**Title**: Supporting Ecosystem-Based Fisheries Management in meeting multiple objectives for sustainable use of coral reef ecosystems

**Running title**: Fishing policy scenario explorations in Hawai'i

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**Abstract**

Ecosystem-Based Fisheries Management is a holistic management approach that integrates the dynamics of an entire ecosystem, including societal dimensions. However, this approach seldom lives up to its promise because economic and social objectives are rarely specified. To fill this gap, we explored how an ecosystem model could better integrate economic and social objectives, using the coral reef ecosystem around Hawai`i as a case study. After meeting with stakeholders and conducting a literature review of policy/strategy documents, we identified societal and ecological objectives and associated performance indicators for which data existed. We developed a social-ecological system (SES) conceptual framework to illustrate the relationships between ecological and social state components. This framework was the foundation for the development of the final SES model which we simulated using an Ecopath with Ecosim model. We simulated four gear/species restrictions for the reef-based fishery, two fishing scenarios associated with the opening of hypothetical no-take Marine Protected Areas for the deepwater-based fishery, and a Constant Effort (No Action) scenario. Despite limitations in the model, our approach shows that when social and economic objectives and social-ecological relationships are defined, we can visualize and quantify the trade-offs among the identified societal objectives to support managers in choosing among alternative interventions.

## Introduction

In the last decades, many national and international organizations have moved away from single-species management to embrace Ecosystem-Based Fisheries Management (EBFM), an approach that explicitly integrates political, governance, social, and economic considerations (Link and Browman, 2017). For example, the U.S. NOAA Fisheries' vision and policy statements promote moving towards EBFM with regional implementation programs (Townsend *et al.*, 2019). The agency outlines six guiding principles in its EBFM roadmap: implement ecosystem-level planning, advance understanding of ecosystem processes, prioritize vulnerabilities and risks to ecosystems and their components, explore and address trade-offs within an ecosystem, incorporate ecosystem considerations into management advice, and maintain resilient ecosystems (NOAA Fisheries, 2016). EBFM's holistic approach considers the dynamics of and feedbacks between components of the social-ecological system (SES) with the overall goal to sustain or increase the ecosystem goods and services upon which society relies. Fisheries management has generally focused on biological objectives while economic and especially social objectives were stated in very broad, non-specific terms (Benson and Stephenson, 2018). However, for EBFM to be effective, comprehensive (social and natural) scientific research should clearly be linked with a complete set of management objectives (Harvey *et al.*, 2017). Implementation of EBFM has been slow in part because the non-biological objectives are often underdeveloped and overlooked (Arkema *et al.*, 2006; Link and Browman, 2017). Managers need tools to help them assess trade-offs among all objectives – biological, social, and economic – from potential management alternatives.

A key tool for EBFM, ecosystem models can provide natural resource managers with an integrative view of how an ecosystem will likely respond to a diverse set of management options (Clark *et al.*, 2001) and help understand to what extent these options will achieve objectives to meet society's needs (e.g., Weijerman *et al.*, 2016). Ecosystem models represent essential ecosystem dynamics and have the ability to simulate the entire ecosystem from primary producers through top predators to human uses (an "end-to-end" model) under climate projections (Grüss *et al.*, 2017). Ecopath with Ecosim (EwE; Christensen and Walters, 2004) is an example of an end-to-end ecosystem model that can integrate physical, ecological, and some socio-economic dynamics. For fisheries management, EwE models generally represent socio-economic dynamics through commercial fisheries. In general, the ability of ecosystem models to quantify economic and social impacts is still far behind their capacity to quantify ecological impacts, partly because of the lack of specificity in social objectives, but also because the social-ecological relationships are often poorly defined (Link and Browman, 2017).

