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Frontiers in modelling social–ecological dynamics of recreational fisheries: A review and synthesis

Christopher T. Solomon[1] | Colin J. Dassow[2] | Carolyn M. Iwicki[3] | Olaf P. Jensen[3] | Stuart E. Jones[2] | Greg G. Sass[4] | Ashley Trudeau[3] | Brett T. van Poorten[5] | Dane Whittaker[6]

[1]Cary Institute of Ecosystem Studies, Millbrook, NY, USA

[2]Department of Biological Sciences, University of Notre Dame, Notre Dame, IN, USA

[3]Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, USA

[4]Wisconsin Department of Natural Resources, Boulder Junction, WI, USA

[5]British Columbia Ministry of the Environment, Vancouver, BC, Canada

[6]School of Sustainability, Arizona State University, Tempe, AZ, USA

Correspondence
Christopher T. Solomon, Cary Institute of Ecosystem Studies, Box AB, Millbrook, NY 12545, USA.
Email: solomonc@caryinstitute.org

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Abstract

Recreational fisheries are culturally and economically important around the world. Recent research emphasizes that understanding and managing these systems requires a social–ecological perspective. We systematically reviewed quantitative social–ecological models of marine and freshwater recreational fisheries to summarize their conceptualization of social, ecological, and social–ecological dynamics and identify research frontiers. From a candidate set of 626 studies published between 1975 and 2018, 49 met criteria for inclusion in our review. These studies, though diverse in terms of focal species and processes considered, were geographically limited to a few locations and ignored large regions of the globe where recreational fishing is important. There were also important gaps in the social and ecological processes that were included in published models. Reflecting on these patterns in the context of previous conceptual frameworks, we define five key frontiers for future work: 1) exploring the implications of social and behavioural processes like heuristics, social norms, and information sharing for angler decisions and fishery dynamics; 2) modelling governance with more realistic complexity; 3) incorporating ideas from resilience thinking and complex adaptive systems, including slow variables, destabilizing feedbacks, surprises and diversity; 4) considering key ideas in fisheries systems, including spatial and temporal effort dynamics, catch hyperstability, and stocking; and 5) thinking synthetically about the models that we use to describe social–ecological dynamics in recreational fisheries, via explicit comparisons and formal integration with data. Exploration of these frontiers, while remembering the distinction between model complexity and model usefulness, will improve our ability to understand and sustain recreational fisheries.

KEYWORDS

ecology, governance, information, resilience, social, synthesis

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1 | INTRODUCTION

Recreational fisheries are culturally and economically important at a global scale, yet can be vulnerable to overexploitation and collapse (Arlinghaus et al., 2019; Arlinghaus & Cooke, 2009; Hughes, 2015; Post et al., 2002). Understanding and managing these vulnerabilities, and building resilience to them, require considering a broad suite of social and ecological processes and conceptualizing recreational fisheries as linked social–ecological systems (Arlinghaus et al., 2017; Brownscombe et al., 2019; Hunt, Sutton, & Arlinghaus, 2013; Post, 2013). Although we have not always succeeded in bringing an interdisciplinary perspective to bear on fisheries issues (Fenichel, Abbott, & Huang, 2013), increasingly both the data that we collect about recreational fisheries and the models that we use to describe and understand them are rooted in this social–ecological systems perspective (e.g. Fujitani, McFall, Randler, & Arlinghaus, 2017; Ziegler, Golebie, Jones, Weidel, & Solomon, 2017).

Quantitative dynamic models are important tools for building understanding, intuition, and practical guidance about managing social–ecological and other complex systems (Canham, Cole, & Lauenroth, 2003; Schlüter et al., 2012). Such models have been a core piece of fisheries science almost from the inception of the field, although early efforts focused chiefly on demographic and other ecological processes (Hilborn & Walters, 1992; T. J. Quinn, 2003). It was not until the 1950s that economic decision-making and bioeconomic principles were regularly incorporated into fisheries models, and other social processes were not regularly considered before the 1970s (Arlinghaus, 2014; Fuller, Kling, Krotz, Ross, & Sanchirico, 2013; T. J. Quinn, 2003). Since that time, social–ecological modelling of fisheries has expanded considerably, in parallel with developments in the study of social–ecological systems more broadly (Ostrom, 2009; Pulver et al., 2018; Walker, Holling, Carpenter, & Kinzig, 2004). The rapid growth in development and uptake of such models has generated important insights and opened new lines of inquiry in recreational fisheries. To date, though, there has been little systematic synthesis of this growing body of literature.

In this study, we conducted a review and synthesis of published social–ecological dynamic models of recreational fisheries in freshwater and marine systems. We reasoned that the processes that researchers build into models are those that they think are most important to the dynamics of the system, or most important to understand; while other considerations like data availability also may influence model structure, the set of published models should thus provide a good picture of how the field conceptualizes social–ecological dynamics in recreational fisheries. Our goal was to summarize this conceptualization, highlight areas of consensus and identify gaps in the work to date relative to processes that have been identified in the fisheries and resilience literatures as essential to understanding social–ecological dynamics in recreational fisheries and other systems.

2 | MATERIALS AND METHODS

We reviewed published, peer-reviewed dynamic models of coupled social–ecological processes in recreational fisheries. We excluded studies that focused only on data, purely statistical models, and/or conceptual models, without any dynamic modelling component. Our focus on dynamic models helped us to constrain the review to a relatively cohesive and manageable set of studies, and reflected our interest in the ability of dynamic models to integrate the strengths of conceptual and statistical models by distilling a system to its essential pieces while demanding a quantitative reckoning with the implications of that distillation. We undertook a "descriptive review," using a structured, broadly scoped search to identify relevant studies, extracting data on the characteristics of each study, and analysing these data to identify and discuss patterns in the literature and the current state of the field (Paré, Trudel, Jaana, & Kitsiou, 2015).

We identified an initial candidate set of 626 studies using a keyword search in Web of Science, covering the period from January 1975 through September 2018. The search terms were as follows: TI=(fishery OR fisheries OR fishing OR angler* OR angling) AND TS = recreation* AND TS = model. Studies published after September 2018, and those not indexed in Web of Science, were not included in our candidate set.

We filtered this candidate set down to a focal set of studies in two stages. First, two readers (from a set of nine) independently scanned the title and abstract of each paper to identify whether it might include a dynamic model, with a third reader arbitrating any disagreements. This first step reduced the candidate set to 179 studies, and excluded studies that used conceptual or statistical but not dynamic models. One reader (from a set of two) then read each paper in as much detail as necessary to confirm that it included a dynamic model that incorporated both social and ecological processes (see Table 1 for our definitions of all three of these criteria). This second step reduced the candidate set to 44 studies. We added five studies which had not shown up in our original candidate set (for instance, because they used a term like "resource" instead of "fishery" in the title or because they were in press at the time of our search) but which we knew of or saw cited in one of the other focal studies. This resulted in a final set of 49 focal studies for analysis. Two of these 49 studies were in peer-reviewed conference proceedings and the rest were in peer-reviewed journals. Although we likely missed some relevant published research, this focal set of studies is a systematic, representative and reasonably complete sample of the relevant literature.

TABLE 1 Definitions used to determine whether a candidate paper included a dynamic model with both social and ecological processes

A *dynamic model* follows changes in the state of the system through time, for instance via differential or difference equations. We included papers that focused on steady-state solutions of dynamic models. We excluded papers that included only statistical modelling (even if the statistical modelling was then used to make predictions) and papers in which a series of arithmetic calculations from empirical data were described as a model.
Social processes involve human decision-making of some kind, conscious or sub-conscious. Examples include decisions about where to fish; how much satisfaction, value or utility to derive from a fishing trip; whether to pressure fishery managers for increased stocking; whether to comply with regulations or social norms; and how to manage a fishery. Models that consider angler heterogeneity and those that include monitoring or assessment as part of the model probably include some social process. We excluded papers that considered one or more possible strategies for management or regulation of the fishery but did not model the social process of choosing management strategies nor include any other social processes in the model. Many standard stock assessment papers fall into this category.
Examples of non-human *ecological processes* include fish population dynamics, effects of environmental factors on fish populations, effects of fish populations on the environment, and intra- or interspecific interactions like predation or competition. Evolutionary processes were included as part of this definition.

From each of the focal studies, we recorded information about the structure of the model. We extracted data about a broad range of social, ecological and social–ecological characteristics of the models (Table 2). The list of model characteristics for which we extracted data was influenced largely by two recent syntheses which identified features that are likely to be important in determining whether recreational fisheries collapse or are resilient: Post (2013) summarized mechanisms "that could, or should, lead to collapse of heavily harvested recreational fisheries," and Biggs, Schlüter, and Schoon (2015) identified principles for resilient social–ecological systems. Data for each characteristic were extracted from all 49 studies by a single reader to ensure consistency; there were nine unique readers, each responsible for extracting data on approximately four characteristics.

