








ORIGINAL ARTICLE

Untangling social–ecological interactions: A methods portfolio approach to tackling contemporary sustainability challenges in fisheries

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Abstract

Meeting the objectives of sustainable fisheries management requires attention to the complex interactions between humans, institutions and ecosystems that give rise to fishery outcomes. Traditional approaches to studying fisheries often do not fully capture, nor focus on these complex interactions between people and ecosystems. Despite advances in the scope and scale of interactions encompassed by more holistic methods, for example ecosystem-based fisheries management approaches, no single method can adequately capture the complexity of human–nature interactions. Approaches that combine quantitative and qualitative analytical approaches are necessary to generate a deeper understanding of these interactions and illuminate

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pathways to address fisheries sustainability challenges. However, combining methods is inherently challenging and requires understanding multiple methods from different, often disciplinarily distinct origins, demanding reflexivity of the researchers involved. Social–ecological systems' research has a history of utilising combinations of methods across the social and ecological realms to account for spatial and temporal dynamics, uncertainty and feedbacks that are key components of fisheries. We describe several categories of analytical methods (statistical modelling, network analysis, dynamic modelling, qualitative analysis and controlled behavioural experiments) and highlight their applications in fisheries research, strengths and limitations, data needs and overall objectives. We then discuss important considerations of a methods portfolio development process, including reflexivity, epistemological and ontological concerns and illustrate these considerations via three case studies. We show that, by expanding their methods portfolios, researchers will be better equipped to study the complex interactions shaping fisheries and contribute to solutions for sustainable fisheries management.

KEYWORDS

analytical methods, fisheries management, interdisciplinarity, multi-method approaches, reflexivity, social–ecological systems

1 | INTRODUCTION

Achieving fisheries sustainability requires simultaneously embracing multiple objectives, including conservation, food security and livelihoods. Fisheries scientists attempting to realise these multiple objectives must consider a vast set of complex interactions between humans, institutions and ecosystems (Duarte et al., 2020; FAO, 2020). This presents methodological and analytical challenges that are difficult to solve using traditional fisheries science approaches. While traditional approaches often focus on policies that prioritise conservation and economic aspects, sustainability science expands the focus to include societal objectives of equity and well-being (Stephenson et al., 2018). Hence, managing for sustainability requires interdisciplinary methodological approaches to analyse fisheries as intertwined social–ecological systems (SES; Phillipson & Symes, 2013). Specifically, understanding the complex relationships within and among diverse ecological and social system components, that is social–ecological interactions is critical to meeting the multiple objectives of sustainability (Bodin et al., 2019; Schlüter, Haider, et al., 2019). The importance of such interactions in shaping the causes, consequences and outcomes of fisheries management is well acknowledged (Berkes, 2012; Hunt et al., 2013; Leslie et al., 2015). Even so, operationalising the analysis of fisheries as SES remains a core challenge and represents an important avenue for further advancement of fisheries sustainability studies.

The goal of this paper is to address this need to better equip fisheries researchers with ways to analyse social–ecological interactions and associated outcomes for sustainable fisheries management. In particular, we emphasise the added value of utilising

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multiple analytical methods as a way to compensate for the inherent limitations of individual methods. To this end, we present a selection of method categories and elaborate how to use them to create methods portfolios through engagement in a reflexive, inter- and

transdisciplinary research process, with illustrations from members of the author team.

Traditional fisheries science approaches often focus on managing at the maximum sustainable yield of single-species populations, taking a simplistic view of the processes that drive population dynamics (Barber, 1988; Martell & Froese, 2013). More recent developments have broadened the approach by considering multiple species (Kolding et al., 2016; Stewart & Long, 2016), adaptive processes of fish stocks through, for example Bayesian modelling (Jiao et al., 2016; Mäntyniemi, 2006) and more holistic ecosystem-based approaches to fisheries management (Collie et al., 2016; Kroetz et al., 2019). Despite significant developments in understanding ecological and environmental dynamics and including more social science in fisheries research, the interactions between people and marine systems have still not received adequate consideration. This may be attributed to issues such as the failure to include social-ecological interactions in the framing of research problems and questions (Wisz et al., 2020), epistemological issues concerning how different knowledges are valued, defined and generated (Lee et al., 2019; Moon et al., 2021; Phillipson & Symes, 2013) and the content of educational curriculum in knowledge production programmes versus training programmes for managers (Ciannelli et al., 2014). Moreover, the most commonly employed methods in fisheries research and management do not adequately account for the human dimension, and as a consequence, those methods that do analyse human-environment interactions are less developed in fisheries research (Fulton et al., 2011; Syed et al., 2018; van Putten et al., 2012).

Social-ecological systems research includes approaches and methods for understanding and analysing fisheries as integrated systems of humans and marine environments (Berkes, 2012; Biggs et al., 2021; Kittinger et al., 2013). Through the wide variety of philosophical assumptions, theories, frameworks and methods across the natural and social sciences, SES research embraces epistemological pluralism and social-ecological integration (Miller et al., 2008; Preiser et al., 2018). While SES research is still a relatively young domain, several methods have emerged that are commonly applied to understand the structure and dynamics of SES (Biggs et al., 2021; de Vos et al., 2019; Glaeser et al., 2009). Although methods for data collection or knowledge co-production are often part of the methodological design of a research project (Bennett & Zurek, 2006; Biggs et al., 2021), in this paper, we limit our scope to methods intended for analytical purposes because of recent computational advancements and promising novel applications of analytical methods in fisheries. We demonstrate how to utilise multiple analytical methods while relating them to data collection methods through examples from the author team. We build on our own experiences to show and discuss how researchers can engage in a more reflexive process, together with managers, to recognise and reflect on how their training and background constrain research questions and methods and how to overcome these constraints (Finlay, 2002).

The paper proceeds as follows: we begin by presenting the more common analytical methods in fisheries research traditionally, that is (i) statistical modelling, then continue with; (ii) network analysis; (iii) dynamic modelling methods; (iv) qualitative analysis; and (v) controlled behavioural experiments (Section 2). We then detail three examples from our own research to demonstrate how we have combined methods and developed a methods portfolio to deepen our understanding of social-ecological interactions and outcomes relevant to tackling fisheries sustainability challenges (Section 3). We discuss the reflexive process and the assumptions about how we see the world (ontology) and study it (epistemology) that influence the selection, application and combination of methods (Section 4). As a group of inter- and transdisciplinary researchers working mostly in academia, but also as practitioners (science advisors, fisheries consultants and conservation practitioners), with a wide range of backgrounds (incl. marine ecology, sustainability sciences, ecological economics and cognitive sciences), we hope to inspire fisheries scholars to consider expanding their methods portfolios to enable a more comprehensive and deeper understanding, as well as more adequate problem-solving strategies for analysing complex interactions in fisheries.

2 | METHODS FOR ANALYSING INTERACTIONS AND OUTCOMES

The analysis process of studying fisheries can be understood as drawing conclusions from analysing, describing and combining available data with other information sources such as literature and theory. Analysing fisheries as SES requires working across quantitative and qualitative realms to account for the diverse interactions among the social, economic, institutional and ecological aspects across time and space (Figure 1). This also implies utilising and combining methods that originate from different disciplines.

By providing a brief introduction to the method categories with fisheries examples and applications, our aim is to highlight the complementarity of different categories with respect to their typical features, summarised in Table 1, as a first step towards explaining the role of a methods portfolio for a more holistic study of fisheries as SES. Our choice of method categories below is not only broadly based on the way in which they disentangle interactions and associated outcomes, but also reflects recent developments in fisheries research in combination with the author team's expertise. Note that the five method categories presented below are neither comprehensive, nor do we assume that they have equal weight with respect to the number of methods or approaches nested within them. A mix of quantitative and qualitative approaches are presented as well as different modelling approaches and controlled behavioural experiments that do not fit into the qualitative or quantitative typologies. Furthermore, we acknowledge that controlled behavioural experiments combine data collection and analysis, but we have included the category because of its utility in understanding social-ecological

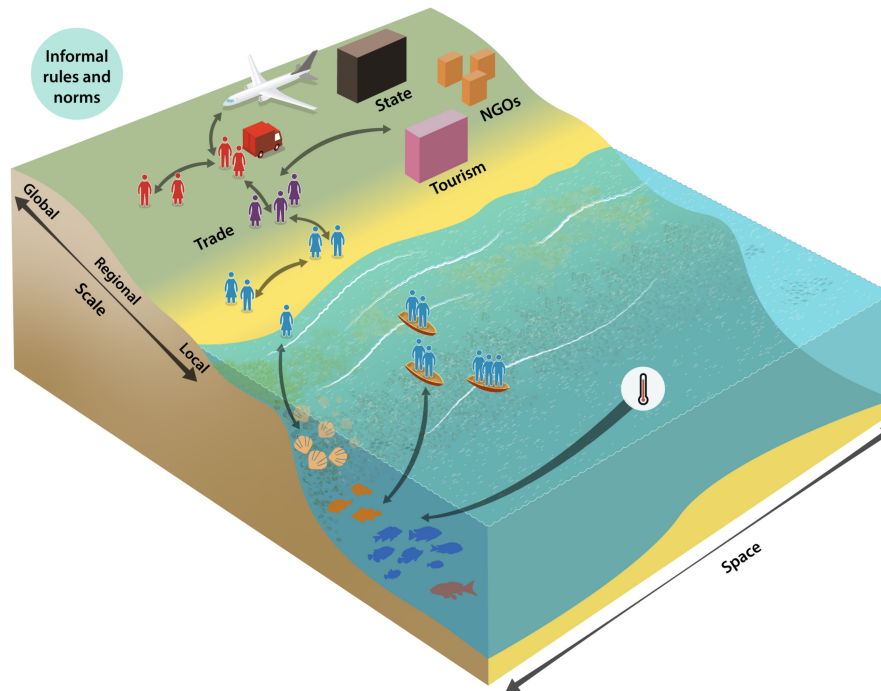


FIGURE 1 Conceptual figure of a small-scale fishing community with a selection of relevant variables and interactions. The arrows represent interactions between environmental conditions, marine species, fishers, traders, the tourism sector, state institutions and NGOs that are influenced by informal rules and norms and occur across multiple institutional, temporal and spatial scales. The red individuals represent regional traders, the purple individuals represent local traders, the blue individuals represent fishers, the truck represents regional trade, and the airplane represents international trade. Other icons represent state institutions (incl. formal rules and regulations), NGOs, the tourism sector, marine ecosystems and environmental conditions that are relevant for understanding and analysing fisheries' sustainability

interactions. For each method category, we describe its background, example applications in fisheries research and strengths and limitations.

2.1 | Statistical modelling

Statistical modelling aims to identify relationships between variables to identify patterns, make inferences and potentially predict focal variables (Ogle, 2018). In fisheries, linear regression, analysis of variance, multiple regressions, factor analysis, generalised linear models and non-parametric models are common methods to test how an independent variable or factor might be driving a dependent response variable (Hilborn & Walters, 1992). However, to capture interactions, more advanced techniques are needed. We highlight Bayesian network modelling (Scutari & Denis, 2021) and structural equation modelling (SEM; Hoyle, 2012), as increasingly adopted techniques within social-ecological systems research and management. Bayesian network models are probabilistic, graphical network models where the nodes in the network model represent random variables and the arrows represent conditional dependencies. SEMs are multivariate statistical models that aim to uncover the linear relationships between multiple variables, which can include both observed and unobserved (latent) variables.