The ability of the ecological system to support desired social outcomes is tied to biological, climate, and ocean characteristics (Nadon *et al.*, 2012; Williams *et al.*, 2015), and to human impacts on these systems (e.g., Mora *et al.*, 2011; Williams *et al.*, 2011). Unfortunately, unsustainable exploitation and habitat degradation have led to less productive coral reef ecosystems globally (Birkeland, 2019) and in Hawaiʻi (Friedlander *et al.*, 2008; Williams *et al.*, 2008), reducing the benefits to society (Kittinger *et al.*, 2015). Hawai‘i is an ideal case study for integrating social and economic objectives in ecosystem models as multiple management agencies have embraced an SES approach. Federal managers (NOAA) have embraced EBFM specifically; the State of Hawai‘i Division of Aquatic Resources (DAR) is working to effectively manage 30% of the coastline by 2030 and three of the four project pillars are economic, social, and governance; for the West Hawai‘i Integrated Ecosystem Assessment and the development of the Hawai‘i Atlantis ecosystem model, NOAA scientists in collaboration with local stakeholders have been working to identify social objectives and indicators of ecosystem services and human well-being. While the overall conceptual foundation is stipulated for many of these initiatives, the next step is to operationalize in an integrated way. This study builds on the foundational work of ecosystem-level planning conducted by NOAA scientists and colleagues (e.g. Weijerman, 2017; Leong *et al.*, 2019; Weijerman *et al.*, 2019) and explores the remaining five guiding principles to operationalize EBFM.

Our objectives for this study were: (1) to develop an SES framework; (2) to identify specific social and economic objectives; and (3) to quantify social-ecological trade-offs by linking social and economic components to an ecological model. While the social and ecological systems around the individual Hawaiian islands are heterogeneous (e.g. with differences in coral cover, fish biomass, human population, accessibility to coastlines, fishing pressure, etc), this research demonstrates an approach to include social and economic objectives in an integrated SES model, providing quantitative and predictive information on the response of marine ecosystems to alternative scenarios. The approach could guide EBFM in coral reef areas.

## Methods

### Study area

The Hawaiian Archipelago is a chain of islands, atolls, islets, and seamounts spanning a distance of about 2,400 km from the island of Hawai‘i at the southeast to Kure Atoll furthest northwest. Our study area encompassed the nearshore marine ecosystems of the inhabited Hawaiian Islands with, from southeast to northwest, the islands of Hawai‘i, Kaho‘olawe, Maui, Lāna‘i, Moloka‘i, O‘ahu, Kaua‘i, and Ni‘ihau (Fig. 1). These eight islands span from 155° East to 160° West and 19° to 22° North. While Kaho‘olawe is not inhabited, its coral reefs are linked to those of the inhabited islands. Population per island ranges from < 200 on Ni‘ihau to about one million on O‘ahu where nearly 70% of the state’s inhabitants live (U.S. Census Bureau).

### Development of social-ecological conceptual system framework

Based on literature and available data, we developed a conceptual SES framework to visualize existing relationships between the societal importance of ecological state components and the changes in ecological and social state components as a response to anthropogenic impacts. We generally followed a Driver, Pressure, State, Ecosystem Service, and Response (DPSER) approach (Kelble *et al.*, 2013) where we first considered broader drivers of ecological state. We then considered how to represent core elements of the social state that depend on the ecological state. In the DPSER approach, desired social outcomes (state of the social system) are related to ecosystem services (the benefits people receive from nature) and human well-being (measures of quality of life; Kelble *et al.*, 2013). Multiple frameworks have been developed to quantify ecosystem services and broader dimensions of human well-being. Most suggest a number of domains (such as, economic and material well-being, social relations, health) and some have identified thousands of potential indicators (e.g., Breslow *et al.*, 2016). Yet, in Hawaiʻi, there are few existing datasets that represent desired social outcomes, let alone enough to represent each domain. To frame our modeling effort, we examined the literature and identified five core domains of human well-being important in the region: Economic and Material Well-being, Health, Culture and Spirituality, Social Relations, Safety and Security (McKinnon *et al.*, 2015; Breslow *et al.*, 2016; Leong *et al.*, 2019; Wongbusarakum *et al.*, 2019). We then explored how themes related to these domains may be further grouped to encompass existing data and adequately represent important social concepts in Hawaiʻi.