We summarized the extracted data (Supplementary Information S1) about the frequency of model characteristics in narrative and graphical form using approaches typical of descriptive reviews (Paré et al., 2015). Our goal was to identify, contextualize and interpret patterns in the data that we had extracted. Reflecting on the results and thinking about them in the context of previous conceptual frameworks (Arlinghaus et al., 2017; Hunt et al., 2013; e.g. Schlüter et al., 2012; Ward et al., 2016), we found that we could usefully aggregate them into five thematic groups, which we present here as research frontiers. In presenting each frontier, we combine our results (i.e. quantitative patterns that we observed in the data) with background and interpretation to provide context, sketch the state of the art, identify knowledge gaps, and offer opinions about likely avenues for future research. As a complement to these thematic frontiers, we also conducted a hierarchical clustering analysis to help visualize groups of studies that shared similar model characteristics. For the clustering analysis, we used the average linkage method in the hclust() function and calculated the dissimilarity matrix with the daisy() function using the Gower distance metric to accommodate the mix of numerical, categorical and ordered categorical variables in our data (Maechler, Rousseeuw, Struyf, Hubert, & Hornik, 2016; R Core Team, 2016).

3 | RESULTS AND DISCUSSION

3.1 | Geographic distribution of modelled ecosystems

The studies that we reviewed considered a diverse set of study systems, although a small handful of systems received most of the research focus (Figure 1). Ecosystem types included lakes (17 studies),

TABLE 2 Descriptions of the model characteristics for which we extracted data. The first four rows describe basic background or contextual information about the study and study system. The remaining rows are loosely organized with primarily ecological characteristics listed first, followed by social and social–ecological characteristics. Many of the model characteristics were chosen because they have previously been identified as important for resilience or collapse of recreational fisheries or other social–ecological systems in reviews by Post (2013) and Biggs et al. (2015); we indicate this at the end of the definition where applicable. Asterisks indicate characteristics involving interactions among fish, anglers and managers that we considered to be "fisheries systems processes" for the purposes of the analysis presented in Figure 5

Characteristic	Description
Citation	Brief citation (author and date). Complete citations are in the main text
Focus	Brief (~1 sentence) description of the focus of the paper
System	Brief description of study system
Data	The most formalized way in which the study uses empirical data. Options, from least to most formal, are as follows: none (no use of data); to inspire the model structure; to parameterize the model; to ground-truth the model (e.g. informal, more-or-less fitting of the model to data); and to fit the model
n species	How many fish species are modeled? Identified by Biggs et al. (2015)
Ecological diversity	Is there other ecological diversity in the model, aside from species diversity or things covered under habitat (such as differences in productivity between lakes)? Identified by Biggs et al. (2015)
Age structure*	Does the fish population model include age or stage structure? Identified by Post (2013)
Habitat*	Are effects of habitat quality on ecological processes modeled in any way? (For instance, effects of habitat complexity on juvenile survival)
FIE*	Does the model include fisheries-induced evolution? Identified by Post (2013)
Allee*	Are there processes in the model that can lead to Allee effects (where the per-capita population growth rate is lower when population size is lower)? Examples include reduced reproductive success (e.g. because of difficulty finding a mate) or increased susceptibility to predators (e.g. because predator-swamping mechanisms cease to work). Identified by Post (2013)
Cultivation depensation*	Does the model include a cultivation depensation mechanism, in which fishing down the abundance of a piscivore releases its prey from predation pressure, increasing prey abundance to the point that they compete with juvenile predators and so reduce productivity of the predator population? Identified by Post (2013)
Density-dependent catchability*	Does the model include a mechanism that allows for density-dependent catchability, potentially leading to "hyperstability" of CPUE even as abundance declines? This can occur due to fish aggregation (which may be habitat mediated) or to angler sorting. Identified by Post (2013)
Effort dynamic*	Can angler effort change in response to fish abundance, catch rate (CPUE), or other factors? Identified by Post (2013)
Utility	Is there a model of angler utility that drives angling decisions? (In a few cases, there was not an explicit utility model but there was some other kind of benefit maximization; these are recorded as "other benefit maximization")
Information	Is the information that anglers have about fishing opportunities (or that other human agents have about decisions that they need to make) implicitly perfect, explicitly perfect, or explicitly imperfect? Or is information not included or not applicable to the model?
Learning*	Does the model consider learning about the system by agents (e.g. anglers, managers), or other changes in their mental models? Identified by Biggs et al. (2015)
Angler heterogeneity*	Is heterogeneity in the preferences or behaviors of anglers part of the model? Identified by Biggs et al. (2015)
Spatial dynamics*	Does the model consider movements of anglers between locations explicitly, implicitly, or not at all? Identified by Post (2013) and Biggs et al. (2015)
Memory*	Is there memory in angler behavior, such that decisions in time step t depend in part on behavior at t−1?
Catch–release*	Does the model consider catch-and-release fisheries?
Release mortality*	If the model considers the possibility that fish may be caught and released, does it include post-release mortality (also known as hooking mortality)?
Stocking*	Does the model include stocking? Identified by Post (2013)

(Continues)

TABLE 2 (Continued)

Characteristic	Description
Regulation compliance*	Does the model allow for non-compliance with fishing regulations? Identified by Post (2013)
Monitoring*	Is monitoring or assessment of the fishery included as part of the model?
Governance	Brief description of how the governance structure of the system is conceptualized in the model. Identified by Biggs et al. (2015)
governanceCat	Categorization of governance structure: none, simple or complex
Policy diversity	Is policy diversity or the process of choosing a policy included as part of the model? Note: this is not the same as saying that the authors use the model to explore several policy alternatives. Identified by Biggs et al. (2015)
Social diversity	Is social diversity in actors, knowledge systems, or institutions considered in the model in any way beyond angler heterogeneity? Identified by Biggs et al. (2015)
Social norms	Does the model consider the influence of social norms on angler behavior, or the dynamics of social norms through time?
Slow variables	Does the model consider gradual change in any underlying driver variables, such as climate or social context? Identified by Biggs et al. (2015)
Feedbacks	Do the authors discuss any feedback loops in the model that reinforce (positive feedback) or dampen (negative feedback) change in a state variable? Identified by Biggs et al. (2015)

coastal and estuarine marine habitats (16 studies), and rivers (7 studies). An additional 10 studies focused on theoretical or conceptual models without reference to a particular study ecosystem, although in eight of these cases the model was inspired by a generalized lake ecosystem. A substantial portion of the studies built models describing or inspired by a small handful of fisheries landscapes, including the Ningaloo Marine Park in Western Australia (7 studies), rainbow trout in lakes of British Columbia, Canada (5 studies), lakes of northern Wisconsin, USA (5 studies) and northern pike in German lakes (4 studies). Many regions where recreational fisheries are known to be important were not represented by any studies in our review (Figure 1). For instance, no studies examined fisheries in Latin America or Asia, and only one examined an African fishery. Even in some of the better-studied regions like North America and Europe, there is clustering of research effort that clearly omits regions or whole countries where recreational fishing is important. Thus, the range of social and ecological conditions under which the social–ecological system (SES) dynamics of recreational fisheries have been modelled is considerably more limited than the range of conditions under which those fisheries exist.

3.2 | Frontiers in modelling social–ecological dynamics of recreational fisheries

We organized the results of our review into five thematic frontiers in which future modelling efforts could make important progress towards guiding sustainable and resilient use of recreational fisheries and informing broader social–ecological theory (Figure 2). In the following sections, we present the results of our review in the context of these five frontiers. We found substantial diversity in the processes that were included in the models that we reviewed; for instance, of the characteristics that we considered (Table 2) only effort dynamics, implicit or explicit spatial dynamics, age structure, catch–release, and feedbacks were included in half or more of the models. Our purpose here is not to imply that any particular model, past or future, should incorporate a particular feature or process; the best model is the one that is best suited to answering the question at hand. Instead, we seek to glean some insights into what we as a field have and have not done in modelling social–ecological dynamics of recreational fisheries, and so identify potentially productive avenues for future work.

3.3 | Frontier 1: Decisions

Human decisions lie at the heart of important fishery processes like effort dynamics, voluntary release, regulation setting and regulation compliance. Accordingly, recent syntheses have called for more and better integration of human behaviour and decision-making into models of fisheries and SES more broadly (Fulton, Smith, Smith, & van Putten, 2011; Hunt et al., 2013; Rounsevell, Robinson, & Murray-Rust, 2012; Schlüter et al., 2012; Ward et al., 2016). Efforts along these lines are still in their infancy, despite a great deal of progress (e.g. Fujitani et al., 2017). A key frontier for recreational fishery SES modelling is to engage more deeply with the behavioural literature (e.g. Ajzen, 1985), better understand the implications of human behavioural and social processes for system-level dynamics, and separate those processes that are essential for system dynamics from those that are not.

