2021, 2023; Cueto-Vega et al., 2022; Sanchez et al., 2017). While this research comes from a natural scientific background, this exploratory case study aims to help understand the social and economic dimensions of HABs in Peru.

In summary, this thesis has two objectives. On the one hand, the case study aims to fill the empirical gap related to the socio-economic aspects of HABs in Peru. On the other hand, the thesis deconstructs the participatory aspects of the FCM method based on my case study experience. With this approach, I hope to encourage critical reflections on the participatory potential of FCM and promote the development of best practices and realistic expectations.

1.1 Structure of The Thesis

The thesis is divided into three chapters. Chapter 1 introduces the theoretical framework on participation in research. I first discuss the arguments favouring participation, then focus on the views prevalent in the PM literature and present the assumptions behind FCM. Afterwards, I provide a literature review discussing some of the shortcomings of participatory research, including the degree of participation, issues of representation and power, knowledge integration, and its impacts. Chapter 2 presents my case study of HABs in Peru. I introduce the case context, discuss the research design, and explain the findings from the fieldwork. The chapter helps to understand how FCM plays out in practice and addresses the case-study goal of my thesis. Chapter 3 reflects on the shortcomings of my case study. It analyses the weaknesses of my FCM design and questions whether the process can be considered participatory. Lastly, I provide an outlook regarding the participatory potential of FCM and PM more broadly based on the literature and the experience from my case study.

2 Strengths and Weaknesses of Participation in Sustainability Research

A process is defined as participatory “if a variety of different stakeholders are involved, if their views, values, and preferences enter into the (…) process with some weight and some element of cooperation between them takes place” (Dahler-Larsen, 2018, p. 1503; Greene, 1997). Nevertheless, participation can range from the selective involvement of people in an externally controlled research project to projects with complete ownership by the local community of stakeholders (Banks et al., 2013, p. 265). The motivations behind the participatory design determine how knowledge – and the participatory process behind it – are framed and designed. The following section outlines these motivations and then shows the most prevalent arguments among scholars engaging in (and researching) participatory modelling.

2.1 The Case for Participation in Sustainability Science

Participation in the sustainability field can be differentiated between (1) the involvement of citizens to democratize and legitimize transformations towards sustainability (Muradova et al., 2020; R. Willis et al., 2022); and (2) people’s participation in the process of knowledge production (Voinov et al., 2016, p. 197). This review focuses on the latter. Moreover, on a general level, one can distinguish between framing participation as an end in itself (*normative*) or as a means to achieve specific goals (*instrumental*) (Cornwall, 2008, p. 274; Reed, 2008, p. 2420). Oliver et al. (2019) introduce an even more fine-tuned typology by differentiating between *substantive*, *instrumental*, *political*, and *normative* participation goals (p. 2).

The *substantive* arguments claim that participation is needed to improve the quality of research by mobilizing ‘new forms of knowledge’ that are necessary since conventional science alone cannot address sustainability challenges, given conflicting values, the uncertainty of changes, and their urgency (Lang et al., 2012; Raymond et al., 2010; Tengö et al., 2017). While these types of knowledge are conceptualized differently across studies, they are typically viewed in contrast with scientific knowledge, being described as "informal, lay, personal, often implicit or tacit, yet potentially expert." (Raymond et al., 2010, p. 1767). Some common designations of these types of knowledge include “local perception”, “indigenous knowledge”, “traditional ecological knowledge”, or “experiential knowledge” (Agrawal, 1995a; Bennett, 2016; Berkes et al., 2000; Raymond et al., 2010). Their integration is expected to make research more socially robust and context-sensitive (Oliver et al., 2019, p. 2). Additionally, the consideration of the practical skills and acquired intelligence of participants arguably leads to better results, reduced uncertainties, and solutions that complement scientific knowledge ontologically and epistemologically (Lang et al., 2012, p. 26; Tengö et al., 2017, pp. 17–18).

This is closely linked to *Instrumental* arguments, where participation is used as a tool to achieve desired outcomes (Reed et al., 2009, p. 1936). Participatory research can produce results quickly and cost-effectively, especially in contexts of uncertainty where little research has been conducted (Bennett, 2016, p. 588; Williams, 2004, p. 559). Moreover, the results are more likely to be integrated into decision-making processes and are expected to improve the outcomes by promoting trust and dialogue between participants (Bennett, 2016, p. 588; Oliver et al., 2019, p. 2). This trust, in turn, can lead to reduced conflict and a feeling of ownership over the process, facilitating long-term stakeholder support (Reed, 2008, p. 2420; Stringer et al., 2006). Moreover, more participation should translate into priorities and interventions that meet the needs of the local population and help to anticipate conflict and unforeseen adverse outcomes by providing more holistic information (Reed, 2008, p. 2420). Lastly, the deliberative process can lead to social learning and the transfer of knowledge, where people’s perceptions may be changed because of their interaction with the researcher and other stakeholders, while researchers become more sensitive to societal issues (Banks et al., 2013, p. 264; Stringer et al., 2006, p. 4).

Political arguments take a different direction. Including stakeholders, for instance, arguably democratises expertise and makes the work of research and related policy-processes more legitimate (Mielke et al., 2016, pp. 72–74; Stringer et al., 2006, p. 4). Alternatively, according to Cornwall (2008), the public nature of the participatory process provides the stakeholders with “a space for the airing of grievances that may become more difficult for those in power within and beyond the community to ignore“ (p. 274). By transforming them into research output, the stakeholder claims become validated to be used as “a key pressure-point at which to deploy and build (…) political capabilities”

(Williams, 2004, p. 571). Issues previously invisible can now serve as a ‘hook’ to demand action from public authorities and other relevant actors (Mielke et al., 2016, p. 73; Williams, 2004, p. 571).

This ‘empowerment’ of previously marginalised actors is also a *normative* argument for participation. Robert Chambers (1983, 1997) argued that participatory methods can potentially reverse relationships of power by *Putting The Last First* and *Putting The First Last*. Moreover, the normative claims focus on the possibility of building better societies with active citizenship, greater accountability and dialogue between science and society (Felt et al., 2012, p. 13; Oliver et al., 2019, p. 2; Reed, 2008, p. 2420). In this line of argument, democracy, equity, fairness, and empowerment are valuable results of participation in themselves (Reed, 2008, p. 2420). From a philosophical standpoint, many normative arguments are supported by the theories of deliberative democracy by philosophers such as Jürgen Habermas or Paulo Freire that highlight the role of ‘communicative action’, consensus and learning as pathways towards emancipation (Few et al., 2007, p. 47; Godin et al., 2007, p. 453). Habermas (1981), for instance, argues that rationality is not the result of possessing particular knowledge but arises through “speaking and acting” (p. 11).

Nevertheless, these theories have been criticized for being overly optimistic about assuming the possibility of an ‘ideal speech situation’ – a form of communication that is free from coercion, power imbalances, and distorted discourse where different perspectives are voiced to enable collective action (Maru et al., 2009, p. 3015). That this form of communication rarely occurs has been shown by the experience of scholars engaging with participatory research over the last fifty years. Nevertheless, before considering the limitation of participatory research, I will discuss the arguments for participation most prevalent in the PM literature.

2.2 Why Engage in Participatory Modelling?

According to Voinov et al. (2016), PM is a form of citizen science because people are “active participants in checking, assessing, or commenting on scientific observations” (p. 197). While motivations for participation in research are diverse, I argue that instrumental and substantive arguments are more common than normative and political motivations in PM. Some of the most common goals could be classified along four dimensions: (1) problem-solving and planning, (2) knowledge generation under uncertainty, (3) communication and learning, and (4) funding.

Firstly, one use of PM is engaging stakeholders to identify problems and knowledge gaps with societal relevance and then help improve decision-making and management plans to solve them (Edwards & Kok, 2021, p. 1; Gray et al., 2015, p. 3; Voinov & Bousquet, 2010, p. 1268). It does so by providing a method to represent stakeholder's individual and group beliefs formally and assesses how they might respond to a given management intervention or changing system state (Henly-Shepard et al., 2015, p. 110; Özesmi & Özesmi, 2004, p. 43). Moreover, modellers can create simulations or predictions of the future from the analysis of a system (Jetter & Kok, 2014). This is particularly useful in the case of 'wicked' environmental problems with no easy solution and involving actors with conflicting interests – something pervasive in social-ecological research (Özesmi & Özesmi, 2004, p. 44). If done well, PM can arguably lead to more informed decisions, better management plans and greater adaptive capacities of the community (Birkmann & Pelling, 2006; Henly-Shepard et al., 2015; Singh & Chudasama, 2017). Moreover, it might increase the acceptance of modelling results (Basco-Carrera et al., 2017, p. 96).

Secondly, PM tools can help researchers and stakeholders better understand a given system and how it changes under varying conditions (Edwards & Kok, 2021, p. 1; Voinov & Bousquet, 2010, p. 1268). In situations where quantitative data is lacking, and people are willing to share the knowledge they acquired from living with and adapting to a local social-ecological system, participation is considered a viable option to gather data and complement or substitute scientific information (Aminpour et al., 2021, p. 1; Özesmi & Özesmi, 2004, pp. 43–44). However, participatory research is rarely just for knowledge generation but is often linked to the objective of *problem-solving*.

Thirdly, the participatory process aims to improve communication and collaboration between managers, scientists, and other stakeholders (Voinov & Bousquet, 2010, p. 1278). The primary motivation behind this is initiating a learning process where agreements and conflicts are highlighted and then addressed through deliberation and the exchange and negotiation of different norms, policies and worldviews (Henly-Shepard et al., 2015, p. 110; Voinov et al., 2018, p. 6). An assessment of the change in the participants' mental models can then be used to assess whether learning has occurred (Chi, 2008; Henly-Shepard et al., 2015).

Lastly, from a more instrumental perspective, given the ‘mainstreaming’ of the participation discourse in sustainability sciences and among public authorities, using participatory tools can increase the likelihood that a project is supported by funding bodies (Voinov et al., 2016, p. 202).

2.3 Introducing Fuzzy-Cognitive Mapping

This thesis focuses on the participatory potential of FCM, one type of PM that gained popularity in the past decade (Papageorgiou & Salmeron, 2013). Most of the general arguments behind PM also apply to FCM; nevertheless, there are some specificities to the method that differentiate it from other PM tools (for an overview of methods, see Voinov et al., 2018). The following section will, therefore, introduce FCM and its main epistemological assumptions and arguments.

FCM is a modelling approach where participants create a formalized and shared representation(s) of reality in a concept map (Voinov et al., 2018, p. 39). These maps have a specific format: the participants draw variables related to a central phenomenon and then connect them with causal arrows that “show the direction of influence between concepts” (Jetter & Kok, 2014, p. 46). These causal relations can be categorical (e.g. weak-medium-strong) or numerical, and the concept represented can be anything from social (e.g. education), non-material factors (e.g., trust) to physical variables (e.g., temperature) (Henly-Shepard et al., 2015, p. 111). Initially, these maps are only qualitative models complemented by the storyline of the participants. They become semi-quantitative when the qualitative connections are assigned values between 0-1 based on fuzzy logic (Kosko, 1986), to allow for the aggregation of maps, numerical analysis and scenario-building (Voinov et al., 2018, p. 11). Figure 1 provides an example of an FCM from the conducted case study.

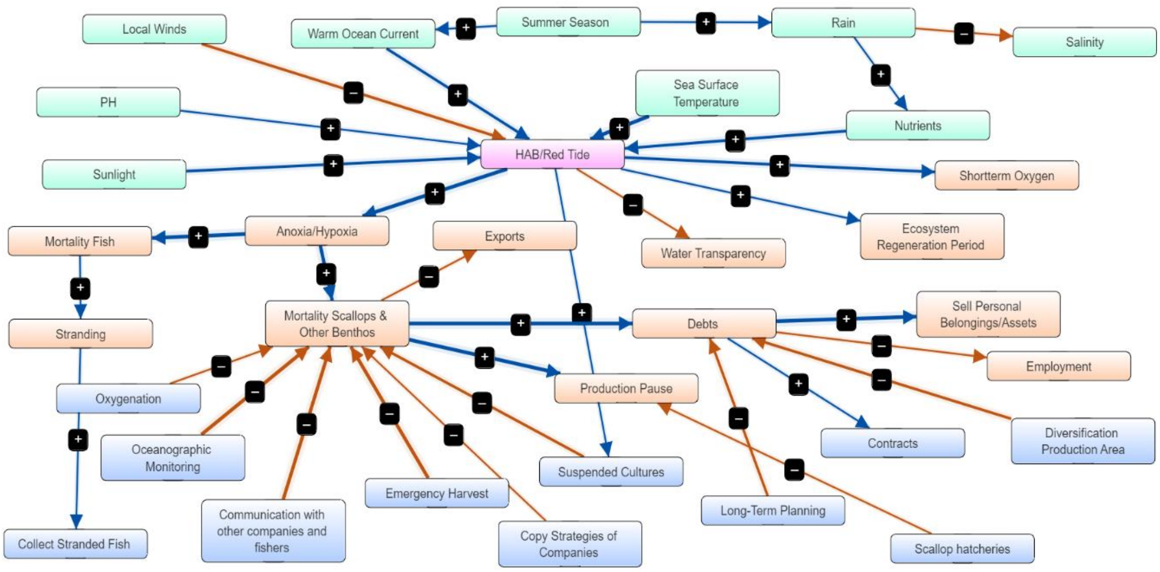

Figure 1. ***Example of an FCM***.

Shows the drivers (green), impacts (orange) and adaptation strategies (blue) in the context of HABs in Peru as perceived by representatives from a scallop mariculture company. Digitized with Mental Modeler Software.

FCM as a method originated in qualitative social research but was then applied to mathematics and computer science in the 1980s (Jetter & Kok, 2014, p. 45). It has become popular over the past twenty years, especially among applied sciences such as business planning, medicine, environmental management and research (p. 45). Consequently, FCM's diverse areas of application and the mixed qualitative and semi-quantitative scope make it challenging to determine an ontological and epistemological position. This ambiguity of the knowledge foundation of FCM is exacerbated since few studies make explicit their underlying epistemological and ontological assumptions. Generally, there are two common approaches/goals to FCM. One lies in developing a model that emphasizes stakeholder consensus or collective knowledge. Alternatively, FCM compares the perception of diverse individual actors or groups to shed light on the intricacies of a given social-ecological context. The following section will discuss these two approaches in more detail.

Many of the more technical FCM publications focus on capturing so-called "crowd wisdom" (Aminpour et al., 2020; Malone et al., 2009; Sterling et al., 2017). The argument is that we can better explain and predict real-world phenomena by merging expertise from diverse actor groups, drawing on the strengths of both scientific and local knowledge (Aminpour et al., 2020, p. 1). By mathematically aggregating people's beliefs and viewpoints, "crowd models" are expected to overcome individual biases and "produce more complete and potentially more accurate representations of complex problems" (Aminpour et al., 2021, p. 1). Moreover, FCM can help collect data in data-scarce environments, which can prepare the ground for more complex modelling (Mehryar et al., 2017, p. 360). Furthermore, the maps can be analysed through metrics and scenario-analysis software tools to test outcomes and interventions of the studied social-ecological system (Jordan et al., 2018, pp. 18–19). Compared to other modelling techniques, FCM is relatively simple and intuitive, meaning several modelling stages could be done in collaboration with stakeholders. These technical applications of FCM are characterized by a (post)positivist ontological stance: An external reality is assumed to exist and can be studied but never fully be understood because methods are imperfect and probabilistic (Creswell & Clark, 2017, p. 88; Guba & Lincoln, 1994, p. 110). The postpositivist stance is also reflected within the methodology of FCM: FCM restructures local narratives into quantifiable causal relations. FCM's "Cause-And-Effect Thinking" (p. 86) reduces complex qualitative data into limited sets of variables (Creswell & Clark, 2017). By restructuring qualitative perception into mental models, researchers argue that they "enable individuals to reason and make decisions, similar to a computer simulation, allowing different scenarios to be examined" (Henly-Shepard et al., 2015, p. 110).

Nevertheless, FCM studies are not always entirely (post)positivist. FCM studies investigate human-environment interactions that contain quantifiable environmental variables (e.g., temperature) and subjective social factors (e.g., well-being). Assumptions from interpretivism partly influence FCM since the goal is to better 'understand' and 'describe' the complexity of local social realities by designing qualitative storylines and comparing diverse perceptions (Özesmi & Özesmi, 2004, p. 44). The assumption is that reality is perceived in "the form of multiple, intangible mental constructions, socially and experientially based, local and specific in nature, (…) and dependent (…) on the individual person or group holding the constructions" (Guba & Lincoln, 1994, pp. 110–111). However, many FCM studies treat 'scientific' or 'expert' knowledge as a reference category to assess the validity of those 'other' representations of reality (Aminpour et al., 2020; Olazabal, Chiabai, et al., 2018). In other words, FCM assumes that diverse contextually bound claims about reality exist, which does not mean that all these claims are equally valid. Another epistemological aspect is that many FCM studies argue that the deliberative process of FCM leads to social learning and new types of consensus co-constructed between researchers and respondents (Henly-Shepard et al., 2015, p. 110). Strict ‘objectivity’ as understood by positivist approaches is therefore rejected. Instead, the researcher and the research subject are directly connected, influence each other and mediate knowledge through their values (Brent, 2022, p. 36; Guba & Lincoln, 1994, p. 111). This is not considered a weakness of the method, but recognizing and embracing the researcher's and stakeholder's subjectivities can be a crucial motivation behind FCM as a ‘participatory’ tool.