Bayesian network models have been used to predict environmental responses to changes in external drivers like climate change

and fish biodiversity (Trifonova et al., 2017; Uusitalo et al., 2018), examine trophic dynamics in fisheries (Trifonova et al., 2015) or link social and ecological data directly to fisheries management (Naranjo-Madrigal et al., 2015; Parsons et al., 2021; Varkey et al., 2016). SEMs have been used to examine relationships between governance and ecological surprise in fisheries using the social-ecological systems framework (Filbee-Dexter et al., 2018), the factors underpinning livelihood resilience in small-scale fisheries (Amadu et al., 2021), the conditions leading to sustainability in small-scale fisheries (Robotham et al., 2019) and feedbacks in fisheries systems (Grilli et al., 2018).

Traditional statistical models are often limited by their inability to explore multiple relationships simultaneously, and thus, they are not well-suited to examine interactions and interdependencies among and between social and ecological variables. The use of interaction effects within models—or studying how the relationship between an independent and dependent variable is affected by a third variable—can help study social-ecological interdependencies, but this approach could be cumbersome when dealing with large sets of variables. While traditional statistical modelling approaches provide critical information about fisheries, Bayesian network models and SEMs can give researchers a more complete understanding of the complex interactions within fisheries. Bayesian network modelling and SEMs allow for the specification of complicated, multiple and entangled pathways between social and ecological variables within the same model. Bayesian network models can test hypothesised

relationships with data or learn the relationships inductively from the data, while SEMs can test the strength of hypothesised causal pathways, but cannot learn the structure of the model inductively from data. Bayesian network models typically cannot include feedbacks or cycles between variables (Scutari & Denis, 2021), whereas accounting for both direct and indirect feedbacks is a particular strength of SEMs (Filbee-Dexter et al., 2018; Grilli et al., 2018; Hoyle, 2012).

In sum, advanced statistical techniques play an important role in addressing sustainability-related questions in fisheries. Nonetheless, there are cases that necessitate approaches beyond statistical techniques, in particular, to better capture social and social-ecological interactions that affect fisheries outcomes. Accordingly, we turn next to a method category that builds on other theories and assumptions to study fisheries sustainability challenges.

2.2 | Network analysis

Network analysis studies the patterns of interactions among entities, allowing for the representation of multiple relationships between them (Sayles et al., 2019). A key strength of network analysis is that it offers a broad range of conceptual and analytical tools to investigate the patterns of the relations in which entities interact. For instance, descriptive analyses can characterise a network in terms of the density of links, and statistical analyses can untangle how, for example, certain node attributes (e.g. a fisher's preferred gear type) are related to certain propensities to form links (e.g. Alexander et al., 2018). In short, network analysis specifically allows for the integration of various social and ecological entities, along with the interactions within and across all types of entities, within the same network model (social-ecological network).

In fisheries, network analysis has been used to investigate ecological relationships such as trophic interactions (Bascompte et al., 2005), spatial connectivity such as larval dispersal (Munguia-Vega et al., 2018), social-ecological relationships such as harvesting (Alexander et al., 2020; Bodin et al., 2014) and social relationships such as collaboration (Alexander et al., 2017), communication (Barnes et al., 2019) and trade (González-Mon et al., 2019). The analysis of network structures can reveal implications for collaboration in natural resource governance (Bodin, 2017) and for understanding power and influence of actors or organisations based on their network positions (Crona & Bodin, 2010). Recently, social-ecological network analysis has been used to study the interactions between diverse fisheries and fishing locations created through fishers' diversification strategies and effort allocation, with implications for ecosystem-based management (Fuller et al., 2017; González-Mon, Bodin, et al., 2021; Kroetz et al., 2019; Nomura et al., 2021).

The resources required to collect network data are a common limitation of empirical network research. However, some studies are beginning to address this limitation by using existing datasets in new ways (Fuller et al., 2017; González-Mon, Bodin, et al., 2021; Pace & Gephart, 2017). Another critique is that the larger context in which


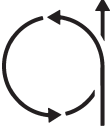



entities interact is often left out in the network analysis itself (Smith-Doerr & Powell, 2005); however, comparative network analysis is capable of including broad contextual characteristics of study systems, such as institutions, culture and policy, and remains a research frontier in the fisheries literature and elsewhere (Bodin et al., 2019). While most network studies are based on a snapshot in time, longitudinal network analysis is possible where long time series data exists and represents an important avenue for further development of empirical network studies (Bodin et al., 2019; Sayles et al., 2019). The non-dynamic nature of most network data has led to methods such as exponential random graph modelling (ERGM) that can be used to hypothesise about underlying processes that explain network structures by inferring dynamics based on data from a single point in time (Robins et al., 2007; Sayles et al., 2019). If longitudinal network data are available, stochastic actor oriented models (SAOM; Snijders et al., 2010) can be utilised to analyse the dynamic evolution of a network. Statistical network models like ERGM and SAOM are constructed to not only account for data interdependencies (i.e. the ties between entities/nodes), but also specifically investigate whether and how such interdependencies endogenously interact in shaping the patterns of interactions among system components.

In sum, network analysis is increasingly applied to address sustainability-related questions in fisheries and increasingly focuses on the analysis of social-ecological interactions. However, to understand the dynamics of how networks change over time, network analysis faces important challenges. In the following sections, we explore other method categories that can address these limitations, for example by studying feedbacks between system components and the emergence of new system configurations.

2.3 | Dynamic modelling

Dynamic modelling allows us to understand how factors and processes interact and lead to system outcomes (Schlüter, Haider, et al., 2019). This broad category refers to a suite of computational modelling approaches that can range from purely theoretical to fully data driven, with purposes spanning from policy assessments and identification of optimal management strategies, to co-learning through participatory modelling and explorations of system behaviour (see Edmonds, 2017, or Epstein, 2008, for more examples on modelling purposes). Through modelling, one can explore how different system structures may influence the evolution of the system and the system's behaviour (e.g. dynamical systems modelling or system dynamics modelling; Sterman, 2001). Other approaches focus on identifying optimal management strategies or policies through optimisation (e.g. bioeconomic modelling; Clark, 2010). More structurally realistic models, for example individual- or agent-based models, focus on understanding micro-macro dynamics, enabling patterns at the macro-level to emerge from interactions between human and non-human entities at the micro-level (Burgess et al., 2020; Glaser, 2012; Lindkvist et al., 2020).

TABLE 1 Overview of method categories presented in Sections 2.1–2.5, including examples of methods, their typical objectives, data needs and outputs and strengths and limitations for analysing interactions and outcomes in fisheries as social–ecological systems

Method category	Statistical modelling	Dynamic modelling	Network analysis	Qualitative analysis	Controlled behavioural experiments
					
Methods	Generalised linear models; Bayesian network models; Structural equation models.	Dynamical systems modelling; System dynamics modelling; Bioeconomic modelling; Agent-based modelling.	Descriptive network analysis; Statistical network analysis (e.g. ERGM, SAOM)	Ethnography; process tracing; Content analysis; Discourse analysis.	Common-pool resource experiments; Field experiments; Dynamic game experiments.
Objective	Identify patterns, relationships and interactions between variables; make inferences; prediction.	Understand how diverse factors and processes interact to shape outcomes.	Understand the patterns of relationships in which entities interact.	Understand interactions between people and the various contexts they live within.	Understand the effect of specific variables or conditions on individual or group behaviour.
Role and type of input data	Inputs are commonly social and/or ecological quantitative data.	Inputs to the model can be quantitative data, qualitative data or theories. Data can be ecological and/or social.	Inputs can be quantitative and/or qualitative data about relationships that can be social and/or ecological.	Input is qualitative raw data (any N). Most data come from interpretation of spoken word or text situated in a fishery context.	No input data are used as controlled behavioural experiments are also a data collection tool.
Outputs	The outputs depend on the type of method used, but can be conditional dependencies, strengths of relationships, covariance, and others.	The outputs can be quantitative data, for example time series, or patterns, or qualitative analysis of model dynamics.	The outputs are specific quantitative descriptive and statistical measures of network data.	The outputs are qualitative patterns, themes or discourses.	The outputs are quantitative patterns on participants' decisions given different conditions, often combined or triangulated with both quantitative and qualitative data from interviews and/or observations of participants.
Analytical Strengths	To examine quantitative empirical relationships between variables or quantitative relationships between observed and unobserved (latent) variables.	To perform simulated experiments to explore and test understandings of a system, to generate new hypotheses, explanations and/or to make management decisions. Specifically useful for analysing interactions as feedbacks.	To capture specific patterns of relationships between diverse entities that can be human, non-human or both. The focus is on analysing relationships between entities for understanding underlying processes.	To provide an in-depth and rich understanding of human-environment interactions, identifying context-sensitive causal relationships. Particularly useful for analysing how decisions and behaviours change with changing social and/or ecological conditions.	Decision-making, for identifying causal relationships between individual (or group) behaviour and context. Particularly useful for analysing how decisions and behaviours change with changing social and/or ecological conditions.
Limitations	Many methods assume linear and stationary relationships between variables; some cannot account for feedbacks between variables.	Results risk being misunderstood or misused if model assumptions and/or purpose are not transparent. Depending on model type, its development can be time consuming and data intensive.	Lack of data to study large spatial scales and longitudinal data. Statistical analyses can be challenging due to the inherent interdependencies in network data.	Clarifying and understanding positionality and ethical dilemmas may be challenging. Data processing and analysis is time consuming.	Compliance with best practices associated with experiments can be resource intensive. Data collection may be costly. Concerns about external validity.

Note: For more thorough descriptions, fisheries examples and references for each method category, please see the corresponding section.

Dynamic modelling has a long history in fisheries and includes research on phenomena such as overfishing, regime shifts and poverty traps as well as strong focus on integrated models for sustainable management (Collie et al., 2016; Nielsen et al., 2018; Plagányi et al., 2014). In studies of fisheries, we find dynamical systems modelling applied to study the interactions between social and ecological processes that contributed to the temporary persistence of the cod boom as well as to its subsequent collapse (Lade et al., 2015), and bioeconomic modelling for optimising long-term harvests in relation to cost and effort (Crépin, 2007; Dowling et al., 2012). The structurally realistic models include studies on how cooperation between fishers can emerge and influence fishery sustainability (Gutierrez et al., 2017; Lindkvist et al., 2017), the emergence of harvesting strategies (Klein et al., 2017; Plank et al., 2017; Wilson et al., 2007) and negotiations between interest groups in the Baltic Sea (Orach et al., 2020).

The diversity of modelling approaches presented naturally encompasses different limitations and strengths. A notable challenge with dynamic modelling in general is to be transparent about model assumptions, so the results are not misunderstood or misused (Schulze et al., 2017). Depending on model type and purpose, the model design and development phase can be time consuming and data intensive; models intended for policy making may require large and diverse datasets, while a simpler educational or theoretical model may be less data intense (Lindkvist et al., 2020). Models also are exemplary tools for transdisciplinary research that brings together knowledge from people with diverse backgrounds through collaborative and/or participatory modelling processes (Biggs et al., 2021; Glaser, 2012; Schlüter, Orach, et al., 2019).

In sum, a core strength of dynamic modelling is that it provides an explicit representation of the dynamics in a system to investigate causal relationships. However, for model design as well as interpretation of results, an in-depth understanding of the systems investigated is central. Next, we turn to a method category that may be suitable for providing some of this in-depth knowledge: qualitative analysis.

2.4 | Qualitative analysis

Qualitative analytical methods produce rich insights about humans' interactions with one another, fished species and socio-economic, institutional and political contexts (Barclay et al., 2017). These methods are valuable for understanding causality behind interactions because they are able to explain; for instance, how fishers or traders make decisions in certain contexts, which is critical to the design of effective fisheries management. Qualitative analytical methods can not only help in unravelling what people think or how they act in relation to their environment but also why they think or act in certain ways (Sutherland et al., 2018). Such methods may reveal interdependencies among fishery entities and enable the combination of diverse types of knowledge (Jentoft, 2006). Qualitative analytical methods include methods such as content analysis, discourse analysis, ethnography, process tracing, and participatory methods, that originate from diverse disciplines (e.g. anthropology, political

science, sociology and human geography). This broad group of methods often rely on data from spoken word, visual representations, written text and observation (Barclay et al., 2017).