Utility theory has formed the basis for most efforts to model decisions in recreational fishery SES models to date. Utility models describe the preferences of anglers for different aspects of the fishing experience (e.g. catch rate, fish size and solitude) or for non-fishing activities, and assume that anglers make decisions about if, when, and where to fish in order to maximize their utility (Fenichel et al., 2013;

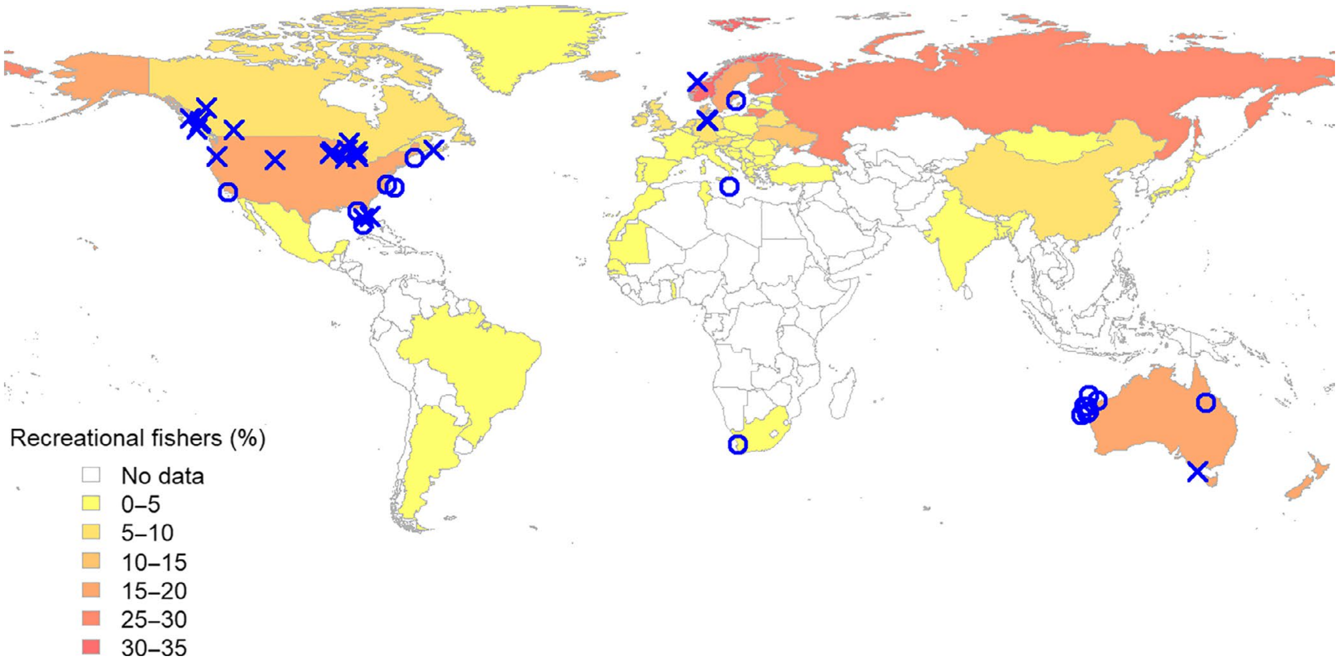

FIGURE 1 Locations of fisheries for which social–ecological modelling studies have been published (crosses are freshwater systems, and circles are marine), overlaid on rate of participation in recreational fishing by country (coloured fill). Points are for the studies included in the present review; participation rate data are from Arlinghaus et al. (2019), Arlinghaus, Tillner, and Bork (2015). Points are jittered to reduce overplotting

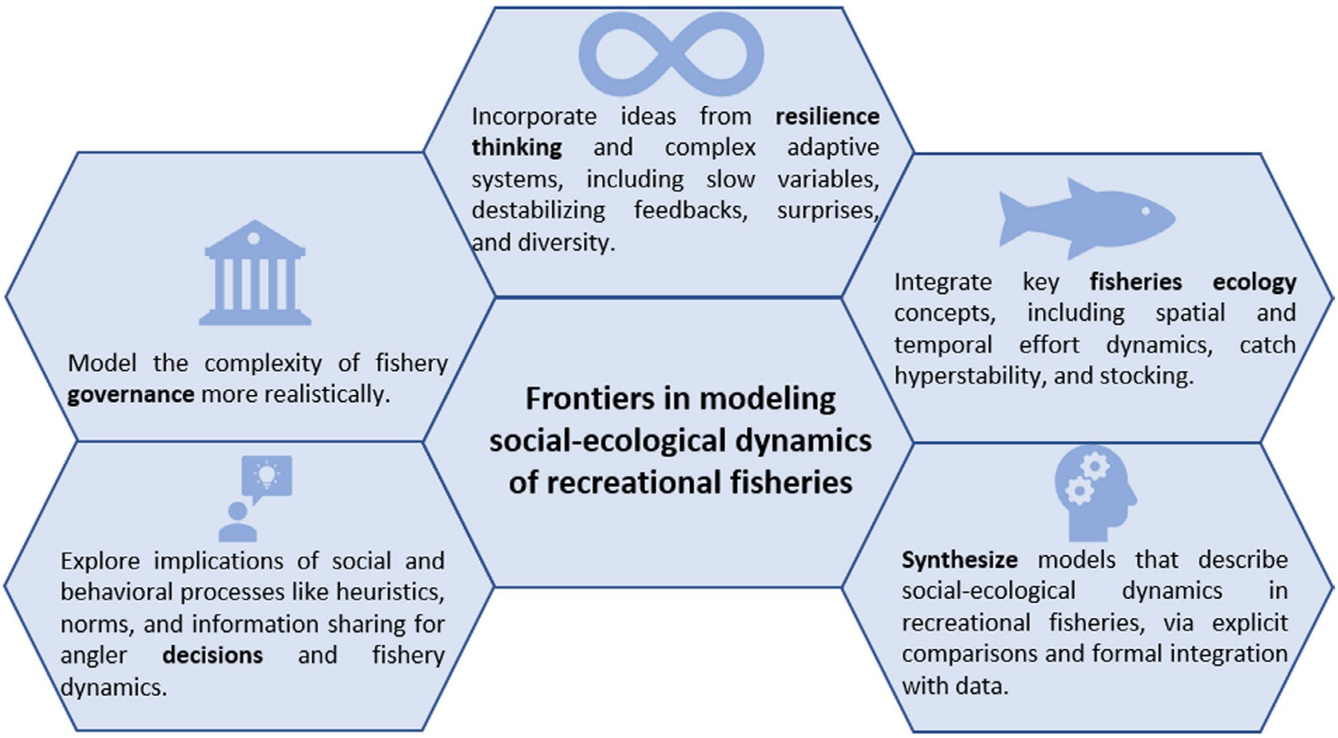

FIGURE 2 Five frontiers in modelling social–ecological dynamics of recreational fisheries. Additional details about each frontier are in the main text

Hunt, 2005; Hunt, Camp, van Poorten, & Arlinghaus, 2019). Utility models provide a mechanistic way, with theoretical grounding in the economics literature, to describe the spatial and temporal dynamics of fishing effort and latent effort as fishery conditions change. The use of utility in recreational fishery SES models has enabled researchers to explore heterogeneity in angler preferences and the management challenges and opportunities that this heterogeneity creates. Of the 40 studies in our review that included dynamic angling effort, nearly half (19 studies) modelled effort decisions with simple utility analogs based on fishing quality, the abundance of vulnerable fish or similar quantities, while another 17 used explicit utility functions that could capture important determinants of fishing effort like travel costs and non-catch benefits of fishing. Models for managers' decision processes were dominated by approaches based on aggregate utility measures. The only types of decisions that were often modelled in a context other than utility theory were decisions about regulation compliance and voluntary release. Even these were typically modelled as constant rates, despite abundant empirical evidence that they can be highly variable within and among fisheries (Gaeta, Beardmore, Latzka, Provencher, & Carpenter, 2013; Page & Radomski, 2006; Sullivan, 2002; Wilberg, 2009).

Utility models have clearly been a productive approach to the problem of understanding human decisions in recreational fishery SES. On the other hand, these models ignore some important aspects of decision-making processes, including heuristics, social norms and information. Our results point to some ways that these concepts have begun to be incorporated in fisheries SES models, and suggest some avenues for further exploration.

