Received: 6 May 2023 | Revised: 11 November 2023 | Accepted: 18 November 2023
DOI: 10.1111/faf.12809

ORIGINAL ARTICLE

FISH and FISHERIES WILEY

Global synthesis of effects and feedbacks from artificial reefs on socioecological systems in recreational fisheries

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Abstract

Artificial reefs have been widely deployed with the intention of increasing fish habitat, enhancing recreational fishery opportunities and providing socio-economic benefits to surrounding communities. Substantial work has been done to understand the ecology of artificial reefs but the efficacy of artificial reefs as a management tool hinges on socioecological feedbacks that are not well understood. Socioecological feedbacks are difficult to discern because they depend on multiple and complex interactions between fish, fishers, managers and habitats. To better understand the net effects of artificial reefs on recreational fisheries, we conducted a literature review to catalogue effects and feedbacks of artificial reefs. Our global synthesis revealed that artificial reefs may result in a net negative effect on fish populations, at least in the short-term, as catch-driven effects bolstering socio-economic objectives occur more often or at greater intensities than positive biological effects. We have highlighted important effects of artificial reefs and feedbacks that need to be accounted for when considering their deployment in fishery management. There may be unintended consequences if biological benefits from habitat-to-fish and fish-to-fish feedbacks are outweighed by population losses due to greater socio-economic benefits from fish-to-fisher feedbacks. Taken in concert with their semi-permanent nature and apparent popularity with stakeholders, a view emerges of artificial reefs possibly functioning as a 'social-ecological trap'. This work emphasizes the need for robust assessments of the effects of artificial reefs, as well as more formal decision science approaches for implementing of these structures.

KEYWORDS
behavioural feedbacks, fishery management, habitat enhancement, social-ecological trap, socioecological fishery system, systematic literature review

1 | INTRODUCTION

Artificial reefs are semi-permanent structures (e.g. vessels and concrete modules) that are deployed on the seafloor to augment degraded habitats or add new habitat (Komyakova et al., 2019; Paxton, Newton, et al., 2020; Paxton, Shertzer, et al., 2020). These habitat additions are often part of government-managed artificial reef programmes intended to enhance recreational fishing opportunities (Brochier et al., 2021; NOAA, 2007). Artificial reefs are increasingly regarded as a management measure that can potentially enhance conservation and fishery sustainability (Komyakova et al., 2019; Lima, Zalmon, & Love, 2019; Lima, Zappes, et al., 2019; Puckeridge et al., 2021). This may be true if artificial reefs primarily increase biological productivity of reef fish populations. However, other research shows artificial reefs alter fisher behaviours in ways that may increase fishing effort and catchability, which would increase fishing mortality, ceteris paribus (Feary et al., 2011; Karnauskas et al., 2017). If the increased fishing mortality outpaces biologically driven population production, artificial reefs could cause population decline and potentially exacerbate stricter reef fish harvest regulations, which are especially unpopular (Arostegui et al., 2021). Interactions between fishers and managers may therefore be partially mediated by the net and interactive effects of artificial reefs on fish and fishers. The characteristics of artificial reefs as a habitat-based management action emphasize the critical importance of understanding their direct and indirect effects and feedbacks through ecological, socio-economic and governance systems.

Socioecological systems (SES) approaches recognize that ecological and social systems are intricately and dynamically connected (Berkes et al., 2000; Kittinger et al., 2013). In most recreational fisheries that are often characterized as coupled SESs (Arlinghaus et al., 2013; Fenichel et al., 2013; Hunt et al., 2013), social and ecological outcomes are dependent on states and behaviours of each actor—fish, fishers and managers (Walters & Martell, 2004; Ward et al., 2013). Fisher behaviours can drive short-term exploitation and impact fish abundance (Lewin et al., 2006), and catchable abundance in turn can affect future fisher behaviour, including site choice, species targeted and fishing effort (Camp et al., 2015; Cox & Walters, 2002; Ward et al., 2016). These feedbacks can be mediated by fish behaviours, such as aggregations and habitat use, which can influence how strongly changes in fishing effort affect catch (via catchability; Askey et al., 2006; Erisman et al., 2011; Klefoth et al., 2013; Matthias et al., 2014) and catch-related utility (Johnston et al., 2010; Ward et al., 2013). These linkages need to be considered to anticipate potential effects of management actions and avoid unintended outcomes (Ward et al., 2016).

Unintended consequences are not rare in recreational fisheries and can follow both restrictive and augmentative management actions (Pine et al., 2009). Restrictive recreational fishery management actions are usually regulatory, such as size, bag, seasonal or spatial closures (Abbott & Haynie, 2012; Ahrens et al., 2020; Gwinn et al., 2015; Pine et al., 2009). Unintended consequences of these actions can occur if the harvest restriction accidentally increases overall fishing mortality, for example restrictive length limits increasing dead discards and, in turn, increasing overall mortality (Coggins et al., 2007; Duffin, 2019). Augmentative fishery management strategies include stock enhancement, facilities improvement or habitat restoration and enhancement, and these strategies can lead to unintended consequences to ecological or social objectives (e.g. stocked fish negatively affecting wild fish; Baer & Brinker, 2010; Camp et al., 2017; Hühn et al., 2014; Lorenzen et al., 2012; van Poorten et al., 2011). Whereas most regulatory actions can be relatively quick to reverse, enhancement actions are difficult to reverse due to the logistics of removing fish or habitat, social expectations and the political environment (Degnbol et al., 2006; van Poorten et al., 2011). For example, artificial reef removal is logistically difficult and expensive if even possible (Sherman & Spieler, 2006; Techera & Chandler, 2015), and such removal or even ceasing additional deployments may be unpopular given stakeholder affinity and previous participation in artificial reef programmes (Becker et al., 2018; Lindberg, 1997; Vivier et al., 2021). Therefore, the logistic and social challenges of reversing artificial reef deployment increase the risks of unintended consequences since they cannot easily be undone.