These ontological and epistemological tensions are why FCM, as a mixed method, is best justified by a ‘pragmatist’ worldview associated with post-normal science. Pragmatism claims that both post-positivist and interpretivist ontologies are correct. According to Dewey (1925), our experiences are constrained by an external reality that can be studied, but understanding this reality is limited to the “interpretations of our experience” (as cited in D. L. Morgan, 2014, p. 1048). Pragmatism, therefore, rejects the philosophical conflict over ontology and epistemology between (post)positivism and constructivism. For pragmatists, it is not the abstract relationship between the researcher and research object that matters but the “continual interaction of beliefs and actions” (D. L. Morgan, 2014, p. 1049). Consequently, research should not be limited to one of the paradigms but draw on various assumptions and methods based on what works best to solve particular problems (p. 1175).

2.4 Critique of Participation: Who Participates in What, How, Where, And Why?

Participatory research promises ‘learning’, ‘empowerment’, ‘democratization’ or more effective outcomes, but it often fails to critically reflect on whether these goals have been realised (Reed, 2008, p. 2421). In their book *Participation: The New Tyranny?* Cooke and Kothari (2001) distinguish between an ‘internal’/processual critique of participation and a more fundamental critique of the participatory discourse (p. 5). In the coming section, I aim to summarize some of the main arguments from both the processual and more fundamental critiques of participatory research processes.

What Degree of Participation?

The first question is, at what point does a process qualify as participatory? Over the years, many typologies have emerged to answer this question. Arnstein's (1969) "Ladder of Participation" is one of the oldest and most well-known of these typologies (Fig. 2). Using a ladder metaphor, she describes the levels of citizen participation in decision-making processes.

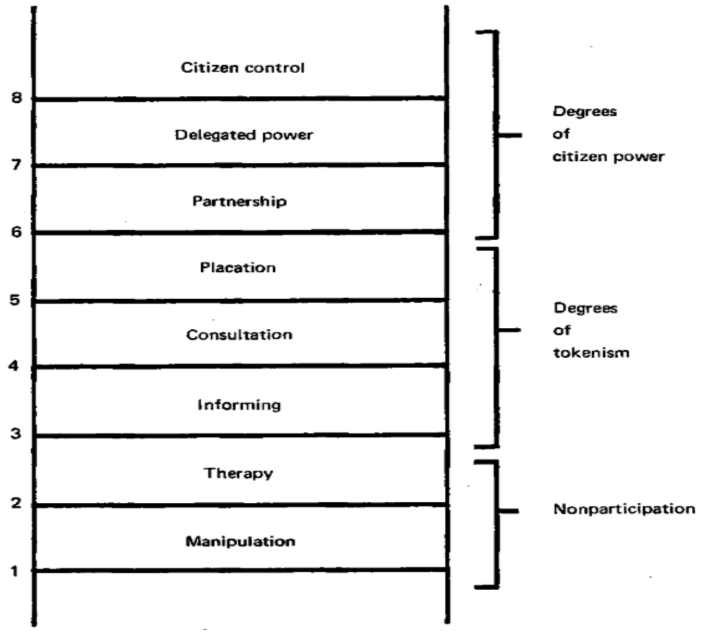

Figure 2. ***Arnstein's Ladder of Participation.***

Reprinted from: Arnstein, S. R. (1969). A Ladder Of Citizen Participation. Journal of the American Institute of Planners, 35(4), 216–224. https://doi.org/10.1080/01944366908977225.

The ladder consists of eight rungs, each representing a different degree of citizen power and involvement. It goes from non-participation, where people have no influence or power over the process, to consultation, which allows citizens to express their opinions and provide feedback on proposed decisions, to citizen control, where decision-making authority lies entirely with citizens. Here, they can initiate, develop, and implement decisions without relying on intermediaries or external authorities (Arnstein, 1969, p. 223). Arnstein's typology shows that participation is fundamentally about power and control (Cornwall, 2008, p. 271). Yet, her typology follows a relatively simple "logic of the more participation, the better" (Fritz & Binder, 2018, p. 3) and applies better to decision-making rather than research processes (Defila & Di Giulio, 2019, p. 93). Scholars who have built on Arnstein have emphasized that the significance lies not only in increasing the quantity of participation but also in understanding the intentions of those who initiate and participate in it and how they consequently utilize it (Pretty, 1995). Sarah White's (1996) typology, for instance, asserts that on the lowest level, participation is just a display to get funding or gain legitimacy for the process (nominal). On a higher level, people's involvement targets more efficient and cost-effective processes (instrumental). A third deeper level is about representing people's voices to ensure they have leverage over the process and are less dependent on the external researcher/practitioner. And the deepest level of participation empowers people to take the process into their own hands and challenge the injustices of the status quo (transformative) (pp. 7-9).

For PM, specifically, there have been different perspectives regarding what is considered participatory. Some assume a process to be participatory if data-gathering takes place in cooperation with the population during focus groups or interviews (Király et al., 2016, p. 6). Meanwhile, FCM is considered participatory because the stakeholder can directly co-create the initial models (Mielke et al., 2016, p. 75; Wiek, 2007, p. 55). Voinov et al. (2016) summarize the different claims into a typology similar to Arnstein's ladder of participation (pp. 197-199), which should be considered alongside typologies about the purpose/motivation of participatory research, like the ones by Pretty (1995) and White (1996) previously mentioned (see Fig. 3).

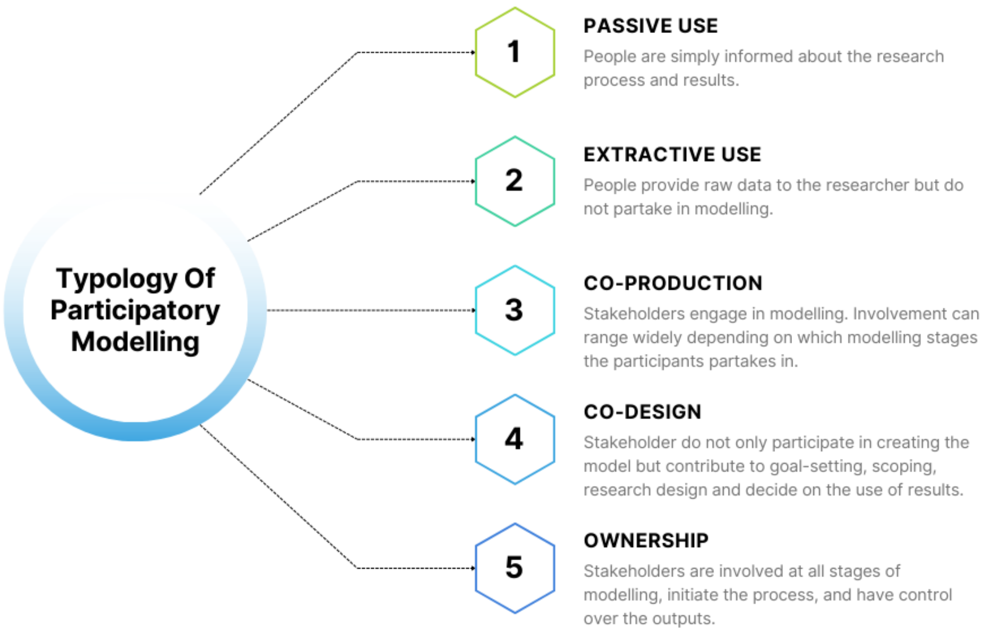

Figure 3. ***Degrees of Participation in Participatory Modelling.***

The author's own elaboration based on Voinov et al.'s (2016, p. 197) and Mielke et al. (2016, p. 75).

The Challenge of Power

The preceding sections have demonstrated that participatory research often centres around aspirations, highlighting the importance of coproduction in governance and knowledge generation (Turnhout et al., 2020, p. 15). However, a growing body of work addresses why these processes often fail to achieve their intended objectives and what can be done to improve the process (Cvitanovic et al., 2022; Few et al., 2007). A helpful framework of participatory challenges is Pohl's et al. (2010) distinction between the “challenge of power”, the “challenge of integration”, and the “challenge of sustainability” (pp. 271-273), which I used as a starting point to discuss the pitfalls of participatory approaches.

The “challenge of power” relates to the issue of who gets a voice in the process and whose interests are represented. It challenges Habermas’ vision of rational communication where viewpoints are equally heard “regardless of their values, power, expertise and argumentative skills” (Maru et al., 2009, p. 3015). In practice, communities are never homogenous. If power relations are not well understood, there is a risk that the results only reinforce the interests of an already-privileged group of actors while hiding behind a cloud of participatory/emancipatory rhetoric invisibilizing the concerns of marginalized groups (Cornwall, 2008, p. 281; Few et al., 2007, p. 50; Stringer et al., 2006, p. 17). This is a problem, especially in research where the end goal is to represent a community consensus, as often is the case for FCM. Too often, though, the analysis of power relations is missing, or the conception of power is simplistic. This is why Fritz and Binder (2020) call for multidimensional frameworks of power when reflecting on whose reality counts in the research process (p. 3).

Gaventa and Cornwall (2008) created a framework related to three dimensions of power in participatory processes building on the works of Dahl (1957), Foucault (1977, 1979), Bachrach and Baratz (1970) and Lukes (1974). First, the *instrumental* dimension of power is the ability of A to force B to do something they might otherwise not do (Gaventa & Cornwall, 2008, p. 173). It is fundamentally about power as a resource determining whose perspective dominates knowledge production (p. 173). In practice, researchers have shown that gender-dynamics, educational background, language barriers, and other social factors have led to research processes being dominated by some, disregarding the views of minorities and marginalized groups that are uneasy about expressing their opinions in a context of social stigmatisation (Lang et al., 2012, p. 35; Nyumba et al., 2018, p. 28; Stringer et al., 2006, p. 10). A second dimension shows that power is not just about who dominates the process itself but also relates to who takes part and whose knowledge is represented, which is associated with certain *structural* conditions (Fritz & Binder, 2018, p. 3; Gaventa & Cornwall, 2008, p. 174). For instance, Stringer et al., (2006) illustrate the dilemma that researchers face regarding the issue of inclusion:

> *"Should the issues identify the stakeholders? If so, how do we know we are focusing on the most relevant issues? Alternatively, should the stakeholders identify the issues? If so, how do we know the right stakeholders are included?" (p. 17)*

Often researchers struggle to include diverse actors in the group and focus on the issues of those that already have power in a community. There are many structural reasons behind this: (1) Researchers have limited time- and financial resources and decide to involve the 'usual suspects' that are easy to reach and have participated before (Lang et al., 2012, p. 36). (2) Researchers depend on the information of local gatekeepers that might be associated with one interest group, preventing others from participating (Cornwall, 2008, p. 274). (3) Those that struggle financially might not have the time and money to participate in the discussion. This is particularly an issue when the 'timing' of the group discussion is not sensitive to local work conditions. (4) The spaces of participation chosen by the researcher are not neutral but associated with specific interest groups (Cornwall, 2008, pp. 275-276). Moreover, whiteboards, pens and seating arrangements might create an 'academic' environment that deters people from participating (Cornwall, 2008, p. 275). (5) Similarly, the choice of method might be too demanding or alienating, and people might feel that they cannot contribute (Király et al., 2016, p. 14; Reed, 2008, p. 2421). Besides, there tends to be a trade-off between including a more diverse range of actors and a deeper, more meaningful participatory process (Cornwall, 2008, p. 276).

These two first dimensions of power are about whether and how forms of knowledge and expertise openly compete (p. 174). Nevertheless, Gaventa and Cornwall (2008) argue that the third and most pervasive form of *discursive* power prevents this open conflict between different perspectives from emerging in the first place (p. 174).

Based on Gramsci's 'hegemony' and Freire's (1981) 'culture of silence', they argue that the powerful influence consciousness in a way that particular grievances are not expressed (p. 174). For instance, the participatory process often only starts after project priorities have already been identified (Fritz & Binder, 2018, pp. 12–13). Researchers, powerful partners, and funding bodies exercise discursive power over what counts as priorities and which ideas, values and norms shape the process (p. 3-4). For example, communities are commonly structured into broad, bounded stakeholder group categories, and only those interests that fall into these groups will crystalize within the research process, often regardless of how people self-identify (Cornwall, 2008, p. 277). Overall, if the participatory approach does not pay attention to underlying power structures, it can contribute to the naturalisation of power relations and depoliticise the sustainability process (Williams, 2004, p. 562). However, Gaventa and Cornwall (2008) argue that power is not always negatively-connotated and repressive. Based on Foucault's work, they highlight that power and knowledge directly imply one another as a network of social boundaries or "regimes of truth" that set limits to the actions of all actors (p. 176). These boundaries can be shifted when "through a more open and democratic process, new categories of knowledge, based on local realities, are framed and given voice" (Gaventa & Cornwall, 2008, p. 179). This has become a key goal of recent 'participatory action research' (p. 179).

From a different point of view, theorists with a more formalistic understanding of power might agree that power in itself may not be inherently problematic; nevertheless, they would argue that it is the informal or improper exercise of power that gives rise to concerns (Luhmann, 1965, p. 146, 1984, p. 40). While participatory sustainability sciences are often built on the idea of democratizing knowledge, promoting civic culture and addressing sustainability challenges, researchers do not have an official democratic mandate, and they are rarely subjected to accountability mechanisms (Lang et al., 2012, p. 36). Nevertheless, Strohschneider (2014) points out that in democracies, political legitimacy does not derive from processes of knowledge production or truth claims but from electoral processes (p. 188). By promising learning and consensus-building, this type of participatory research risks downplaying the inherent antagonism between interest groups and undermining the political processes and institutions that deal with these power struggles (p. 190).

The Challenge of Integration: Whose Reality?

The mobilization and integration of diverse forms of knowledge, with their unique identities, worldviews and ethics, lie at the heart of the promises of participatory sustainability research (Raymond et al., 2010; Tengö et al., 2017). Addressing the complexities associated with this goal is called the "challenge of integration" (Pohl et al., 2010, p. 271).

Participatory research faces a tension between making knowledge legible and applicable to find solutions for sustainability challenges beyond a context but avoiding treating it only as a cost-efficient resource in data-scarce environments that is transformed under the logic of the researcher’s knowledge system (Cooke & Kothari, 2001, p. 6; Cornwall, 2006, p. 72; Mohan & Stokke, 2000, p. 255). This is especially a risk in fields like PM, which are deeply grounded in a positivist knowledge system and often aim to inform or improve management or decision-making. Critical scholars have highlighted that in this type of participatory research, too much authority is given to “scientific expertise vis-à-vis other knowledge systems” (Turnhout et al., 2020, p. 16). Moreover, some participatory methods can force the participants into pre-established cognitive frames, limiting their ability to express their perspectives freely and instead conform to the researcher's predetermined vision (Király et al., 2016, p. 14). The epistemological frame relates to the third ‘discursive’ dimension of power, where “the asymmetrical control of knowledge productions of ‘others’ can severely limit the possibilities which can be either imagined or acted upon” (Gaventa & Cornwall, 2008, p. 176). For instance, a tendency has emerged favouring forms of knowledge that can be measured or quantified while other types of information are disregarded (Bennett, 2016, p. 583; Norström et al., 2020, p. 186). This bias raises concerns regarding cognitive justice, which advocates for scientific knowledge to be placed on an equal footing with different ways of knowing (Santos, 2014, p. 42). An additional issue related to knowledge integration is the tendency to treat ‘local/traditional knowledge’ and ‘scientific knowledge’ as uniform categories with specific characteristics rather than recognizing their fluid nature and heterogeneity (Raymond et al., 2010, pp. 1767–1769; Scott, 1998, p. 347).

A related critique revolves around the lack of direct representation and control of local knowledge by the local population initially providing it since “few theorists accept the utility of indigenous knowledge in itself, and most writings first propose the validation of indigenous knowledge by means of scientific criteria" (Agrawal, 1995b, p. 5). Agrawal (2002) calls this "scientization", which can be broken down into three stages (p. 290). In the first stage of "particularization", all valuable elements are separated from other practices, pieces of knowledge and beliefs next to which they co-existed (Agrawal, 2002, p. 290). The second stage is to test that information according to the criteria and procedures of science. During this "validation" (p. 290), local knowledge and practices are abstracted into models, statistics, or theoretical frameworks. Lastly, the validated and abstracted information is to be transferred to other contexts during the process of "generalization" (p. 291). Through these three stages, the "truth-content" of local knowledge is established, and it becomes legible for governance and decision-making processes (Foucault, 2000, pp. 60–61). This perspective is particularly prevalent in problem-solving sciences like sustainability studies, where global priorities and discourses significantly influence research agendas. Nevertheless, in his book *Seeing Like A State*, James Scott (1998) problematizes this simplification of local practical knowledge. He argues that the "Scientization" strips of the characteristics that make these forms of knowledge valuable in the first place: local knowledge – that he describes as *Mētis* – consists of practical skills and acquired intelligence that people gain by constantly adapting to a changing natural and human environment (Scott, 1998, p. 347). The intricate nature of this knowledge, with its detailed, time- and context-specific characteristics, subtle nuances, and practical applications, will necessarily be lost when being transformed into formal representations (Agrawal, 2002, p. 292). As Scott (1998) argues, the risk associated with abstractions such as maps and models is that they hold the potential and even the intention to reshape much of the reality they depict (p. 18). The depicted reality, however, will necessarily ignore features of the far-more complex existing social order, which might have negative consequences when policies and solutions are derived from it that do not consider the whole picture (p. 21).

I pointed towards this fundamental criticism not to question participatory modelling research but to advocate for deeper reflection on its epistemological challenges. This aspect has received limited attention in the existing literature on FCM. While it is impossible to eliminate the epistemological issues inherent in participatory modelling, researchers can strive to mitigate challenges associated with knowledge integration by being more mindful of these arguments from the outset of the research process.

The Challenge of Sustainability: What Impacts of Participation?

In their paper, Pohl et al. (2010) argue that participatory sustainability research aims to improve institutions, values, norms, and practices to achieve more sustainable use of resources and more equitable access (p. 272). Within my framework, I approach this third challenge broadly as a critical discussion about what is achieved by the participatory process and what happens with the results.