Heuristics are rules of thumb that people use to make quick decisions while ignoring some of the relevant information. Influential research in behavioural economics argues that many decisions are best explained as quick, intuitive reactions guided by heuristics rather than as the fully or boundedly rational deliberations implied by utility models (Gigerenzer & Gaissmaier, 2011; Tversky & Kahneman, 1974). Sometimes, heuristics lead to suboptimal decisions, for example when anglers apparently inaccurately interpreted high bag limits as a sign of abundant walleye in a mixed recreational and tribal fishery (Beard, Cox, & Carpenter, 2003). On the other hand, in situations where some of the information relevant to a decision is unknown, or known imperfectly, heuristics can sometimes lead to better decisions than more deliberative processes (Gigerenzer & Gaissmaier, 2011). Despite the ubiquitous use of heuristics in human decision-making and the potential that they yield different behaviours than other decision-making processes, none of the models in our review considered heuristic models of decision-making by anglers or managers.

Social norms—informal understandings about acceptable behaviour within a society—influence many of the decisions that humans make in recreational fisheries (Cooke, Suski, Arlinghaus, & Danylchuk, 2013; Hunt et al., 2013). Psychological models emphasize that social norms influence behaviour via their effects on personal or subjective norms (Ajzen, 1985; Schwartz, 1973). We focus on social norms in particular because of their potential to be influenced by managers or other agents. This potential suggests that social norms may be an interesting and important component of fisheries SES models. Social norms can have strong effects on fishery processes; for instance, the spread of a voluntary catch–release ethic for largemouth bass and muskellunge has greatly reduced fishing mortality rates for these species in many places, sometimes demanding the re-evaluation of traditional management approaches (Allen, Walters, & Myers, 2008; J. F. Hansen et al., 2015; Myers, Taylor, Allen, & Bonvechio, 2008; S. Quinn, 1996; Shaw, Sass, & Eslinger, 2019). These kinds of changes in social norms suggest that angler utility may be much more dynamic than fisheries SES models typically assume. Management agencies and environmental NGOs recognize the importance of social norms and sometimes use educational campaigns to try to create or reinforce norms that support desired fishery outcomes (Butler, Green, & Galvin, 2013; Mackay, Jennings, van Putten, Sibly, & Yamazaki, 2018). Yet while social norms may be powerful and widespread determinants of behaviour in recreational fisheries, they received relatively limited and simplistic consideration in the models that we reviewed. Ten studies allowed for voluntary catch-and-release behaviour by anglers, and 14 allowed for some non-compliance with fishery regulations. In a limited number of these cases, social norms were treated as heterogeneous among angler types or dynamic in time; for instance, Johnston and colleagues varied the propensity for voluntary catch-release behaviour among angler types, Johnston, Arlinghaus, and Dieckmann (2010), Johnston, Arlinghaus, and Dieckmann (2013), Johnston, Beardmore, and Arlinghaus (2015) and Carpenter and Brock (2004) explored how different regulations influenced the payoff for non-compliance and thus the strength of norms or enforcement mechanisms necessary to maintain compliance. Further consideration of social norms in recreational fishery SES models seems likely to be interesting and fruitful, perhaps by incorporating them as state variables and considering how they may change, either slowly or rapidly, in response to social change or management actions. One empirical motivation for this kind of modelling comes from work in walleye fisheries of Alberta, Canada, where rates of non-compliance with length limits were inversely related to catch rates (Sullivan, 2002). Management actions themselves might also be modelled with social norms, because the range of policy options open to a manager may be prescribed, in part, by shared social understanding about what behaviours by managers are acceptable.

Acquisition and application of information is essential in decision-making, but research to date has largely ignored the role of information in recreational fishery SES (Hunt et al., 2013). Most of the studies that we reviewed assumed that anglers were omniscient and had perfect, up-to-date information about expected catch rates or other features of different potential fishing opportunities, though this assumption was rarely made explicit. The one exception considered agents seeking to maximize their harvests from one of several resource pools and showed that the social network structure via which the agents shared information about the resources influenced their collective harvest (Little & McDonald, 2007). In this model, highly connected information networks led all agents to have similar perceptions of the resource landscape and thus to concentrate effort on a limited number of resource pools, where their aggregate harvest was substantially lower than the MSY level achieved when they had perfect information and an ideal free distribution of effort. Bodin and Norberg (2005) found similar results in a stylized model of agents managing croplands: highly linked social networks led to synchronized agent behaviour and frequent resource collapses. These results suggest that information exchange, and presumably information quality, may have substantial effects on the dynamics of recreational fisheries, but the research to date is insufficient to permit much insight into the nature and magnitude of these effects or the contexts in which they are important, despite the obvious effects of technological change on the information available to anglers. Potentially fruitful topics for further exploration include 1) the consequences—in terms of dynamic behaviours like stability, time lags and cycles—of varying the accuracy, precision and immediacy of information available to anglers; 2) the implications of social network structure (including personal and Internet-enabled networks) when anglers are seeking to maximize multi-faceted utilities that include things like solitude in addition to harvest; and 3) the conditions under which the assumption of angler omniscience is a satisfactory simplification. Progress on these ideas will likely be aided by new empirical research, and by turning to parts of the commercial fisheries literature (e.g. Gezelius, 2007; Little et al., 2004; Mangel & Clark, 1983) and other literatures where researchers have considered the dynamic consequences of information flow.

3.4 | Frontier 2: Governance

Governance arrangements—the structures and processes by which people make decisions and share power (Folke, Hahn, Olsson, & Norberg, 2005)—are known to be important for outcomes and resilience in social–ecological systems, including artisanal and commercial fisheries (Cinner et al., 2012; Gutiérrez, Hilborn, & Defeo, 2011; Leslie et al., 2015). In recreational fisheries, governance arrangements are varied and often complex (Daedlow, Beard, & Arlinghaus, 2011; Daedlow, Beckmann, & Arlinghaus, 2011). In many cases, it is not just the state agency or other formally recognized government institution that works to manage the resource, but a suite of formal and informal institutions operating at a variety of scales, influencing and influenced by anglers via codified and ad hoc processes (Figure 3a). Nonetheless, most of the studies that we reviewed assumed very simple governance structures (Figure 3b). This focus on simple governance structures may have occurred because they are simple to model, match well with traditional areas of interest like the effects of length limits on fisheries, align with de jure (if not de facto) power structures, or simply because governance is rarely a prominent piece of the mental models that managers and researchers use to conceptualize their systems (Ziegler, Jones, & Solomon, 2019).

The few studies in our review that did consider more complex governance arrangements were quite diverse. van Poorten, Arlinghaus, Daedlow, and Haertel-Borer (2011) explicitly recognized the pressure that anglers can exert for desired management actions, modelling stocking rates by the manager as a function of angler satisfaction with current harvest levels. This sort of pressure is a widespread feature of recreational fisheries even when managers are primarily focused on sustainability and resilience, and can occur informally or via formalized processes like stakeholder meetings which management agencies institute for inclusivity and transparency. These formalized processes were the focus in a modification of the van Poorten et al. (2011) model presented by Ziegler et al. (2017). Of course, anglers and other stakeholders have diverse desires from and impacts on fisheries and related resources, and are engaged in governance in a variety of ways (e.g. Figure 3a). Some of the studies that we reviewed incorporated stakeholder involvement in identifying management alternatives, objectives and performance indicators, before implementing models focused on simplistic, top-down governance (e.g. Mapstone et al., 2008; Thébaud, Ellis, Little, Doyen, & Marriott, 2014). One unique model explored the perverse incentives that may arise when a central manager alters regulation policing in order to maximize net revenues from non-compliance fines (Crookes, 2016). Finally, only two studies relaxed the common assumption that managers are omnipotent, and instead modelled them as limited in their coercive power over anglers or in the set of policy options that they have available to choose from (Carpenter & Brock, 2004; Horan, Fenichel, Drury, & Lodge, 2011). The diversity of governance arrangements captured in this small set of studies illustrates the richness of ideas about governance that might usefully be explored with models. Exploring the implications of more complex, realistic and flexible governance alternatives may help to illuminate important but underappreciated controls on the dynamics of recreational fisheries SES, and broaden the discussion about the strengths and weaknesses of different governance arrangements (Arlinghaus et al., 2017; Hunt et al., 2013). A particular challenge—which has not yet been adequately resolved even in the general political science literature, let alone in fisheries—will be to extend models to higher levels of rule-making than the operational settings that we emphasize here, to encompass collective choice and perhaps even constitutional rules (Ostrom, Gardner, & Walker, 1994). Although changes in rules at these levels may be rare even in times of great upheaval (Daedlow, Beckmann, Schlüter, & Arlinghaus, 2013), understanding the pros and cons of structurally different governance arrangements could help scientists and managers envision and work towards better futures.