**Identify specific social and economic objectives, indicators, and management scenarios**

To compile an initial list of socio-economic objectives, we reviewed mandates and strategy and policy-related documents of state and federal management agencies and NGOs (Supplementary information 1), as well as objectives that emerged from an Atlantis modeling workshop held in January 2017 (Weijerman, 2017). We particularly looked for objectives with the most overlap between sources, which we interpreted as an indication that they are common to multiple stakeholder groups. The objectives related to human well-being retrieved from the policy/strategy documents were in general at a high level with few or no specific goals. Therefore, a second workshop was conducted in May 2019 (Weijerman *et al.*, 2019). In this workshop, 29 participants with diverse expertise (e.g. natural resource fisheries management, habitat management, community engagement, coral reef ecology, fisheries economics), were asked to identify social and economic objectives for each well-being domain (Economic and Material Well-being, Health, Culture and Spirituality, Social Relations, Safety and Security) that were directly related to the biophysical condition of the coral reef ecosystem. The authors then honed the list of objectives to those that are policy-relevant (i.e., match NOAA policy mandates), and with sufficient data to measure them.

Workshop participants were also asked to suggest indicators that directly or indirectly measure the degree to which the identified objective was met. From this list the authors selected indicators that met the following criteria:

1. Measured concepts identified in mandates or organization’s policy or strategy documents;
2. Related to the marine resources and marine resource dependent communities;

3. Can be linked to the input (e.g., fishing effort) or output (e.g., catch, biomass) of an end-to-end ecosystem model;
4. Existing, accessible data to quantify indicators.

We then compared the resulting list of indicators with our conceptual SES framework to ensure consistency and examined the quality of existing datasets to ensure their accuracy, before finalizing the set of indicators to test in our quantitative model. In some cases, identifying relevant data for the indicators was straightforward (e.g., total fisheries value) but in other cases, we had to use a proxy indicator due to lack of data. In these cases, we used our best professional judgment about the relevance and appropriateness of proxies and existing data. An example is the biomass of culturally important species. Many studies, such as Friedlander *et al*. (2013), provide examples of species that are important in certain areas for certain purposes. However, to our knowledge there is not a systematically produced list of species considered "culturally important," nor has there been a discussion of "culturally important to whom" or how to prioritize species important to different stakeholder groups. Compiling such a list is a research endeavor in itself. Economic importance is one aspect of culture, and can be used to generate a list of species for prioritization. Therefore, we selected "Biomass of culturally important species" to demonstrate how an indicator that focuses on select species could propagate throughout the model.

At the 2019 workshop, participants discussed and selected linkages among ecosystem state components, ecosystem services, and human well-being domains that were deemed most threatened by current environmental and management regimes, and identified management mitigation scenarios to relieve/reduce the threat (Weijerman *et al.*, 2019). From these identified scenarios, we selected management scenarios we could apply in the developed ecosystem model.

**Quantify social-ecological trade-offs using Ecopath with Ecosim**

***Ecopath with Ecosim***

We developed an Ecopath (snapshot of the ecosystem structure) model (EwE version 6.5.14040.0) with 55 functional groups and calibrated it for the Hawaiʻi nearshore ecosystem (Polovina, 1984; Walters *et al.*, 1997; Supplementary information 2). With Ecosim (time dynamics), we forced the model with known climate change and fisheries impacts for the historical (or hindcast) simulation from 2000–2019 and with projected climate change and adapted fisheries scenarios for the 2020–2040 forecast simulation. For climate change, we included the two most recent coral-mortality events due to increased ocean temperatures (2014–2015 and 2019) in the hindcast simulation. For the forecast simulation, we included the projected increase in temperature events in the next decade (2026 and 2029) and annual events occurring after 2032 (Van Hooidonk *et al.*, 2014). For fisheries impact, we included two fisheries, a reef-based fishery which was further split into four gear-specific fisheries and included both commercial and recreational data, and a deepwater-based fishery with one gear type and which was split into commercial and recreational fisheries. The reef-based fishery is a multispecies, multigear fishery with main gear types being spear, net, and hook and line. Approximately 5% of the total commercial catches were obtained through “other” fishing techniques (e.g., gleaning, traps) and were grouped together as one gear, “other”, for simplicity. Each gear type has a slightly different catch composition with spear fishers mostly targeting grazers and parrotfish, nets catching browsers, grazers and prey fish, hook and line fishers catching benthic carnivores, and other gear types invertebrates (Table S2.3 in Supplementary information 2). Since recreational catches are 3-10 times higher than commercial catches (Weijerman *et al.*, 2013; McCoy *et al.*, 2018) we report them as one gear-specific fishery. The deepwater-based fishery uses hook and line and targets seven deepwater bottomfish species which we have grouped in two functional groups (bottomfish feeding in water column, BFW; bottomfish feeding on bottom, BFB). The deepwater-based fishery is partly regulated by no-take Marine Protected Areas (MPAs) and the historical catches reflect this restriction. There is no recreational data present for the deepwater-based fishery but it is assumed that recreational catch is equal to commercial catch (Langseth *et al.*, 2018).