Assessing artificial reefs in a SES framework is necessary to make good management decisions and develop more resilient governance systems. Artificial reefs can introduce at least local changes on fish behaviour and potentially abundances (Becker et al., 2018; Blount et al., 2021; Layman & Allgeier, 2020; Paxton et al., 2022) and influence fisher behaviour and fishing effort (Lima, Zalmon, & Love, 2019; Lima, Zappes, et al., 2019; Simard et al., 2016). Feedbacks between fish abundance and effort may be expected in artificial reef systems given the prevalence of these in recreational fishery systems (Arlinghaus et al., 2017; Camp et al., 2016; Carruthers et al., 2019; Matsumura et al., 2019; Ward et al., 2016). However, because fish-fisher feedbacks in artificial reef systems may trigger unintended consequences (e.g. increased fishing-related mortality and corresponding stricter harvest regulations), additional feedbacks between fishers and managers are also possible. Despite increasing warnings to consider feedbacks among fish, fishers and managers when making management decisions (Arlinghaus et al., 2022; Potts et al., 2020; Solomon et al., 2020), artificial reefs have rarely been reviewed in the SES context for fisheries. Therefore, this work synthesizes direct effects, indirect effects and potential feedbacks of artificial reefs on reef fish populations, habitat, fishers, managers and the overall SES. We also empirically compared the direct and indirect effects of artificial reefs vs. natural reefs to gain a relative understanding of the impacts of artificial reefs.

2 | METHODS

2.1 | Overview

We based our framework on Ward et al. (2016), which described several behaviour-driven, two-way feedbacks among the actors, fish, fishers and managers, and identified the most common ways in which the behaviour of one component impacted another in recreational fisheries. In this manuscript, we define 'manager' as someone responsible for overseeing the management and conservation of resources, including fish populations, fishers and their habitats (e.g. stock enhancement measures). We included an additional 'actor', habitat, as artificial reefs constitute a semi-permanent alteration of the habitat that can affect behaviours of fish and fishers. We first synthesized and described via a formal literature review and quantitative analysis the direct and indirect effects of artificial reefs upon the actors (fish, fisher, managers and habitat). We then described potential feedbacks among actors that artificial reefs might catalyse based on broader fishery SES literature. In this manuscript, we distinguish among a 'direct effect', an 'indirect effect' and 'feedback'. A 'direct' effect is the immediate impact of artificial reefs on one actor (e.g. enhancement of growth potential by improving foraging opportunities and efficiency at artificial reefs). An 'indirect' effect is the impact of artificial reefs on an actor mediated by the direct effect(s) of another actor (e.g. increased fishing effort around artificial reefs driven by fish aggregating around them). Feedbacks refer to a direct or indirect effect of one actor onto another resulting in a subsequent effect or 'feedback' on the initial actor. An example of a feedback is when the aggregation of fish around reefs leads to increases in catchability, which then alters fishing effort which further affects the fish population. The actors of a SES with artificial reefs, indirect and direct effects, and feedbacks are depicted in Figure 1.

2.2 | Artificial reef literature screening

We conducted a formal literature review to evaluate the effects of artificial reefs in marine/estuarine waters around the world. We first screened primary literature to define and describe direct and indirect effects of artificial reefs on each actor of the SES (Figure S1). We specifically examined biological and social effects that have been commonly highlighted as significant processes that impact fish: natural mortality, growth, recruitment, site fidelity and those that impact fishers and/or managers: 'catch-related' metrics (includes catchability, catch rate, and catch), fishing mortality, effort and utility (Bohnsack, 1989; Solomon et al., 2020). Given the objective of our work, we focused on fish species targeted by and managed for recreational fisheries. We conducted a structured search in the English language using Web of Science and Google Scholar for the period 1980–2021. This yielded 235 potentially relevant articles (Table S1, Figure S1). We first screened the titles and abstracts of each article for applicability to our research question.

We then conducted a full-text screening on 88 articles according to the inclusion and exclusion criteria listed in Table S1. The definitions of each metric are in Table 1. Assessing the effects of artificial reefs on SES was not straightforward because few researchers directly estimated how the implementation of artificial reefs affected local fish or fisher populations (but see Lindberg et al., 2006 for an exception). Instead, most studies compare metrics or rates observed on artificial reefs to those observed on non-artificial reefs, which can include either natural reefs or reference reefs that are not artificial. To draw inferences of the effects of artificial reefs on SES, we must assume the differences between artificial and non-artificial reefs reflect the effects of artificial reefs upon SES when they are implemented. For the 88 articles found relevant after the initial screening, we conducted another full-text screening to include only field-based studies that reported on the effects of artificial vs. non-artificial reefs of the eight metrics. We did not consider characteristics of artificial or non-artificial reef structures such as type, complexity, relief, depth and location, as we are only interested in the relative impacts between artificial and non-artificial reefs and other papers have studied these factors in their analyses (e.g. Paxton, Newton, et al., 2020; Paxton, Shertzer, et al., 2020). After the full-text screenings, we retained 30 articles for the data extraction and quantitative analysis.

For each of the metrics, we recorded the value (units described in Table 1) estimated from artificial and non-artificial reefs for each species in each study. When multiple groups were presented for a reef type (e.g. multiple reefs of the same material with metrics reported separately or multiple years at the same site), we calculated either the mean or the weighted mean if sample size was available. We then calculated the mean percent difference (MPD) between the values from artificial and non-artificial reefs for each