Governance often focuses on outcomes, and the studies that we reviewed measured outcomes in a variety of ways (Figure 4). Most often, a mixture of catch-related (CPUE, fish size), ecological (biodiversity, spawning stock biomass), angler welfare (utility, satisfaction) and economic (surplus and profit in models that considered mixed commercial-recreational fisheries) criteria were used. Aggregate angler satisfaction or utility was the most common single outcome reported in these studies. This aggregate utility measure often accommodated heterogeneous preferences among two or more angler typologies (e.g. catch- or harvest-oriented), in an effort to capture some of the real-world challenges and opportunities that agencies face in managing for a diverse constituency. Only one paper addressed equity of outcomes, weighting utility for different angler groups by group abundance (Johnston et al., 2010). Further exploration of social equity and the trade-offs and synergies between

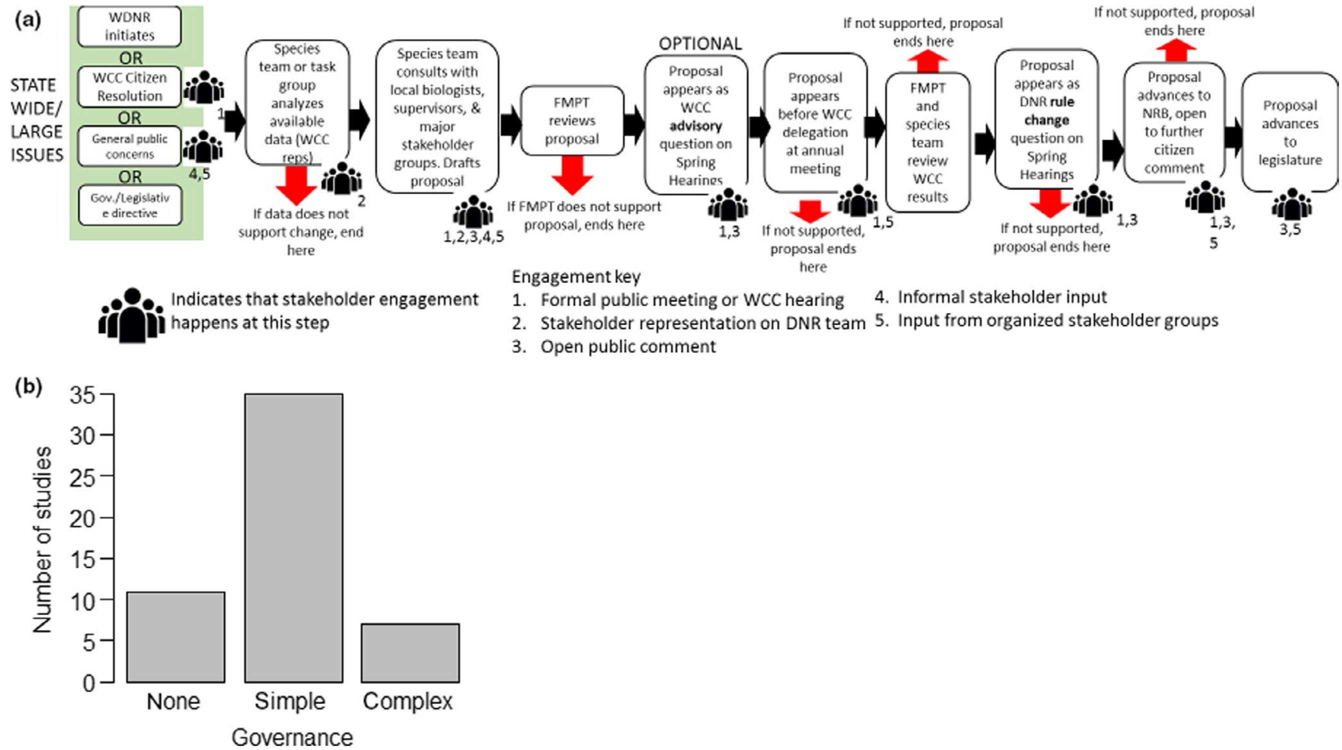

FIGURE 3 Governance of recreational fisheries is often complex in reality but simple in models. (a) Summary of the process for changing a state-wide fisheries regulation in Wisconsin (courtesy of the Bureau of Fisheries Management, Wisconsin Department of Natural Resources). Even in this one limited slice of fisheries governance writ large, there are complex interactions involving managers, data, multiple stakeholders, and elected and appointed officials. WCC is Wisconsin Conservation Congress, FMPT is Fisheries Management Policy Team, NRB is Natural Resources Board, and DNR or WDNR is Wisconsin Department of Natural Resources. (b) Recreational fisheries SES models in our review classified according to how governance is modelled. "None" means that the study assumed unregulated open access; "simple" that full decision-making and regulating power were explicitly or implicitly assumed to be under full control of a single management authority; and "complex" that some other, more complex governance structure was assumed. A few studies are counted twice because they considered scenarios in more than one of these categories (three times for "none" and "simple"; one time for "simple" and "complex")

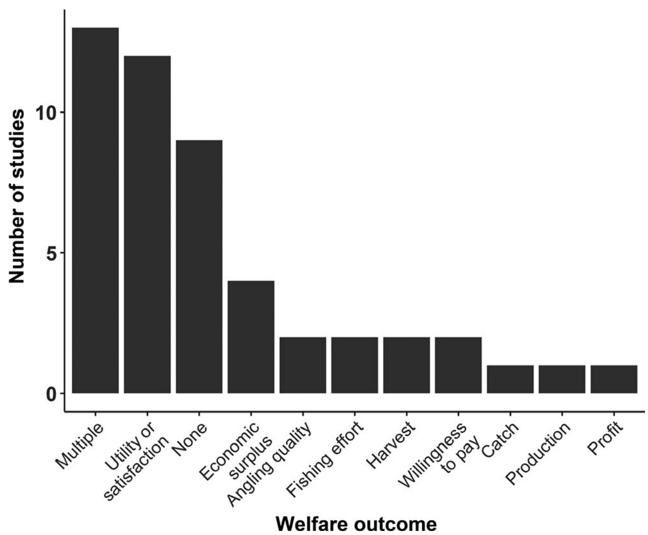

FIGURE 4 Measures of aggregate welfare used in the studies that we reviewed. "Multiple" indicates use of a combination of social, ecological and/or fisheries welfare outcomes. "None" indicates that the study did not present a measure of welfare

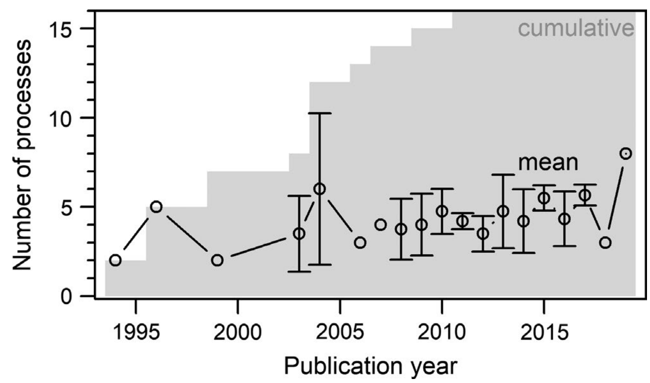

FIGURE 5 Number of fisheries systems processes included in the recreational fisheries SES models that we reviewed. Points show the average number of processes included in models published in a given year (±1 sd); the grey area shows the cumulative number of processes considered in any model up to that year

ecological and social outcomes is an important challenge for managers and modelers.

3.5 | Frontier 3: Resilience thinking

Several ideas about complex adaptive systems that have been influential in the broader literature on resilience of social–ecological systems—including slow variables, destabilizing feedbacks, surprises and diversity—have not yet been explored extensively in the models of recreational fisheries SES that we reviewed (Arlinghaus et al., 2017; Biggs et al., 2015; Camp et al., 2020; Daedlow, Beckmann, et al., 2011; Daedlow et al., 2013).

Slow variables change gradually yet have the capacity to transform the social–ecological system (Walker, Carpenter, Rockstrom, Crépin, & Peterson, 2012). They are fundamentally important but often invisible to human actors. Exploring the effects of slow variables has been essential to building understanding and improving outcomes in many SES, and accounting for them is essential for defining the safe operating space of fisheries (Carpenter et al., 2017; G. J. A. Hansen et al., 2019). Yet these sorts of dynamics received very little attention in the studies that we reviewed. Only two models truly incorporated a dynamic slow variable. Massey, Newbold, and Gentner (2006) used a bioeconomic model to consider how long-term improvements in water quality interacted with angler site choice and fish demographic processes and behaviour to influence the value of a fishery. Biggs, Carpenter, and Brock (2009) explored whether regime shifts between piscivore- and planktivore-dominated states in a simple fisheries food web, driven by slow changes in littoral habitat, could be detected sufficiently early to permit management to forestall them. Another eight studies explored model outcomes over a static gradient of some variable (e.g. fish habitat, water temperature and human population size) that could be considered in the context of a slowly changing driver. These static gradient studies are an imperfect substitute for ones that incorporate a dynamic slow variable, because they cannot capture the time lags and memory effects that make slow variables challenging to deal with in real social–ecological systems. Further consideration of slow variables in a dynamic context seems essential, especially given the ubiquity of changes in climate, land use, exurbanization, and other important slow drivers, and the potential for slow change in collective choice and constitutional rules (see Frontier 2). Even angler preferences—which are usually considered as fixed even when they are heterogeneous—might be subject to slow change that drives important social–ecological dynamics.