Historical recreational fishing data of the reef-based fishery came from the Ocean Tipping Point project (http://www.pacioos.hawaii.edu/projects/oceantippingpoints/#data) and McCoy *et al.* (2018) and included only finfish. Historical commercial fishing data, including both reef-based and deepwater-based fisheries, came from the Western Pacific Fisheries Information Network (https://www.fisheries.noaa.gov/resource/tool-app/western-pacific-fisheries-information-network-data-portal). To create catch time series for Ecosim, we summarized these catch data by gear type, functional group, and year, and assumed that the recreational catches of “other” in the reef-based fishery and of the bottomfish functional groups in the deepwater-based fishery was equal to the commercial catches.

Fishing can be simulated in Ecosim by (1) a time series of catches; (2) gear-specific fishing effort; and/or (3) species or functional group specific fishing mortality. For the historical simulation we used gear-specific annual catch time series. For the projections we used gear-specific fishing effort and functional group specific fishing mortality in correspondence with the management scenarios. These simulations assume 100% compliance which in reality can be hard to enforce due to the nature of the multi-species fisheries employed. For example, in the “No Herbivore fishing” scenario, fishing mortality for the herbivorous groups was set to zero assuming that herbivores are not caught at all by any gear type. In practical terms, not catching any herbivores with a non-discriminatory net would mean that fishers would need to place their nets in areas where large schools of roaming herbivores are absent, e.g. on sandy areas, or they would need to actively monitor their nets and release any herbivores that get trapped. An example of the implementation of this scenario is the Kahekili Herbivore Fisheries Management Area on Maui, Hawai`i (Williams *et al.*, 2016).

### *Simulation of management scenarios*

Table 1 explains how we incorporated the scenarios in Ecosim.

To explore the increased fishing pressure on species under the gear restrictive scenarios (the gear-limited reef-based fishery scenarios in Table 1), we also simulated those scenarios with effort displacement (Supplementary information 5). Results showed only slight differences in outputs (Supplementary information 5), thus we further focused on the scenarios mentioned above.

### *Evaluate trade-offs*

To quantify the efficacy of management scenarios to reach the desired outcomes, we compared the biomass, catch, and the identified indicators at the start (2019) and end (2040) of the simulation. For indicators that required time series, we repeated the process for the time series of forecasted (2019–2040) simulations. To assess how much better or worse an alternative scenario was compared to the Constant Effort scenario, we quantified the relative change in the end value (2040) of each indicator between the alternative and the Constant Effort scenarios.

## RESULTS

### Social-ecological conceptual systems framework

The developed conceptual SES framework provides the foundation for the relationships between system components and undergirds the quantitative modeling effort (Fig. 2). Management and climate change – the focus of EBFM and the scenarios we simulate – influence ecological state. The ecological state of the system directly influences the social state, which is grouped into three elements (Fig 2): economic benefits (e.g., economic livelihood), consumptive benefits (e.g., social connections), and non-consumptive benefits (e.g., recreation, existence value) ( Kittinger *et al.*, 2015; Grafeld *et al.*, 2017). The social state can influence how people engage with the ecosystem outside of marine management initiatives. Double-sided arrows between ecological state and the elements of social state indicate this reciprocal relationship often not included in SES models (Leong et al., 2019).