Among many examples, qualitative analytical methods have been used to study interactions between fishers and target species (Brewer, 2013; Pellowe & Leslie, 2019), fishers' involvement in ecological monitoring (Quintana et al., 2020), power relations in fisheries (Gelcich et al., 2005), fishers and their environment (Sievanen, 2014) and fishers and the institutional, social and economic contexts in which they operate (Barclay et al., 2017; Pellowe & Leslie, 2020b). They have also been used for investigating fishing styles in detailing how fishers pursue different styles of fishing and thus interact with fish resources in different ways in the Baltic Sea (Boonstra & Hentati-Sundberg, 2016). Furthermore, Voyer et al. (2015) identified and integrated the values and perspectives of diverse coastal users and how they influence peoples' perceptions of marine protected areas. Qualitative analysis as a tool in fisheries has been predominantly used to study social and social-ecological interactions, although it has, in some cases, been used to understand historical changes in ecological conditions, through the perspectives of resource users (Lee et al., 2019).

Qualitative methods also pose a set of challenges. Many qualitative methods, such as ethnography which relies on observation and informal conversations to understand the culture and behaviours of groups of people, require long, up-front time investment to build trust and rapport among study participants. Generally, these methods are not possible to replicate, although replication is typically not the goal. Instead, rigorous qualitative analysis establishes trustworthy causal relationships (i.e. internal validity) and acknowledges the researcher's subjectivity and positionality—for example a researcher's pre-conceived notions of the phenomenon under scrutiny (Cox, 2015). To increase the validity of conclusions, often, multiple qualitative data sources are combined to triangulate observations and conclusions (Lubet, 2018; Pellowe & Leslie, 2020b).

Another way to uncover causal relationships in human-environment interactions is to use controlled behavioural experiments, the final method category we present in this paper. This method category allows for gaining an empirically based understanding about the effect of specific social-ecological factors and contexts on individual and group behaviour.

2.5 | Controlled behavioural experiments

In controlled behavioural experiments, individuals or groups of people are randomly assigned to control or treatment groups, to test the causal effect of a specific variable or certain conditions on individual or group behaviour. Such experiments allow the researcher to construct a proper counterfactual and to manipulate a context in a 'controlled' fashion (see e.g. Friedman & Sunder, 1994; or Lindahl et al., 2021). In recent years, more and more researchers have employed controlled behavioural experiments to understand how people behave and make decisions in complex SES, using designs that are informed by both social and ecological complexities

of the system (Janssen et al., 2015; Lindahl et al., 2021; Poteete et al., 2010). These experiments are typically framed; the instructions reflect the particular social–ecological context of interest. For example, when fishers are participants, one could frame the experiment around a shared fishing ground (Finkbeiner et al., 2018). They are also often set-up as games in which participants interact with each other and a shared resource over several rounds, for example so-called common-pool resources games (Lindahl et al., 2021). For example, in each round, participants decide how much of a shared resource they would like to harvest and the availability of the resource depends on how much was harvested in the previous round (Schill et al., 2015). Such dynamic experimental designs allow for the capture of social–ecological interactions over time (Cardenas et al., 2013; Lindahl et al., 2021; Rivera-Hechem et al., 2021).

Experimental studies that investigate social–ecological interactions in relation to specific ecological complexities or institutions are of high relevance for fisheries research. Examples include how resource users might deal with phenomena such as tipping points in their shared resource (Lindahl et al., 2016; Schill et al., 2015), or temporal and spatial resource dynamics (Janssen et al., 2015). Studies with fishers as participants include work investigating harvest efforts in the face of ecological uncertainties (Finkbeiner et al., 2018; Rocha et al., 2020), changing market and price dynamics (Drury O’Neill et al., 2019) and external regulation (Moreno-Sánchez & Maldonado, 2010).

Drawbacks of the experimental approach are that testing the interactions of several variables is quite resource intensive, and depending on the incentives used (e.g. monetary incentives), costs can be substantial (Lindahl et al., 2021). Additionally, running controlled experiments in the field requires a relatively large research team. While experiments are useful tools for understanding how behaviour changes as a function of a treatment, they do not elucidate underlying mechanisms of behaviour (Poteete et al., 2010). In most cases, experiments are therefore complemented with post-experimental questionnaires, in-depth interviews or focus group discussions, to elicit behavioural drivers and motivations and to help contextualise the experimental results (Castillo et al., 2011; Lindahl et al., 2021; Rojas et al., 2021). Lastly, there is always the question of external validity: to what extent can the experimental outcomes, such as the decisions made by participants, be generalised beyond the experimental setting (see e.g. Torres-Guevara & Schlüter, 2016)? This question goes beyond experimental studies and brings attention to the importance of triangulating and validating results through the combination of multiple complementary methods.

3 | TOWARDS A METHODS PORTFOLIO FOR ANALYSING INTERACTIONS AND OUTCOMES

Each analytical method category has strengths and limitations, and each contributes to understanding distinct aspects of interactions in fisheries systems. A methods portfolio can be understood as a collection of methods that a researcher or research team draws upon

to answer their research question (Young et al., 2006), often with the aim of informing action, management or policy. While a single method can illuminate important interactions in fisheries, it often falls short of understanding the complex web of social–ecological interactions that occur across multiple spatial, temporal and institutional scales (Figure 1). Thus, combining methods that take different analytical approaches and approach complex causality in different ways allows for a more holistic understanding of the dynamics and complexity of fisheries systems (Lee et al., 2019; Saltelli et al., 2020).

The process of selecting which methods to apply to a specific study is not straightforward. Important considerations include the exact questions and objectives of the study, the data available and their spatial and temporal coverage, and the context of the fishery, for example whether it is a small-scale artisanal or large-scale industrial fishery. The resources available within a research project, such as time, expertise and funding, place constraints on the methods that can be employed. As such, the selection of methods needs to be tailored to the specific context of each project. The supplementary material provides a more in-depth elaboration on important factors and considerations to guide the selection of methods and the development of methods portfolios in fisheries research (Appendix S1).

3.1 | Methods portfolio development

The pathways towards and motivations for selecting methods and developing a methods portfolio can unfold in different ways. In this section, we provide specific examples from fisheries case studies, demonstrating this diversity and underlying motivations.

3.1.1 | Three case studies

The cases we present all focus on different interactions and outcomes across different scales, but share the broader objective of improving fisheries sustainability (Table 2; Figure 2). The small-scale clam fishery case combines statistical analysis and statistical modelling with qualitative analysis and finally applies a dynamic modelling approach to identify future avenues for sustainable management of the Mexican chocolate clam fishery in Loreto Bay, Baja California Sur, Mexico (Box 1). The cross-scale trade-network case combines qualitative analysis, network analysis and dynamic modelling to study the traders and the trade system in Baja California Sur, Mexico, and their potential influence on fisheries’ adaptation to environmental changes (Box 2). The value chain analysis case combines qualitative analysis, statistical analysis and controlled behavioural experiments to unpack the value chain in small-scale fisheries in Zanzibar, Tanzania (Box 3).

3.1.2 | Reflections on the development process

As illustrated by the three case studies, there are multiple motivations for and ways of developing a methods portfolio. The

development of a methods portfolio can be either planned from the start of a research project or take place iteratively, and thus, there is no singular approach to creating one (e.g. [Box 1–3](#)). While the development of a methods portfolio may be driven by the need to include additional methods as new research questions arise, others may choose to combine methods because the first methods employed do not provide a complete answer to the original research question ([Table 2](#)). Still other researchers who choose to use multiple methods

may be motivated by the need to analyse multiple types of data and combine knowledge types (see e.g. [Lee et al., 2019](#)).

As demonstrated in [Box 1–3](#), one possible approach to developing a methods portfolio is for researchers to start with the methods they know best and to develop awareness of the biases, strengths and weaknesses of those primary methods. Next, they may consider other methods that complement their primary methods and provide a more holistic lens through which to view their study system,

TABLE 2 Overview of the three cases outlining the development of a methods portfolio

Cases	Case 1. Small-scale clam fishery. Interactions between institutions and clam fishers for sustainable management of the Loreto Bay clam fishery, State of Baja California Sur, Mexico.	Case 2. Cross-scale trade networks. Interactions across local and regional scales and their role for adapting to environmental changes in the State of Baja California Sur, Mexico	Case 3. A value chain analysis. The role of markets, relations and incentives for fishing behaviour and ecosystem health in Zanzibar and the Philippines.
Methods	Statistical fisheries population modelling, qualitative analysis, agent-based modelling.	Social network analysis, qualitative analysis, agent-based modelling, social-ecological network analysis.	Value chain analysis, controlled behavioural experiments, qualitative analysis.
Research question	What are the critical interactions for sustainable management of the Loreto Bay clam fishery?	What is the role of trade networks and traders' interactions across local and regional scales for adapting to environmental changes?	How do market relationships, and the benefits they provide, influence fishing behaviour and ecosystem health?
Outcomes from each method	The statistical modelling identified relationships between harvested clams, gear type, fishing styles and fishing location. The qualitative analysis revealed how different types of fishers take harvest decisions and alter their fishing activities in response to formal fisheries regulations and informal norms. Preliminary results of the agent-based model reveal that fisheries policies have differential effects on fishers, depending on their access to resources, and that ensuring equitable and sustainable outcomes will likely require a move away from high-barrier-to-entry and high-tech fisheries management strategies towards strategies that create opportunities for diverse fishers.	The first network analysis led to the question of how trade relationships can constrain or enable traders' capacities to adapt to environmental changes. The qualitative data analysis revealed motivations for trading, the stability and dynamics of trade relationships, and the fact that diversification between species and between fishing regions was a common strategy that fishers and traders use to deal with environmental change. The results from the agent-based model showed that the way regions are connected through trade has implications for overexploitation and sustainable resource use outcomes across regions and species fished. A social-ecological network analysis using official fisheries landings data allowed for the empirical mapping of both spatial and species diversification patterns and dynamics.	The value chain analysis was done through a mixed-methods approach. Interview and observational data were analysed through descriptive statistics, statistical tests and qualitative coding, and through this, the researchers were able to map the numerous and complex interactions between markets and fish extraction. The behavioural economic experiments and complementary methods, such as focus group discussions, post-experiment surveys and semi-structured interviews, enabled learning about fisher decision-making. Experiments identified the importance of gender roles over price in fishers' tactical decisions, which were shaped in part by the space that patrons created through the mechanism of financing and moral and economic indebtedness.
Motivation for development of methods portfolio	Earlier methods revealed new information about SES dynamics that required additional methods to investigate.	Earlier methods focused on investigating structures and subsequent methods were added to gain deeper understanding of feedbacks and dynamics.	Earlier methods were unable to reveal an answer to the key research question. Therefore, additional methods were added.
Results of methods portfolio application	Enabled researchers to capture and explore the complexity of social-ecological interactions in the clam fishery, to illuminate pathways towards sustainable management (Box 1).	Enabled researchers to disentangle the social-ecological structures and interactions that shape fishers' and traders' adaptation strategies that ultimately may influence fishery sustainability outcomes (Box 2).	Provided more traction in assessing change in small-scale fisheries and opportunities to create better descriptions and explanations of markets and fisher behaviour, which can lead to more durable policies for sustainable and equitable development (Box 3).

guided by their core research questions and objectives. This in turn may lead to new collaborations with experts on those new methods (Box 1–3).