Feedbacks are processes that dampen (negative feedback) or reinforce (positive feedback) changes in a system. Two negative feedback mechanisms were often included in the models that we reviewed: density-dependent individual or population growth rates were included in 42 studies, angling effort was negatively related to catch rates or similar variables in 33 studies, and both mechanisms were included in 31 studies. These stabilizing feedbacks have been an essential part of understanding fishery dynamics for many years (Beverton & Holt, 1957). In contrast, positive (destabilizing) feedback mechanisms that might produce alternate stable states were included in only three of the studies that we reviewed, even though the feedback mechanisms in these models—intraguild predation and refuge habitat—may be fairly common in the real world (Biggs et al., 2009; Carpenter & Brock, 2004; Ziegler et al., 2017). Other positive feedback mechanisms may also be present in recreational fisheries; for instance, selective harvest of large individuals could drive evolution of smaller size at maturation, reinforcing changes in size structure in ways that would be slow to recover even if harvest were subsequently reduced (Enberg, Jørgensen, Dunlop, Heino, & Dieckmann, 2009; Matsumura, Arlinghaus, & Dieckmann, 2011). Although six of the studies that we reviewed included evolutionary feedbacks, none focused on this kind of potential hysteresis. Broader consideration of possible positive and negative feedback mechanisms, especially those generated by links between social and ecological dynamics, is likely a fruitful avenue for future work (Schlüter et al., 2012).

Irreducible uncertainties and surprises are characteristic features of complex adaptive systems, but they have not been explored extensively in the fisheries SES models that we reviewed. Fewer than one third of the models incorporated uncertainty, most commonly by introducing stochasticity into a stock–recruitment relationship, but also by a variety of other mechanisms such as variability in fish and angler behaviour, uncertainty about environmental conditions, and uncertainty about the true state of viability indices in a Management Strategy Evaluation context. Only one paper embraced the idea of surprises—events that are difficult or impossible to predict a priori yet have substantial consequences. This paper focused on evaluating management options for walleye in Saginaw Bay, Lake Huron (Fielder, Jones, & Bence, 2016). Recognizing that alewife abundance strongly influences walleye recruitment, and that future alewife recovery seemed possible but unlikely, the authors estimated the fisheries mortality rate that maximized sustainable harvest conditional on the estimated likelihood of a surprise alewife recovery. Surprises and uncertainties are much more common in recreational fishery SES than their representation in the reviewed studies would suggest (e.g. Pine, Martell, Walters, & Kitchell, 2009). This is probably because researchers have focused largely on the tractability and mechanistic insights that deterministic models offer; uncertainty has little heuristic value if it only muddies the waters. Nonetheless, greater attention to uncertainty and surprises will be important for building insights among researchers and practitioners about the dynamic responses of these complex systems to such events, and the proactive or reactive responses that may be needed to maintain desired outcomes in the face of such events. It will also likely be useful to think about uncertainty and surprise as they affect the behaviour of agents in fisheries models. How do agents behave in the presence of uncertainty, and are there typologies of agents who approach uncertainty in distinct ways and perhaps share other characteristics as well?

Diversity and redundancy can buffer systems from change. This idea is familiar to fisheries ecologists, for instance in the portfolio effect of population diversity on overall fishery yields (Hilborn, Quinn, Schindler, & Rogers, 2003; Schindler, Armstrong, & Reed, 2015); somewhat less familiarly, it also applies to diversity in actors, policy choices, sources of knowledge or other system components

(Carpenter & Brock, 2004; Grêt-Regamey, Huber, & Huber, 2019; Horan et al., 2011). Diversity in angler characteristics such as preferences and skills was a feature of approximately one third of the studies that we reviewed, and has increasingly been incorporated into recreational fisheries SES models in recent years (logistic regression of the binary "angler heterogeneity" data from S1 on year of publication, p = .04). The focus has generally not been on the implications of angler diversity for resilience, but at least some analyses suggest that angler diversity may reduce rather than enhance resilience, by increasing the universe of attractive fishing opportunities and so promoting higher effort and risk of recruitment overfishing (Johnston et al., 2010; Matsumura, Beardmore, Haider, Dieckmann, & Arlinghaus, 2019). This presents an interesting contrast to typical resilience thinking about diversity. Conversely, by intentionally providing diverse opportunities to cater to diverse anglers, resilience is improved (van Poorten & Camp, 2019). Other aspects of diversity that might influence fishery dynamics have rarely been considered. For instance, the vast majority of models (37 of 49) considered only one fish species, with no explicit interactions with other species. The few exceptions were generally more conceptual models, not focused on a particular species, that modelled interacting "herbivore" and "piscivore" species or a set of life history types; one paper considered 45 different trophic groups as part of an Ecopath with Ecosim model (Townsend, 2013). Similarly, although many models considered the implications of different policy options, only two explicitly considered policy diversity as a feature of the system, despite the potential importance to fisheries outcomes of the available set of policies and the mutability of policies over space and time (Carpenter & Brock, 2004; Horan et al., 2011). Increased focus on diversity in modelling studies will help us think about whether mechanisms inherent in fisheries (like interspecific compensatory responses) or those that we can insert into the fishery (like increased policy diversity and experimentation) can help to sustain desired fishery outcomes over the long term.

3.6 | Frontier 4: Fisheries systems

A suite of processes involving the interactions among fish, anglers and managers have received increasing attention in the general fisheries literature and have been incorporated into the fisheries SES models that we reviewed (Table 2). Many of these processes—such as effort dynamics, stocking, fisheries-induced evolution and others—have been identified as important determinants of recreational fisheries sustainability (Post, 2013). Both the cumulative number of these processes that have been explored in recreational fisheries SES models and the mean number of them included in a given model have increased over time (Figure 5). More complex models are not necessarily better models; nonetheless, it seems likely that important insights will emerge from continued efforts to incorporate these processes into SES models, especially for processes that link social and ecological dynamics or interact with slow variables and feedbacks. We briefly discuss a few of these ideas here.

The response of angler effort to catch rates and other aspects of the fishing experience is a key determinant of fisheries outcomes, especially in the open access conditions that predominate in North America and some other regions. Accordingly, almost all of the studies that we reviewed modelled effort as dynamic, usually via one of two mechanisms: simple negative feedbacks with fish population density or catch rates, or utility maximization by anglers considering catch and non-catch aspects of a fishing trip. The functional form of the effort–abundance relationship used in the models sometimes differs, with most using a sigmoidal relationship, that is a strong relationship between effort and abundance only at intermediate abundance. There are only a few places in the world in which the data exist to parameterize effort–abundance relationships and predict the spatial distribution of effort across multiple fishing locations on the landscape; further empirical research would help guide future modelling of these important dynamics.

Effort varies not just through time, but also across space. Modelling spatial dynamics explicitly—as one third of the studies in our review did—can illustrate the metapopulation dynamics that arise from movements of anglers and/or fish, and illuminate the ways in which successful management may require a landscape-level perspective (Hunt, Arlinghaus, Lester, & Kushneriuk, 2011; Mapstone et al., 2008; Post, Persson, Parkinson, & van Kooten, 2008). Recognizing spatial heterogeneity and dynamics can create opportunities to diversify management and thereby increase social welfare; ignoring them, and implementing static one-size-fits-all policies, can reduce social welfare and lead to propagating collapses of individual fisheries (Carpenter & Brock, 2004; Carruthers et al., 2019; van Poorten & Camp, 2019). Most of the studies in our review that explicitly modelled spatial dynamics focused on a small handful of systems, including coral reefs in Australia and a few lake districts in the United States and Canada, where the spatial structure of ecologically discrete fishing locations is an immediately salient feature of the landscape. One unexplored question is if and how spatial dynamics are important in other fishery landscapes, for instance where fishing opportunities are limited to stream networks, scattered large reservoirs or abundant but small farm ponds. It could also be useful to develop some general guidance about the situations in which explicit spatial dynamics will or will not be essential components of fisheries SES models. Certainly, they will remain essential when actionable, location-specific model predictions are desired (e.g. Carruthers et al., 2019), but in other cases, an adequate understanding of the system may be gained by incorporating spatial dynamics implicitly (e.g. Askey, Parkinson, & Post, 2013), or perhaps even by excluding them entirely.