Lang et al. (2012) argue that the results from participatory research are usually criticized from two sides. On the one hand, the science community questions the findings' reliability, validity, and autonomy (p. 26). Additionally, they contend that due to its emphasis on “issues of immediate social relevance” (Mielke et al., 2016, p. 78), participatory research produces, at times, shallow, repetitious research outputs with relatively little theoretical weight (Mielke et al., 2016, p. 78; Oliver et al., 2019, p. 5; Strohschneider, 2014, pp. 181–182). Besides, scholars criticize that studies do not include clear indicators of whether participation outcomes have been met: In the case of social learning, for instance, Reed et al. (2010) advocate for researchers to claim social learning only when there is evidence of individuals undergoing a change in attitudes, demonstrating that this change extends beyond the individual level and influences the broader community while being the result of social interactions among the actors involved in the process (p. 2). For the case of ‘empowerment’, meanwhile, Williams (2004) has called for an explicit political analysis of impacts to see whether the participatory process has influenced political networks, representation or changed the salience or language of political claims (pp. 567-568).

In contrast to the scientific community, participants might be disappointed about the practical or societal impact of the research process (Lang et al., 2012, p. 26). Participants usually expect concrete and applicable results. If they took part in research processes several times without drawing direct benefits, they might grow cynical or tired of the process – which is described as ‘participation fatigue’ (Cornwall, 2008, p. 274; Reed, 2008, p. 2420). This is common because the research process is slow, does not guarantee outputs and lacks channels to influence managerial decisions (Oliver et al., 2019, p. 3; Williams, 2004, p. 571). Additionally, there is an issue of ownership and control over the results. Often participants spend substantial time, energy and resources on the process and provide sensitive information, only then to see how that information is re-arranged according to the needs of the research agenda, published without sufficient credits to the participants and disseminated without explicit consent (Banks et al., 2013, p. 267; Oliver et al., 2019, p. 6). This is partly due to the limits of institutional and conventional research standards and ethics to deal with multiple actors' involvement and close cooperation (Banks et al., 2013, p. 263).

As a result, a trade-off exists between the goals of participatory research. Researchers in sustainability studies often seek legitimacy for their work based on three distinct aspects: (1) producing robust and credible outcomes regarding sustainability challenges (scientific legitimacy), (2) generating relevance and usefulness for the stakeholders they collaborate with (practical legitimacy), and (3) meeting normative conditions such as equality, fairness, and broader societal significance (Defila & Di Giulio, 2019, p. 100). These priorities cannot be equally addressed within a single project (p. 100). Researchers, therefore, should be realistic, explicit and transparent regarding their expectations about what the participatory process will most likely have as an outcome to “avoid potential disappointment and escalating frustration during and/or after a particular process” (Defila & Di Giulio, 2019, p. 102; Király et al., 2016, p. 5). Finally, Reed (2008) argues that “the evaluation of participatory processes should itself be participatory, with stakeholders selecting and applying the evaluation criteria “ (p. 2421).

3 Case Study: Fuzzy Cognitive Mapping of Harmful Algal Blooms with Coastal Communities in Peru

3.1 Case Selection & Study Context

To evaluate the strength and weaknesses of the participatory aspects of FCM, I applied the method to a case study of the socio-economic dimension of HABs in Peru. I investigated the social- and economic impacts of HABs in two coastal communities that depend heavily on mariculture and fishing – Sechura Bay and Paracas Bay in Peru. During two months of fieldwork, I conducted 17 focus group discussions with around 50 fishers, mariculture producers, local officials, and scientists in Lima, Sechura and Paracas to map the drivers, impacts and adaptation strategies related to HABs. The group discussion were supplemented by 6 individual interviews with scientists and scallop producers for more in-depth qualitative information. The following section introduces the issue of HABs in Peru, justifies the case selection and presents the research objectives. The subsequent chapter outlines the research design and the FCM analysis approach. The third chapter of the case study provides the findings and a short conclusion.

3.1.1 The Social Dimension of Harmful Algal Blooms

The term "Algal Bloom" refers to an overgrowth of microalgae or cyanobacteria in oceans, rivers, and lakes (Lehman et al., 2021, p. 1). Due to the associated discolourations, they are also known as Red Tides worldwide. HABs can be harmful for several reasons: Some algae species produce toxins (Anderson, 2009, p. 342) that lead to diseases like Paralytic shellfish poisoning (PSP) which can even be life-threatening (Trainer et al., 2010, p. 34). Additionally, HABs can cause mass mortality of marine fauna as the breakdown of their biomass causes low oxygen levels (hypoxia) or even complete oxygen depletion (anoxia) and their presence in the water column can lead to light attenuation (Anderson, 2009, p. 342; G. Pitcher & Jacinto, 2020). HABs can impose significant burdens on communities through the closure of fishing grounds and coastal recreational areas, as well as leading to mass mortality of marine life. HABs occur worldwide and have intensified rural poverty, food insecurities and led to declines in seafood exports and tourism in some places (Ekstrom et al., 2020, p. 1; Van Dorah et al., 2016, p. 578). The 2022 algae bloom in Germany's river Oder and the 2016 collapse of the Chilean salmon industry at Chiloé Island are two recent examples of these profound socio-economic impacts (Free et al., 2023; Mascareño et al., 2020). Currently, the economic costs of HABs are estimated at approximately 8 $billion per year globally (Brown et al., 2020, p. 1). These costs are likely to increase since HABs in the marine realm have grown in frequency due to increased nutrient run-offs from anthropogenic activities, maritime traffic and the spread of invasive species, as well as factors related to climate change, such as rising ocean temperatures, longer and more frequent marine heatwaves, acidification and changing patterns in rainfall (Anderson, 2009; Dai et al., 2023; Heisler et al., 2008; Paerl, 1997; Wurtsbaugh et al., 2019).

In recent years, more HABs have been recorded in Latin America (Hallegraeff, 2021; López-Cortés et al., 2019). The impacts of HABs can be catastrophic since coastal communities heavily depend on fishing, aquaculture and marine tourism (Ferrol-Schulte et al., 2013, p. 253). Until recently a majority of studies on HABs have emerged from the natural science community, and information on the human impacts of HABs is still very scarce (Bauer et al., 2010; López-Cortés et al., 2019, p. 7; Ritzman et al., 2018, p. 36). To develop compelling and legitimate disaster responses to extreme events like HABs, researchers highlight the need for more data on people's perceptions and local social dynamics to promote people's ability to cope with social-ecological crises (Armstrong et al., 2022, p. 588; Kriegl et al., 2021, p. 2; Schwermer et al., 2021, pp. 8–9). Incorporating the stakeholders into the research process is, therefore, expected to help identify adaptation pathways that are locally accepted (C. Willis et al., 2018, p. 232). Nevertheless, relatively few studies on HABs draw on local perception.

3.1.2 Harmful Algal Blooms in Peru

In Peru, research on HABs is growing: HABs are frequently observed in coastal areas of the Humboldt Upwelling System, and toxins and mortality events related to low oxygen levels are increasingly reported (G. C. Pitcher et al., 2017; Sunesen et al., 2021; Trainer et al., 2010, p. 48). Currently, most studies analyse the presence of potentially-toxic microalgae species and characterise the oceanographic conditions that lead to the blooms (Alcántara-Rubira et al., 2018; Romero et al., 2022; Sanchez et al., 2017; Tenorio et al., 2018). Others focus on direct ecological impacts such as the evolution of anoxic conditions or shellfish poisoning (Cuellar-Martinez et al., 2021; Cueto-Vega et al., 2022).

Even though previous studies indicated that HABs were perceived as a burden by coastal communities, these impacts are seldom reported or analysed (see Badjeck et al., 2009, p. 226; Kluger et al., 2022a, p. 318). The stakeholders' concerns, the scientific evidence, and the broader call for social science research on HABs provided the motivation to conduct an exploratory study on the social dimension of HABs in Peru.

3.1.3 Case Study Objectives

According to Bauer et al. (2010), social science research on HABs should cover their causes, consequences and people's responses to them (p. 76). Therefore, I decided to conduct a participatory modelling of the drivers, impacts and adaptation strategies. My two case-study objectives are the following:

(1) *What are the drivers and socio-economic impacts of Harmful Algae Blooms in coastal Peru, and how do diverse stakeholders and institutions adapt to them?*
(2) *To what extent do the adaptive capacities to HABs vary among stakeholders?*

My case study investigates these questions through a 'social-ecological system' lens, whose goal is to understand social-ecological interactions in a given context and see how that understanding can help us work towards sustainability goals (Berkes et al., 2003; Ostrom, 2009; Partelow, 2018, p. 3). FCM is useful in this context because it enables local actors to construct a narrative about how a certain natural phenomenon unfolds socially (see Partelow et al., 2021; Schwermer et al., 2021). Moreover, FCM is used to combine individual or interest group models into the aforementioned 'crowd models' (Aminpour et al., 2020, pp. 6–7; Gray, 2021; Voinov et al., 2016, p. 197). These crowd models can then be used to run 'what-if' scenarios: certain variables in the system are artificially changed to see how the overall system responds to such changes according to stakeholder's perception (Özesmi & Özesmi, 2004, p. 55). Scenario analysis then permits assessing the effectiveness and desirability of adaptation strategies (Özesmi & Özesmi, 2004, p. 43). Overall, participatory modelling of the social-ecological system is expected to mitigate some problems of traditional modelling, such as oversimplification of local social realities and the lack of context-sensitivity (Garteizgogeascoa et al., 2020, p. 15; Zainal, 2007, p. 1). Since the aim of my study was to identify the most important drivers, impacts and adaptation strategies related to HABs but also compare the differences in perception and adaptive capacity of diverse interest groups, I decided to:

(1) Create models for the individual stakeholder groups to explore perception differences of HABs.
(2) Create a ‘crowd model’ to see what factors were most important across all groups and explore adaptation strategies' effectiveness through scenario analysis.
(3) Complement the FCM models with qualitative data from focus groups and semi-structured interviews to gain detailed knowledge of stakeholders’ understanding of system components and the contexts of HABs (Schwermer et al., 2021, p. 4).

3.1.4 Two Ocean-Economy Hotspots in Peru: Sechura and Paracas

My study focused on two sites: Sechura Bay and the bays around Paracas. Sechura Bay is located in the northern province of Piura, while Paracas is in the central Peruvian region of Ica – south of Pisco (Fig. 4). Both bays are influenced by the Humboldt Current Upwelling System, which is one of the most productive marine ecosystems worldwide because of the upwelling of cold, nutrient-rich waters to the surface layer (Garteizgogeascoa et al., 2020, p. 3). Peru’s fishing and aquaculture is the country’s third-largest sector in terms of GDP and an essential source of employment (Ministerio de la Producción [PRODUCE], 2021, p. 102).

There are several reasons why I chose these sites. In Sechura and Paracas, small-scale fisheries (SSF), tourism, and, above all, mariculture take place relatively close to the shore, where the effects of HABs can be most severe (Brown et al., 2020, p. 1663; Díaz et al., 2019, p. 2; Mendo et al., 2016, p. 1089); hence the populations are vulnerable to the impacts of HABs. Moreover – being critical economic zones – much of the national HAB research focuses on them (Aguirre-Velarde et al., 2019; Cuellar-Martinez et al., 2021, 2023; Cueto-Vega et al., 2022; Orozco et al., 2017; Romero et al., 2022; Sanchez et al., 2017). Research on HAB’s social aspects can complement these studies and enable comparison between the local stakeholder’s perceptions and the scientific perspective.

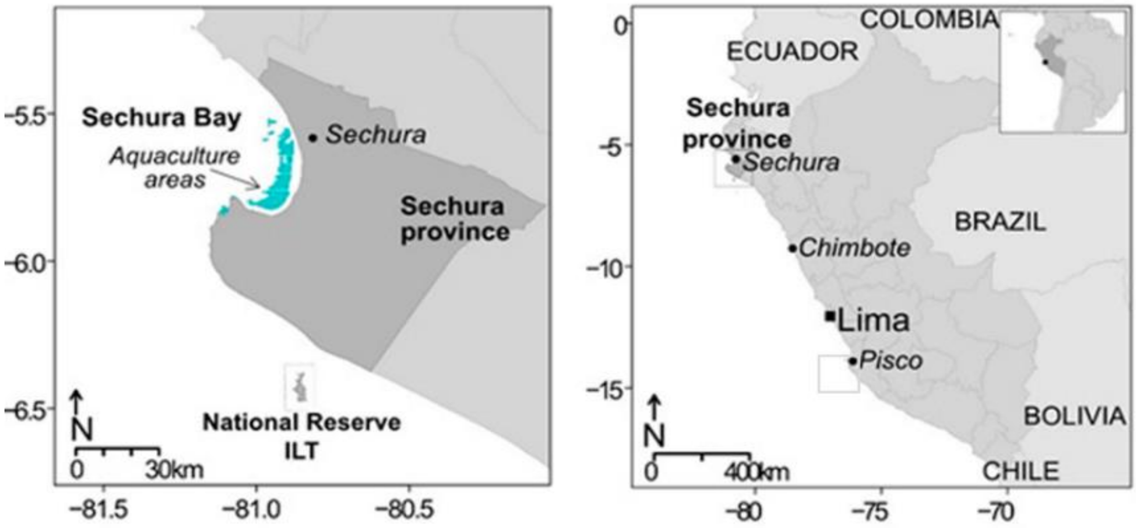

Figure 4. ***Map of Peru and Case Study Sites.***

Reprinted from Kluger, L. C., Schlüter, A., Garteizgogeascoa, M., & Damonte, G. (2022). Materialities, discourses and governance: Scallop culture in Sechura, Peru. Journal of Environmental Policy & Planning, 24(3), p. 311. https://doi.org/10.1080/1523908X.2022.2047620.

Sechura

Sechura Bay is one of the most important aquaculture sites in Peru: as of 2013, it accounted for 83% of national scallop production and 50% of Latin America's scallop production, making Peru the third largest scallop producer worldwide (2019) after China and Japan (Kluger, Taylor, et al., 2019, p. 188; Mendo & Quevedo, 2020, p. 30). In Sechura alone, the sector is estimated to employ 3,000 seasonal workers, 5,000 artisanal fishers, and 20,000 indirect jobs in processing plants, logistics, and other associated services (Kluger, Kochalski, et al., 2019, p. 1124). Until recently, most scallops were cultivated as bottom cultures throughout the bay (an activity called sea ranching or mariculture). The production in the open ocean makes mariculture vulnerable to natural shocks such as HABs (Kluger et al., 2022a, p. 310). Indeed, regular mortality events of scallops have been reported in the bay due to factors such as HABs, marine heatwaves and sulfuric plumes (Cueto-Vega et al., 2022, p. 156). In some years, up to 100% of the yearly production was destroyed, primarily due to low oxygen levels (p. 156). Moreover, the El Niño Southern Oscillation (ENSO), a climate-oceanic phenomenon that causes extreme climatic variation, strongly influences the bay (Romagnoni et al., 2022, p. 390). During the warm El Niño phase, sea surface temperature and precipitation increase, altering the dynamics of marine species and making certain HABs more likely (Cuellar-

Martinez et al., 2023, p. 6; Sánchez et al., 2022, p. 460). In recent years, these effects were felt during the localized *Coastal El Niño* in 2017 that heavily affected the SSF sector and paralyzed scallop production for more than a year (Kluger, Kochalski, et al., 2019; Kriegl et al., 2021, 2022).

Scallop production in Sechura started in the 1990s under an open-access regime operated primarily by Small-Scale Mariculture producers (SSM). Throughout the 2000s, it evolved into an activity formally and informally managed by SSM associations (Schlüter et al., 2021, p. 14). Since 2009, scallops can be exported to international markets (Kluger et al., 2022a, p. 313). This focus on exports led to the entry of large-scale mariculture companies (LSM) that invested in scallop concessions, processing plants and new production methods (Kluger et al., 2022a, p. 316; Schlüter et al., 2021, p. 7). Currently, 85% of the production is exported, with Europe and the US being the most important markets (Kluger et al., 2022a, p. 313; Mendo & Quevedo, 2020, p. 91). SSM producers increasingly depend on larger companies, given their control of processing plants, their investments and changes in the governance framework (Schlüter et al., 2021, p. 7). While SSM and LSM producers continue to coexist in Sechura Bay, the bay can now be characterized as a private property regime: three-quarters of the scallop concessions are informally or formally controlled by private investors, and several smaller producers work for the companies through contracts (Schlüter et al., 2021, p. 8).

Next to the Mariculture-Sector, SSF is another sector potentially affected by HABs. Most of Peru’s artisanal fishers operate informally but have exclusive fishing rights up to 5 nautical miles from the coast (Romagnoni et al., 2022, p. 391). The Piura region – where Sechura is located – hosts one-third of Peru’s artisanal fleet, and most of the population depends directly or indirectly on the sector (p. 392). The fleet constantly adapts to natural variabilities such as ENSO and targets diverse species with different types of gears such as purse seine, gillnets or with small rafts that use hooks and lines (Kluger, Kochalski, et al., 2019, p. 1124). The artisanal fishers not only supply the national markets with fish but are also an essential food source in the region.

Paracas

While Sechura is now the largest scallop producer, the Paracas region was historically an important production site. Most production shifted to Sechura in the early

2000s due to better seed supply, more favourable ecological conditions and mismanagement (Kluger, Taylor, et al., 2019, pp. 190–191). Nevertheless, SSM production remains in the southern bays. In contrast to Sechura, however, output from Paracas is mostly for national markets. The artisanal- and industrial fishing sector is another important source of employment and income (Garteizgogeascoa et al., 2020, p. 3). Several large fish processing plants are operated by multinational companies that produce primarily canned fish, fish oil and fish meal (p. 4). Lastly, the area has developed into Peru’s third most-visited tourist region, with 3.5 million visitors annually (pp. 3-4).