In Hawaiʻi, consumptive use related to fishing feeds and supports the livelihoods of tens of millions of people a year (Bryant *et al.*, 1999). It also has benefits to society in the domains of social relations (e.g., through sharing the catch), health (e.g., both physical and mental), and cultural well-being (e.g., continuation of traditional practices) (Breslow *et al.*, 2016; Leong *et al.*, 2019). For example, in Hawaiʻi, approximately 1/3 of the residents identify themselves as fishers and place a high importance on fishing (OmniTrack Group, 2011). By tracing the fate of the caught seafood, a supply chain emerges (Grafeld *et al.*, 2017) and social connections become apparent (Kittinger *et al.*, 2015). Catch can be sold, shared, eaten at home, or used in cultural/social practices. The multi-dimensional social importance of fisheries is reflected in the fact that the nearshore non-commercial sector is larger than the nearshore commercial sector (McCoy *et al.*, 2018). Indeed, the 2011 National Survey of Fishing, Hunting, & Wildlife-Associated Recreation identified 27 non-commercial fishers in Hawaiʻi for every licensed commercial fisher. As non-market benefits can far outweigh market returns to fisheries, impacts to non-commercial activities should be considered in management decisions alongside market-based impacts (Finkbeiner *et al.*, 2018). These important benefits are reflected in the conceptual framework by economic benefits and consumptive benefits (Fig. 2).

Snorkeling and scuba diving are examples of non-consumptive activities that result in benefits, such as recreational opportunities (Cesar and Van Beukering, 2004). In one marine reserve well-known for snorkeling in Hawaiʻi, Hanauma Bay, the entrance fee grossed nearly $6 million per year in revenue for the park's management (Hawaiʻi News Now, 2014[1]). For comparison, this value is the same magnitude as the total state commercial and non-commercial fisheries catches combined. People's interest in recreation can also be demonstrated by strong visitation of high-quality sites. For instance, the north shore of Kauaʻi is visited by approximately 2,000 visitors a day who swim and snorkel (Vaughan and Ardoin, 2014). A recent dive expenditure study conducted in Hawaiʻi (unpublished) indicated that divers strongly valued the presence of high live coral cover and fish populations that are abundant, diverse, and large in size. These results are similar to a dive preference study in Guam (Grafeld *et al.*, 2016).

## Identification of objectives and indicators

Our review of policy documents, workshop results, and available data resulted in three socio-economic objectives and one ecological objective with in total ten associated indicators for which existing data sets or adequate proxies were available (Table 2). These indicators span all three elements of the social state (economic, consumptive and non-consumptive benefits).

The social importance of fishing led us to select the indicators "Catch allocated for home consumption or shared within community" and "Biomass of culturally important functional groups" for the first objective (Maintain culturally appropriate food system) which corresponds to consumptive benefits in Figure 2. Also included in this category is variability of catch expressed as the coefficient of variation of the total catch (catch CV), which reflects the reliability and food security of marine resources. The second objective corresponds with non-consumptive benefits in Figure 2. The dive enjoyment indicator was chosen because data exist on the importance of diving/snorkeling in Hawaiʻi (PIFSC unpublished survey). Monk seal and dolphin biomass was chosen to include the importance of rare wildlife (which could have non-consumptive benefits from viewing or just knowing they exist (e.g., Kittinger *et al.*, 2012)). The total fisheries value was included as an indicator for the third objective corresponding to

[1] Available at: https://www.hawaiinewsnow.com/story/27521510/group-raises-concerns-over-hanauma-bay-money/. Accessed on April 6, 2020.

economic benefits in Figure 2. The four ecological indicators for the fourth objective came from literature (Weijerman *et al.*, 2013, 2018; Wongbusarakum *et al.*, 2019).

We then modified our conceptual SES framework (Fig. 2) to represent the identified measurable objectives and indicators in the final SES model (Fig. 3). Management actions (influenced by objectives [Table 2]) affect fishing effort (Fig. 3). The extraction of marine life (and climate change) leads to changed ecosystem state components that are important to divers thus influencing dive enjoyment, an important non-consumptive benefit of marine resources (Table 2, Objective 2). A change in fishing effort also likely changes the biomass of culturally important species (Objective 1). Additionally, the variability (and hence reliability), consumption, and sharing of catch are all indicators for maintaining food systems (Objective 1). A change in catch could lead to a change in revenue from the catch (Objective 3).