3.2 | The role of reflexivity and epistemological tensions in utilising a methods portfolio

How methods complement one another in theory (Section 2), and how methods can be practically combined (Section 3.1), is only part of the process of developing and using a methods portfolio. Combining methods from different disciplinary perspectives, and engaging with researchers who may have different goals and views about science and knowledge, is a non-trivial endeavour (Brister, 2016; Knaggård et al., 2018). Two critical areas that influence opportunities for successful inter- and transdisciplinary endeavours to tackle fisheries sustainability questions are the role of reflexivity and the importance of working through epistemological tensions that may emerge from combining methods with different ontological conceptualisations (Eigenbrode et al., 2007).

Reflexivity can be understood as the critical examination of how we, as researchers, shape research processes and outcomes within a given study objective (Finlay, 2002). It is an essential step towards broadening research perspectives and creating awareness of disciplinary and other training (Ciannelli et al., 2014; Haider et al., 2018). Although reflexivity as a part of the research process is well acknowledged in the social sciences, it has not been as widely adopted beyond these disciplinary bounds. Taking time to reflect critically on our subjectivities, biases and disciplinary constraints as fisheries researchers (for an early example see Pauly, 1994), both individually and collectively, can help to broaden not only the questions we can answer but the range of methods we can employ as well. Reflexivity creates awareness of the bounds of our own knowledge, experience and training, and can help us identify gaps that may be filled through collaboration or additional training (Ciannelli et al., 2014; Eigenbrode et al., 2007; Miller et al., 2008). While inter- and transdisciplinary collaboration may require more time and effort, assembling teams

with complementary knowledge and experience can facilitate the untangling of fisheries' social–ecological complexities (Eigenbrode et al., 2007; Phillipson & Symes, 2013).

To illustrate how reflexivity may surface in research projects we draw on the cases presented in Box 1–3. First, in the clam fishery case (Box 1), limitations for achieving sustainable management from the first study led to simultaneous training in ecology and sociology by the primary researcher, as well as an expansion of the project's advisory team to include a mix of natural and social scientists. This facilitated the development of the interdisciplinary study of fisheries sustainability that emerged as a result of new findings and realisations of the complex nature of social–ecological interactions in the fishery. Second, in the trade networks case (Box 2), the first study revealed the need to further investigate the interactions between traders and trader heterogeneity during changes in fish availability. A collaboration with experienced agent-based modellers was set up to explore how a trader network could respond to variations in fish availability. Finally, in the value chain case (Box 3), the research team started a collaboration with behavioural experimental scientists to enable the investigation of fishers' responses to different incentives for choosing when and where to fish. This was after the first methods applied failed to capture motivations for fisher behaviour.

Epistemological tensions can arise from integrations or combinations of qualitative and quantitative data, or when combining methods with different ontological assumptions, that is whether the methods' disciplinary origins recognise a single or multiple versions of reality (Eigenbrode et al., 2007; Moon et al., 2021). To provide a simplified example, some quantitative approaches focus on an objective understanding of reality, whereas qualitative approaches typically involve the understanding that there are multiple ways of seeing the world. When these two types of approaches and their underlying assumptions come into contact through the use of multiple methods, epistemological tensions emerge (Haider et al., 2018; Miller et al., 2008). Such tensions occurred in all cases.

For example, in the fisheries population dynamics model developed for the clam fishery case (Box 1), a measure of fishers' compliance with harvestable size restrictions from the fieldwork was

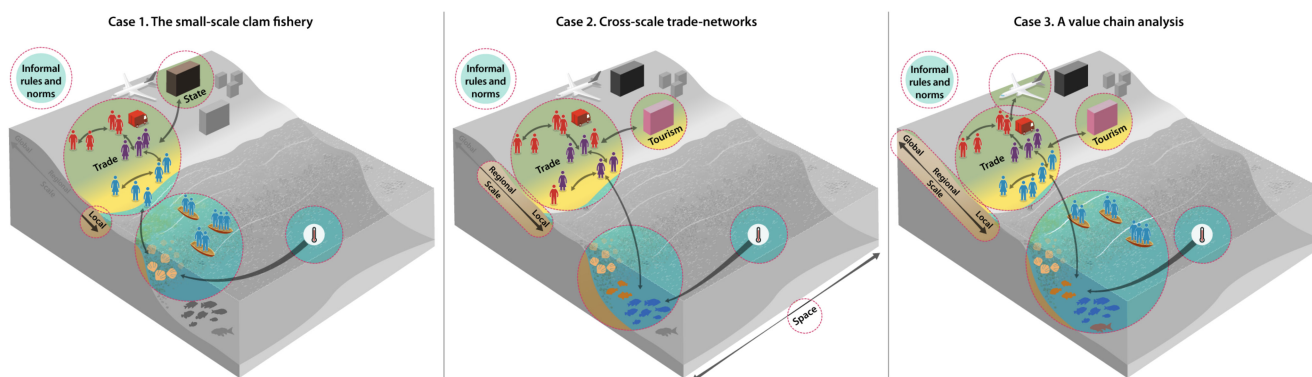


FIGURE 2 Three illustrative cases summarised in Table 2 and described in detail in Box 1–3. The coloured entities, and the arrows between them, indicate the key focus of each study. Red/purple individuals represent different types of traders and the blue individuals represent fishers. The red circle on the space axis of case 2 aims to illustrate the regional cross-scale focus

BOX 1 The development of a methods portfolio for sustainable management of a Mexican small-scale clam fishery

Understanding how fished species life history interacts with fisheries regulations is at the core of sustainable fisheries management (Pauly et al., 2002). Reliable data on target species biology and fishing effort are key to the design of sustainable management that protects economic value and livelihoods (Salas et al., 2007). Given the rapid change and uncertainty experienced by coastal SES around the world, it is especially important to try to untangle key processes that shape sustainable outcomes and anticipate how these processes may change in the future. In the Mexican state of Baja California Sur, one of the most highly productive fishing regions in Mexico, a lack of resources for data collection, missing life history information for target species and underreporting of catch threaten managers' ability to design sustainable and adaptive fisheries policies. One of the top species harvested by biomass in Baja California Sur, the Mexican chocolate clam, *Megapitaria squalida*, is a data-limited fishery in which few key life history parameters are known (Pellowe & Leslie, 2020a).

In a series of studies, we worked to untangle the key interactions that give rise to the current state of the fishery and the resilience of the fishery to future environmental and economic change in a key fishing area, Loreto Bay National Park (Figure 2, Case 1). In order to address the lack of basic life history data that are essential to statistical fisheries population modelling, our investigations began with a set of studies to estimate population density, size structure, distribution, growth and mortality rates of the Mexican chocolate clam. Our methods included systematic subtidal population surveys at a range of depths, as well as a mark-recapture enclosure study of clam growth and mortality. To estimate size selectivity of fishing activities, another key parameter for estimating fishery sustainability, we compared the size structure of the clam population in situ to the size structure of harvested clams. To obtain estimates of size selectivity, as well as to accurately estimate the length–weight relationship of the species, we measured and weighed clams from fishers' daily harvests over a three-year period (Pellowe & Leslie, 2020a). It became apparent through our interactions with fishers that there are multiple types of fishers harvesting clams in different ways, and that many fishers operate outside the formal sector without reporting their catch (Pellowe & Leslie, 2019). Underreporting of catch and non-compliance with formal regulations can have severe consequences for sustainable fisheries management.

We realised that to understand the possibilities and limitations of sustainable outcomes in the Mexican chocolate clam fishery, we needed to understand much more about how fishers respond to and are affected by fisheries regulations, and how clam population abundance and size structure are affected by both legal-size limits and fishers' size selectivity. We engaged in a series of qualitative data collection efforts relying heavily on social science methods, including semi-structured interviews and participant observation. Qualitative analysis of our conversations, observations and interviews shed light on how different types of fishers make harvest decisions and alter their fishing activities in response to formal fisheries regulations and informal norms (Pellowe & Leslie, 2019, 2020b). This approach revealed that in addition to missing key life history parameters, fisheries managers were challenged by a lack of information about the complexity of human–nature interactions within the fishery. Non-compliance and underreporting of catch are related to conflicts between different types of fishers and between formal regulations and local norms, and are exacerbated by economic inequality among fishers. Combining data from multiple field studies, we engaged with modelling experts and designed an empirically informed dynamic agent-based model to explore how various possible policy scenarios might influence fishery sustainability and inequality outcomes for the Mexican chocolate clam fishery (manuscript in preparation). Preliminary results reveal that equitable and sustainable management will require a move towards strategies that create opportunities for diverse fishers. Designing sustainable fisheries management requires not only reliable biological data, but also a deeper understanding of the social–ecological processes that shape sustainability outcomes at the fishery scale. In our case, a methods portfolio approach allowed us to better capture and explore the complexity of social–ecological interactions in the Mexican chocolate clam fishery and illuminate pathways to sustainable management.

incorporated, but the model could not represent fishers' motivations for deciding whether or not to comply. In the trade-network case (Box 2), the qualitative analysis revealed numerous and often-contradictory actions by the traders. This led to a long process of selecting the most critical actions necessary for formalising trade dynamics and fishing decisions into algorithms and mathematical expressions for designing the agent-based model. In the value chain case (Box 3), the behavioural experiments could not represent the diversity of traders nor the diversity of targeted species important

for deciding when, where and what to fish. In each of the three cases, moving from qualitative analysis to modelling, or from mixed methods to behavioural experiments, necessitated simplifying rich data into mathematical forms or algorithms that could not fully represent the full complexity of the fishery system. This type of challenge may create tensions around external validity and generalisability of insights gained from models which are, by definition, always simplified versions of a system. However, they also give rise to new questions that can guide further qualitative analysis and

BOX 2 The development of a methods portfolio to explore trade networks in a diversified fishery and their role for adapting to environmental changes

As the influence of trade on small-scale fisheries increases, it is important to understand how trade structures and processes mediate interactions across scales and influence sustainability outcomes locally (Gephart et al., 2016; Pedroza-Gutiérrez & Hernández, 2020). Trade structures often comprise trading processes that are embedded in social relationships. Even if trade structures have received increased attention in recent years, little research has investigated the contribution of these networks of social and trade relations to the ways in which fisheries actors adapt to the increasing environmental and socio-economic changes that they experience. Previous research in Mexico had documented the tight social relationships between fishers and traders and the multiple functions and consequences of these trading arrangements (Basurto et al., 2013; Cinti et al., 2010). We aimed to further investigate the interactions between different traders, and the social-ecological factors that influence their adaptation in the state of Baja California Sur, Mexico (Figure 2, Case 2).

By conducting a network analysis, we identified five different types of traders based on the specific network patterns representing traders' relations. In combination with semi-structured interviews with traders, we were able to hypothesise how the trade structures can constrain or enable traders' capacities to adapt to changes, such as short-term fluctuations in fish availability (González-Mon et al., 2019). To understand the meaning of these trade relationships and inform our hypotheses, we drew on a thematic analysis of qualitative data collected through semi-structured interviews that revealed motivations for trading, the stability and dynamics of trade relationships and the characteristics of the different trader types (González-Mon et al., 2019). However, we were missing a dynamic approach to investigate how trade networks could influence responses to change and ultimately affect trader's fish supply as well as system-level outcomes for example the sustainability of fish populations or availability of fish in the markets. We therefore combined the insights gained from the network with qualitative analyses of additional interviews with traders to design an agent-based model that explicitly represented different trade-network structures (González-Mon, Lindkvist, et al., 2021; Lindkvist & González-Mon, 2021). This modelling process allowed us to better understand the trading processes within these networks, and to identify mechanisms that could influence individual and system-level outcomes in response to changes in fish availability (González-Mon, Lindkvist, et al., 2021).