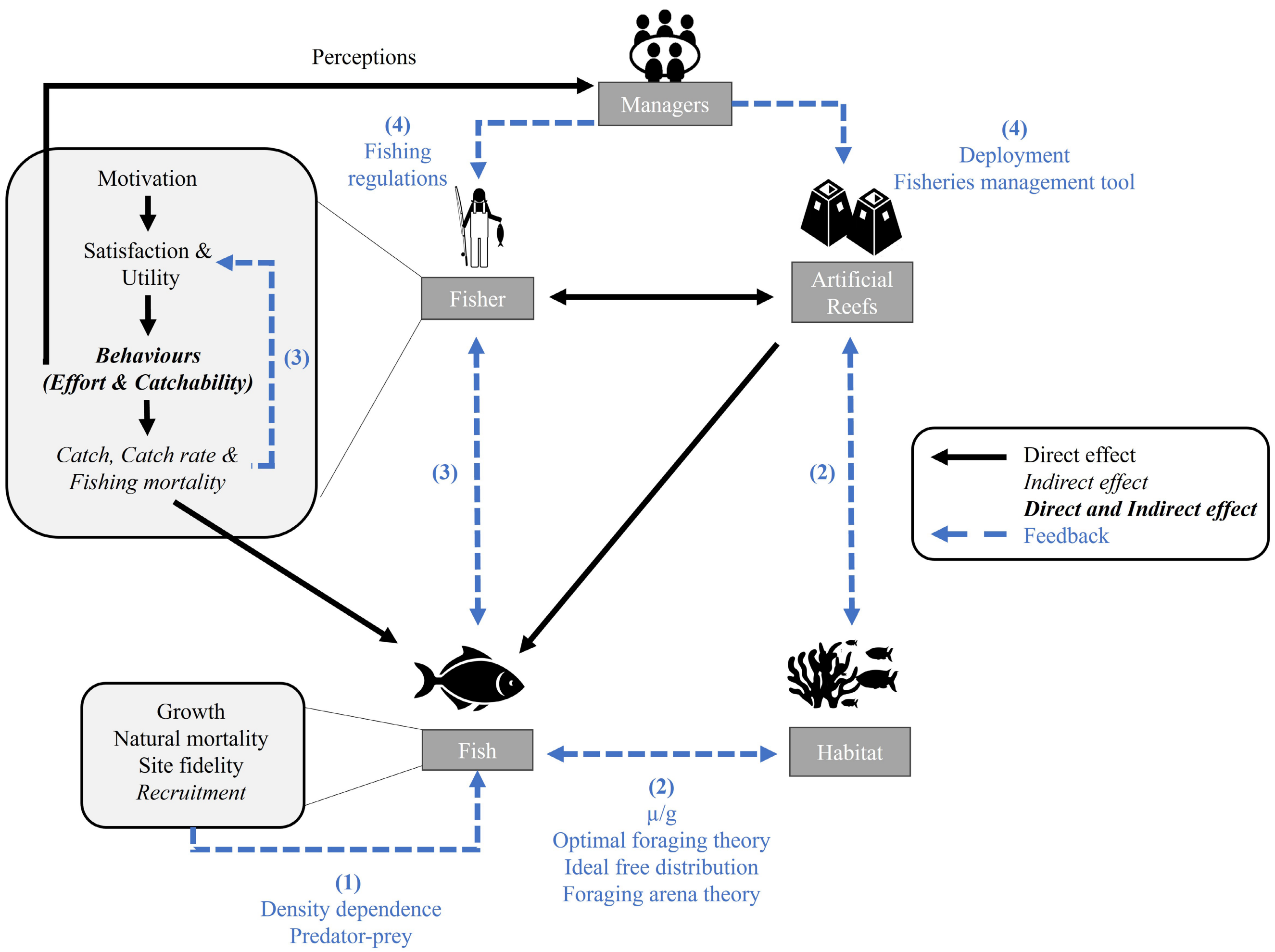

FIGURE 1 Summary figure of the components of a socioecological system with artificial reefs. The main components are fish, fisher, habitat and managers, of which are affected by the deployment of artificial reefs. We define 'managers' as someone responsible for overseeing the management and conservation of resources, including fish populations, fishers and their habitats. The direct effects (regular text), indirect effects (italicized text), and direct and indirect effects (italicized and bolded text) are shown with the black arrow. The feedbacks (blue text) are shown with the dotted blue arrow, which include (1) fish-to-fish, (2) habitat-to-fish, (3) fish-to-fisher and (4) habitat-to-fish-to-fishers-to-manager.

metric. The percent difference value was positive if the metric was greater on artificial reefs than non-artificial reefs and negative if the opposite. We reported the mean percent difference for each metric as the result.

2.3 | Broader literature screening

Using the information gathered from the literature in the first screening, we then synthesized common feedbacks and linkages describing the effects and relevance of artificial reefs to the components of the SES. To understand this information in broader context (i.e. beyond artificial reefs), we briefly summarized key studies describing recreational fishery SES and especially their particular feedbacks. Recreational fisheries are considerably diverse in their appearance and motivations (Arlinghaus et al., 2019; Nyboer et al., 2022), including purely leisure-based activity associated with wanting to spend time in nature, food-gathering that may have personal or cultural importance and may be associated with social motivations, competitive sport fishing which often has challenge motivations, and any combination thereof. This revealed four key feedbacks likely to occur in recreational fishery SES enhanced with artificial reefs: (i) fish to fish, (ii) habitat to fish, (iii) fish and fishers and (iv) habitat-to-fish-to-fisher-to-manager.

3 | RESULTS

3.1 | Direct and indirect effects of artificial reefs

The proportion of artificial reef publications from the United States and Australia are notable (Figure S2) as recreational reef fisheries in these countries tend to be harvest-oriented fisheries. These fisheries usually exert substantial harvest pressure and the management

TABLE 1 Definition and unit of each metric described in the literature review.

Metric	Definition	Units
Catch and catch rate	Includes catch, catchability and catch rate. Catch is the total quantity (in number or weight) caught by fishing operations. Catchability is the fraction of a fish stock which is caught by a defined unit of the fishing effort. Catch rate is defined as catch per unit of effort (CPUE), which is the quantity of fish caught (in number or weight) with one standard unit of fishing effort. CPUE is often an indirect/relative measure of abundance	Catch—weight, numbers; Catch rate—fish/set, fish/# hour, hook^{-1}/# min^{-1}, Catchability—per 100 m^2
Effort	The measure of fishing intensity or the amount of fishing gear of a specific type used on fishing grounds over a given unit of time	Hours, hours × # m^2
Fishing mortality[a]	The rate of death or removal of fish from a population due to fishing activities, whether from direct removals (fish which are caught and kept) or indirect removals (fish which are not kept but die from fishing activities)	
Growth	The mechanism in which fish increase their lengths and weights over the course of a lifetime	Mean total length and body weight, L_∞, k
Natural mortality[a]	The loss of fish from a population due to all causes other than fishing or other impacts from human activity. The natural mortality rate refers to the changes in numbers of fish over time.	
Recruitment	(i) Natural mortality and survival of larval fish (ii) Growth of young of the year (YOY) or juvenile fish into recruit size (iii) The number or density of YOY or juvenile fish found in the habitat	Juvenile density (100 m^2), young of the year density (100 m^2), recruitment density (#/m^2)
Site fidelity	The return of an individual to a location where it previously resided after having left it for some defined period	Residency index (% of cumulative days present at site, percentage of detections in specific site), presence index (time present at site divided by total monitoring period)
Utility	The measure of participation rates or usage of the fishing site	Harvest cost in dollars, travel time in minutes, VPUE (Euro per standard unit of effort, Indian Rupee per standard unit of effort), mean visitation rate

[a]Not in the quantitative analysis of literature review.

TABLE 2 Five-summary statistics including mean and sample size for each direct effect.