Like in Sechura, in Paracas, HABs were also reported to cause regular die-offs of scallops and fish because of anoxic conditions (Cueto-Vega et al., 2022). Kahru et al. (2004) provide one of the few accounts of the socio-economic impacts of these blooms. Their study and a similar publication by Cabello et al. (2002) established that pollution from local fish processing plants resulted in eutrophication, leading to the proliferation of HABs in the bay. The blooms resulted in the stranding of tons of dead fish and the mortality of scallops, which forced the local authorities to close fishing plants and ports (Kahru et al., 2004, p. 1). This caused a revenue loss of $27.5 million for the anchovy industry and $1 million for the mariculture sector, resulting in roadblocks and protests by the local population against the fishing companies (p. 1). Even though the fishing companies established waste treatment facilities and renewed their 12-km long wastewater pipeline in 2006, the social conflict between fishing companies, mariculture producers, and fishers remains high (Gonzalez, 2008, p. 203).

3.2 Research Design & Methodology

As mentioned in the first part, FCMs are semi-quantitative models consisting of concepts and causal relations representing how an individual or group thinks about a given system or phenomenon (Özesmi & Özesmi, 2004, p. 44). In my case, the maps represent the stakeholder’s perception of the social-ecological system of HABs in Sechura and Paracas. I followed a ‘dynamical’ FCM approach: the idea behind this is to represent vague and imprecise information quantitatively and to see how causal influences travel “through a system when it is subject to change or intervention” (Barbrook-Johnson & Penn, 2022, p. 80). It is semi-quantitative because values are not absolute but only show the relative size of an effect compared to other system components or the baseline (Jetter & Kok, 2014, p. 46). I decided first to use three levels of effect strength (+, ++ and +++) and (-, -- and ---) during the focus groups to make the mapping more intuitive for the participants. The three weights were then treated as (0.33, 0.66, 1) and digitized into adjacency matrices to enable aggregation and semi-quantitative analysis. The FCM literature has been criticized for lack of transparency during the data collection stage and analysis process; to address this issue, I applied Olazabal, Neumann, et al.'s (2018) transparency and reporting procedure (Appendix A).

The following steps summarize my research design: (1) Map creation with focus groups in Peru, (2) Qualitative Processing, (3) Map Translation into Adjacency Matrices, (4) Quantitative Aggregation, (5) Analysis with Graph Statistics and Scenarios (see Özesmi & Özesmi, 2004). The coming sections present an overview of my research design choices (outlined in Appendix B), shaping the model's final appearance.[1] The limitations of the design choices will be critically discussed in the last part of this thesis, focusing on their participatory aspects.

3.2.1 Stakeholder Analysis & Selection

In most FCM studies, the researcher pre-defines broad stakeholder groups and sets criteria for who qualifies for these groups. Power dynamics significantly influence this critical decision-making stage, as it determines who is given a voice and influence within the process. Even though FCM studies aim to represent diverse knowledge, discussions on the representation and selection of participants are often relatively short, a limitation that also applies to my case study. Often homogenous stakeholder groups are assumed to exist without details on how these groups were “defined, verified and recruited” (Nyumba et al., 2018, p. 28).

Based on the literature and stakeholder reports about HABs in Peru, I selected five stakeholder groups. These include Scientific Experts (LE), Local Authorities (LA), Small-Scale Mariculture (SSM), Large-Scale Mariculture (LSM) and Small-Scale Fishers (SSF). The aim was to represent diverse knowledge and expertise in different areas, from

[1] For more comprehensive discussions on the methodological and technical aspects of FCM, I recommend referring to the works of Felix et al. (2019), Gray et al. (2014), Jetter & Kok (2014)

local-ecological knowledge to scientific understanding (Olazabal, Neumann, et al., 2018, p. 801). Specifically, I chose to include the mariculture and SSF sectors due to their reported disproportional impact from HABs. Both categories are vast and homogenize a diverse group of people, so more information can be found in Appendix C and the Supplementary Materials. I distinguished between SSM and LSM since the literature suggests that their production modes differ, as do their strategies for responding to HABs (Kluger, Kochalski, et al., 2019, p. 1124). Specifically, LSM control the whole value chain (harvest, processing, export), operate as companies, and possess substantial concessions in the bay (Kluger et al., 2022; Schlüter et al., 2021). I interviewed representatives from the largest scallop production company in Sechura, employing over 100 individuals (Mendo & Quevedo, 2020, p. 53; Focus Group 5, Sechura, 07.10.22). Additionally, I engaged with SSM producers from diverse backgrounds, such as divers, heads of SSM associations, independent producers, family members, and former producers who transitioned to work in tourism or fishing.

The last two stakeholders' categories, Scientific Experts (LE) and Local Authorities (LA), I chose because I wanted to include scientific knowledge and compare the perspective of local state authorities with the producer's perception. I talked to representatives of the local municipality, which I classified as LA. Moreover, I organized focus groups with scientists from the Peruvian Institute of the Sea (IMARPE) and the National Agency for Fisheries Health (SANIPES), which I considered scientific experts. Here it becomes clear that it is challenging to categorize diverse individuals into broad stakeholder categories: even though SANIPES and IMARPE are technically part of the Ministry of Production and state authorities, I classified them as Local (Scientific) Experts because they were talking to me as scientists rather than state representatives. However, the lines between stakeholder groups are blurred. Some scientists are also state representatives; many fishers work in mariculture, and several mariculture operators in SSF or tourism.

3.2.2 Focus Group Design

Instead of creating maps with individual participants, I collected data during group discussions. The literature argues that focus groups are time- and resource-efficient (Nyumba et al., 2018, p. 28). Moreover, they provide an integrated map already representing a particular group's consensus (Jetter & Kok, 2014, p. 50). Additionally, focus groups might facilitate social learning and knowledge exchange (Gray et al., 2014, p. 42). Disadvantages of focus group mapping include power imbalances during the discussion, less knowledge diversity, less time to clarify what participants said and a bias towards shared beliefs (Jetter & Kok, 2014, p. 50). I invited people from within a specific stakeholder group (e.g. scientists) to each meeting rather than have mixed-stakeholder groups to minimize social unease (Nyumba et al., 2018, p. 28). I also restricted the number of participants per focus group to five to ensure I could facilitate the meeting. Moreover, I aimed to keep them no longer than two hours to avoid participants' fatigue (Nyumba et al., 2018, p. 23). Overall, 18 focus group discussions with 48 participants took place, of which one had to be excluded from the FCM analysis (see Appendix C). Five focus groups were with scientists, two groups with local authorities, seven groups with SSM (one excluded), one group with LSM, two groups with SSF and one group with a fishing company.

My strategies to reach out to the stakeholders differed between groups and locations. As part of the long-standing research project *Humboldt-Tipping*, I received contacts from project colleagues who had previously worked in the study locations. Moreover, I participated at an international conference on the Humboldt Upwelling System in Lima and during the project’s Symposium, where I made contacts mainly with local scientists, fishers, and scallop producers. Afterwards, I contacted the institution’s offices, fishing/mariculture associations, and producers and attended events in Sechura and Paracas. The snowball sampling worked relatively effectively but also introduced certain selection biases I will discuss later.

The next choice was about how to run the group discussion. While concepts can be pre-defined by the researcher to make post-processing and model creation easier, I let the participants brainstorm and arrange concepts freely (Gray et al., 2014, p. 43). This option was appropriate since my study objective was to explore HABs based on people’s perceptions. Introducing pre-defined concepts would have defeated the purpose of the explorative design and limited the generation of new knowledge (Olazabal, Neumann, et al., 2018, p. 801). A disadvantage of this approach is that the maps might look too different to be aggregated, making subjective post-processing necessary, where the researcher standardizes names, relations and re-groups concepts (Gray et al., 2014, p. 43).

Another question is whether the researcher should ‘activate knowledge’ by asking questions and introducing ideas or should only moderate the discussion (Jetter & Kok, 2014, p. 50). My choice was to reduce the researcher's influence and leave as much as possible to the participants. Table 1 outlines the structure of the focus groups.

Focus Group Agenda
(1) Presentation Round: Name, Profession (2) Short Introductory Brainstorm a. What Are HABs to you? (Definitions) b. When did the last event occur and how did you experience it? (3) Researcher explains the method of FCM using an example. (4) Mapping (Brainstorm Concepts & Assign Weights, Ask for Definitions of Concepts, Clarifications) a. What are the drivers of HABs? b. What are the impacts of HABs? c. What are (potential) adaptation strategies? (5) Outro Discussion: What adaptation strategies would you suggest? What could work best?

Table 1. ***Structure of the Focus Group Discussions.***

I took a role as a moderator, highlighting that I had limited knowledge about HABs in Peru (Jetter & Kok, 2014, p. 49). Nevertheless, focus group discussions remain a process where knowledge is constructed by the participants as much as by the researcher. All maps were created with coloured Post-its and written on portable whiteboards (see Fig. 5). This setup allowed me to organize the focus groups in different places, including office spaces, people’s houses, and restaurants. All the original/unedited stakeholder maps are accessible in Appendix A. It was recommended to record the focus group discussion (after consent was given) to be able to trace meanings of concepts, which is essential to avoid making mistakes and misrepresent information during the post-processing stage (Olazabal, Neumann, et al., 2018, p. 797).

Figure 5. ***FCM Created by Mariculture Producers in Sechura***.

Drivers of HABs are yellow, impacts are red and adaptation strategies orange.

3.2.3 Qualitative Analysis & Pre-Processing of Maps

FCM offers the possibility for qualitative and quantitative analysis (Gray et al., 2015, p. 12; Kok, 2009, p. 130). I complemented the semi-quantitative analysis through a qualitative content analysis of the focus group recordings. The aim was to see how stakeholders define and describe the components in their maps and provide contextual information to these definitions (Schwermer et al., 2021, p. 4). Content analysis reduces complex narratives into codes and categories that can be analyzed (Margolis & Zunjarwad, 2018, p. 1061). Qualitative coding is essential because the maps must be pre-processed to prepare them for quantitative analysis. Pre-processing is about establishing a common terminology, improving the coherence of maps and "establishing a common level of detail to which the problem will be modelled" (Olazabal, Neumann et al., 2018, p. 804). It includes standardizing names, inversing relationships, correcting errors, merging variables into categories and deleting concepts that go beyond system boundaries or that are strictly definitional (Jetter & Kok, 2014, pp. 51–52; Olazabal, Neumann et al., 2018, p. 803). This is the stage where the researcher influences the representation of the stakeholder's knowledge most (Olazabal, Neumann, et al., 2018, p. 802). I describe my qualitative processing steps in Appendix D and reproducibility documents in Appendix

A. While processing reduced the number of concepts, the maps were still extensive compared to the final maps of other FCM studies. Large maps are more difficult to interpret and make quantitative analysis less comprehensive (Fig. 6); nevertheless, I tried not to significantly alter the participant's representation since participants were not directly involved during the processing and analysis stages (Jetter & Kok, 2014, p. 53).

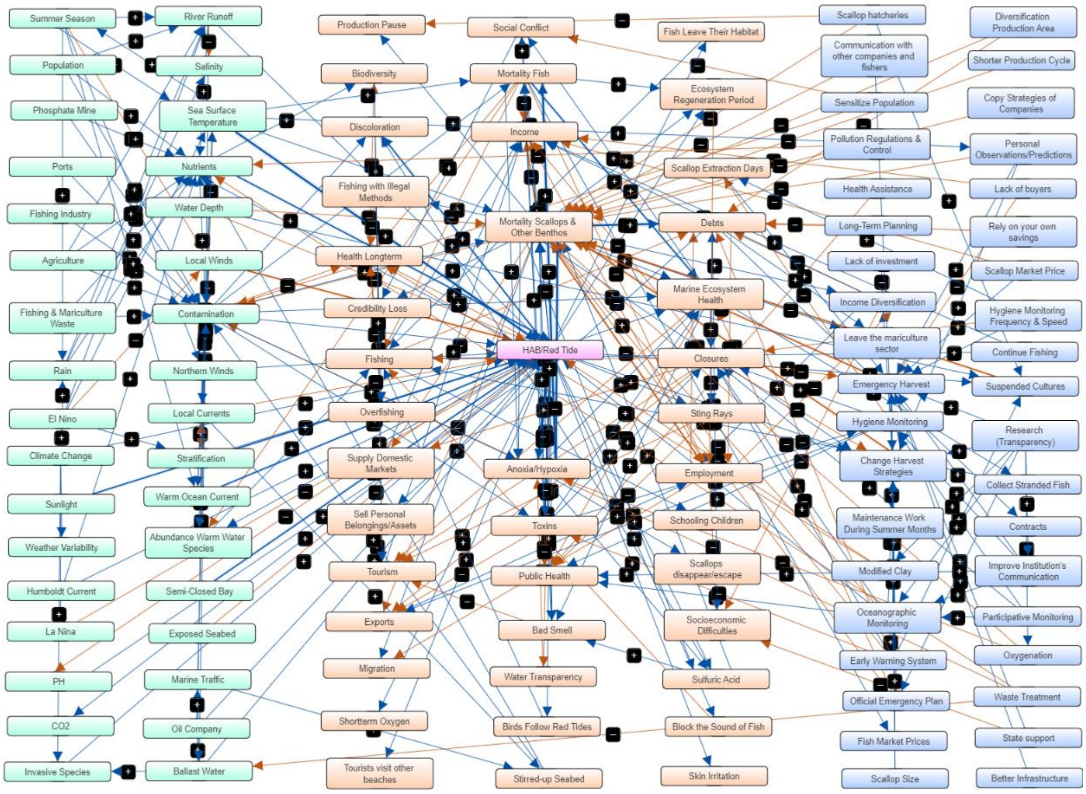

Figure 6. ***Crowd Map of Drivers, Impacts and Adaptation Related to Harmful Algal Blooms.*** Aggregated and processed FCM that includes concepts and causal relations from all individual maps. The processed maps were digitalized using the Mental Modeler Software.

3.2.4 Quantitative Analysis of Maps

Translation into Adjacency Matrices & Quantitative Aggregation

To quantitatively analyze FCM, maps are first transformed into adjacency matrices, a type of square matrix where the map components are listed pairwise on the vertical and horizontal axis (Özesmi & Özesmi, 2004, p. 49). When a connection between two map components exists, the strength of the relation is listed in the cell (Özesmi & Özesmi, 2004, p. 49). Table 2 provides an example of an adjacency matrix.

	Summer Season	Warm Ocean Current	Sea Surface Temperature	Block the Sound of Fish	HAB/Red Tide	Fishing	Fish Leave Their Habitat	Birds Follow Red Tides	Abundance Warm Water Species
Summer Season									
Warm Ocean Current			0.33		0.33				
Sea Surface Temperature	0.66								1
Block the Sound of Fish						-0.33			
HAB/Red Tide				0.66			0.33	0.33	
Fishing									
Fish Leave Their Habitat						0.33			
Birds Follow Red Tides						0.33			
Abundance Warm Water Species						0.33			

Table 2. ***Excerpt from an adjacency matrix*.**

Derived from an FCM of SSF in Sechura. The interface of the adjacency matrix is from the mental modeller software.

My case study aimed to describe the social-ecological system of HABs by exploring the perception of different stakeholder groups and creating a ‘crowd model’. Therefore, my next analysis step was aggregation: Individual maps are overlaid during the aggregation process, reinforcing relations mentioned in multiple maps. Meanwhile, concepts mentioned only once are added to the map without reinforcement (Gray et al., 2012, p. 91). Different methods exist for aggregation (Aminpour et al., 2020, p. 8). I decided to use an approach where individual adjacency matrices are first summed and then divided by the total number of adjacency matrices (Jetter & Kok, 2014, p. 51; Kosko, 1986). This method emphasized shared beliefs which aligned with my research objective of identifying the most important factors of HABs. Using Python and the Mental Modeller Software, I created five stakeholder models (SSM, LSM, SSF, LE, LA) and one crowd model that included 17 maps.[2] Small sample sizes were an issue for some stakeholder groups. However, since focus groups already represent a form of consensus of several participants, this might mitigate the issue.

[2] The script was an adapted version of Aminpour's (2019) Python Code. As mentioned before, map 18 was excluded, going beyond system boundaries.

Structural Analysis & Scenario Simulation

I first analysed the system's structure of the crowd model and stakeholder group models to identify key drivers, impacts, and adaptation strategies of HABs. I focused on measures like the number of concepts, centrality score, indegree and outdegree (see Appendix E-G and Tables 3 & 4 for detailed results). Outdegree represents the strength of causal links leaving a concept, while indegree measures the strength of entering connections (Singh & Chudasama, 2017, pp. 341–342). By using outdegree, I pinpointed the drivers and adaptation strategies with the most significant influence on the system. To identify the most central impacts, I computed the centrality score, which is the sum of indegree and outdegree (Furman et al., 2021, p. 3). Additionally, I compared the percentage of drivers, impacts, and adaptation strategies of the stakeholder group models to identify potential differences in their perceptions (Appendix E).

FCMs can be used to run “what-if scenarios”, allowing researchers to analyse where the system would go if certain conditions changed or adaptation strategies were implemented (Kosko, 1986; Özesmi & Özesmi, 2004, p. 55). This can be done by activating/clamping specific variables, which results in a new system state that can be compared to the system's original state (Gray et al., 2015, p. 5). A value of 1 means a concept is fully activated, while 0 represents no activation (Singh & Chudasama, 2017, p. 5). The activation spreads through the system by multiplying the activation vector with the square connection matrix of the FCM graph (Jetter & Kok, 2014, p. 46). When activated, a concept affects all the concepts it relates to in the map (p. 46). If the threshold level of neighbouring concepts is reached, these concepts are activated, and the effects spread further through the system (p. 46).[3] The values produced by this scenario run show a component's relative increase or decrease compared to its original value during the steady-state (Kok, 2009, p. 124). However, it is important to remember that this is not a statistical prediction but a representation of the participant’s perception. I followed the approach of Furman et al. (2021) and Singh et al. (2019), running a scenario analysis using the crowd model to assess how the system would respond to a simulated increase

[3] There are different types of activation functions to run the scenario analysis. I used a hyperbolic transformation function that according to Singh & Chudasama (2017), works well for complex social-ecological systems with negative and positive relations (p. 344).

in HABs.[4] The scenario analysis results are shown in Table 5. First, I clamped HABs to a maximum of one without changing any other variables (Baseline). Then, I ran three types of adaptation strategy scenarios to see how they would mitigate the effects of HABs on the system (Table 5). I only focused on the impacts and adaptation strategies related to the mariculture sector because the previous qualitative and structural analysis showed that mariculture is most affected by the HABs. Moreover, I decided to focus on the four impacts with the highest centrality scores. These included *Mortality of Scallops, Debts, Employment,* and *Income.*

Since my second research objective was to see whether adaptive capacities differ between stakeholders, I also focused on the difference in adaptation strategies between SSM and LSM, which emerged as a theme during the qualitative analysis process. I ran three different adaptation scenarios, clamping all individual adaptation strategies to a medium activation of 0.4: (1) Adaptation Strategies practised by SSM, (2) Adaptation Strategies practised by LSM, (3) All current and hypothetical adaptation strategies. I wanted to see which adaptation strategies seemed to work best and whether the advantage of LSM that was perceived during the discussion would be confirmed by the FCM of the crowd model.