The qualitative analysis of the interviews with traders revealed that diversification between species and between fishing regions was a common strategy that traders use to deal with the variability in fish resources, and such diversification strategies can influence sustainability and management outcomes. The agent-based model only provided a stylised, semi-theoretical representation of such a diversification process. Next, we aimed to gain a deeper empirical understanding of the dynamics and patterns of fisheries diversification. To that end, we analysed an official fisheries landings database through social-ecological network analysis, which allowed us to map the spatial and species diversification patterns of fisheries actors (i.e. fishers and traders with a fishing permit). The analysis made it possible to investigate changes in diversification over time in light of potential environmental and institutional factors that enable or constrain diversification within these fisheries (González-Mon, Bodin, et al., 2021).

We used different methods and combinations to study trade networks in the context of fisheries adaptation strategies and each study revealed limitations of the methods applied; limitations that we partially counteracted with complementary methods in an iterative research process. By using a methods portfolio approach, we were able to investigate fishery actors' adaptation through trade from diverse angles. We disentangled social-ecological structures and interactions that shape fishers' and traders' adaptation to understand better how they may influence fishery sustainability outcomes.

new hypotheses to test in the field such as in the trade-network case (Box 2).

A methods portfolio may be utilised to complement and create synergies between different methods; however, selected combinations of methods require careful consideration. The expansion of methods portfolios, that is the inclusion of additional methods to study different aspects of a fishery, may require a change in the level of detail of the fishery context, as the study trades off between context-specificity and generalisability. Thus, a clear study objective is key for methods selection (c.f. Table 1) to be able to adequately address different social, ecological and/or social-ecological interactions that influence

fishery sustainability outcomes. On the contrary, study objectives may need to change based on changing context and new knowledge. Thus, adopting a methods portfolio approach may also require researchers to lean into the unknown; by venturing beyond the bounds of disciplinary methods, they may need to challenge their existing biases and let go of pre-conceived notions about what constitutes good science. While we are still driven by our objectives and research questions, and inevitably influenced by our backgrounds, our engagement with other individuals, knowledge and methods will generate new hypotheses and questions that may be essential to make progress on contemporary sustainability questions.

BOX 3 The development of a methods portfolio for a value chain analysis of the markets, relations and incentives for fishery actors in Zanzibar and the Philippines

One of the gaps in academic knowledge addressed in this research project was the understanding of interactions between trade, the incentives trade creates for small-scale fishery actors and its effect on the environment through fishing behaviour (Crona & Bodin, 2010; de la Torre-Castro, 2012; Ferrol-Schulte et al., 2014). We focus particularly on the interactions between markets and fishing, and how this interaction is mediated through traders in influencing fishers' extraction (Figure 2, Case 3). Trader-fisher relationships, henceforth patron-client relationships, are becoming increasingly important to understand due to the growing integration of low-income tropical fisheries and global economics via the linking role they play (Basurto et al., 2013; Crona et al., 2015; Ferse et al., 2014). Because of the focus on this trade relationship and seafood market dynamics like price as an incentive, we initially adopted a value chain (VC) approach. This is largely a descriptive tool for studying the interactions between different actors and the dynamics that emerge through their interactions. Contemporary VC research in small-scale fisheries encompasses a wide range of non-economic values like reciprocity and contextual dimensions, for example local norms, beyond the traditional economic focus (Fabinyi et al., 2018; Rodrigues & Villasante, 2016).

Using mixed methods, we analysed interview and observational data through descriptive statistics, statistical tests and qualitative coding, and were able to map the complex interactions between markets and fish extraction (Drury O'Neill et al., 2018; Drury O'Neill & Crona, 2017). However, using the VC approach, we encountered some methodological challenges in accounting for social-ecological and behavioural dynamics in the trade relations we were studying. It was difficult to account for the social *and* ecological values of the chains simultaneously, that is to address SES dynamics as a whole.

Although the data collection and analysis methods were selected from extensive VC-related literature in small-scale production systems, we were not able to address motivations and values in fisher behaviour. The survey-based case study methods and design proved lacking for better understanding fisher decision-making, particularly with respect to patron-client relations and the direct influence we assumed was created by patron-traders. Asking actors to state perceived influences from interactions in the market system only took account of conscious reasoning (e.g. calculated cost/benefit decision-making), which is only one small part of people's decision modes (Weber & Lindemann, 2007). These methods also presented hypothetical biases in asking people how they would behave given a certain situation (Schulze et al., 1981).

To better address fisher behaviour in relation to the market, we turned to controlled behavioural experiments and, in particular, 'lab-in-the-field' experiments (Harrison & List, 2004). With this approach and using qualitative analysis of data from complementary methods such as focus group discussions, post-experiment surveys and semi-structured in-depth interviews, we were able to assess revealed (experimental) fisher behaviour and appropriately interpret it (Drury O'Neill et al., 2019). This combination of methods proved fruitful and the results highlighted the importance of gender roles over price in fishers' tactical decisions. We were able to see that fishers' decisions were shaped in part by the space that patrons created through the mechanism of financing and moral and economic indebtedness, rather than short-term economic incentives such as price (*ibid*). Fishers were thus influenced or incentivised in their fishing by the indebtedness (of both types) to patrons and the financing options (e.g. fuel, or money for new vessels), rather than price. They were also influenced by gender roles in that men went 'big' in terms of maximising landings in the experiment. We linked this to masculine identities in fishing in that area and the need to land a lot and exhibit good skills, among other motivations. These findings are important for addressing the long-standing knowledge gap related to human behaviour in fisheries research and governance (Fulton et al., 2011; Wijermans et al., 2020). They directly answer the most recent call for advancing our understanding of the psychosocial (mental and social factors) and cultural influences (morality, gender and reciprocity) in decision-making (*ibid*). Combining these types of findings will provide more traction in assessing change in small-scale fisheries and provide opportunities to create better descriptions and explanations of fisher behaviour which can lead to more durable policies for sustainable and equitable development (Drury O'Neill et al., 2018).

4 | CONCLUSIONS

Analysing social-ecological interactions for fisheries sustainability requires approaches that incorporate multiple, complementary methods that are disciplinarily and theoretically rooted across the social and natural sciences. Such work calls for a reflexive research process that includes collaboration and communication across

disciplines and sectors, and brings together experts that represent the diversity of stakeholders. These inter-, multi- and transdisciplinary approaches can help facilitate effective decision-making. One pathway towards a more holistic understanding of fisheries, and an enhanced ability to solve contemporary fisheries challenges, is to strategically combine the methods and approaches available to study them. This paper takes a step towards this transition by

outlining some of the most promising analytical methods in fisheries research, and showcasing how methods may be combined through an emergent collaborative process. We argue that resulting methods portfolios have the capacity to generate deeper understandings of social–ecological interactions and processes, and thus, better support sustainable fisheries management.

By continuously developing our methods portfolios, researchers will be better equipped to treat fisheries as the complex, adaptive systems they are, with an eye to uncertainty and emergent dynamics. Collaborations among researchers from diverse disciplinary backgrounds and managers are essential to achieve a more holistic understanding of fisheries and support the goals of conservation, food security and livelihoods for fishers, fish workers and marine resource-dependent communities. Moreover, co-creating portfolios with managers will ensure that the resulting insights, findings and advice are useful, relevant and appropriate for informing management decisions. This approach to research opens up opportunities for a wider range of research questions, improves the identification of knowledge gaps and provides new ways to tackle fisheries sustainability challenges.






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REFERENCES

- Alexander, S. M., Armitage, D., Carrington, P. J., & Bodin, Ö. (2017). Examining horizontal and vertical social ties to achieve social–ecological fit in an emerging marine reserve network. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27(6), 1209–1223. <https://doi.org/10.1002/aqc.2775>
- Alexander, S., Bodin, Ö., & Barnes, M. (2018). Untangling the drivers of community cohesion in small-scale fisheries. *International Journal of the Commons*, 12(1), 519–547.
- Alexander, S. M., Staniczenko, P. P., & Bodin, Ö. (2020). Social ties explain catch portfolios of small-scale fishers in the Caribbean. *Fish and Fisheries*, 21(1), 120–131. <https://doi.org/10.1111/faf.12421>
- Amadu, I., Armah, F. A., Aheto, D. W., & Adongo, C. A. (2021). A study on livelihood resilience in the small-scale fisheries of Ghana using a structural equation modelling approach. *Ocean & Coastal Management*, 215, 105952. <https://doi.org/10.1016/j.ocecoaman.2021.105952>
- Barber, W. E. (1988). Maximum sustainable yield lives on. *North American Journal of Fisheries Management*, 8(2), 153–157.
- Barclay, K., Voyer, M., Mazur, N., Payne, A. M., Mauli, S., Kinch, J., Fabinyi, M., & Smith, G. (2017). The importance of qualitative social research for effective fisheries management. *Fisheries Research*, 186, 426–438. <https://doi.org/10.1016/j.fishres.2016.08.007>
- Barnes, M. L., Bodin, Ö., McClanahan, T. R., Kittinger, J. N., Hoey, A. S., Gaoue, O. G., & Graham, N. A. J. (2019). Social–ecological alignment and ecological conditions in coral reefs. *Nature Communications*, 10(1), 2039. <https://doi.org/10.1038/s41467-019-09994-1>
- Bascompte, J., Melián, C. J., & Sala, E. (2005). Interaction strength combinations and the overfishing of a marine food web. *Proceedings of the National Academy of Sciences*, 102(15), 5443–5447. <https://doi.org/10.1073/pnas.0501562102>
- Basurto, X., Bennett, A., Weaver, A. H., Rodriguez-Van Dyck, S., & Aceves-Bueno, J.-S. (2013). Cooperative and Noncooperative Strategies for Small-scale Fisheries’ Self-governance in the Globalization Era: Implications for Conservation. *Ecology and Society*, 18(4), 38. <https://doi.org/10.5751/ES-05673-180438>
- Bennett, E., & Zurek, M. Z. (2006). Integrating Epistemologies through Scenarios. In W. Reid, F. Berkes, T. Wilbanks, & D. Capistrano (Eds.), *Bridging scales and epistemologies: Concepts and applications in ecosystem assessment* (pp. 275–293). Island Press.
- Berkes, F. (2012). Implementing ecosystem-based management: Evolution or revolution? *Fish and Fisheries*, 13(4), 465–476. <https://doi.org/10.1111/j.1467-2979.2011.00452.x>
- Biggs, R., De Vos, A., Preiser, R., Clements, H., Maciejewski, K., & Schlüter, M. (2021). *The Routledge handbook of research methods for social-ecological systems* (1st ed.). Taylor & Francis.
- Bodin, Ö. (2017). Collaborative environmental governance: Achieving collective action in social-ecological systems. *Science*, 357(6352). <https://doi.org/10.1126/science.aan1114>
- Bodin, Ö., Alexander, S. M., Baggio, J., Barnes, M. L., Berardo, R., Cumming, G. S., Dee, L. E., Fischer, A. P., Fischer, M., & Garcia, M.