The potential for catchability to vary such that catch rates are not linearly related to abundance is so well known in the fisheries literature that it seems hard to believe that this could be a frontier in modelling recreational fisheries SES. For example, an influential meta-analysis of the relationship between abundance and catch rates has been cited hundreds of times (Harley, Myers, & Dunn, 2001). Yet despite prominent warnings that density-dependent catchability can contribute to collapses of recreational as well as commercial fisheries (Post, 2013; Post et al., 2002; Rose & Kulka, 1999), only three of the studies that we reviewed incorporated this process. Hunt et al. (2011) considered the implications of catch hyperstability for patterns of overfishing at the landscape scale, Schueller, Fayram, and Hansen (2012) included an empirically derived hyperstable catch–abundance relationship in a model exploring management of walleye, and Stoeven (2014) considered hyperstable, proportional, and hyperdepletion relationships between catch rate and abundance in a theoretical economic analysis of the implications of effort utility for fishery outcomes. A handful of additional models may have allowed for the emergence of hyperstability or hyperdepletion via mechanisms like foraging arena dynamics or invulnerable states, though these studies did not explicitly examine this possibility. Studies including multiple competing angler types (e.g. Johnston et al., 2010; Johnston et al., 2013; Johnston et al., 2015) implicitly allow for hyperstability through effort switching (van Poorten, Walters, & Ward, 2016; Ward, Askey, & Post, 2013), though this is rarely recognized or discussed. Given the increasing evidence that hyperstability and hyperdepletion can occur in recreational fisheries due to mechanisms including habitat and spawning aggregation and effort sorting (Askey, Richards, Post, & Parkinson, 2006; Dassow et al., 2020; Mrnak, Shaw, Eslinger, Cichosz, & Sass, 2018; van Poorten et al., 2016; Ward et al., 2013), greater attention to these dynamics in our models of recreational fisheries SES seems essential.

Stocking is one of the most commonly applied fisheries management tools, but its cost and implications for wild fish stocks also make it controversial (Lorenzen, 2014). Perhaps surprisingly, stocking has received relatively little attention in the models that we reviewed. In cases where stocking was included, a major focus was on optimizing the size and abundance of stocked fish to maximize benefits given angler effort responses, interactions with wild populations, and competing objectives like satisfaction and conservation (Askey et al., 2013; Camp, Larkin, Ahrens, & Lorenzen, 2017; Camp, Lorenzen, Ahrens, & Allen, 2014; Carruthers et al., 2019; Varkey et al., 2016). These studies have tended to conceptualize stocking programs as being controlled by managers to maximize angler satisfaction. More recently, a set of studies has begun to explore variations on this traditional power structure, viewing managers' stocking decisions as more explicitly responsive to angler satisfaction and examining the incentives for local organizations to stock fish outside the bounds of traditional centralized management agency actions (van Poorten et al., 2011; Ziegler et al., 2017; Ziegler et al., In review). Future research on stocking in recreational fisheries SES should continue to consider both the social–ecological dynamics that influence success and efficiency of stocking programs, and also those that drive stocking to occur and whether those lead to socially optimal outcomes. These questions are potentially complex, due for instance to variation in the objectives of stocking programs (e.g. population rehabilitation vs. put–take or put–grow–take) or in the interactions of stocking with habitat suitability (Johnston et al., 2018).

Several other fishery system processes are likely avenues for future advances. Depensatory processes can contribute to stock collapses but have rarely been incorporated into the models that we reviewed; aside from five studies that included cultivation/depensation (Walters & Kitchell, 2001), no other potentially depensatory mechanisms were included in the models that we reviewed. In part, this is due to the focus so far on single-species models, because cultivation/depensation requires at least two interacting species. Other depensatory processes like Allee effects can be incorporated into single-species models, though empirical evidence regarding the strength of Allee effects in harvested fish populations is mixed (Hilborn, Hively, Jensen, & Branch, 2014; Hutchings, 2013; Perälä & Kuparinen, 2017). Release mortality has received more attention in the models that we reviewed; here, some of the important frontiers include incorporating good empirical estimates and considering the implications of multiple capture-and-release events (Kerns, Allen, & Harris, 2012). More broadly, fisheries dominated by catch and release received relatively little attention in the models that we reviewed but are becoming increasingly common in some contexts; more attention is needed on the ways in which these changes feed back to influence other components of the SES including population structure, angler satisfaction and management options (Hessenauer, Vokoun, Davis, Jacobs, & O'Donnell, 2018; Miranda et al., 2017; Sass & Shaw, 2019). Finally, the interactions between habitat, fish and people probably deserve more exploration, for instance in defining empirically supported relationships between habitat characteristics and fish population dynamics and in exploring the social processes that lead to degradation, conservation or improvement of habitat quality (Sass, Rypel, & Stafford, 2017; Sass et al., 2019; Ziegler, Dassow, Jones, Ross, & Solomon, 2019).

3.7 | Frontier 5: Synthesis

With increased attention over the past decade to social–ecological dynamics in recreational fisheries, the time is ripe to start thinking critically and comparatively about the models that we use to describe these systems. Two approaches seem particularly useful.

First, it is worth considering what we might gain from more formal integration of our models with data. In our review, we considered five levels at which a model might use data, whether from the literature or from new field research. From least formal to most formal these were as follows: not using data; using data for inspiration in structuring the model; using data to parameterize the model without any fitting; using data to ground-truth or informally fit the model; and explicitly fitting the model to data. Most of the studies that we reviewed were at the informal end of that spectrum, using data to inspire or parameterize the model (Figure 6). Only 9 studies ground-truthed their model against data, and only 4 explicitly fit the model to data. These patterns may in part reflect the limitations of available social–ecological data and the opportunistic ways that people structure models to make use of available data. Models that use data more formally are not necessarily inherently better or more useful; often, the models that do the most to advance research and management focus on elucidating concepts and key mechanisms rather than explicitly predicting or explaining observations. Nonetheless, in many fields formal integration of data and models has helped to test and refine understanding in powerful ways (Peng, Guiot, Wu, Jiang, & Luo, 2011). In the context of recreational fisheries SES, the goals of such analyses might include testing hypotheses about the functional forms of key relationships (e.g. fishing effort vs. fish abundance), identifying minimal models that provide satisfactory predictive power, and building decision support tools that are sufficiently inclusive of social and ecological processes that they provide real value to managers and other stakeholders.

Perhaps the best example to date of this kind of analysis in recreational fisheries is the recent work by Carruthers et al. (2019), who built a model including an empirically estimated model for angler site choice and an empirically supported model of population and fishery dynamics, and fit the integrated model to effort data from hundreds of British Columbia lakes. Although few other regions have as much recreational fishery data, basic information on catch, effort and relative abundance is widely available for many recreational fisheries and could be better integrated in SES models and help to identify which processes are critical to include in these models. Conversely, thoughtful modelling analyses could help to focus empirical work on the social and ecological data sets most likely to enhance understanding of system dynamics.

Second, we should begin to compare the models that we use to describe recreational fisheries SES in different places, and to think critically about key similarities and differences. These sorts of comparisons would be further strengthened by broadening the set of systems in which SES dynamics of recreational fisheries have been explored. Currently, the literature is heavily dominated by work in a few study systems, limiting the extent to which we can understand how social and biophysical context structure SES dynamics in ways that create challenges and opportunities for sustainable management and governance.

3.8 | Bridging the five frontiers

Although we have discussed the five frontiers above largely in isolation, there are of course also important ideas that lie at the intersections between them. Two examples help to illustrate this idea. First, hyperstable catch rates are important because they provide biased information to anglers and managers about the status of fish stocks. This reduces the likelihood of fishing effort redistribution across the landscape, which otherwise might help stabilize the fishery even in the absence of formal effort limits. Thinking about hyperstability in the context of information networks points towards actions that managers might take—such as providing fishery-independent estimates of abundance, or indices of angler catch rates adjusted for angler skill—to inject unbiased information back into angler information networks. Second, compliance with fishery regulations is determined partly by social norms and partly by governance actions such as initiating dialog to get angler buy-in about regulations, conducting enforcement patrols to penalize non-compliance, or even running outreach efforts aimed at nudging social norms in desired directions. For both of these examples and many others, it is easy to imagine how future modelling efforts might explore the outcomes that emerge from interactions among the frontiers described in this paper.