3.3 Results & Discussion

This section will present the results obtained from analysing the focus group recordings, graph metrics, and scenario simulations. Appendix D offers insights into the divergences in perception and knowledge among stakeholder models, as indicated by the graph metrics. Furthermore, I discuss the most important drivers, impacts, and adaptation strategies and provide the results from the scenario analysis that focused on the effects of a simulated increase in HABs and the ability of the mariculture sector to adapt to them.

[4] However, I only used the built-in “Mental Modeler” Software tool, which is easier to use but provides less control than other tools such as Python or R.

3.3.1 Perceived Drivers of HABs in Peru: Convergence Between Scientific and Local Knowledge?

The focus group discussion started with a debate about the definition of HABs to determine whether all stakeholders perceive the phenomenon similarly. Most participants defined HABs as patches of water (*Manchas*) composed of microalgae that cause water discolouration and a decrease in oxygen levels. While fishers and scallop producers used the term *Red Tide*, scientists preferred *HABs*, arguing that they do not necessarily have to be 'red', as the colouring might be misguiding, and other alternative names (such as *brown/black waters*) exist. Another term, *Aguaje*, had multiple interpretations, with some considering it a synonym for HABs/Red Tides, others relating it to warm water currents in summer, and some linking it to the mortality of marine fauna due to pollution.

While there was some ambiguity regarding the terminology and disagreement on the attribution of mortality events, there was a relative consensus on the key drivers of HABs. Scallop producers and fishers explained the occurrence of HABs similarly to scientific experts, which supports the 'crowd-wisdom' argument of FCM scholars that local ecological knowledge can supplement scientific knowledge quickly and effectively. Based on the community FCM, I identified the ten perceived drivers with the highest outdegree scores (Table 3).

Community Map	SSM	LSM	SSF	LE	LA
Sea Surface Temperature (0.8)	Contamination (1.72)	Sea Surface Temperature (1)	Sea Surface Temperature (1.6)	Nutrients (0.78)	Sea Surface Temperature (0.66)
Contamination (0.7)	Local Winds (1)	Sunlight (0.66)	Warm Ocean Current (0.83)	Sea Surface Temperature (0.66)	Humboldt Current (0.5)
Local Winds (0.5)	Sea Surface Temperature (0.6)	Local Winds (0.66)	Summer Season (0.49)	Climate Change (0.53)	Contamination (0.5)
Nutrients (0.4)	River Runoff (0.6)	Rain (0.66)	Climate Change (0.33)	Agriculture (0.46)	Semi-Closed Bay (0.5)
River Runoff (0.39)	Local Currents (0.49)	Summer Season (0.66)	Northern Winds (0.16)	Summer Season (0.46)	Nutrients (0.33)
Summer Season (0.33)	Fishing Industry (0.44)	Warm Ocean Current (0.66)	La Nina (0.16)	Sunlight (0.4)	Local Winds (0.33)
Semi-Closed Bay (0.27	Northern Winds (0.38)	Nutrients (0.66)		Stratification (0.4)	Local Currents (0.16)
Local Currents (0.25)	Warm Ocean Current (0.33)	PH (0.33)		River Runoff (0.39)	Fishing & Mariculture Waste (0.16)
Warm Ocean Current (0.25)	Semi-Closed Bay (0.33)			Population (0.39)	Summer Season (0.16)
Northern Winds (0.25)	Ballast Water (0.33)			Local Winds (0.33)	Phosphate Mine (0.16)

Table 3. ***Drivers of HABs With the Highest Outdegree Across Stakeholders and in the Crowd Map*.**

A high outdegree means that the variables have a great causal influence on the other components in the system and are therefore considered important drivers. Variables that are the same/or similar are coded with the same colour.

First, participants agreed that HABs occur regularly but only create an impact when they stay for more than three days. This happens when several factors coincide, usually during the *Summer Season* (December – April) or when *Warm Ocean Currents* dominate, especially during *El Niño* years. The factors that promote the occurrence of HABs were higher *Sea Surface Temperature* and less water renewal, which was caused by weaker *Local Winds* (except for the rare cases of strong *Northern Winds)* and weaker *Local Currents.* Moreover, the *Semi-Closed Shape* of the bays and higher *Nutrient loads/Contamination* caused by factors such as *Population, Fishing* and *Mariculture Waste, River Runoffs, Ballast Water,* and local *Mining* were perceived to make HABs more likely and intense. The academic literature confirms many of these drivers mentioned by the participants, showing that blooms occur at their highest density during the summer months and are associated with high sea surface temperatures, a stratified water column, river discharges, El Niño conditions and warm water currents, but also anthropogenic pollution (Cabello et al., 2002; Cuellar-Martinez et al., 2021, 2023; Gonzales et al., 2012; Kahru et al., 2004; Orozco et al., 2017; Sánchez et al., 2022; Sonia Sánchez et al., 2018).

The most controversially discussed issue was the attribution of mortality events of scallops and fish. In Sechura, participants across all stakeholder groups believed that HABs were a central driver of mass mortality and that natural processes determined the abundance of HABs. Meanwhile, in Paracas, anthropogenic contamination was considered much more essential, and perception differed significantly between stakeholders. While the local scientific experts argued that mortality was primarily explained by HABs, SSM and SSF believed that mortality events were due to the waste disposal of the local fishmeal factories and that the local authorities only used HABs as a pretext to cover up the activities of the fishing industry (Focus Group 15, 24.10.22). This perception difference is also reflected in the structure of the maps: In Sechura, the driver with the highest outdegree was *Sea Surface Temperature* (1.2), and in Paracas *Contamination* (1.7). Contamination in Paracas has been a conflict between SSM, the fishing industry and local authorities for a long time. It was also identified as the primary cause of mortality events during the 1990s and early 2000s, leading to a HAB resulting in anoxia (Cabello et al., 2002; Gonzalez, 2008; Kahru et al., 2004). The local fishing industry installed waste treatment facilities and a 12-km waste pipeline in 2006. However, local fishers and scallop producers have criticized that pollution-driven mortality events have increased recently (Focus Group 15-17, 24-26.10.22). Despite this conflict regarding the role of pollution, there have been no recent studies on the relationship between anthropogenic eutrophication and HABs in Peru.

3.3.2 Perceived Socio-Economic Impacts of HABs

The focus group analysis and FCM structure revealed a consensus on the human activities most affected by HABs. Algae blooms typically result in socioeconomic harm by causing water discolouration, foam, and oxygen depletion (anoxia/hypoxia), leading to mortality in marine life (Díaz et al., 2019, pp. 1–2). Additionally, some species produce toxins that can enter the food chain and potentially cause neurological and gastrointestinal disorders, leading to fishery and aquaculture closures (pp. 1-2). From the centrality scores of the community map (Table 4), Anoxia (2.74) emerged as a significantly more impactful issue than Toxins (0.95). Other direct impacts include discolouration, bad smell, and a decline in ecosystem health.

Community Map	SSM	LSM	SSF	LE	LA
Mortality Scallops & Other Benthos (4.8)	Mortality Scallops & Other Benthos (5.56)	Mortality Scallops & Other Benthos (7.65)	Anoxia/Hypoxia (3.1)	Mortality Scallops & Other Benthos (5.1)	Anoxia/Hypoxia (1.8)
Anoxia/Hypoxia (2.74)	Anoxia/Hypoxia (3.1)	Debts (3.98)	Fishing (3.1)	Anoxia/Hypoxia (2.59)	Mortality Scallops & Other Benthos (1.66)
Mortality Fish (1.6)	Debts (1.85)	Anoxia/Hypoxia (3)	Mortality Scallops & Other Benthos (2.9)	Stranding (1.98)	Public Health (1.49)
Debts (1.37)	Employment (1.83)	Production Pause (1.33)	Mortality Fish (2.15)	Closures (1.92)	Stranding (0.99)
Stranding (1.19)	Mortality Fish (1.82)	Mortality Fish (1.33)	Marine Ecosystem Health Long term (1.16)	Mortality Fish (1.78)	Sting Rays (0.83)
Income (0.98)	Income (1.49)	Sell Personal Belongings/Assets (1)	Abundance Warm Water Species (1.16)	Toxins (1.45)	Mortality Fish (0.66)
Toxins (0.95)	Toxins (1.16)	Stranding (0.66)	Overfishing (1)	Bad Smell (1.32)	Income (0.5)
Closures (0.89)	Socioeconomic Difficulties (1)	Short term Oxygen (0.66)	Fishing with Illegal Methods (0.99)	Tourism (1.31)	Marine Ecosystem Health Longterm (0.5)
Employment (0.82	Stranding (0.67)	Employment (0.33)	Debts (0.99)	Income (1.06)	Bad Smell (0.49)
Bad Smell (0.52)	Closures (0.66)	Contracts (0.33)	Employment (0.66)	Debts (0.99)	Toxins (0.49)

Table 4. ***Impacts of HABs with the Highest Centrality Scores (Indegree + Outdegree) Across Stakeholder Groups and in the Crowd Map.***

Variables with high centrality are most important to a system because they influence/and are influenced by other factors. Variables that are the same/or similar are coded with the same colour.

Health, Tourism, Fishing and *Scallop Mariculture* were the four impacted sectors mentioned during the discussions. However, not all these sectors were equally affected, as shown by the centrality scores (Table 4) and the results from the sensitivity simulation (Fig. 7). There was consensus that the scallop sector is the most vulnerable. Meanwhile, the consequences for fishing, public health and tourism were comparably minor in the case of Sechura and Paracas. The most important indirect impacts were increasing debts, income losses, closures, and lower employment. These indirect impacts were primarily explained by mortality events of scallops and toxin-related closures.

In addition to the centrality scores, the sensitivity analysis provided insight into the perceived trajectories of the social-ecological system when an increase in HABs is simulated. The relative values show how the system components differ between the steady-state (no rise in HAB) and the HAB increase. In the coming section, I outline these direct and indirect impacts focusing more on the sectors of *Health, Tourism, Fishing* and *Scallop Mariculture.*

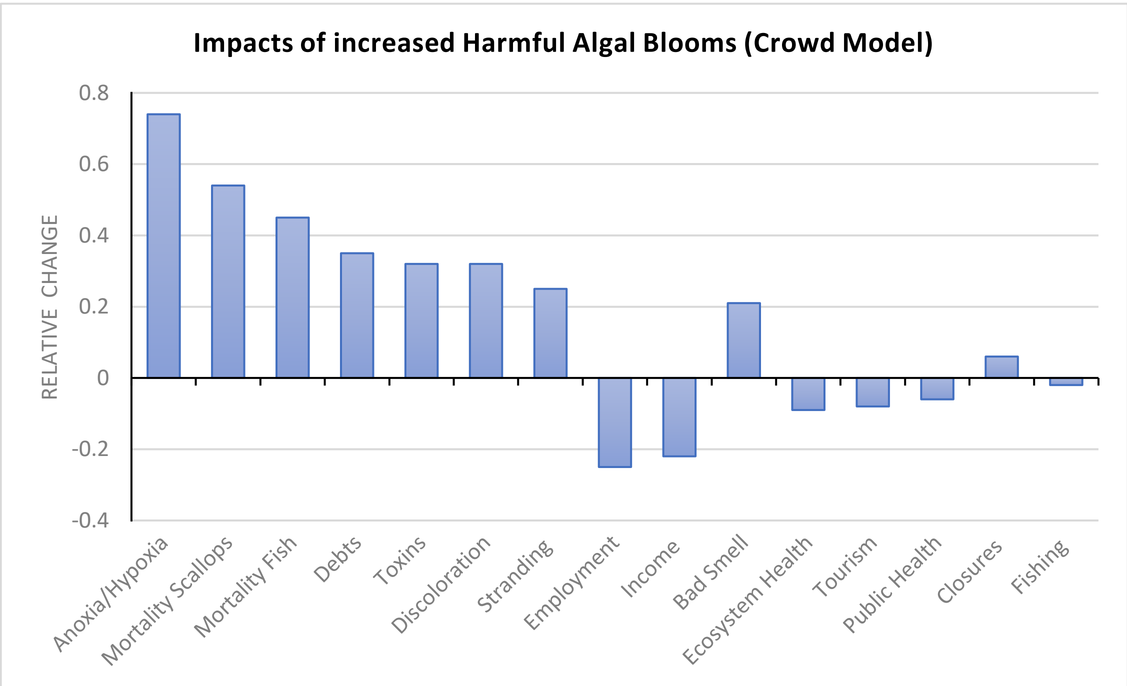

Figure 7. ***Sensitivity Analysis of the Most Central Impacts Mentioned in the Crowd Model***.

For the sensitivity analysis, the HAB variable was increased to a maximum of 1 to simulate the occurrence of more frequent and intense HABs and potential impacts on the social-ecological system.

Health

There are many reports of the occurrence of potentially toxic algae species in Peru, such as *Alexandrium ostenfeldii*, *Pseudo-nitzschia* sp. and *Azadinium* sp., that have caused mortality events and intoxications in other areas (Alcántara-Rubira et al., 2018; Cuellar-Martinez et al., 2021, 2023; Tenorio et al., 2018; Tillmann et al., 2017). The risk of toxins being absorbed by scallops and fish has necessitated a toxin monitoring program currently administered by the fisher hygiene agency SANIPES. Hygiene and toxin monitoring has been essential since 2009 because it determines whether seafood products can be exported to the EU and the US (Kluger, Taylor, et al., 2019, pp. 194–195). However, based on the input from the participants, instances where toxins exceed regulatory levels, are not common (Interview LE, Lima, 29.09.22). In this case, scallop harvesting is stopped until toxin concentrations naturally decrease. This usually leads to closures of around two weeks if the HAB events pass quickly (Focus Group 13, Paracas, 23.10.22). While the regulatory toxin levels were exceeded in some instances, there have been no reports on direct human intoxication. SANIPES participants argued that this is due to the low toxin concentration and effective monitoring (Focus Group, 9, Sechura, 13.10.22). Nevertheless, scallop divers have reported skin irritations after diving during HAB events (Focus Group 3, Sechura, 06.10.22). Additionally, participants have also raised concerns that there is currently no direct cooperation between SANIPES and the health sector and little awareness of the issue of algae toxins among health officials and the population. Consequently, intoxication might simply not be reported or attributed to HABs (Interview LE, Lima, 29.09.22). Therefore, monitoring gaps and a lack of cross-institutional communication might be a barrier to adaptation to HABs. While currently not creating substantial health and economic impacts, these toxins have the capacity to completely paralyze scallop exports and lead to longer closures.

Tourism

The impacts on tourism, as perceived by the participants, are minor, especially in the case of Sechura, where only a small local tourist sector exists. The discolouration of the water and the bad smell of decomposing algae and stranded fish can deter tourists from coming to the beaches. However, in Paracas, the water's milky discolouration has even been said to have a ‘positive effect’ on tourism because tourists perceive the

'Caribbean water colour' as pleasant. The significant negative effect on tourism in Paracas is the proliferation of sting rays. These rays come closer to the shore when HABs occur and regularly injure tourists and fishers (Focus Groups 14, Paracas, 24.10.22).

Fishing

In contrast to scallops, fish are mobile and can typically move to other areas when HAB cause anoxic conditions in the bays. Moreover, HABs are less likely to occur in the open ocean, and fish shoals can avoid them. Therefore, offshore fish stocks like anchovies and industrial fishing fleets are not much affected by HABs (Focus Group 16, Paracas, 26.10.22). Occasionally, however, shoals of fish can become trapped between the shoreline and patches of algae. When oxygen levels drop, fish and other marine organisms suffocate or are physically damaged by algae. Fish starts floating on the surface, strands on the beach, and its decomposition speeds up the process of oxygen depletion. Overall, the *mortality of fish* (1.6) and *stranding* (1.19) events were among the crowd model's most significant impacts.

When fish are stranded along the shore, they are often collected and consumed by the local population. Since fish quickly decomposes and is potentially affected by algae toxins, this is perceived as a health risk by experts and the local authorities. Nevertheless, according to the latter, there is currently no emergency plan to deal with fish mortality events (Focus Group 4, Sechura, 26.10.22). According to SSFs, significant mortality events in the bay can also lead to the collapse of targeted fish species, resulting in a decline in fish catches for several months. However, the economic impact on fishing is lower than on mariculture because fish stocks typically recover within 2-3 months; fishers can target different species and only lose small investments associated with fuel and labour (Focus Group 6, Sechura, 05.10.22). Hence, while these mortality events cause a temporary decrease in catches and income for the short to medium term, they do not necessarily push fishers into debt or unemployment. The most important adverse effect of HABs on fishing perceived by SSFs is indirect: Large HABs can lead to more than 80% of production losses in the mariculture sector. Consequently, divers and crew members experience unemployment in the scallop sector for up to one year and transition to fishing as an alternative livelihood. As a result, the pressure on the already strained stocks has been increasing. According to SSFs, many scallop producers do not come from a fishing background and use unsustainable and illegal fishing methods, which has accelerated the decline of stocks, putting SSFs under extra financial pressure (Focus Group 6, Sechura, 05.10.22). SSFs in Paracas have even argued that HABs mortality events and the extra fishing pressure contributed to the long-term decline of fishery resources that burdens an SSF sector already struggling for subsistence given unfavourable political, economic, and ecological conditions (Focus Group 15, Paracas, 24.10.22).