- M. (2019). Improving network approaches to the study of complex social–ecological interdependencies. *Nature Sustainability*, 2(7), 551–559. <https://doi.org/10.1038/s41893-019-0308-0>
- Bodin, Ö., Crona, B., Thyresson, M., Golz, A.-L., & Tengö, M. (2014). Conservation success as a function of good alignment of social and ecological structures and processes. *Conservation Biology*, 28(5), 1371–1379. <https://doi.org/10.1111/cobi.12306>
- Boonstra, W. J., & Hentati-Sundberg, J. (2016). Classifying fishers' behaviour. An invitation to fishing styles. *Fish and Fisheries*, 17(1), 78–100. <https://doi.org/10.1111/faf.12092>
- Brewer, J. F. (2013). From experiential knowledge to public participation: social learning at the community fisheries action roundtable. *Environmental Management*, 52, 321–334. <https://doi.org/10.1007/s00267-013-0059-z>
- Brister, E. (2016). Disciplinary capture and epistemological obstacles to interdisciplinary research: Lessons from central African conservation disputes. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences*, 56, 82–91. <https://doi.org/10.1016/j.shpsc.2015.11.001>
- Burgess, M. G., Carrella, E., Drexler, M., Axtell, R. L., Bailey, R. M., Watson, J. R., Cabral, R. B., Clemence, M., Costello, C., Dorsett, C., Gaines, S. D., Klein, E. S., Koralus, P., Leonard, G., Levin, S. A., Little, L. R., Lynham, J., Madsen, J. K., Merkl, A., & Wilcox, S. (2020). Opportunities for agent-based modelling in human dimensions of fisheries. *Fish and Fisheries*, 21(3), 570–587. <https://doi.org/10.1111/faf.12447>
- Cardenas, J.-C., Janssen, M., & Bousquet, F. (2013). Dynamics of rules and resources: Three new field experiments on water, forests and fisheries. In *Handbook on experimental economics and the environment*. Edward Elgar Publishing.
- Castillo, D., Bousquet, F., Janssen, M. A., Worrappimphong, K., & Cardenas, J. C. (2011). Context matters to explain field experiments: Results from Colombian and Thai fishing villages. *Ecological Economics*, 70(9), 1609–1620. <https://doi.org/10.1016/j.ecolecon.2011.05.011>
- Ciannelli, L., Hunsicker, M., Beaudreau, A., Bailey, K., Crowder, L. B., Finley, C., Webb, C., Reynolds, J., Sagmiller, K., & Anderies, J. M. (2014). Transdisciplinary graduate education in marine resource science and management. *ICES Journal of Marine Science*, 71(5), 1047–1051. <https://doi.org/10.1093/icesjms/fsu067>
- Cinti, A., Shaw, W., Cudney-Bueno, R., & Rojo, M. (2010). The unintended consequences of formal fisheries policies: Social disparities and resource overuse in a major fishing community in the Gulf of California, Mexico. *Marine Policy*, 34(2), 328–339. <https://doi.org/10.1016/j.marpol.2009.08.002>
- Clark, C. W. (2010). *Mathematical bioeconomics: The mathematics of conservation* (Vol. 91, 3rd ed.). Wiley.
- Collie, J. S., Botsford, L. W., Hastings, A., Kaplan, I. C., Largier, J. L., Livingston, P. A., Plagányi, É., Rose, K. A., Wells, B. K., & Werner, F. E. (2016). Ecosystem models for fisheries management: Finding the sweet spot. *Fish and Fisheries*, 17(1), 101–125. <https://doi.org/10.1111/faf.12093>
- Cox, M. (2015). A basic guide for empirical environmental social science. *Ecology and Society*, 20(1). <https://doi.org/10.5751/ES-07400-200163>
- Crépin, A.-S. (2007). Using Fast and Slow Processes to Manage Resources with Thresholds. *Environmental and Resource Economics*, 36(2), 191–213. <https://doi.org/10.1007/s10640-006-9029-8>
- Crona, B., & Bodin, Ö. (2010). Power asymmetries in small-scale fisheries: A barrier to governance transformability. *Ecology and Society*, 15(4), 32. <https://doi.org/10.5751/ES-03710-150432>
- Crona, B. I., Van Holt, T., Petersson, M., Daw, T. M., & Buchary, E. (2015). Using social–ecological syndromes to understand impacts of international seafood trade on small-scale fisheries. *Global Environmental Change*, 35, 162–175. <https://doi.org/10.1016/j.gloenvcha.2015.07.006>
- de la Torre-Castro, M. (2012). Governance for sustainability: Insights from marine resource use in a tropical setting in the Western Indian Ocean. *Coastal Management*, 40(6), 612–633. <https://doi.org/10.1080/08920753.2012.727738>
- de Vos, A., Biggs, R., & Preiser, R. (2019). Methods for understanding social–ecological systems: A review of place-based studies. *Ecology and Society*, 24(4). <https://doi.org/10.5751/ES-11236-240416>
- Dowling, N. A., Wilcox, C., Mangel, M., & Pascoe, S. (2012). Assessing opportunity and relocation costs of marine protected areas using a behavioural model of longline fleet dynamics. *Fish and Fisheries*, 13(2), 139–157. <https://doi.org/10.1111/j.1467-2979.2011.00422.x>
- Drury O'Neill, E., & Crona, B. (2017). Assistance networks in seafood trade—A means to assess benefit distribution in small-scale fisheries. *Marine Policy*, 78, 196–205. <https://doi.org/10.1016/j.marpol.2017.01.025>
- Drury O'Neill, E., Crona, B., Ferrer, A. J., Pomeroy, R., & Jiddawi, N. (2018). Who benefits from seafood trade? A comparison of social and market structures in small-scale fisheries. *Ecology and Society*, 23(3). <https://doi.org/10.5751/es-10331-230312>
- Drury O'Neill, E., Lindahl, T., Daw, T., Crona, B., Ferrer, A. J. G., & Pomeroy, R. (2019). An Experimental Approach to Exploring Market Responses in Small-Scale Fishing Communities. *Frontiers in Marine Science*, 6, 491. <https://doi.org/10.3389/fmars.2019.00491>
- Duarte, C. M., Agusti, S., Barbier, E., Britten, G. L., Castilla, J. C., Gattuso, J.-P., Fulweiler, R. W., Hughes, T. P., Knowlton, N., & Lovelock, C. E. (2020). Rebuilding marine life. *Nature*, 580(7801), 39–51. <https://doi.org/10.1038/s41586-020-2146-7>
- Edmonds, B. (2017). Different Modelling Purposes. In B. Edmonds & R. Meyer (Eds.), *Simulating social complexity: A handbook* (pp. 39–58). Springer International Publishing.
- Eigenbrode, S. D., O'Rourke, M., Wulfhorst, J. D., Althoff, D. M., Goldberg, C. S., Merrill, K., Morse, W., Nielsen-Pincus, M., Stephens, J., & Winowiecki, L. (2007). Employing philosophical dialogue in collaborative science. *BioScience*, 57(1), 55–64. <https://doi.org/10.1641/B570109>
- Epstein, J. M. (2008). Why model? *Journal of Artificial Societies and Social Simulation*, 11(4), 12.
- Fabinyi, M., Dressler, W., & Pido, M. (2018). Moving beyond financial value in seafood commodity chains. *Marine Policy*, 89–92. <https://doi.org/10.1016/j.marpol.2018.04.033>
- FAO. (2020). *The State of World Fisheries and Aquaculture 2020: Sustainability in action*. FAO.
- Ferrol-Schulte, D., Ferse, S. C., & Glaser, M. (2014). Patron–client relationships, livelihoods and natural resource management in tropical coastal communities. *Ocean & Coastal Management*, 100, 63–73. <https://doi.org/10.1016/j.ocecoaman.2014.07.016>
- Ferse, S. C., Glaser, M., Neil, M., & Máñez, K. S. (2014). To cope or to sustain? Eroding long-term sustainability in an Indonesian coral reef fishery. *Regional Environmental Change*, 14(6), 2053–2065. <https://doi.org/10.1007/s10113-012-0342-1>
- Filbee-Dexter, K., Symons, C. C., Jones, K., Haig, H. A., Pittman, J., Alexander, S. M., & Burke, M. J. (2018). Quantifying ecological and social drivers of ecological surprise. *Journal of Applied Ecology*, 55(5), 2135–2146. <https://doi.org/10.1111/1365-2664.13171>
- Finkbeiner, E. M., Micheli, F., Saenz-Arroyo, A., Vazquez-Vera, L., Perafan, C. A., & Cárdenas, J. C. (2018). Local response to global uncertainty: Insights from experimental economics in small-scale fisheries. *Global Environmental Change*, 48, 151–157. <https://doi.org/10.1016/j.gloenvcha.2017.11.010>
- Finlay, L. (2002). Negotiating the swamp: The opportunity and challenge of reflexivity in research practice. *Qualitative Research*, 2(2), 209–230. <https://doi.org/10.1177/146879410200200205>