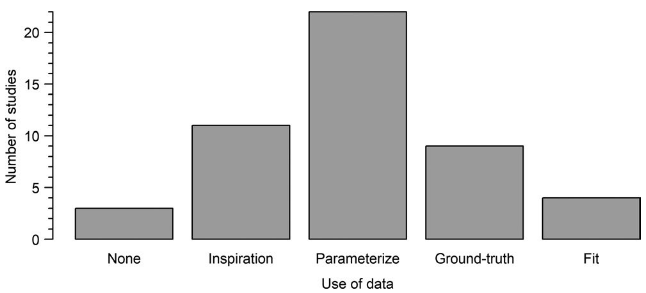

FIGURE 6 Ways in which recreational fisheries SES models used empirical data to inform models, arranged from least to most formal integration with data. Each study is classified according to the most formal way in which it used data

One way to visualize the bridges that have and have not been built between these five frontiers is to examine the clusters of model characteristics that are present in the studies that we reviewed (Figure 7). This provides a cross-cutting typology of the recreational fisheries SES models published to date, to complement the thematic summary of model characteristics that we have presented up to this point. The most deeply rooted distinction in our clustering analysis distinguished two models (cluster 1 in Figure 7) that focused on complex governance arrangements and incorporated cultivation/depensation dynamics. The next split distinguished the models in clusters 5 and 6, which rarely included dynamic responses of angler effort to changing conditions, from those in other clusters, which usually did include dynamic effort. The three models in cluster 6 were theoretical, using data only to inspire the model rather than to parameterize or fit it, and often focusing on a generalized rather than real ecosystem; all three also incorporated a memory effect into their model of angler behaviour, which was included in only three other models outside of cluster 6. The models in cluster 5, in contrast, were more empirically grounded and included effects of habitat quality on ecological processes, typically in lakes. Models in cluster 2 often incorporated catch–release dynamics. This cluster also included most of the models that considered fisheries-induced evolution. Cluster 3 included only studies with explicit spatial dynamics; most of these were in a single marine system and considered two interacting species, but none used an age-structured model. Finally, models in cluster 4 always considered catch–release dynamics and regulation compliance in single-species (and usually age-structured) models. These patterns, and the tendency for multiple publications by a given research team to cluster fairly closely together in the dendrogram, suggest that there are still important opportunities to explore the intersections of the frontiers that we identify with each other and with the social and ecological dynamics of different geographic locations.

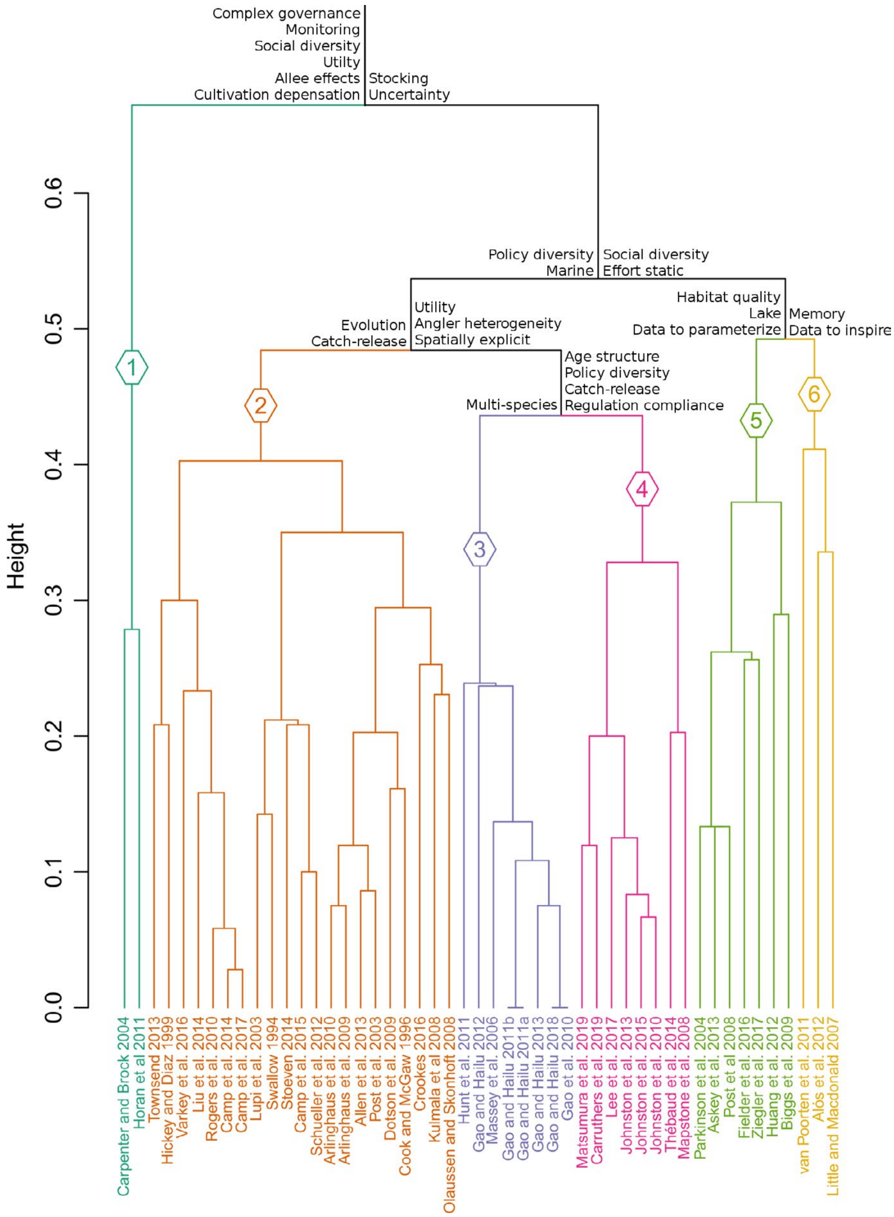

FIGURE 7 Dendrogram of recreational fisheries SES models, hierarchically clustered based on similarity in model characteristics. Colours indicate six distinct clusters, which are referred to in the text by the numbers shown inside hexagons at the base of each cluster. At each of the bifurcation points that define these clusters, model characteristics that are indicative of the left and right branches of the bifurcation are listed; see Table 2 for descriptions of these characteristics

4 | CONCLUSION

The frontiers that we have discussed in this review are, for the most part, familiar ones. Several recent conceptual frameworks, narrative reviews (sensu Paré et al., 2015) and other syntheses of social–ecological dynamics in recreational fisheries have identified one or more of these frontiers, albeit often with different emphasis or terminology (e.g. Arlinghaus et al., 2017; Arlinghaus, Cooke, & Potts, 2013; Hunt et al., 2013; Ward et al., 2016). Our fifth frontier, about comparing different dynamic models and integrating them with data, is perhaps an exception, as those ideas have not been broadly discussed elsewhere. The high-level overlap of our frontiers with major themes identified by previous syntheses is encouraging, though perhaps not surprising given that we defined the set of model characteristics for which we gathered data in part by referring to lists of key concepts from previous syntheses of recreational fisheries and social–ecological systems (Biggs et al., 2015; Post, 2013). Our key contribution is not in identifying or naming the five frontiers, but rather in conducting a systematic and quantitative review of social–ecological models and endeavouring to place the quantitative results within a reflective and prospective context. The literature on modelling social–ecological dynamics in recreational fisheries is diverse and somewhat fragmented; for instance, of the 49 papers that we reviewed 15 were published in fisheries journals, 11 in general ecological or environmental journals, 9 in economics journals and the remaining 12 in journals in aquaculture, evolution, computer science, or inter- and multi-disciplinary fields. By synthesizing this literature we hope to have helped identify promising new avenues for model development and encouraged some cross-pollination of ideas across related but sometimes isolated parts of the field.

Finding the right level of complexity at which to model social–ecological dynamics, given the motivations of a particular study, will remain an important challenge (Schlüter et al., 2012). We observed a trend in the models that we reviewed towards increasing complexity through time, and our discussion up to here seems to point towards even greater complexity by emphasizing processes that have received little attention or have been treated fairly simplistically in the models that we reviewed. Certainly, there are clear reasons to consider a richer set of processes and interactions in social–ecological models of recreational fisheries, and a wide range of important emerging questions that such models could help answer, such as how to combine open access and effort control fisheries, how to structure co-management regimes or how best to incorporate crowd-sourced data from anglers into fisheries management. Yet we do not think that a simple march towards ever greater complexity is the best path forward for recreational fisheries SES models, because increasing their complexity will sometimes decrease their tractability and heuristic value. Indeed, in some cases, the absence of a process from the dynamic models that we reviewed, even when that process is firmly established in conceptual models, may reflect unpublished judgements about its complexity relative to its value. Ultimately, the most important advances in modelling recreational fishery SES will not be those that add complexity for its own sake, but rather those that most enrich our understanding of the dynamics of these systems or of the ways that we can enhance their sustainability and resilience.

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DATA AVAILABILITY STATEMENT

The data that we extracted from the reviewed studies are available in .csv (supplementary file S1) and .pdf (supplementary file S2).

ORCID

Christopher T. Solomon https://orcid.org/0000-0002-2850-4257

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SUPPORTING INFORMATION

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

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