Mariculture

HABs occur yearly and cause anoxia across mariculture production zones. Their effect is usually localized: while one producer loses their whole harvest, the neighbouring production areas might not be impacted. Consequently, producers leave their scallops in the water during smaller HABs, hoping not to be affected (Focus Group, 1, Sechura, 03.10.22). In the case of Sechura, the zones further within the bay have been perceived to be more frequently affected. These zones, however, are also known for being very productive because of their higher nutrient concentration. Therefore, scallop producers within the bay have to judge between more productive scallop cultivation and facing more significant risks of HABs. Consequently, when asking about the impacts of HABs, the perception diverges significantly between producers depending on which zone they work in. Nevertheless, every few years, HABs cause significant bay-wide mortality events. Producers in Sechura have said that *Red Tides* events contributed to production losses of over 80% in 2012, 2016, 2017 and 2019 (Focus Groups 1, 5, 7, Sechura). A producer in Lagunillas Bay (South of Paracas) said that in the last twenty-five years, she lost ten of her yearly harvests to HABs (Focus Group 17, Paracas, 26.10.22). A recent study by Cueto-Vega et al. (2022) confirms this perceived mortality.

The socio-economic impacts on the mariculture sector are more significant than on small-scale fishing activities due to the high level of investment involved in mariculture activities. A scallop's production cycle can take 7 to 18 months, depending on the production method, natural conditions, and location (Focus Groups 1 & 5, Sechura, 03/07.10.22). During this time, producers invest in scallop seeds, fuel, crewmembers, logistics and monitoring. Until 2012, producers could acquire loans from banks; however, after the mortality of the production in 2012, banks stopped handing out loans because of associated high risks (Focus Group 7, Sechura, 11.10.22). Since then, producers have acquired capital through alternative channels such as personal contacts (e.g., friends and family employed in mining, agriculture, etc.) or by seeking bank loans for other projects that they then invest in mariculture. Additionally, smaller producers increasingly accept agreements (*Convenios)* with larger scallop companies that provide an initial investment in return for a share of the profit (Kluger et al., 2022, p. 318; Focus Group 5, Sechura, 07.10.22). When a small-or large HAB destroys the production, the scallop producer loses their product, the initial investment, and they usually continue to pay fixed costs for the maintenance of their plot. This exacerbates the issue further, as large-scale mortality events frequently occur during the summer months when the scallops have already reached their commercial size. In sum, producers lose their primary source of income for up to a year, are heavily burdened by debts and need to find alternative employment. Scallop producers must acquire substantial capital to afford seeds and hold on to their production zone to restart production. Consequently, they may find themselves compelled to sell their property, including items like televisions, cars, and even houses, to repay creditors and secure funds for new investments (Kluger, Kochalski, et al., 2019, p. 1127; Focus Group 1, Sechura, 03.10.22). While having more financial backup and several options to react (see next section), large-scale producers are also heavily impacted by HAB mortality events. When mortality events occur in consecutive years, they threaten the survival of the business. For instance, the largest scallop producer in Sechura had to reduce its workforce from hundred to thirty after a heavy mortality event (Focus Group 5, Sechura, 07.10.22). There are no labour securities; if the harvest is lost, employees do not receive their wages or are dismissed (Focus Group 3, 5, Sechura, 06-07.10.22). HAB-related mortality events also affect secondary economic activities. Especially in Sechura, where mariculture is a critical economic sector, participants argued that up to 30.000 indirect jobs, such as logistics, processing plants, gastronomy, shipbuilding, and shops, indirectly depend on it (Focus Group 3, Sechura, 06.10.22). Furthermore, it is common for workers to migrate in search of employment opportunities in fishing, agriculture, or mariculture in other locations following mortality events (Focus Group 3, Sechura, 06.10.22).

These impacts are similar to the findings of Kluger et al. (2020) and Kluger, Kochalski, et al. (2019) regarding the effects of the Coastal El Niño 2017. Nevertheless, HABs are regular environmental events that happen several times a year. Therefore, the adaptation and institutional response to HABs will look different than the strategies for more extreme but less frequent events such as a Coastal El Niño. Since the mariculture sector was perceived to be the most impacted by HABs, the coming section will focus on adaptation strategies in the mariculture sector.

3.3.3 Exploring Adaptation Strategies to Harmful Algal Blooms in the Mariculture Sector

Pooling the knowledge of diverse stakeholder groups produced a list of 38 adaptation strategies. These variables encompassed both current adaptation strategies being practised, potential future strategies that should be implemented, and factors that currently hinder the implementation of adaptation measures. Appendix F provides the outdegree scores of these variables, showing which adaptation strategies influence the system most according to the participants. Of all adaptation strategies, implementing an *Early Warning System* was perceived to be potentially the most effective adaptation strategy (0.54). Out of all the presently practised strategies, *Hygiene Monitoring* (0.39), *Emergency Harvests* (0.31), *Income Diversification* (0.31), *Changes in Harvest Strategies* (0.31) and *Suspended Cultures* (0.29) were considered the strategies with the highest impact on the system (Appendix E). Overall, there was more disagreement regarding the adaptation strategies than drivers and impacts.

Moreover, the response strategies to HABs varied between LSM and SSM, as shown in Table 5. The scenario simulation on the 'crowd model' compared the adaptation pathways of SSM and LSM to assess how they could potentially mitigate the impacts of *Scallop Mortality*, *Debts*, *Employment*, and *Income* caused by increased HABs (Fig. 8). The results indicate that all adaptation measures are perceived to contribute to some extent in mitigating the impacts of HABs. However, the adaptation pathways pursued by LSM are perceived to be more effective in reducing the adverse effects than those employed by SSM. Additionally, implementing hypothetical adaptation strategies is perceived to have the most significant potential for reducing the negative impacts of HABs. These results show a perceived inequality in adaptive capacities, confirming findings from other studies on HABs, where existing inequalities are reproduced and enforced after the environmental extreme (Jardine et al., 2020). The following section will discuss the issue of greater vulnerability of small-scale producers based on the qualitative findings.

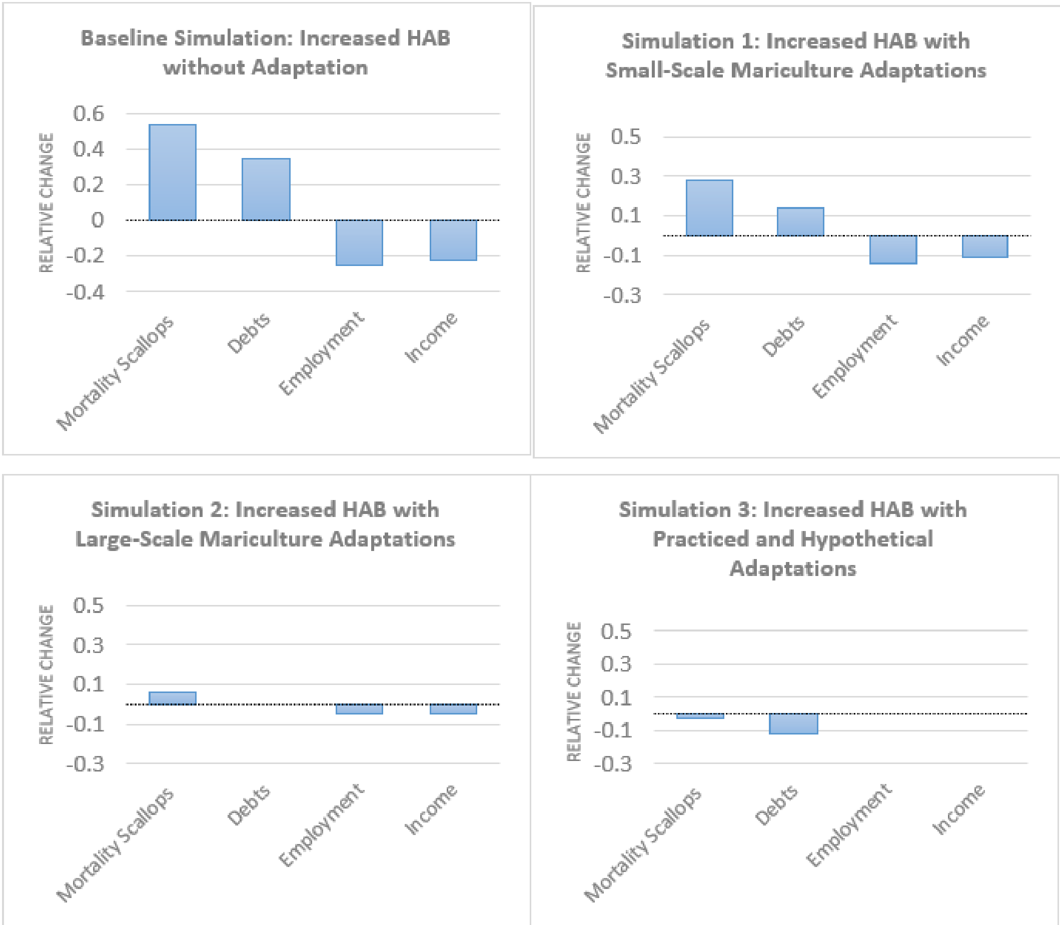

Figure 8. ***Scenario Analysis of Adaptation Strategies in the Mariculture Sector (Crowd Model)***. The baseline model shows how perceived impacts related to the mariculture sector change after a simulated increase of HABs to a maximum of 1. The change is "relative" to the steady-state model (no simulated change in the system). Simulations 1-3 then simulate modest increases (0.4) of 3 sets of adaptation strategies on top of the increased HABs. Set 1 includes all adaptation strategies practised by SSM. Set 2 consists of those by LSM. Set 3 contains all currently practised adaptation strategies and those that the participants hypothesized.

Unequal Adaptive Capacities Between Small- and Large-Scale Mariculture

While the previous section showed that HABs heavily impact both LSM and SSM, companies are perceived to have better information and more options to respond to an emergency and find it easier to recover after the event. The most important current adaptations of both SSM and LSM were to *Change Harvest Strategies* and perform an *Emergency Harvest*. While the emergency harvest is the 'last minute' extraction of scallops, a change in harvest strategies entails that producers do not grow scallops throughout the year but harvest at the beginning of the summer months (November – January) to avoid the HABs of the warm-water season. Nevertheless, there are incentives to leave the scallops longer in the water: firstly, the summer months potentially create conditions where scallops grow more quickly. Secondly, since many producers harvest early to avoid the risk, the supply of scallops might be lower further into the summer months, translating into higher prices. Thirdly, the summer months in the Northern Hemisphere are the season with the highest demand. Therefore, harvesting at a later stage can be more profitable because of a better product and favourable market conditions and scallop producers "play with the probability of natural risks and make decisions on harvesting based on the information they have" (Focus Group 5, Sechura, 07.10.22). Companies have better information when it comes to taking these decisions. They have access to real-time satellite data of oceanographic conditions and directly communicate with researchers and other companies along the coast to share information. SSM producers also criticized their complicated relationship with the state's ocean institutions (IMARPE, SANIPES) and limited access to *research* and technical solutions (Focus Group 3, Sechura, 06.10.22).

Moreover, SSMs said that official HABs or the Coastal El Niño warnings came too late, resulting in uncoordinated and chaotic emergency harvests. Therefore, the participants agreed that constant, transparent monitoring by state institutions and an *early warning system* with buoys in the open ocean could help make more informed decisions on harvest- and seeding strategies. Several other production strategies put LSM at an advantage. Since HABs often only affect certain parts of the bay, companies have started diversifying their production area, while many smaller producers only produce in specific zones. SSM, therefore, can lose their whole harvest to a local HAB, while companies only risk a part of it. Additionally, companies have invested in *Suspended Cultures* in Sechura, where the scallops are not cultivated on the seafloor but on long lines that can - to a certain degree - be moved up and down during blooms (see Fig. 9). Usually, the producers bring the scallops closer to the surface, where more oxygen is available. While suspended cultures can also be moved to other zones during a HAB, this is not yet practised in Sechura because of the heavyweights (Focus Group 5, Sechura, 07.10.22). These suspended cultures are capital-intensive and only work in deeper waters, so SSMs have not used them on a larger scale. Nevertheless, during the heavy mortality events in 2012 and 2017, even the suspended cultures were affected by a complete loss of production.

Table 5. *FCM Simulations of the Adaptation Strategies of the Mariculture Sector to Harmful Algal Blooms*

Concepts	Baseline: Increase in HAB	Scenario 1: Small-Scale Mariculture	Scenario 2: Large-Scale Mariculture	Scenario 3: All + Hypothetical
Harmful Algal Bloom	1	1	1	1
Impacts				
Mortality Scallops	**0.54**	**0.28**	**0.06**	**-0.03**
Debts	**0.35**	**0.14**	**0**	**-0.12**
Employment	**-0.25**	**-0.14**	**-0.05**	**0**
Income	**-0.22**	**-0.11**	**-0.05**	**0**
A. Adaptations SSM & LSM				
Emergency Harvest	0	0,4	0,4	0,4
Change Harvest Strategies	0	0,4	0,4	0,4
Communication with Other Companies and Fishers	0	0,4	0,4	0,4
Oxygenation	0	0,4	0,4	0,4
Personal Observations/Predictions	0	0,4	0,4	0,4
C. Adaptations SSM				
Income Diversification	0	0,4	0	0,4
Rely on Your Own Savings	0	0,4	0	0,4
Copy Strategies of Companies	0	0,4	0	0,4
B. Adaptations LSM				
Oceanographic Monitoring;	0	0	0,4	0,4
Long-Term Planning	0	0	0,4	0,4
Diversification Production Area	0	0	0,4	0,4
Suspended Cultures	0	0	0,4	0,4
Hatcheries	0	0	0,4	0,4
D. Adaptations Hypothetical				
Research (Transparency)	0	0	0	0,4
Early Warning System	0	0	0	0,4
Official Emergency Plan	0	0	0	0,4
Modified Clay	0	0	0	0,4
Pollution Regulations & Control	0	0	0	0,4
Waste Treatment	0	0	0	0,4
Improve Institution’s Communication	0	0	0	0,4
State Support	0	0	0	0,4
Participative Monitoring	0	0	0	0,4
Hygiene Monitoring Frequency & Speed	0	0	0	0,4
Better Infrastructure	0	0	0	0,4

Finally, companies also operate *Scallop Hatcheries* in which they grow the seeds for scallop production rather than just relying on inputs from the natural banks, which has enabled them to retake production more quickly after a mortality event (Kluger et al., 2022a, p. 318).

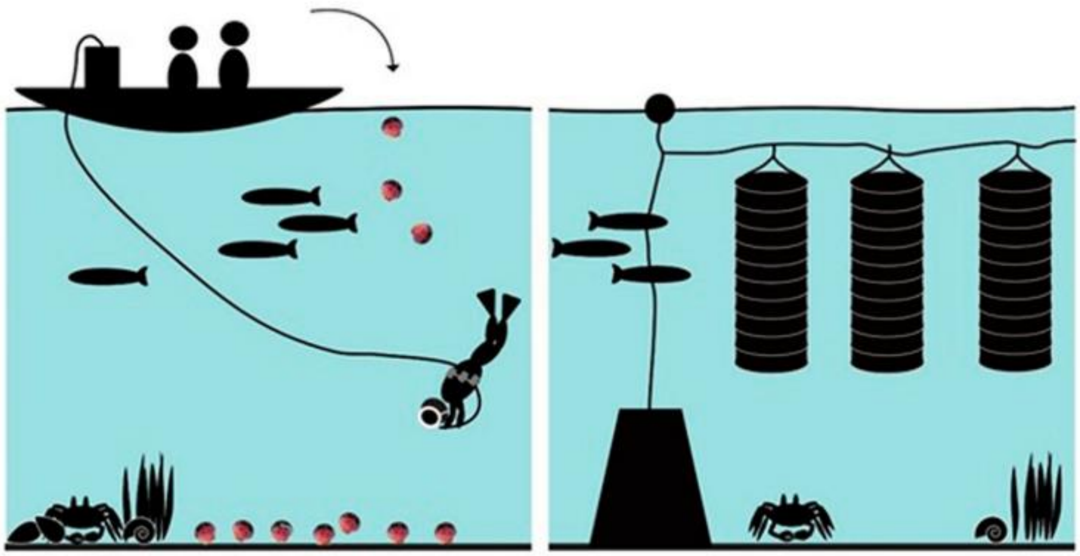

Figure 9. ***Scallop Farming in suspended vs. bottom culture***.
Reprinted from Kluger, L. C., Schlüter, A., Garteizgogeascoa, M., & Damonte, G. (2022). Materialities, discourses and governance: Scallop culture in Sechura, Peru. Journal of Environmental Policy & Planning, 24(3), p. 311. https://doi.org/10.1080/1523908X.2022.2047620

Producers initiate *emergency harvests* under conditions when HABs are likely to occur or already approaching the bay. SSMs have highlighted that they face many constraints regarding these harvests, such as logistical bottlenecks at the landing sites. Moreover, scallops need to be directly processed or cooled, but since the companies control the processing facilities, they determine whether smaller producers can access them. Consequently, the companies influence prices and might turn down the product of SSMs if not the desired size or quality. Therefore, some SSM producers have demanded that the state serves as a *'buyer-of last resort'* during HABs (Focus Group 17, Paracas, 26.10.22). Additionally, SSM reported that they cannot extract during a HAB because they must wait for results from the toxin- and hygiene monitoring by SANIPES. The monitoring is done only on Fridays, and results typically arrive by Monday, so producers can only harvest for approximately three days a week. SSM producers report losing their harvest while waiting for monitoring results. Therefore, SSM producers demand that public institutions speed up procedures during emergencies and establish an official plan to enable SSM producers to extract their products (Focus Group 1 & 3, Sechura, 03/06.10.22). Companies have an advantage because they can harvest even though the results from SANIPES are still pending. They keep the scallops under "quarantine" in their storage facilities until the checks are done (Focus Group 5, Sechura, 07.10.22).