- Friedman, D., & Sunder, S. (1994). *Experimental methods: A primer for economists*. Cambridge university press. <https://doi.org/10.1017/cbo9781139174176>
- Fuller, E. C., Samhouri, J. F., Stoll, J. S., Levin, S. A., & Watson, J. R. (2017). Characterizing fisheries connectivity in marine social-ecological systems. *ICES Journal of Marine Science*, 74(8), 2087–2096. <https://doi.org/10.1093/icesjms/fsx128>
- Fulton, E. A., Smith, A. D. M., Smith, D. C., & van Putten, I. E. (2011). Human behaviour: The key source of uncertainty in fisheries management. *Fish and Fisheries*, 12(1), 2–17. <https://doi.org/10.1111/j.1467-2979.2010.00371.x>
- Gelcich, S., Edwards-Jones, G., Kaiser, M. J., & Watson, E. (2005). Using discourses for policy evaluation: The case of marine common property rights in Chile. *Society and Natural Resources*, 18(4), 377–391. <https://doi.org/10.1080/08941920590915279>
- Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L., & Brännström, Å. (2016). Vulnerability to shocks in the global seafood trade network. *Environmental Research Letters*, 11(3), 035008. <https://doi.org/10.1088/1748-9326/11/3/035008>
- Glaeser, B., Bruckmeier, K., Glaser, M., & Krause, G. (2009). Social-ecological systems analysis in coastal and marine areas: A path toward integration of interdisciplinary knowledge. In P. Lopes & A. Begossi (Eds.), *Current trends in human ecology* (pp. 183–203). Cambridge Scholars Publishing.
- Glaser, M. (2012). Transdisciplinary multi-agent modelling for social-ecological systems analysis: Achievements and potentials. In *Human-nature interactions in the anthropocene: potentials of social-ecological systems analysis* (pp. 141–160). Taylor and Francis, Scopus. <https://doi.org/10.4324/9780203123195>
- González-Mon, B., Bodin, Ö., Crona, B., Nenadovic, M., & Basurto, X. (2019). Small-scale fish buyers' trade networks reveal diverse actor types and differential adaptive capacities. *Ecological Economics*, 164, 106338. <https://doi.org/10.1016/j.ecolecon.2019.05.018>
- González-Mon, B., Bodin, Ö., Lindkvist, E., Frawley, T. H., Giron-Nava, A., Basurto, X., Nenadovic, M., & Schlüter, M. (2021). Spatial diversification as a mechanism to adapt to environmental changes in small-scale fisheries. *Environmental Science & Policy*, 116, 246–257. <https://doi.org/10.1016/j.envsci.2020.11.006>
- González-Mon, B., Lindkvist, E., Bodin, Ö., Zepeda-Domínguez, J. A., & Schlüter, M. (2021). Fish provision in a changing environment: The buffering effect of regional trade networks. *PLoS One*, 16(12), e0261514. <https://doi.org/10.1371/journal.pone.0261514>
- Grilli, G., Curtis, J., Hynes, S., & O'Reilly, P. (2018). Sea bass angling in Ireland: A structural equation model of catch and effort. *Ecological Economics*, 149, 285–293. <https://doi.org/10.1016/j.ecolecon.2018.03.025>
- Gutierrez, N. L., Halmay, P., Hilborn, R., Punt, A. E., & Schroeter, S. (2017). Exploring benefits of spatial cooperative harvesting in a sea urchin fishery: An agent-based approach. *Ecosphere*, 8(7), e01829. <https://doi.org/10.1002/ecs2.1829>
- Haider, L. J., Hentati-Sundberg, J., Giusti, M., Goodness, J., Hamann, M., Masterson, V. A., Meacham, M., Merrie, A., Ospina, D., Schill, C., & Sinare, H. (2018). The interdisciplinary journey: Early-career perspectives in sustainability science. *Sustainability Science*, 13(1), 191–204. <https://doi.org/10.1007/s11625-017-0445-1>
- Harrison, G. W., & List, J. A. (2004). Field experiments. *Journal of Economic Literature*, 42(4), 1009–1055.
- Hilborn, R., & Walters, C. J. (Eds.), (1992). *Quantitative fisheries stock assessment: Choice, dynamics and uncertainty*. Springer Science & Business Media.
- Hoyle, R. H. (Ed.). (2012). *Handbook of structural equation modeling*. Guilford press.
- Hunt, L. M., Sutton, S. G., & Arlinghaus, R. (2013). Illustrating the critical role of human dimensions research for understanding and managing recreational fisheries within a social-ecological system framework. *Fisheries Management and Ecology*, 20(2–3), 111–124. <https://doi.org/10.1111/j.1365-2400.2012.00870.x>
- Janssen, M. A., Lindahl, T., & Murphy, J. J. (2015). Advancing the understanding of behavior in social-ecological systems: Results from lab and field experiments. *Ecology and Society*, 20(4). <https://doi.org/10.5751/ES-08097-200434>
- Jentoft, S. (2006). Beyond fisheries management: The phronetic dimension. *Marine Policy*, 30, 671–680. <https://doi.org/10.1016/j.marpol.2005.10.001>
- Jiao, Y., O'Reilly, R., Smith, E., & Orth, D. (2016). Integrating spatial synchrony/asynchrony of population distribution into stock assessment models: A spatial hierarchical Bayesian statistical catch-at-age approach. *ICES Journal of Marine Science*, 73(7), 1725–1738. <https://doi.org/10.1093/icesjms/fsw036>
- Kittinger, J. N., Finkbeiner, E. M., Ban, N. C., Broad, K., Carr, M. H., Cinner, J. E., Gelcich, S., Cornwell, M. L., Koehn, J. Z., Basurto, X., Fujita, R., Caldwell, M. R., & Crowder, L. B. (2013). Emerging frontiers in social-ecological systems research for sustainability of small-scale fisheries. *Current Opinion in Environmental Sustainability*, 5(3–4), 352–357. <https://doi.org/10.1016/j.cosust.2013.06.008>
- Klein, E. S., Barbier, A., Matthieu, R., & Watson, J. R. (2017). The dual impact of ecology and management on social incentives in marine common-pool resource systems. *Royal Society Open Science*, 4(8), 170740. <https://doi.org/10.1098/rsos.170740>
- Knaggård, Å., Ness, B., & Harnesk, D. (2018). Finding an academic space: Reflexivity among sustainability researchers. *Ecology and Society*, 23(4). <https://doi.org/10.5751/ES-10505-230420>
- Kolding, J., Jacobsen, N. S., Andersen, K. H., & van Zwieten, P. A. (2016). Maximizing fisheries yields while maintaining community structure. *Canadian Journal of Fisheries and Aquatic Sciences*, 73(4), 644–655. <https://doi.org/10.1139/cjfas-2015-0098>
- Kroetz, K., Reimer, M. N., Sanchirico, J. N., Lew, D. K., & Huetteman, J. (2019). Defining the economic scope for ecosystem-based fishery management. *Proceedings of the National Academy of Sciences of USA*, 116(10), 4188–4193. <https://doi.org/10.1073/pnas.1816545116>
- Lade, S. J., Niiranen, S., Hentati-Sundberg, J., Blenckner, T., Boonstra, W. J., Orach, K., Quaas, M. F., Österblom, H., & Schlüter, M. (2015). An empirical model of the Baltic Sea reveals the importance of social dynamics for ecological regime shifts. *Proceedings of the National Academy of Sciences, USA*, 112(35), 11120–11125. <https://doi.org/10.1073/pnas.1504954112>
- Lee, L. C., Thorley, J., Watson, J., Reid, M., & Salomon, A. K. (2019). Diverse knowledge systems reveal social-ecological dynamics that inform species conservation status. *Conservation Letters*, 12(2), e12613. <https://doi.org/10.1111/conl.12613>
- Leslie, H. M., Basurto, X., Nenadovic, M., Sievanen, L., Cavanaugh, K. C., Cota-Nieto, J. J., Erisman, B. E., Finkbeiner, E., Hinojosa-Arango, G., & Moreno-Báez, M. (2015). Operationalizing the social-ecological systems framework to assess sustainability. *Proceedings of the National Academy of Sciences, USA*, 112(19), 5979–5984. <https://doi.org/10.1073/pnas.1414640112>
- Lindahl, T., Crépin, A.-S., & Schill, C. (2016). Potential Disasters can Turn the Tragedy into Success. *Environmental and Resource Economics*, 65(3), 657–676.
- Lindahl, T., Janssen, M. A., & Schill, C. (2021). Controlled behavioural experiments. In R. Biggs, A. de Vos, R. Preiser, H. Clements, K. Maciejewski, & M. Schluter (Eds.), *The Routledge Handbook of Research Methods for Social-Ecological Systems* (pp. 295–306). Routledge. <https://doi.org/10.4324/9781003021339>
- Lindkvist, E., Basurto, X., & Schlüter, M. (2017). Micro-level explanations for emergent patterns of self-governance arrangements in small-scale fisheries—A modeling approach. *PLoS One*, 12(4), e0175532. <https://doi.org/10.1371/journal.pone.0175532>

- Lindkvist, E., & González-Mon, B. (2021). *Small-Trade Model: Exploring the role of trade networks in small-scale fisheries (1.1.0)* [Netlogo]. CoMSES Computer Model Library.
- Lindkvist, E., Wijermans, N., Daw, T. M., González-Mon, B., Giron-Nava, A., Johnson, A. F., van Putten, I., Basurto, X., & Schlüter, M. (2020). Navigating Complexities: Agent-Based Modeling to Support Research, Governance, and Management in Small-Scale Fisheries. *Frontiers in Marine Science*, 6, 733. <https://doi.org/10.3389/fmars.2019.00733>
- Lubet, S. (2018). *Interrogating ethnography: Why evidence matters*. Oxford University Press.
- Mäntyniemi, S. (2006). *Bayesian fisheries stock assessment: Integrating and updating knowledge*. University of Helsinki. <https://researchportal.helsinki.fi/en/publications/bayesian-fisheries-stock-assessment-integrating-and-updating-know>
- Martell, S., & Froese, R. (2013). A simple method for estimating MSY from catch and resilience. *Fish and Fisheries*, 14(4), 504–514. <https://doi.org/10.1111/j.1467-2979.2012.00485.x>
- Miller, T., Baird, T., Littlefield, C., Kofinas, G., Chapin, F. S., III, & Redman, C. (2008). Epistemological Pluralism: Reorganizing Interdisciplinary Research. *Ecology and Society*, 13(2). <https://doi.org/10.5751/ES-02671-130246>
- Moon, K., Cvitanovic, C., Blackman, D. A., Scales, I. R., & Browne, N. K. (2021). Five questions to understand epistemology and its influence on integrative marine research. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.574158>
- Moreno-Sánchez, R., & Maldonado, J. H. (2010). Evaluating the role of co-management in improving governance of marine protected areas: An experimental approach in the Colombian Caribbean. *Ecological Economics*, 69(12), 2557–2567. <https://doi.org/10.1016/j.ecolecon.2010.07.032>
- Munguia-Vega, A., Marinone, S. G., Paz-Garcia, D. A., Giron-Nava, A., Plomozo-Lugo, T., Gonzalez-Cuellar, O., Weaver, A. H., García-Rodríguez, F. J., & Reyes-Bonilla, H. (2018). Anisotropic larval connectivity and metapopulation structure driven by directional oceanic currents in a marine fish targeted by small-scale fisheries. *Marine Biology*, 165(1), 1–16. <https://doi.org/10.1007/s00227-017-3267-x>
- Naranjo-Madriral, H., van Putten, I., & Norman-López, A. (2015). Understanding socio-ecological drivers of spatial allocation choice in a multi-species artisanal fishery: A Bayesian network modeling approach. *Marine Policy*, 62, 102–115. <https://doi.org/10.1016/j.marpol.2015.09.003>
- Nielsen, J. R., Thunberg, E., Holland, D. S., Schmidt, J. O., Fulton, E. A., Bastardie, F., Punt, A. E., Allen, I., Bartelings, H., & Bertignac, M. (2018). Integrated ecological-economic fisheries models—Evaluation, review and challenges for implementation. *Fish and Fisheries*, 19(1), 1–29. <https://doi.org/10.1111/faf.12232>
- Nomura, K., Samhour, J. F., Johnson, A. F., Giron-Nava, A., & Watson, J. R. (2021). Fisheries connectivity measures of adaptive capacity in small-scale fisheries. *ICES Journal of Marine Science*, 79(2), 519–531. <https://doi.org/10.1093/icesjms/fsab178>
- Ogle, D. H. (2018). *Introductory fisheries analyses with R*. Chapman and Hall/CRC.
- Orach, K., Duit, A., & Schlüter, M. (2020). Sustainable natural resource governance under interest group competition in policy-making. *Nature Human Behaviour*, 4(9), 898–909. <https://doi.org/10.1038/s41562-020-0885-y>
- Pace, M. L., & Gephart, J. A. (2017). Trade: A driver of present and future ecosystems. *Ecosystems*, 20(1), 44–53. <https://doi.org/10.1007/s10021-016-0021-z>
- Parsons, D. M., Hartill, B. W., Broekhuizen, N., McKenzie, J. R., Stephenson, F., Petersen, G. L., & Lundquist, C. J. (2021). Integrating multi-disciplinary data sources relating to inshore fisheries management via a Bayesian network. *Ocean & Coastal Management*, 208, 105636. <https://doi.org/10.1016/j.ocecoaman.2021.105636>
- Pauly, D. (1994). *On the sex of fish and the gender of scientists: A collection of essays in fisheries science* (Vol. 14). Springer Science & Business Media.
- Pauly, D., Christensen, V., Guénette, S., Pitcher, T. J., Sumaila, U. R., Walters, C. J., Watson, R., & Zeller, D. (2002). Toward sustainability in world fisheries. *Nature*, 418, 689–695. <https://doi.org/10.1038/nature01017>
- Pedroza-Gutiérrez, C., & Hernández, J. M. (2020). Social Networks and Supply Chain Management in Fish Trade. *SAGE Open*, 10(2), 1–18. <https://doi.org/10.1177/2158244020931815>
- Pellowe, K. E., & Leslie, H. M. (2019). Heterogeneity among clam harvesters in northwest Mexico shapes individual adaptive capacity. *Ecology & Society*, 24(4), 25. <https://doi.org/10.5751/ES-11297-240425>
- Pellowe, K. E., & Leslie, H. M. (2020a). Size-selective fishing leads to trade-offs between fishery productivity and reproductive capacity. *Ecosphere*, 11(3), e03071. <https://doi.org/10.1002/ecs2.3071>
- Pellowe, K. E., & Leslie, H. M. (2020b). The interplay between formal and informal institutions and the potential for co-management in a Mexican small-scale fishery. *Marine Policy*, 121, 104179. <https://doi.org/10.1016/j.marpol.2020.104179>
- Phillipson, J., & Symes, D. (2013). Science for sustainable fisheries management: An interdisciplinary approach. *Fisheries Research*, 139, 61–64. <https://doi.org/10.1016/j.fishres.2012.09.012>
- Plagányi, É. E., Punt, A. E., Hillary, R., Morello, E. B., Thébaud, O., Hutton, T., Pillans, R. D., Thorson, J. T., Fulton, E. A., Smith, A. D. M., Smith, F., Bayliss, P., Haywood, M., Lyne, V., & Rothlisberg, P. C. (2014). Multispecies fisheries management and conservation: Tactical applications using models of intermediate complexity. *Fish and Fisheries*, 15(1), 1–22. <https://doi.org/10.1111/j.1467-2979.2012.00488.x>
- Plank, M. J., Kolding, J., Law, R., Gerritsen, H. D., & Reid, D. (2017). Balanced harvesting can emerge from fishing decisions by individual fishers in a small-scale fishery. *Fish and Fisheries*, 18(2), 212–225. <https://doi.org/10.1111/faf.12172>
- Poteete, A. R., Janssen, M. A., & Ostrom, E. (2010). *Working together: Collective action, the commons, and multiple methods in practice*. Princeton University Press.
- Preiser, R., Biggs, R., De Vos, A., & Folke, C. (2018). Social-ecological systems as complex adaptive systems: Organizing principles for advancing research methods and approaches. *Ecology and Society*, 23(4). <https://doi.org/10.5751/ES-10558-230446>
- Quintana, A., Basurto, X., Rodríguez Van Dyck, S., & Weaver, A. H. (2020). Political making of more-than-fishers through their involvement in ecological monitoring of protected areas. *Biodiversity and Conservation*, 29(14), 3899–3923. <https://doi.org/10.1007/s10531-020-02055-w>
- Rivera-Hechem, M. I., Guzmán, R. A., Rodríguez-Sickert, C., & Gelcich, S. (2021). Effects of experience with access regimes on stewardship behaviors of small-scale fishers. *Conservation Biology*, 35(6), 1913–1922. <https://doi.org/10.1111/cobi.13758>
- Robins, G., Pattison, P., Kalish, Y., & Lusher, D. (2007). An introduction to exponential random graph (p^*) models for social networks. *Social Networks*, 29(2), 173–191. <https://doi.org/10.1016/j.socnet.2006.08.002>
- Robotham, H., Bustos, E., Ther-Rios, F., Avila, M., Robotham, M., Hidalgo, C., & Muñoz, J. (2019). Contribution to the study of sustainability of small-scale artisanal fisheries in Chile. *Marine Policy*, 106, 103514. <https://doi.org/10.1016/j.marpol.2019.103514>
- Rocha, J. C., Schill, C., Saavedra-Díaz, L. M., Moreno, R. P., & Maldonado, J. H. (2020). Cooperation in the face of thresholds, risk, and uncertainty: Experimental evidence in fisher communities from