Direct effect	*n*	Min	First Qu.	Median	Mean	Third Qu.	Max
Catch-related	51	−1.5238	−0.3193	0.4542	0.4334	1.1501	1.9825
Effort	9	−1.2046	−0.8703	1.5459	0.7522	1.9601	1.9765
Utility	6	0.0872	0.1329	0.4928	0.5872	0.7529	1.6578
Growth	20	−0.2742	−0.0946	0.0018	0.0127	0.0299	0.7895
Recruitment	20	−1.8401	−1.3155	−0.5300	−0.2832	0.7614	1.9226
Site fidelity	8	−0.5306	−0.1088	0.2401	0.3830	0.8436	1.4023

Note: Natural and fishing mortality were not included as we did not find any papers that reported on these metrics.

of which is increasingly contentious (Becker et al., 2018; Ihde et al., 2011; Scyphers et al., 2021). The goal of the quantitative analysis was to provide some measure about the effects of artificial reefs by comparing metrics between artificial and non-artificial reefs. Our quantitative analysis results show that catch-related metrics (catch, catch rate and catchability), effort, utility and site fidelity are higher at artificial reefs than non-artificial reefs, while growth was relatively the same between artificial and non-artificia reefs and recruitment was higher at non-artificial reefs (Table 2, Figure 2). This means that artificial reefs may be attracting fish (via site fidelity) and increasing socio-economic effects without enhancing biological productivity, that is playing purely an attraction role.

All the references for the potential effects of artificial on metrics are available at Chong (2023). We considered the direct effects to be growth, natural mortality and site fidelity, whereas we considered the indirect effects to be recruitment, catch, catch rate, fishing mortality and effort (Table 3). Lastly, we considered catchability and utility as a direct and indirect effect (Table 3).

3.1.1 | Direct effects

Our literature review suggested the identification and directionality of effects were inconsistent for most direct effects. Growth was

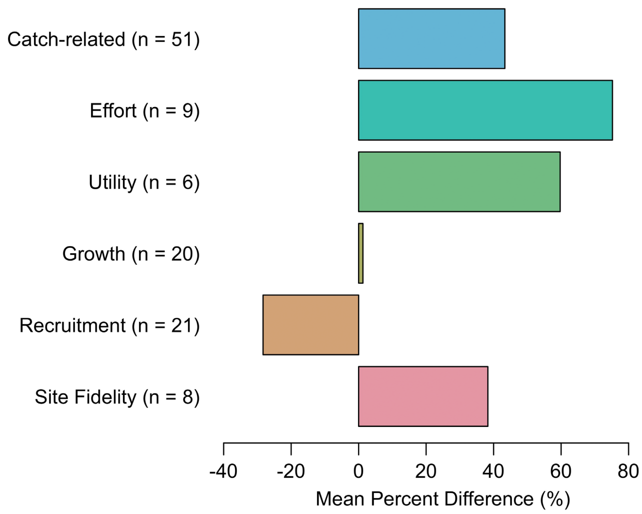

FIGURE 2 The mean percent difference of the values of catch, effort, utility, growth, recruitment and site fidelity calculated in artificial vs. non-artificial reefs. The mean percent difference value was positive if the metric across all studies was higher on artificial reefs than non-artificial reefs and negative if the metric was higher on non-artificial reefs. The sample size of each metric is also reported.

studied in 17 out of 88 studies, inferred from body size and from direct incremental measurements (e.g. tagging). It was similar between non-artificial and artificial reefs (MPD = 0.0127; Table 2). We found no quantitative studies that compared natural mortality between artificial and non-artificial reefs. However, we found 10 out of 88 studies mentioning that the dynamic between predators and prey is what causes changes in natural mortality and survival of certain species, suggesting that the effects of artificial reefs on natural mortality do vary by species and their abundance. We found 14 out of 88 studies that discussed how artificial reefs affect site fidelity and movement of fish, and the quantitative analysis suggests that site fidelity was higher on artificial reefs than non-artificial reefs (MPD = 0.3830; Table 2), implying that fish have some degree of attraction to artificial reefs. These mixed results suggest effects of reefs are variable and likely mediated by location and species studied.

3.1.2 | Indirect effects

The indirect effects were generally different between artificial and non-artificial reefs. While many studies (29 out of 88) discussed the potential for artificial reefs to affect recruitment, in the quantitative analysis, we found that recruitment at artificial reefs was on average lower than non-artificial reefs (MPD = −0.2832; Table 2). Conversely, effort (measured in terms of visitation or usage) was greater at artificial reefs compared to non-artificial ones ($n = 5$, MPD = 0.7522; Table 2). Both catch and catch rate were also reported higher at artificial reefs than non-artificial ones (MPD = 0.4334; Table 2). Although several studies have found 'high' fishing mortality at artificial reefs (Addis et al., 2008; Streich, Ajemian, Wetz, Shively, et al., 2017; Streich, Ajemian, Wetz, Williams, et al., 2017; Williams-Grove & Szedlmayer, 2016) and other studies have inferred differential fishing mortality between published and unpublished reefs based on observed catch rates (Addis et al., 2008; Jaxion-Harm & Szedlmayer, 2015; Syc & Szedlmayer, 2012), we did not find any studies that compared directly estimated fishing mortality between artificial and non-artificial reefs. This is likely owing to fishing mortality typically being estimated at regional and population scales rather than site-specific. This absence of direct comparisons makes it is difficult to confidently conclude that artificial reefs increase fishing mortality, however indications that this is the case remain. A study of Gulf of Mexico red snapper found a fishing mortality rate at artificial reefs of 1.04 (Addis et al., 2016), which is an order of magnitude greater than the regional exploitation rate (across all fleets) for the Gulf of Mexico red snapper stock (0.15 as of 2016; SEDAR, 2018). Additionally, the evidence that other processes such as catchability (Karnauskas et al., 2017) and effort (Simard et al., 2016) can increase on artificial reefs does suggest that this is likely the case.

3.1.3 | Indirect and direct effects

We found seven out of 88 papers that discussed the importance of catchability on artificial reefs; however, we only found one paper in our literature search that actually calculated catchability at artificial reefs. Harris et al. (2019) found similar mean catchability via spearfishing between artificial and natural (non-artificial) reefs of red lionfish. Although there are no other studies that explicitly compared catchability between reefs, the Karnauskas et al. (2017) study supports the idea that artificial reefs have higher catchability as they found that artificial reefs had increased catch rates 20-fold compared to non-artificial reefs. This study, combined with anecdotal accounts from fishers, has led other studies to consider increased catchability associated with artificial reefs (Chagaris et al., 2019; Garner et al., 2019; White et al., 2022). Seven out of 88 studies discussed various types of utilities gained from artificial reefs, and utility is higher on artificial reefs than non-artificial ones. Recreational functions and benefits for artificial reefs have been recognized in these studies, but there are no studies that have measured the direct utility or benefits of catch or non-catch related activities due to artificial vs. non-artificial reefs.