Lastly, SSM and LSM have different abilities to respond to the socio-economic impacts of HABs (see also Kluger et al., 2022, p. 313). Larger companies have better access to financial capital, while SSMs struggle to acquire the necessary investments since banks stopped providing loans for scallop production. As a result, LSM plans their scallop production long-term (up to five years), incorporating the expected losses from the natural variability into their business plan and negotiating the loan conditions and investments accordingly. Meanwhile, SSMs work only in the short- to medium-term, trying to get the necessary capital to pay back debts from an unsuccessful season and be able to reinvest in the next season. The key response of SSM to avoid the insecurities linked to the volatile scallop production is to *diversify* their sources of income. SSM producers have started cultivating alternative products such as macro-algae, and mussels, commercializing scallops' shells, or working in other sectors such as tourism (in Paracas) to reduce dependencies on scallop production. Nevertheless, many of these initiatives are struggling because SSM cannot find investors or access markets (Focus Group 17, Paracas, 26.10.22). Currently, no state program supports the diversification activities of scallop producers.

3.4 Concluding on the Social-Dimension of HABs in Peru

To conclude, regarding drivers, the findings point towards a shared understanding of HABs among scientific experts and local stakeholders. Regarding impacts, HABs are perceived to have the most effect on the mariculture sector, followed by fishing, while health and tourism are less affected. The analysis of adaptation strategies reveals the significant challenges encountered by small-scale producers, who have limited options and face more obstacles than their larger-scale counterparts when dealing with HABs. The evidence of greater vulnerability aligns with previous studies on Coastal El Niño (Kluger et al., 2020; Kluger, Kochalski, et al., 2019; Kriegl et al., 2022), hygiene standards (Roca, 2023, forthcoming), and the political-institutional context in Peru's mariculture (Damonte et al., 2023; Kluger et al., 2022; Schlüter et al., 2021). The studies have consistently uncovered the growing difficulties small-scale producers encounter, resulting in the concentration of access rights and market shares in the hands of larger producers. My research on HABs confirms this trend of deepened social inequalities, exacerbated by the limited response mechanisms of public institutions: for instance, there is no official emergency plan, early warning system, emergency aid, or public funding for diversification initiatives, and the cooperation between ocean governance and the health sector is limited. These examples illustrate a perceived governance gap surrounding Peru's HABs that has significant socio-economic consequences.

My modelling involving fishers, local experts, and scallop producers in Peru contributed to the *instrumental* goal of bridging the knowledge gap on the social dimension of HABs in Peru and points towards the need to develop socially-just responses to an environmental extreme likely to increase in frequency and intensity in the years to come. Nevertheless, there are concerns regarding whether my FCM case study qualifies as a form of 'participatory' modelling, which is the category under which FCM is typically classified (Gray et al., 2015; Mehryar et al., 2017; Voinov et al., 2018). The last part of this thesis will discuss these concerns investigating some limitations of the collaborative FCM process based on my research's theoretical framework and practical experiences.

4 Limitations of the FCM process

The theoretical framework highlighted various challenges concerning the depth of participation, power dynamics, knowledge integration, and the long-term sustainability of the impacts of the participatory process. These challenges apply throughout the different stages of my FCM research, from project design and extending to model creation, as well as the qualitative and quantitative processing of the data.

4.1 Degree of Participation

First, concerns arise, given the degree of participation. According to the minimal definition of PM, my case study would qualify as participatory since the stakeholders created the initial models during workshops. When considering more nuanced typologies, such as the one depicted in Fig. 3 or Arnstein's (1969) “Ladder of Participation”, the case study would be classified at lower levels of participation. According to Voinov and Bousquet (2010), participants could get involved in various stages: goal-setting, design of modelling, building the models, processing them, defining scenarios and analysing and evaluating them (p. 1273). In my case, stakeholders indirectly influenced the goal-setting as their reports on the impact of HABs shaped the selection of HABs as the research topic. Moreover, stakeholders actively contributed by providing data and constructing models during the workshop. However, the initial models were processed and aggregated at consecutive stages without the participants’ input. Besides, participants did not evaluate the results or decide on their use. Overall, the process was rather ‘extractive’ or ‘consultative’ since the information was flowing mainly in the direction of the researcher (Fig. 3). According to Voinov et al. (2016), the consultation of stakeholders or selective involvement in some stages, such as data provision or evaluation, is most common among the PM literature (p. 199). Nevertheless, researchers have demanded to refrain from labelling consultation processes as participatory (Mobjörk, 2010; Treby & Clark, 2004).

4.2 Power and Representation in the Modelling Process

Secondly, issues of power and representation were not sufficiently considered during the case study. The decisions regarding selecting participants and the categorization into stakeholder groups were of my “own making” (Williams, 2004, p. 561), guided primarily by previous research and practical considerations rather than considering the multidimensional power structures or participants' inputs. As stated in the research design, stakeholder categories, such as SSF or the distinction between SSM and LSM, could not reflect the intricate nature of local social relationships and naturalized to somewhat arbitrary social division while ignoring differences within these categories (Williams, 2004, p. 561). For example, the broad SSM category exhibited significant socio-economic variation, with members ranging from affluent association presidents with large-scale scallop production to divers and crew members and participants from different fishing associations with conflicting goals. There were several reasons, however, why the final SSM would somewhat mask these internal differences within the group: first, gender dynamics and the socio-economic and formal status of the participants resulted in some participants being more vocal during discussions. Furthermore, participants who quickly grasped the causal logic of the FCM framework contributed more. To address the imbalance, I drew variables and connections based on explanations provided by participants who were less inclined to edit the map directly. However, this approach heightened my influence on the model. Therefore, there was, to some degree, a trade-off between more inclusive mapping and the risk of researchers' biases during map creation. Second, the FCM aggregation method emphasized 'consensus' by highlighting the weight of concepts mentioned by many participants and underemphasizing minority views and differences in perception. Third, the FCM mathematical aggregation in itself could not well express perception differences or disagreement between participants on the same socio-ecological factors: if one participant connects A and B with a positive relation and the other participant perceives it as a negative relation, the two will cancel each other or the dominant viewpoint will – somewhat weakened – show up in the final model (Jetter & Kok, 2014, p. 51). These three factors show that group models are not a neutral representation of the diverse views within constructed stakeholder groups since "ideal speech situations" (Habermas, 1981) rarely exist, and aggregation methods will prioritize some aspects over others.

Furthermore, issues of structural power influenced who participated in the first place. Given the time constraints of the fieldwork, my sampling strategy relied on contacts provided by research colleagues and key individuals within the community. Many of these contacts held influential positions in institutions such as fisher associations, research institutes, or the municipality, serving as gatekeepers in determining whom I would be able to connect with during my research. Consequently, there was a noticeable bias towards participants who had previous involvement in research projects, were part of formal organizational structures, and belonged to older male demographics.[5] A bias also stemmed from the spaces and their associated power relations (Cornwall, 2008, p. 279). Many of these spaces were not neutral but associated with the institutions where the people worked, including the municipality, fishing associations and research offices, which limited who could participate and what aspects would be openly discussed. Overall, the dynamic at these official spaces differed significantly from focus groups at informal places such as restaurants or homes chosen by the participants. Finally, as Olson (1965) argued in his *Collective action theory*, different interest groups have varying abilities "of organizing themselves and voicing their values, interests and concerns" (Mielke et al., 2016, p. 78). In my case study, for instance, the concerns of scallop producers have been dominant during the scoping and analysis stage. Capturing and representing their views as a smaller group with high stakes on the issue and mobilizing capacities was relatively more straightforward compared to the SSF sector, being a large and highly dispersed group with interests that are difficult to express through one group model.[6] The dominance of specific interest groups in the research process may intensify debates surrounding the blurred distinction between scientific knowledge production and consultancy work, as critics of collaborative sustainability research have pointed out (Mielke et al., 2016, p. 78; Strohschneider, 2014).

Regarding equity, Turnhout et al. (2020) rightfully argue that sampling biases towards certain interest groups or elite actors are problematic "because they are less likely to result in solutions that resonate with and are usable for non-elite groups" (p. 16). Models created under selection bias are also problematic because they might legitimize specific interests by labelling them objective and scientific (Mielke et al., 2016, p. 78). Consequently, it would have been necessary to involve community members to redefine, conceptualize, and discuss stakeholder categories before starting the modelling process (Reed et al., 2009, pp. 1938–1939). Moreover, more extended discussions around

[5] Only 12 participants were female, of which only three worked in Mariculture or Fishing. Additionally, most participants tended to be older (30-50).

[6] For instance, for the case of SSF in Sechura, I mainly spoke to 'Pinteros' – fishers with small rafts that use hooks and lines. These are just one among many, diverse fisheries in the SSF sector.

participants' identities would have been essential at the beginning of each focus group. This concern extends to the broader FCM literature, where stakeholder categories and sampling are often only marginally discussed (Voinov et al., 2016, p. 200). Yet, a more detailed and nuanced stakeholder analysis would help to see whether the participatory process has been deliberative or interest-driven (Mielke et al., 2016, p. 77). These critical reflections are central, especially in FCM research on ‘crowd-wisdom’ where the final model is supposed to represent a community consensus and is therefore at risk of masking the power structure of the community and depoliticizing the search for solutions (Williams, 2004, p. 562).

4.3 Knowledge Integration and Cognitive Justice

FCM is a method that turns qualitative storylines into models and then models back into stories (Beck, 2018, p. 928). Modelling tools, however, have underlying values, epistemological assumptions and norms that shape what kind of stories can be told (Beck, 2018, p. 928; M. S. Morgan, 2012). Since participatory sustainability research aims to integrate other forms of knowledge, it is essential to reflect on whether these underlying values and assumptions restrict people from diverse backgrounds to articulate their knowledge (Király et al., 2016, p. 14). Moreover, the question arises of who decides what stories are created from these inputs. These epistemological challenges are part of the third ‘discursive’ dimension of power that sets the boundaries of what can be freely expressed (Gaventa & Cornwall, 2008, p. 174).

FCM, as a mixed method with its causal structure, has a clear positivist underpinning. In my case, participants acquainted themselves with the mapping relatively quickly and recognized it as a visual tool to represent complex social-ecological relations. Participants perceived the mapping as a chance to frame their challenges, combine scientific with practical insights and make research more transparent. However, the causal structure and the quantification of variables also made some participants uneasy and limited the expression of certain information. Not considering themselves scientific experts, many participants hesitated to assign weights. As a result, I often had to take a more proactive role when adding the causal relations, as participants primarily confirmed or negated my questions on the strength of the relationship. Participants also struggled to include concepts in the map that they considered essential but lacked a straightforward relationship with other variables in the system. For instance, climate change was widely acknowledged as a crucial factor. Still, it tended to be left out of the analysis due to uncertainties and disagreements regarding its quantitative linkage to the rest of the system. The same applies to multidimensional social variables like well-being. Consequently, there was a bias towards information that was easily quantifiable, straightforward to define and less controversial among the participants. Furthermore, I often had to limit discussions about the broader social context that extended beyond the boundaries of the modelled system to be still able to finish the model on time, overriding some of the participant's priorities and qualitative information.

In FCM, the models are qualitatively processed meaning the researcher changes the participant's initial perception. Despite these usually extensive modifications, this process often goes without involving the participant, as in my study. In one of the most cited methodological frameworks on FCM, for instance, Özesmi and Özesmi (2004) merged 152 original variables into only 16 categories (p. 53). This leads to the question of how well such an approach reflects the initial perceptions of the stakeholders involved. Moreover, it raises concerns about whether the modelling overrides the nuanced, detailed, and context-specific characteristics of the practical knowledge that make it valuable (Agrawal, 2002, p. 292). While I tried to reduce my influence by condensing and renaming as few variables as possible based on the information from the audio transcriptions, the aggregated maps still differed substantially from the original data (see Supplementary Material and Appendix D). The combination of qualitative research and modelling helped to mitigate some of the disadvantages associated with the simplification of data and preserved some detailed, contextual information.

Nevertheless, this research design created an "epistemic divide" (pp. 18) between the researcher and the participant, where the participants were only admitted to the data-collection stage. Meanwhile, I maintained control over data processing and knowledge production (Felt et al., 2012). Participants in my focus groups also expressed concern about researchers extracting knowledge, including audio recordings, without returning concrete results or updates on how that knowledge was utilized (Focus Group 2, Sechura, 05.10.22). The structure of the spaces where the research took place also reinforced the epistemic divide. Even when I went to people's houses or met in neutral spaces like restaurants, the FCM method transformed these spaces into proxies for formal scientific spaces. By bringing whiteboards, pens, post-its, and examples of previous models and pre-structuring the FCM approach, I defined the “rules of the game” (Felt et al., 2012, pp. 23–24). While this is difficult to avoid with modelling tools such as FCM, the long history of *Participatory Rural Appraisal* has shown that modelling and mapping can be closer to the criteria, agendas and categories of the local participants rather than the researcher's pre-conceived structures (Chambers, 1997, pp. 130–131).

Furthermore, the epistemic divide between data-collection and knowledge production and the underlying positivist logic in my study points towards the critique of ‘Scientization’ previously introduced (Agrawal, 2002): External researchers distinguish knowledge that is considered valuable "from those other knowledges, practices, milieu, context, and cultural beliefs in combination with which it exists" (p. 290). Subsequently, they render this knowledge legible and generalizable through the scientific method. As a result, research establishes a hierarchical distinction between local and scientific knowledge, granting scientific knowledge the authority to determine the validity and utility of non-scientific knowledge (Agrawal, 1995a, pp. 26–27). This approach is central to much of the FCM literature given the dominance of instrumental goals, where pooling the perspectives of stakeholders is expected to create ‘objective’ knowledge in data-scarce environments, improve environmental governance or resolve disagreement between groups. This instrumental logic also influenced my case-design, where participation aimed to help fill an empirical gap on the social dimension of HABs in Peru. To achieve this goal, I restructured local narratives around HABs into quantifiable causal relations. The hierarchization of knowledge is common in research on ‘crowd wisdom’, where scientific/expert knowledge becomes the reference category to assess whether pooled local, practical knowledge can help overcome biases and resemble the scientific perspective (Aminpour et al., 2021; Olazabal, Chiabai, et al., 2018). This is something I have done myself in the section on the drivers of HABs. However, privileging specific knowledges undermines FCM’s potential to achieve non-instrumental participation goals such as learning, stakeholder empowerment or cognitive justice. During my study, both scientific and non-scientific actors were involved, raising concerns about whether all actors had an equal influence on the results, given that scientists found it easier to work with the terminology and causal structures of the FCMs. Overall, FCM case studies like mine need to be more explicit about their underlying epistemological and ontological assumptions and reflect whether these enable or prevent “different ways of knowing”

(Raymond et al., 2010, p. 1775). This is not only important to achieve non-instrumental goals but also to respond to the increasing demands for decolonising knowledge production, redefining ocean literacy and promoting epistemological pluralism (Santos, 2014, p. 42; Smith, 2021, p. 270; Spalding et al., 2023, p. 3).

Finally, the process of ‘Scientization’ also raises some ethical concerns about ownership, credits, and impacts of the research process. SSF participants, for instance, criticized that they have provided their time and knowledge to international research projects like mine before without being remunerated, benefiting from concrete results, or being sufficiently briefed about the research process (Focus Group 2, Sechura, 05.10.22). In my study, the lack of remuneration has also raised ethical and social justice concerns because elite actors such as local authorities and scientific experts usually participated during their paid working hours, while SSF and SSM producers came at night after long workdays without receiving compensation (also see Turnhout et al., 2020, p. 16). This resonates with Cooke and Kothari (2001) and the broader critique of ‘parachute science’ where local knowledge is used as information that benefits the careers of external researchers without necessarily translating into direct benefits for the participants. Often the question has been how participants can be meaningfully credited in the final research process (Banks et al., 2013, p. 267). However, due to the ongoing nature of my research process and the incomplete dissemination of results, it is challenging to evaluate the long-term impacts of the research and determine if participants can leverage the results for their benefit.

4.4 Research Expectations vs. Participation

As discussed in the theoretical framework, the researchers that work with participatory methods are squeezed between the expectations of (1) creating valid and meaningful scientific knowledge, (2) fulfilling the pragmatic goals of the case study, and (3) achieving a form of participation that hands over control to the participants. Defila and Di Giulio (2019) argue that these goals are to some degree at odds with each other (p. 100) and evolve around epistemological tensions regarding the role of science that are difficult to resolve (Bäckstrand, 2003, pp. 38–39). In my case study, the ‘pragmatist’ approach was prevalent, using FCM as a mixed method to create knowledge that is most likely useful to local stakeholders and institutions to solve the problem of HABs. As a result, the focus has shifted away from potential transformative and scientific goals. This has manifested through the limited depth of participation, a minimal theoretical scope, and a primarily descriptive level of analysis. For instance, I encountered difficulties in developing a more detailed theoretical framework due to the challenge of discussing FCM's quantitative and qualitative results under a unified theoretical umbrella. Besides, more theoretical preconceptions and an explanatory scope would have further increased the researcher's influence vis-à-vis the participants undermining the depth of participation. Overall, FCM tends to be used in technical fields and often follows the problem-solving/pragmatic approach, entailing less focus on other goals, including theory development or transformations towards social justice (Creswell & Clark, 2017, pp. 90 – 92).

