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...
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 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
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
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 macro-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).
| 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 patterns, connections and relationships, discourses and processes. | To reveal patterns of individual 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 independencies 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   | Motivation for development of methods portfolio | Results of methods portfolio application |
|---------|-----------------------------------------------|----------------------------------------|
| 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. | Earlier methods revealed new information about SES dynamics that required additional methods to investigate. | Enabled researchers to capture and explore the complexity of social-ecological interactions in the clam fishery, to illuminate pathways towards sustainable management (Box 1). |
| 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. | Earlier methods focused on investigating structures and subsequent methods were added to gain deeper understanding of feedbacks and dynamics. | 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). |
| Case 3. A value chain analysis. The role of markets, relations and incentives for fishing behaviour and ecosystem health in Zanzibar and the Philippines. | Earlier methods were unable to reveal an answer to the key research question. Therefore, additional methods were added. | 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). |

**Outcomes from each method**

Case 1: 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.

Case 2: 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.

Case 3: 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.
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; Knaggåard 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

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**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.
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.

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

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.
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.

ACKNOWLEDGEMENTS
We would like to thank Rodrigo Martínez-Peña and Thorsten Blenckner for creative and helpful comments on a previous version of this manuscript, and Sonja Radosavljevic for diligently reviewing the earlier version of this manuscript. We would also like to thank the participants and panellists of the ‘Untangling social–ecological interdependencies: Theoretical and Methodological Insights from Studies of Small-Scale Fisheries’ session at the Resilience 2017 conference, the Stockholm Resilience Centre and the Interacting Complexities Theme and the Human Oceans Theme for inspiration and funding support, and the Beijer Institute of Ecological Economics at the Royal Swedish Academy of Sciences for providing workshop facilities. EL, BGM, KEP, AGN and LDO were supported by the Swedish Research Council, Dnr 2018-00401. SG thanks the Swedish Research Council Formas (Dnr 2020-01551) and the Swedish Research Council (Dnr 2016-04263). NW was supported by the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 682472 – MUSES). CS was supported by the Swedish Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 682472 – MUSES). CS was supported by the Swedish Research Council Formas (Dnr 2018-00401). ÖB was supported by the Swedish Research Council Formas (Dnr 2020-01551) and the Swedish Research Council (Dnr 2016-04263). SG thanks ANID PIA/BASAL FB0002 and Millennium Science initiative program ICN 2019_015.

DATA AVAILABILITY STATEMENT
N/A (there are no unpublished data supporting this publication).

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**How to cite this article:** Lindkvist, E., Pellowe, K. E., Alexander, S. M., Drury O’Neill, E., Finkbeiner, E. M., Girón-Nava, A., González-Mon, B., Johnson, A. F., Pittman, J., Schill, C., Wijermans, N., Bodin, Ö., Gelcich, S., & Glaser, M. (2022). Untangling social–ecological interactions: A methods portfolio approach to tackling contemporary sustainability challenges in fisheries. *Fish and Fisheries, 23*, 1202-1220. https://doi.org/10.1111/faf.12678