3.2 | Feedbacks

We describe four types of behavioural feedbacks among fish, habitat, fishers and managers that are influenced by artificial reefs and determine outcomes of SESs in recreational fisheries: (i) fish-to-fish, (ii) habitat-to-fish, (iii) fish-to-fishers and (iv) habitat-to-fish-to-fishers-to-managers (Figure 1). It may be difficult to parse out the fish-to-fish and habitat-to-fish feedbacks as the most prominent way habitat affect fish is by mediating fish-to-fish relationships (i.e. density dependence and predatory prey dynamics). However, these

TABLE 3 List of metrics and type of effect (direct or indirect).

Metric	Direct or indirect effect	Potential impacts of artificial reefs	Artificial reef literature citation
Growth	Direct	Improve foraging opportunities and efficiency, and thus enhance growth	Champion et al. (2015), Hixon and Beets (1993), Peterson et al. (2003)
		Slower growth compared to non-artificial reefs	Dahl et al. (2019)
		Greater growth (potential)	Jefferson et al. (2019), Powers et al. (2003), Streich, Ajemian, Wetz, Shively, et al. (2017), Streich, Ajemian, Wetz, Williams, et al. (2017), Szedlmayer and Shipp (1994), Wells et al. (2008)
Natural mortality	Direct	Attract more predators and increase natural mortality of prey species	Bohnsack et al. (1994), Folpp et al. (2020), Gorham and Alevizon (1989), Leitão et al. (2008)
		Enhance refuge from predation, decrease natural mortality and enhance survivorship	Paxton, Newton, et al. (2020), Paxton, Shertzer, et al. (2020)
Site fidelity	Direct	Fish with high site fidelity and limited movement will benefit from artificial reefs	Keller, Smith, et al. (2017), Keller, Steffe, et al. (2017)
		Retain highly migratory species closer to fishing ports	Bohnsack (1989)
		High degree of site fidelity at artificial reefs	Schroepfer and Szedlmayer (2006)
		Quality habitat and serve as attractants	Özgül et al. (2019), Strelcheck et al. (2007), Szedlmayer and Schroepfer (2005), Topping and Szedlmayer (2011), Zhang et al. (2015)
Recruitment	Indirect	Increased recruitment due to large number or higher densities at artificial reefs	Komyakova and Swearer (2019), Love et al. (1994), Love et al. (2000), Neira (2005), Pondella et al. (2002), Simon et al. (2011), Syc and Szedlmayer (2012)
		Increased recruitment due to higher growth rates of young of the year (YOY) and juveniles at artificial reefs	Beets and Hixon (1994), Love et al. (2007)
		Lower recruitment at artificial reefs due to increased mortality of newly settled juveniles	Bohnsack et al. (1994), Leitão et al. (2008), Mudrak and Szedlmayer (2012), West et al. (1994)
Effort	Indirect	Alter spatial distribution and magnitude of fishing effort by changing suite of fishing opportunities and costs associated with travel to fishing sites	Keller et al. (2016), Simard et al. (2016)
		Increased effort as a result of increased visitation rates or recreational usage at artificial reefs	Keller et al. (2016), Keller, Smith, et al. (2017), Keller, Steffe, et al. (2017), Masuda et al. (2010), McGlennon and Branden (1994), Simard et al. (2016)
Catch and catch rate	Indirect	Give indication of how much value is gained from fishing at artificial reefs and some estimate of fish abundance and production	Grossman et al. (1997), Roa-Ureta et al. (2019)
		Reported higher at artificial reefs than non-artificial reefs	Azhdari et al. (2012), Holder et al. (2020), Karnauskas et al. (2017), Kasim et al. (2013), Matthews (1985), Santos and Monteiro (1997), Santos and Monteiro (1998), Whitmarsh et al. (2008), Zhang et al. (2021)
Fishing mortality	Indirect	May suffer high rates of fishing mortality if they are easily targeted by fishers, especially if densely aggregated	Granneman and Steele (2014), Matthews (1985), Solonsky (1985)
Catchability	Direct and indirect	Easier to find and catch fish by reducing search time and placing artificial reefs at known locations	Arreguín-Sánchez (1996), Bohnsack (1989)
		Concentrate both fish and fishers, raising efficiency of capture	Whitmarsh et al. (2008)
		Similar mean catchability between artificial and non-artificial reefs	Harris et al. (2019)
		Higher catchability (increased catch rates)	Chagaris et al. (2019), Garner et al. (2019), Karnauskas et al. (2017), White et al. (2022)
Utility	Direct and indirect	Presence of artificial reefs increase utility, which may be perception of potential stock and/or diversity enhancement and future resource availability	McGlennon and Branden (1994), Milon (1988), Schuett et al. (2016)
		Perception of high catch rates at artificial reefs	Milon (1988)
		Trip associated characteristics (distance travelled, number of trips, fuel cost, trip cost and purpose) influenced by additional artificial reefs	Milon (1988), Murray and Betz (1994), Schuett et al. (2016)

Note: Each metric has a description of the potential impacts of artificial reefs on the metric and citations.

fish-to-fish feedbacks occur when artificial reefs are introduced into the system and habitat-to-fish feedbacks occur in relation to other habitat bottoms.

3.2.1 | Fish-to-fish

Implementing artificial reefs can increase fish density via direct and indirect effects that alter abundance or how they aggregate around reefs. Increased density can affect density dependent processes such as competition and predation (Ahrens et al., 2012; Hixon & Carr, 1997; Rose et al., 2001; Walters & Juanes, 1993). These processes should change vital demographic rates of growth, natural mortality, recruitment and site fidelity that ultimately loop back to affect the fish abundances within and among species (e.g. via predator–prey dynamics) at artificial reefs.