Conclusions

In a recent paper, Cvitanovic et al. (2022) have called to “share stories of failure” (p. 2193) in participatory marine social science research to learn from and build on them. This was a central motivation of this thesis. FCM, as a form of PM, can integrate diverse perspectives visually, enables participants to structure mental models and has been shown to facilitate learning, more context-sensitive and equitable decision-making, and lower uncertainties. Nevertheless, weaknesses and limits related to its participatory dimension are not sufficiently discussed (Jordan et al., 2018, p. 1051; Voinov et al., 2016, p. 198). While some preliminary guidelines exist (Gray et al., 2018; Hare et al., 2003; Voinov and Bousquet, 2010), Jordan et al. (2018) argue that no best practices specifically focus on the relationship between participation and modelling. Consequently, researchers often follow the guidelines of their respective institutions or funding bodies or draw on research from related fields (p. 1050). By reflecting on the limitations of my case study, I hope to further encourage the development of best practices tailored explicitly towards FCM as a form of PM. Consequently, the following conclusion provides some preliminary recommendations and an outlook based on the case study on HABs in Peru and the reviewed literature.

1. ***Guidelines regarding when FCM can be considered PM and when it should not*.** Voinov et al. (2018) classify FCM as a PM tool. Nevertheless, the level of participation varies significantly across case studies. It is crucial to establish clear

criteria to ensure that FCM processes that are consultative or extractive are not labelled a form of PM. Voinov & Bousquet (2010) guidelines provide a starting point highlighting “that a truly participatory effort would engage stakeholders in an interactive and iterative mode, where the flow of information is arranged in both directions” (p. 1272). Most importantly, the PM community should not only compare the technical and methodological strengths and weaknesses of different modelling tools (see Voinov et al., 2018) but do the same regarding their participatory potential.

2. ***Opening the stakeholder identification and data-analysis stages to participation.*** Stakeholder participation in PM is most common during the data-collection and evaluation phase (Voinov et al., 2016, p. 199). Yet, if a modelling approach aims to be participatory, it should open more stages to participation. My study illustrates that not involving participants can exacerbate power dynamics and deepen the epistemic divide between researcher and participant. Especially the stakeholder identification and processing and modeling stages would greatly benefit from more participation. FCM approaches commonly identify stakeholder groups based on instrumental motivation, often in a top-down manner. To address this limitation, researchers could establish stakeholder categories based on participants' involvement and feedback while also analyzing the power dynamics within social networks (Reed, 2008, p. 1946). Secondly, Olazabal, Neumann, et al. (2018) have highlighted FCM’s transparency problems during the processing and analysis stages since the information might be “cherrypicked to suit research agendas” (Oliver et al., 2019, p. 6). Transparency issues at the analysis stage undermine its participatory potential because stakeholders might not identify with the final model and feel a lack of ownership over the process and results. Additionally, the separation between data collection and knowledge generation is the primary driver of the epistemic divide between researcher and participant and the associated issues of cognitive justice. Therefore, FCM studies could lower their ambition regarding more complex modelling tools, instead facilitating a greater inclusion of participants. Alternatively, if participants cannot be involved at this stage but the research still follows participatory goals, the initial models should be processed as little as possible.

3. ***Assessing participatory research motivation and going beyond instrumental goals.*** FCM modelers should not only reflect on the depth of participation but also use typologies that critically evaluate the reason behind participation. Consequently, researchers can more realistically communicate to participants what the process can and cannot achieve since trade-offs exist between instrumental, substantive, political and normative goals (Defila & Di Giulio, 2019, p. 100). This might help avoid participants' disappointment over results and help them make an informed decision on whether participating in the research process lies in their interest, which can reduce future research fatigue. At the end of the process, it would also be essential to assess who benefits or not from the final models (Voinov & Bousquet, 2010, p. 1278). Moreover, FCM is usually motivated by instrumental goals, which are frequently linked to shallow levels of participation. Future studies could assess whether FCM and similar PM methods have the potential to contribute towards normative goals like stakeholder empowerment which have gained importance in fields like participatory action research (Bäckstrand, 2003, p. 37).
4. ***Reflections on the underlying epistemological, ontological, and theoretical assumptions of FCM and their implications for the participatory process.*** Due to their often-technical scope, many FCM studies do not reflect sufficiently on underlying epistemological, ontological assumptions. These assumptions within studies utilizing FCM vary significantly depending on the set goals. As my study showed, underlying assumptions determine whether certain types of knowledge get privileged over others during the participatory process and can even limit the possibility of epistemological pluralism, where multiple forms of knowing inform each other (Santos, 2014, p. 42). In this context, the 'crowd wisdom' approach to FCM must be critically examined, as it creates a hierarchy between scientific knowledge and other knowledge forms and, at times, treats local perception as a resource for scientific inquiry in data-scarce contexts. Furthermore, FCM researchers often argue that given the technical language of tools like FCM, there is a need for training participants to enable them to express their views freely and effectively (Jordan et al., 2018, p. 1048; Voinov et al., 2016, p. 203). However, this raises the question of whether the method itself could be designed more inclusively. Alternatively, a thoughtful analysis of discursive

power and cognitive justice becomes necessary in situations with a significant epistemological divide to determine whether a modelling tool suits a particular context. For instance, while a crowd wisdom approach with pre-defined categories and numerical causal relations might be well-suited for collaborative work with environmental managers or local scientists, it could be unsuitable or potentially detrimental when used with local fishers or indigenous communities. It is essential to carefully assess the compatibility of the modelling tool with the knowledge systems, values, and perspectives of the specific stakeholders involved to ensure that the process is respectful, inclusive, and beneficial to all parties.

5. ***Use FCM to highlight the diversity of perception and visually represent the complexity of a given context.*** Even though models' purpose is to condense a far-more complex reality, FCM has great potential to visualize and explain the intricate details of a study context and perception differences of a diverse range of actors, especially when combined with qualitative research methods (see Schwermer et al., 2021). Representing this diversity can be a goal, even when it means that the final models are harder to interpret and more challenging to use during modelling- and scenario analysis. This approach might be a good suit with studies that aim at deeper levels of participation, since it allows for expressing and integrating more diverse forms of knowledge and increases the chances "to take into account the many, small, almost imperceptible variations that a constantly changing context creates." (Agrawal, 2002, p. 292; Scott, 1998)

In this thesis, I argued that an evaluation of participatory modelling must consider power, cognitive justice, and representation issues. By explicitly addressing and seeking to mitigate these and other previously discussed issues, participatory modellers can actively co-create models more likely to be understood, used, and even owned by the participants.

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Appendix A
Reproducibility & Transparency Documents

Following the Transparency Guidelines of Olazabal, Neumann, et al., (2018) I created Supplementary Materials to report the FCM modelling process. The following Drive-Link contains:

https://drive.google.com/drive/folders/1BZJHz8dWGLgNc51PpGY-lf6KQytsBDGD?usp=sharing

(1) **Supplementary Material 1**: Stakeholder/Participant Information.
(2) **Supplementary Material 2**: Original and Processed Fuzzy Cognitive Maps and Focus Group Guidelines.
(3) **Supplementary Material 3**: Codebook of All Concepts in the Fuzzy Cognitive Maps from Qualitative Analysis.
(4) **Supplementary Material 4**: Qualitative Processing and Standardization Stages.
(5) **Data:** Maps, Adjacency Matrices and Python Code.

Appendix B
Choices During the FCM Study Design

Stage 1. Data Collection

- Dynamic or Causal FCM?
- What weight for the causal links?
- What Stakeholder Groups?
- Participant Sampling?
- Individual Interviews of Focus Groups?
- Mixed Groups or Each Stakeholder Group Separate?
- What length for the Focus Group Discussion?
- What System Boundaries?
- Pre-Defined Concepts or Free Drawing?
- Knowledge Activation or Passive Role for the Researcher?

Stage 2. Data Processing

- How to code, categorize the qualitative data?
- How much qualitative pre-processing of the maps?
- What method for aggregation?
- What Software to Use?

Stage 3. Data Analysis

- What activation function?
- Which variables to use for the scenario analysis?
- What variables to focus on during the sensitivity Analysis?
- How strongly should the variables be activated?

Appendix C
List of Participating Agents at FCM Workshops

Each Map Code refers to a group discussion with 2-5 participants from members of the same stakeholder group. The discussion lasted between 40 Minutes and 2.30 hours. 18 Maps were created with a total of 48 participants. One Map (with 4 participants) had to be excluded because it went beyond system boundaries. Moreover, map 16 – the large-scale fishery map- was not included in the stakeholder group analysis since it was the only map representative of large-scale fishing. However, it was still integrated into the ’crowd model’. Interviews took place in Lima, Sechura, Paita and Paracas & San Andrés/Pisco.

Map Code	Area of Expertise	Broader stakeholder category	Type of agent	Action level/Place
M01	Fishing, Diving & Scallop Production, Logistics	Small-Scale Mariculture	Mariculture Association	Local Sechura
M02	Artisanal Fishing (Handline Fishing) & Local Ecosystem	Small-Scale Fishing	Local Artisanal Fishermen	Local Sechura
M03	Fishing, Diving & Scallop Production, Logistics	Small-Scale Mariculture	Independent Mariculture Producers	Local Sechura
M04	Local politics, fishing & mariculture, and other policy areas	Local Authority	Municipality and Local Fishery department	Local/Regional Sechura
M05	Large-scale scallop production, processing & export	Large-Scale Mariculture	Mariculture company	Local/Regional Sechura
M06	Artisanal Fishing (Handline Fishing) & Local Ecosystem	Small-Scale Fishing	Local Artisanal Fishermen	Local Sechura
M07	Fishing, Diving & Scallop Production, Logistics	Small-scale Mariculture	Largest local Mariculture Association	Local Sechura

M08	Hydrobiological resources & Monitoring, Ocean Science, Fishing regulations	Scientific Experts/Regional Authority	Regional Office of Peru's Institute of the sea (IMARPE)	Regional Sechura/Paita
M09	Fisheries Hygiene, Monitoring, Phytoplankton, Marine Biology & Ocean Science	Scientific Experts/Regional Authority	The local office of the agency for fisheries health (SANIPES)	Local/Regional Sechura
M10	Ocean Science, Phytoplankton, Harmful Algae Blooms & Toxins, Monitoring	Scientific Experts	Researchers working on Harmful Algae Blooms	National Lima
M11	Hydrobiological resources & Monitoring, Ocean Science, Fishing Regulations	Scientific Experts/National Authority	National Office of Peru's Institute of the sea (IMARPE)	National Lima
M12	Hydrobiological resources & Monitoring, Ocean Science, Fishing Regulations	Scientific Experts/Regional Authority	Regional Office of Peru's Institute of the sea (IMARPE)	Regional Paracas
M13	Scallop Production, Tourism, Gastronomy	Small-Scale Mariculture	Restaurant and Mariculture	Local Paracas
M14	Tourism, Disaster Risks, Local Politics & other policy areas	Local Authority	Municipality	Local/Regional Paracas
M15	Diving, Small-Scale Fishing, Scallop mariculture, Tourism, Fishery regulations	Small-Scale Fisheries & Aquaculture	Local Artisanal fishery syndicate	Local Paracas/San Andrés
M16 (only included in crowd model)	Waste Water Treatment, Fishing, Industrial fishery production	Large-Scale Fishing	Fishing company and wastewater treatment	Local/Regional Paracas
M17	Scallop Production, Tourism, Macroalgae Cultivation	Small-Scale Mariculture	Independent Mariculture Producer	Local Paracas/Lagunillas
~~**M18**~~	~~Diving, Small-Scale Fishing, Scallop mariculture, Tourism~~	~~Small-Scale Fishing & Mariculture~~	~~Independent Local Artisanal fishery~~	~~Local Paracas/San Andrés~~

Appendix D
Qualitative Coding and Map Processing Steps

I based my coding process on Creswell & Poth's (2016, p. 333) coding procedure and combined it with Olazabal, Neumann, et al. (2018) guidelines for qualitative homogenization of FCMs. First, I coded and defined all the concepts in the maps in a codebook based on the focus group audio. Then, I used this information to pre-process/homogenize the FCMs for quantitative analysis.

Stages in Qualitative Coding
(1) Relisten to the audios and take notes on noteworthy quotes, surprising information, and definitions of concepts, but also on group dynamics and on the FCM approach/participatory aspect. (2) Use the concepts introduced by participants as starting point to structure the information into codes. (3) Write a definition of each code and include contextual information. a. Structure these codes along the three themes of *drivers, impacts, adaptations.* b. Distinguish between the two study locations Paracas, Sechura to highlight differences and commonalities. (4) The final codes are presented in a codebook that is based on a similar document by Olazabal, Neumann, et al., (2018). This document serves as a dictionary that provides detailed definitions for all the concepts included in the processed FCMs.

Map Pre-Processing
(1) Translate Maps from Spanish to English. (2) Standardize names of concepts that mean the same based on the previous qualitative coding (e.g., rename “Spaced-Out Scallop Production” into “Production Area Diversification” in all Maps). (3) Standardize Concepts and Dis-Concepts and adjust connected causal connections (e.g., Change “Lack of Employment” to “Employment”) (4) Correct Errors and Spelling (e.g., “Suspended Culture” vs “Suspended Cultures”). (5) Merge similar variables into one category (e.g., Merge “Direct Employment” and “Indirect Employment” into “Employment”) (6) Delete Variables that were not related to any other variables in the map (e.g., “Climate Change”) or that were only definitional (e.g., “Water Renewal” as caused by “Local Currents”). (7) Digitalize the Maps with the *Mental Modeler Software*

Appendix E
Graph Metrics and General Characteristics of the Stakeholder Models

The final 'crowd model' (aggregation of all maps) of HABs comprised 113 concepts. Of these components, 33 were drivers, 41 were impacts and 38 were adaptation strategies. Moreover, of the five aggregated stakeholder group maps, the SSM had the most variables (78) and connections (147), followed by the expert map with 59 variables and 119 connections.

Stakeholder Groups	Crowd Map	SSM	LSM	SSF	LE	LA
Nr. Of Maps	17	6	1	2	5	2
Nr. Of Variables	113	78	33	35	59	42
Nr. Of Connections	293	147	34	49	119	50
Drivers	33	22	9	8	22	12
Impacts	41	26	12	20	19	17
Adaptation	38	29	11	6	17	12
Drivers (%)	29%	29%	28%	24%	38%	29%
Impacts (%)	37%	34%	38%	59%	33%	41%
Adaptation (%)	34%	38%	34%	18%	29%	29%

Furthermore, there was consensus about key aspects of HABs: the ten most frequently mentioned components were part of more than 65% of individual maps (see Appendix D). Despite this consensus, stakeholder groups emphasized different aspects, which becomes clear when looking at the percentages of drivers, impacts, and adaptation in Table 4. Scientific experts focused most on drivers of HABs (38%) and discussed them from a scientific perspective, while SSF were highlighting the impacts (54%) on their economic- and social activities rather than the drivers (24%). Similarly, the mariculture producers focused more on impacts (34%) and adaptation strategies (38%) especially related to the mariculture sector. Meanwhile, public authorities mentioned broad community-related impacts such as health issues, tourism, and recreation. Overall, this suggests that a combined 'crowd model' can be a more nuanced and complete representation of the complex social-ecological systems of HABs because it combines the local-ecological and scientific expertise of diverse stakeholder groups (Aminpour et al., 2021, p. 1)

Appendix F
Adaptation Strategies With Most Influence on the System (Crowd Model)

Adaptation Strategies	Outgoing Score	Practiced or Hypothetical?	By which Stakeholder?
Early Warning System	0.54	Hypothetical	
Hygiene Monitoring	0.39	Practiced	LE
Emergency Harvest	0.33	Practiced	SSM & LSM; advantages LSM
Income Diversification	0.31	Partly Practiced	SSM & LSM
Change Harvest Strategies	0.31	Practiced	SSM & LSM; advantages LSM
Suspended Cultures	0.29	Partly Practiced	LSM
Research (Transparency)	0.25	Partly Practiced	(LE); advantages LSM
Oceanographic Monitoring	0.25	Partly Practiced	All; advantages LSM
Official Emergency Plan	0.18	Hypothetical	
Modified Clay	0.17	Hypothetical	
Diversification Production Area	0.16	Partly Practiced	LSM
Pollution Regulations & Control	0.14	Partly Practiced	Paracas
Waste Treatment	0.14	Hypothetical	
Improve Institution's Communication	0.14	Limiting Factor	SSM
State Support	0.12	Hypothetical	
Lack of Buyers	0.12	Limiting Factor	SSM
Communication With Other Companies and Fishers	0.1	Practiced	SSM & LSM
Participative Monitoring	0.1	Hypothetical	
Hygiene Monitoring Frequency & Speed	0.1	Limiting Factor	SSM
Oxygenation	0.1	Partly Practiced	advantages LSM
Personal Observations/Predictions	0.1	Practiced	SSM, SSF, LSM
Scallop Market Price	0.08	Limiting Factor	SSM
Scallop Size	0.08	Limiting Factor	SSM
Scallop Hatcheries	0.08	Partly Practiced	LSM
Sensitize Population	0.08	Hypothetical	
Lack Of Investment	0.06	Limiting Factor	SSM
Better Infrastructure	0.06	Limiting Factor	SSM
Scallop Extraction Days	0.04	Limiting Factor	SSM
Long-Term Planning	0.04	Practiced	LSM
Continue Fishing	0.04	Practiced	SSF
Health Assistance	0.04	Hypothetical	
Copy Strategies of Companies	0.02	Practiced	SSM
Shorter Production Cycle	0.02	Partly Practiced	SSM
Collect Stranded Fish	0.02	Practiced	SSF
Rely On Your Own Savings	0.02	Partly Practiced	SSM

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Ich versichere, die Masterarbeit selbstständig und lediglich unter Benutzung der angegebenen Quellen und Hilfsmittel verfasst zu haben.

Ich erkläre weiterhin, dass die vorliegende Arbeit noch nicht im Rahmen eines anderen Prüfungsverfahrens eingereicht wurde.

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