- Colombia. *PLoS One*, 15(12), e0242363. <https://doi.org/10.1371/journal.pone.0242363>
- Rodrigues, J. G., & Villasante, S. (2016). Disentangling seafood value chains: Tourism and the local market driving small-scale fisheries. *Marine Policy*, 74, 33–42. <https://doi.org/10.1016/j.marpol.2016.09.006>
- Rojas, C. A., Cinner, J., Lau, J., Ruano-Chamorro, C., Contreras-Drey, F. J., & Gelcich, S. (2021). An experimental look at trust, bargaining, and public goods in fishing communities. *Scientific Reports*, 11(1), 1–13. <https://doi.org/10.1038/s41598-021-00145-5>
- Salas, S., Chuenpagdee, R., Seijo, J. C., & Charles, A. (2007). Challenges in the assessment and management of small-scale fisheries in Latin America and the Caribbean. *Fisheries Research*, 87, 5–16. <https://doi.org/10.1016/j.fishres.2007.06.015>
- Saltelli, A., Benini, L., Funtowicz, S., Giampietro, M., Kaiser, M., Reinert, E., & van der Sluijs, J. P. (2020). The technique is never neutral. How methodological choices condition the generation of narratives for sustainability. *Environmental Science & Policy*, 106, 87–98. <https://doi.org/10.1016/j.envsci.2020.01.008>
- Sayles, J. S., Garcia, M. M., Hamilton, M., Alexander, S. M., Baggio, J. A., Fischer, A. P., Ingold, K., Meredith, G. R., & Pittman, J. (2019). Social-ecological network analysis for sustainability sciences: A systematic review and innovative research agenda for the future. *Environmental Research Letters*, 14(9), 093003. <https://doi.org/10.1088/1748-9326/ab2619>
- Schill, C., Lindahl, T., & Crépin, A.-S. (2015). Collective action and the risk of ecosystem regime shifts: Insights from a laboratory experiment. *Ecology and Society*, 20(1). <https://doi.org/10.5751/es-07318-200148>
- Schlüter, M., Haider, L. J., Lade, S. J., Lindkvist, E., Martin, R., Orach, K., Wijermans, N., & Folke, C. (2019). Capturing emergent phenomena in social-ecological systems. *Ecology and Society*, 24(3). <https://doi.org/10.5751/ES-11012-240311>
- Schlüter, M., Orach, K., Lindkvist, E., Martin, R., Wijermans, N., Bodin, Ö., & Boonstra, W. J. (2019). Toward a methodology for explaining and theorizing about social-ecological phenomena. *Current Opinion in Environmental Sustainability*, 39, 44–53. <https://doi.org/10.1016/j.cosust.2019.06.011>
- Schulze, J., Müller, B., Groeneveld, J., & Grimm, V. (2017). Agent-Based Modelling of Social-Ecological Systems: Achievements, Challenges, and a Way Forward. *Journal of Artificial Societies & Social Simulation*, 20(2). <https://doi.org/10.18564/jasss.3423>
- Schulze, W. D., d'Arge, R. C., & Brookshire, D. S. (1981). Valuing environmental commodities: Some recent experiments. *Land Economics*, 57(2), 151–172. <https://doi.org/10.2307/3145783>
- Scutari, M., & Denis, J.-B. (2021). *Bayesian networks: With examples in R* (2nd ed.). Chapman and Hall/CRC.
- Sievanen, L. (2014). How do small-scale fishers adapt to environmental variability? Lessons from Baja California, Sur, Mexico. *Maritime Studies*, 13(1), 1–19. <https://doi.org/10.1186/s40152-014-0009-2>
- Smith-Doerr, L., & Powell, W. W. (2005). Networks and economic life. *The Handbook of Economic Sociology*, 2(3), 379–402.
- Snijders, T. A. B., van de Bunt, G. G., & Steglich, C. E. G. (2010). Introduction to stochastic actor-based models for network dynamics. *Social Networks*, 32(1), 44–60. <https://doi.org/10.1016/j.socnet.2009.02.004>
- Stephenson, R. L., Paul, S., Wiber, M., Angel, E., Benson, A. J., Charles, A., Chouinard, O., Clemens, M., Edwards, D., Foley, P., Jennings, L., Jones, O., Lane, D., Mclsaac, J., Mussells, C., Neis, B., Nordstrom, B., Parlee, C., Pinkerton, E., & Sumaila, U. R. (2018). Evaluating and implementing social-ecological systems: A comprehensive approach to sustainable fisheries. *Fish and Fisheries*, 19(5), 853–873. <https://doi.org/10.1111/faf.12296>
- Sterman, J. D. (2001). System dynamics modeling: Tools for learning in a complex world. *California Management Review*, 43(4), 8–25. <https://doi.org/10.2307/41166098>
- Stewart, D. R., & Long, J. M. (2016). Using hierarchical Bayesian multi-species mixture models to estimate tandem hoop-net-based habitat associations and detection probabilities of fishes in reservoirs. *Transactions of the American Fisheries Society*, 145(3), 450–461. <https://doi.org/10.1080/00028487.2016.1143395>
- Sutherland, W. J., Dicks, L. V., Everard, M., & Geneletti, D. (2018). Qualitative methods for ecologists and conservation scientists. *Methods in Ecology and Evolution*, 9(1), 7–9. <https://doi.org/10.1111/2041-210X.12956>
- Syed, S., Borit, M., & Spruit, M. (2018). Narrow lenses for capturing the complexity of fisheries: A topic analysis of fisheries science from 1990 to 2016. *Fish and Fisheries*, 19(4), 643–661. <https://doi.org/10.1111/faf.12280>
- Torres-Guevara, L. E., & Schlüter, A. (2016). External validity of artefactual field experiments: A study on cooperation, impatience and sustainability in an artisanal fishery in Colombia. *Ecological Economics*, 128, 187–201. <https://doi.org/10.1016/j.ecolecon.2016.04.022>
- Trifonova, N., Kenny, A., Maxwell, D., Duplisea, D., Fernandes, J., & Tucker, A. (2015). Spatio-temporal Bayesian network models with latent variables for revealing trophic dynamics and functional networks in fisheries ecology. *Ecological Informatics*, 30, 142–158. <https://doi.org/10.1016/j.ecoinf.2015.10.003>
- Trifonova, N., Maxwell, D., Pinnegar, J., Kenny, A., & Tucker, A. (2017). Predicting ecosystem responses to changes in fisheries catch, temperature, and primary productivity with a dynamic Bayesian network model. *ICES Journal of Marine Science*, 74(5), 1334–1343. <https://doi.org/10.1093/icesjms/fsw231>
- Uusitalo, L., Tomczak, M. T., Müller-Karulis, B., Putnis, I., Trifonova, N., & Tucker, A. (2018). Hidden variables in a Dynamic Bayesian Network identify ecosystem level change. *Ecological Informatics*, 45, 9–15. <https://doi.org/10.1016/j.ecoinf.2018.03.003>
- van Putten, I. E., Kulmala, S., Thébaud, O., Dowling, N., Hamon, K. G., Hutton, T., & Pascoe, S. (2012). Theories and behavioural drivers underlying fleet dynamics models. *Fish and Fisheries*, 13(2), 216–235. <https://doi.org/10.1111/j.1467-2979.2011.00430.x>
- Varkey, D. A., McAllister, M. K., Askey, P. J., Parkinson, E., Clarke, A., & Godin, T. (2016). Multi-criteria decision analysis for recreational trout fisheries in British Columbia, Canada: A Bayesian network implementation. *North American Journal of Fisheries Management*, 36(6), 1457–1472. <https://doi.org/10.1080/02755947.2016.1215357>
- Voyer, M., Gollan, N., Barclay, K., & Gladstone, W. (2015). 'It's part of me': Understanding the values, images and principles of coastal users and their influence on the social acceptability of MPAs. *Marine Policy*, 52, 93–102. <https://doi.org/10.1016/j.marpol.2014.10.027>
- Weber, E. U., & Lindemann, P. G. (2007). From intuition to analysis: Making decisions with our head, our heart, or by the book. In H. Plessner, C. Betsch, & T. Betsch (Eds.), *Intuition in judgment and decision making* (1st ed., pp. 191–208). Psychology Press.
- Wijermans, N., Boonstra, W. J., Orach, K., Hentati-Sundberg, J., & Schlüter, M. (2020). Behavioural diversity in fishing—Towards a next generation of fishery models. *Fish and Fisheries*, 21(5), 872–890. <https://doi.org/10.1111/faf.12466>
- Wilson, J., Yan, L., & Wilson, C. (2007). The precursors of governance in the Maine lobster fishery. *Proceedings of the National Academy of Sciences*, 104(39), 15212–15217. <https://doi.org/10.1073/pnas.0702241104>
- Wisz, M. S., Satterthwaite, E. V., Fudge, M., Fischer, M., Polejack, A., & St. John, M., Fletcher, S., & Rudd, M. A. (2020). 100 Opportunities for More Inclusive Ocean Research: Cross-Disciplinary Research Questions for Sustainable Ocean Governance and Management.

Frontiers in Marine Science, 7. <https://doi.org/10.3389/fmars.2020.00576>

Young, O., Lambin, E., Alcock, F., Haberl, H., Karlsson, S., McConnell, W., Myint, T., Pahl-Wostl, C., Polsky, C., & Ramakrishnan, P. S. (2006). A portfolio approach to analyzing complex human-environment interactions: Institutions and land change. *Ecology and Society*, 11(2). <https://doi.org/10.5751/es-01799-110231>

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