Artificial reefs may affect survival of fish at any life stage; however, the most noticeable population effects can occur if they stimulate feedbacks by mediating density dependent growth and mortality during the recruitment cycle (Ahrens et al., 2012; Lorenzen & Camp, 2019; Lorenzen & Enberg, 2002; Walters & Juanes, 1993). Artificial reefs that increase density of juveniles would be expected to increase inter- and intra-specific competition, which consequently would lead to slower growth and/or lower survival (Granneman & Steele, 2014; Jenkins et al., 1999; Lorenzen & Enberg, 2002; Walters & Juanes, 1993). Juvenile fish experiencing slower growth would spend more time at smaller, more vulnerable sizes (e.g. Dahl et al., 2019; Fowler & Booth, 2012; Glenn et al., 2017), which could lead to lower recruitment and decrease their potential to contribute to the population (Cowan et al., 2011). Therefore, artificial reefs that increase juveniles fish density may lead to negative population-level consequences if the reefs do not alter other attributes, such as forage and refuge (Fowler & Booth, 2012; Glenn et al., 2017; Marshall & Frank, 1994; Tupper & Boutilier, 1995).

Artificial reefs are thought to aggregate fish either because they attract prey and afford the fish greater food availability (Tassetti et al., 2020) or because they provide fish increased refuge from predation (Bulleri & Chapman, 2010; Hixon & Menge, 1991). Survival and recruitment can be enhanced from using artificial reefs as refuge from predation (Alevizon & Gorham, 1989). However, high densities at artificial structures may also disproportionately attract predators, elevating predation risk and heightening the effect of competitive interactions and ultimately increasing predation mortality (e.g. Ricker stock-recruitment relationship; Ricker, 1954). Studies have shown that the presence of predators affected the size distribution within populations at artificial reefs (Grossman et al., 1997; Hixon, 1991; Hixon & Beets, 1993). This can result in stronger negative feedbacks between prey density and to prey species energetics, lower fitness, residence times, other vital demographic rates (e.g. growth) and local abundance (Gallaway et al., 2009; Lindberg et al., 2006). Thus, sheltering and foraging dynamics between predators and prey and their densities on artificial reefs will ultimately drive how strong the demographics rates will be.

3.2.2 | Habitat-to-fish

The most prominent way habitat affect fish populations is by mediating fish to fish (density dependence, predator prey) relationships. Theoretical frameworks, such as μ/g (i.e. Gilliam's rule; Werner & Gilliam, 1984), optimal foraging theory (Perry & Pianka, 1997; Pyke, 1984), ideal free distribution (Fretwell, 1969; Giske et al., 1998) and foraging arena theory (Ahrens et al., 2012; Walters & Juanes, 1993), make assumptions about space- and habitat-use patterns and where fish feed based on their density, availability of prey, avoidance of predators and competition of resources (Biesinger et al., 2011). These theories are not mutually exclusive, and all would suggest habitat alterations could drive fish behavioural changes with possible population-level consequences.

Individuals within populations may show variability in partitioning resources, evaluating risk–reward trade-offs and moving across the seascape, which can vary among individuals according to size and ontogeny (Werner & Gilliam, 1984), but may also be driven by attraction towards artificial reefs. Opportunistic species, transitory fish and large reef associated predators are likely to be attracted to artificial reefs (Bohnsack, 1989; Leitão et al., 2008; Paxton, Newton, et al., 2020; Paxton, Shertzer, et al., 2020). This may initially benefit predators as food resources are guaranteed at artificial reefs. However, if predators deplete their prey species around the reef, optimal foraging theory suggests predators will shift to forage farther distances from reefs or spend more time hunting prey (Anderson, 1984; Brandt & Jackson, 2013; Dahl et al., 2019; Leitão et al., 2009; Tupper & Juanes, 2017). These behavioural changes could result in the fish being predated on by larger predators or having smaller per-capita rates (e.g. growth) as they would expend energy on searching instead of feeding.

Aggregation of larger predators to artificial reefs would also affect smaller fish. Juveniles or smaller species may initially be attracted to artificial structures because of greater forage (Brickhill et al., 2005; Stephens et al., 1994). However, if aggregations of small fish attract larger predators, they would have to disperse away from artificial reefs to avoid predation reefs (e.g. Arney et al., 2017; Froehlich & Kline, 2015; Lowe et al., 2009). Thus, artificial reefs likely present small fish with a trade-off between growth potential and predation risk outside and inside the structures (Ahrens et al., 2012; Paxton, Newton, et al., 2020; Paxton, Shertzer, et al., 2020), following Gilliam's rule (i.e. μ/g). The equilibria densities at reefs should be mediated by the quality of the surrounding habitat if small fish act according to ideal free distribution (Morris, 1987). This may explain why at least some studies have found that small fish settle and recruit on artificial reefs only immediately after their deployment and before they are commonly predated on by larger predators (Folpp et al., 2020; Leitão et al., 2009; Lowry et al., 2014).

It is difficult to intuit how artificial reefs will ultimately affect fish populations because of the way predators and prey are mediated by habitat. The shape, vertical relief, void spaces and unit arrangement of artificial reefs can influence fishes' association with the structure and the surrounding habitat, which is discussed in

Blount et al. (2021). What we may infer from reviewing from the literature is that artificial reefs may have stronger effects on benefit (i.e. forage) or risk (i.e. predation) when they are implemented in regions with little natural habitat compared to when they are placed in areas with richer alternative habitats. Artificial reefs also can be thought of as spot disturbance patches within a seascape that host foraging arenas where reef fish interact (Paxton et al., 2022; Simon et al., 2011), impacting reef fishes at levels of the community, population and individual. These structures can alter the success of certain reef species and change the species assemblage as they bring various predators and prey in proximity with each other depending on where artificial reefs are placed in proximity to natural foraging areas and availability of resources. This predator and prey risk vs. reward field is dynamic over the range of populations, and artificial reefs impact this field; in absence of fishing, it is not clear what the net benefit is.

3.2.3 | Fish-to-fisher

Predator–prey feedbacks from reefs can also extend to fish and fishers, as fishers are expected to dynamically increase effort in response to greater availability of fish and thus catch potential (Camp et al., 2016; Post et al., 2008). In recreational fisheries, fishers make decisions about how much and where to fish depending on expected utility of catch (size, catch rate, harvest) and non-catch (facilities, travel distance) attributes (Hunt, 2005; Hunt et al., 2019). Expected utility can also come from the satisfaction received from past fishing trips and how management regulations or actions affect future catch (Hunt, 2005; Lee et al., 2017). Changes in utility or satisfaction expected by fishers result in effort shifts by fishers searching for alternative fishing sites that may offer greater utilities (Arlinghaus et al., 2017; Birdsong et al., 2021; Matsumura et al., 2019; Post et al., 2008). Therefore, changes to fish populations (e.g. fish aggregations) and enhancement actions, such as artificial reefs, could affect fishing decisions, which in turn further affect fish populations. Artificial reefs will mediate fish-to-fisher feedbacks by altering fish populations (i.e. fish abundance and density), catchability or the expectation of catch if fishers think artificial reefs will support higher catches.

Although this has yet to be directly examined, it is possible that hyperstability could occur in recreational fisheries with artificial reefs. Hyperstability is the illusion that there are plenty of fish that could happen if catch rates remain high or increase as the actual fish population abundance declines and/or slowly recover, especially if catchability is high and fishers preferentially target a specific site (Myers et al., 1997; Sadovy de Mitcheson & Erisman, 2012). Recreational fisheries that are characterized by aggregations of fish at specific habitats and persistent targeting of spawning aggregations often face hyperstability (Erisman et al., 2011; Mrnak et al., 2018; Sadovy de Mitcheson et al., 2008), and it is possible with artificial reefs. Artificial reefs may serve as easy opportunities for fishers to harvest large number of fish quickly with little effort (i.e. increase in catchability) if fish densities are high at these reefs and they remain popular fishing hotspots, concentrating both fish and fishers at these structures (Ambrose & Swarbrick, 1989; Bohnsack & Sutherland, 1985). Artificial reefs may then cause hyperstability and mask overfishing, especially if they do not provide enough biological productivity to offset the amount of fishing (Grossman et al., 1997). Severe overfishing can lead to decreased population levels as biological processes (e.g. recruitment and growth) cannot compensate at high levels of fishing levels (Sadovy, 2001), and no management actions are taken until both the fishery and population collapse (Brown et al., 2012; Post et al., 2002). We posit that this may be the case with artificial reefs, especially in recreational fisheries that are close or at overfishing limits.

3.2.4 | Habitat-to-fish-to-fisher-to-manager

The feedbacks between habitat, fish and fishers interact with management decisions, which could either benefit fisheries or lead to unintended consequences. Artificial reefs appear popular as a management option because they can be deployed without additional restrictive actions, are perceived to benefit fish populations and seem to translate to greater catches and associated satisfaction (Leitão et al., 2008; Polovina & Sakai, 1989). Deployments of artificial reefs have also grown considerably because of intense public support for increased fishing opportunities and economic growth (Lindberg, 1997; Strelcheck et al., 2005; Sutton & Bushnell, 2007; Vivier et al., 2021). If artificial reefs do mediate habitat-to-fish and fish-to-fisher feedbacks such that fish populations proliferate, fishing regulations should be relaxed, leading to high satisfaction of fishing experiences and artificial reefs. This should motivate fishers and managers to demand for more artificial reefs, which would induce a positive reinforcing feedback and meet both conservation and social objectives. However, there would be unintended consequences if biological benefits from habitat-to-fish feedbacks are outweighed by population losses due to greater catchability and effort from fish-to-fisher feedbacks.

Greater catchability and effort would initially make artificial reefs appear to be successful as recreational usage at these reef increase (Keller et al., 2016). There may be short-term increases in recreational benefits due to increases in artificial reefs, catch rates and fisher satisfaction. However, this apparent success could mask long-term negative effects. Under this scenario, artificial reefs may seem to provide socioecological benefits of increased high catch and high abundance, but the initial high catch would be due to hyperstability. As the fish population becomes more depleted and hyperstability persists, fishery management will eventually have to take actions to restrict harvest, which would be especially unpopular because catch rates remain high, and fishers may not believe fish populations have declined (e.g. Gulf of Mexico red snapper fishery; Scyphers et al., 2021). Fishers may also demand for more reefs, which would further compound the problem by increasing catchability and/or effort. If managers resist deploying more artificial reefs, they will face pushback and lose trust from fishers and stakeholders (e.g. Quintana & Basurto, 2021). More restrictions would likely have negative socio-economic consequences, such as reduced fishing opportunities, lower quality fishing experiences and negative economic impacts of communities and businesses that support recreational fishing industries (Arostegui et al., 2021; Post et al., 2003). This situation would be considered a social-ecological trap.

A social-ecological trap can occur when feedbacks between social and ecological systems lead towards an undesirable state that may be difficult to reverse (Cinner, 2011). The feedbacks between social and ecological processes and dynamics may amplify the initial conditions causing the problems (Kittinger et al., 2013). Small-scale fisheries in the Western Indian Ocean highlight an example of a social-ecological trap (Cinner et al., 2011; Kittinger et al., 2013); Fishers in poverty were more likely to use destructive fishing gear that destroys habitat and target vulnerable (e.g. juveniles) and functionally important fishes. These practices compete with other gear types, leading to lower catch and profits and increased vulnerability of fishers. Intensified fishing effort in combination with weak governmental institutions and resource declines make fishers poorer, reinforcing continued use of destructive gear with negative ecological impacts. As artificial reefs are semi-permanent, fisheries are essentially trapped with artificial reefs once they are deployed, becoming too challenging to abandon. Managers will be left with no choice but to implement additional harvest restrictions to offset overfishing. Restricting artificial reef deployments are also likely necessary to avoid further depletion of the fish population; otherwise, more artificial reefs may offset even more unpopular harvest restrictions like shorter seasons. If only the short-term costs and benefits of artificial reefs are examined, fishers and managers are likely to advocate for more deployments and push the fishery further into this social-ecological trap. Otherwise, managers would need to acknowledge that artificial reefs may be problematic and suffer additional loss of trust from fishers.

4 | DISCUSSION

Artificial reefs across the world may result in a net negative effect on recreational fisheries as socio-economic effects (i.e. catch, catch rate, catchability, effort and possibly fishing mortality) outweigh the biological effects (i.e. growth, survival and recruitment). For reef fish to benefit from artificial reefs, the population will need the combined effects of reduced natural mortality, increased growth and recruitment, and increased opportunity for new fish to establish residency in the system (Gorham & Alevizon, 1989). Our literature review suggests that these structures may predominantly act as an attractor. Previous studies testing hypotheses regarding attraction vs. production mechanisms have also implied that most of the artificial reefs worldwide have an attraction/aggregation role (Lima, Zalmon, & Love, 2019; Lima, Zappes, et al., 2019; Vivier et al., 2021).

While it has not been studied yet, there are reasons to suggest that artificial reefs may already be functioning as a social-ecological trap. Initial, short-term outcomes are typically positive for most actors; artificial reef appears to increase fish populations, enhance socio-economic effects and appeal to managers as a fishery management tool. However, in the long-term, each of these apparent benefits may turn into costs or losses. Their semi-permanent nature, popularity and the perception that artificial reefs are beneficial for both fish and fishers create this social-ecological trap. Although there are no artificial reef studies that explicitly use the term 'social-ecological trap', there are a few studies that alluded to this trap (e.g. Brochier et al., 2021; Komyakova et al., 2021; Sutton & Bushnell, 2007; Vivier et al., 2021; Whitmarsh et al., 2008). Despite the lack of evidence and research of the success of artificial reefs as a fishery production enhancement tool (Becker et al., 2018), there is still a push for the deployment of artificial reefs around the world. Under the assumption that structured habitat is limiting, the popularity of artificial reef programmes is increasing worldwide (Sun et al., 2017). The lack of coordination between fishery governance and deployments of artificial reef is a critical social factor that is likely contributing to the social-ecological trap. The perceived value of artificial reefs may be driving stakeholders (e.g. fishers, sportfishing clubs, tourist industry and government agencies) and managers to overlook risks of its unexpected decline and the associated negative consequences. There has not been a comprehensive assessment that assesses governance structures of fisheries with artificial and natural reefs, which may help determine if artificial reefs in many fisheries are becoming social-ecological traps.

With the growing deployment of artificial reefs in fisheries, it is necessary to adopt a more cautious, evidence-based approach for their implementation that is guided by a best-practice management framework. The impact of artificial structures on the population dynamics of fish species and fisher behaviour is still a key uncertainty for fishery management across the world. As the biological and socio-economic benefits of widespread artificial reef deployments are largely untested, their use in fishery management lacks predictability in a management scenario, making managers hesitant to use them as a management alternative (Becker et al., 2018; Bortone et al., 2011). In some fisheries, the broader public or managers are sceptical of their deployment as they are aware of the unintended consequences (e.g. aggregation of fish and stock depletion) of artificial reefs (e.g. Brochier et al., 2021; McAfee et al., 2021). While orientation (e.g. optimal shapes, vertical relief, void spaces and arrangements) and types of artificial reefs have been reviewed for best-practice recommendations (e.g. Blount et al., 2021; Lemoine et al., 2019), the spatial factors such as scale and size of artificial reef deployments (e.g. piles vs. vessels) and proximity settings (e.g. proximity to large urban centres vs. rural) are still largely ignored during the planning and deployment processes. Thus, there is a need for a conceptual framework to collect evidence for the effects of artificial reefs on marine systems and create deployment strategies. A formal framework will help create a step-by-step strategic plan for placing artificial reefs, incorporate important SES concepts and feedbacks, and support best-practice principles for artificial reefs, recreational fishery outcomes and conservation goals.

Operationalizing a formal framework to guide potential artificial reef deployment will be context dependent given the diversity of fishery governance approaches (Spijkers et al., 2023) and capacity to implement model-based advice (Goethel et al., 2023). However, at minimum we recommend fishery management branches to be formally involved in decisions to implement artificial reefs intended or likely to be used by fishers. In systems with greater capacity and/or formal fishery management systems, this may resemble developing custom SES frameworks to consult fishery managers in developing reef objectives, siting and spatial considerations and monitoring programmes (e.g. Becker et al., 2017), ideally using modelling tools to predict likely outcomes. In systems with either less capacity for modelling or more decentralized fishery governance, existing frameworks may still be adapted (Paxton et al., 2022), such as marine spatial planning (Douvere & Ehler, 2011) and more broadly cooperative management like co-management (Brochier et al., 2021; Sen & Raakjaer Nielsen, 1996). We also recommend establishing the role of artificial reef managers in fishery systems. In this manuscript, we described a manager as one who regulates fisheries and their habitats, which implies an overlap of regulating fisheries and supporting deployment of artificial reefs. However, there are typically two distinct roles for a fishery manager and an artificial reef manager. Although this distinction is rarely observed in the literature, it is important to assign these roles separately as they address different aspects of conservation and sustainability; a fishery manager focuses on regulating and managing fish populations and fishers while an artificial reef manager plans and designs the deployment of artificial structures. Lastly, we recommend collecting fine-scale fishery data to estimate fishing mortality and natural mortality at artificial reefs and the surrounding habitat. These frameworks at their simplest should aim to only implement reefs likely to eventually increase harvest rates (beyond any increase in production from enhanced survival or recruitment) in fisheries where increased harvest is desired and expected to be sustainable. The use of these frameworks will lead to collaborative efforts in developing actionable strategies, such as integrated management or habitat enhancement plans, adopting an ecosystem-based approach, creating monitoring plans or coordinating participation with local communities (Gurney et al., 2019; Kittinger et al., 2013; Leenhardt et al., 2015).

Our synthesis reveals that artificial reefs may provide higher fisheries and/or socio-economic benefits compared to natural reefs but may not provide similar biological benefits (i.e. fish production). We have summarized important direct and indirect effects of artificial reefs on important biological and social metrics that influence the actors and feedbacks. Key biological and socio-economic effects of artificial reefs (e.g. degree to which attraction of fish and fishers occur) will need to be considered into systems-level assessments or models for the future (e.g. stock assessments and management strategy evaluations). By acknowledging feedbacks and linkages that lead to certain outcomes such as social-ecological traps, actionable strategies can be developed to work towards making artificial reefs a sustainable fishery management tool. Our study also calls for a comprehensive system-level evaluation of artificial and natural reefs that accounts for SES feedbacks between habitat, fish, fishers and managers, which is needed to anticipate unintended consequences and predict realistic outcomes resulting from widespread deployment.

AUTHOR CONTRIBUTIONS

LC was involved in conceptualization, methodology, investigation, analysis, visualization, writing—original draft, and reviewing and editing. ZAS was involved in visualization, writing—reviewing and editing. KL was involved in methodology, and writing—reviewing and editing. RNMA was involved in writing—reviewing and editing. EVC was involved in supervision, conceptualization, methodology, and writing—reviewing and editing.

ACKNOWLEDGEMENTS

We thank members of the Camp Lab, the two anonymous reviewers, and the editor for comments and feedback that significantly improve the manuscript.

DATA AVAILABILITY STATEMENT

Data that support our research findings are available at https://doi.org/10.6084/m9.figshare.22080719.

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How to cite this article: Chong, L., Siders, Z. A., Lorenzen, K., Ahrens, R. N. M., & Camp, E. V. (2024). Global synthesis of effects and feedbacks from artificial reefs on socioecological systems in recreational fisheries. *Fish and Fisheries*, *25*, 303–319. https://doi.org/10.1111/faf.12809