**Evaluating social-ecological trade-offs**

Management scenarios reduced catches and increased biomass of the groups for which they were intended, e.g., herbivores for the reef-based management scenarios and bottomfishes for the two MPA scenarios (Fig. 4). Despite a >50% reduction in Prey Fish catch relative to the Constant Effort scenario for the No Net and Line Only scenarios, Prey Fish biomass only increased by <10%, likely due to increased predation by apex predators. Invertebrate catches were >25% lower than the Constant Effort scenario for the Line Only and No Spearfishing scenarios, yet invertebrate biomass at the end of the simulation was similar across all management scenarios. Despite including the positive influences herbivores have on coral recovery through the mediation function (Supplementary information 2), coral biomass decreased due to temperature-induced mortalities forced on all scenarios equally. The increased herbivores under the reef-based management scenarios led to increased predation and thus 10–20% lower biomass relative to the Constant Effort scenario of coral and macroalgae (Fig. 4).

There were clear trade-offs among the three socio-economic and the one ecological objectives in the forecast simulation (Fig. 5). When comparing the end status of the indicators across management scenarios relative to the Constant Effort scenario similar trade-offs became apparent (Fig. 6). The four reef-based fishery management scenarios performed better in all four of the ecological indicators associated with Objective 4 relative to the Constant Effort scenario (Fig. 6). However, in these scenarios there were relative decreases in total recreational catch (and thus, sharing of catch and home consumption; Fig. 3, Objective 1), intangible benefits (Objective 2), and total revenue (Objective 3) compared to the Constant Effort scenario. Important to note is that even though recreational catches and revenue decreased under the reef-based fishery scenarios relative to Constant Effort, in absolute terms catches and revenue increased over the projected time period (Fig. 5). Coefficient of variation (CV) of the catch (Objective 1) was lowest for the reef-based fishery scenarios (Fig. 6). Targeted biomass, i.e., the biomass of culturally important species, increased over time only for the No Herbivore and Line Only scenarios, with the increase mostly attributed to reef browsers and parrotfishes which are highly targeted by net and spearfishing (Figs. in Supplementary information 6). Since turtles also compete for algae, turtle biomass decreased when herbivore biomass increased (Figs. in Supplementary information 5). Furthermore, the large decreases in dive enjoyment for these two scenarios were mostly attributed to lowered turtle biomass (Supplementary information 4).

Increases in recreational catch and total revenue as well as the catch CV under the two MPA scenarios were similar to those under the Constant Effort scenario (Fig. 5). Decreases in targeted biomass, i.e. culturally important biomass, were mainly driven by decreases in bottomfish biomass (Fig. 4). Relative changes over time for many of the ecological indicators under the two MPA scenarios were similar to the Constant Effort scenario (Fig. 5) except for biomass of charismatic species and apex predators. The increases in these groups for the two MPA scenarios were sensitive to the assumptions made with regard to effort displacement post-MPA removal. Relative changes in biomass of charismatic species and apex predators were higher under the MPA1 scenario, where fishing mortality stayed constantly higher after opening the MPAs (i.e., fishers will keep catching higher levels of bottomfishes in the re-opened areas) compared to MPA2. This increase was mainly driven by dolphin biomass (Figs. in Supplementary information 6) and sharks to a lesser extent through bottomfish predation release on planktivorous micronekton (myctophids), a main prey source for dolphins.

## Discussion

Our interdisciplinary approach identified relevant regional socio-economic objectives and relationships between people and the natural environment they rely on and influence. These aspects were dependent on the local context of human communities and their engagement with natural resources. Therefore, while our specific results are not globally transferable, the approach we laid out here can be applied to any region. This study demonstrated how an ecosystem model can assist managers in making informed decisions aligned with the main principles of EBFM.

Clear social and ecological trade-offs were illustrated across management scenarios within this study. There were differences in outcomes among reef-based fishery management scenarios just based on restricting certain fishing gears or target fish groups. Line Only and No Herbivore fishing were most beneficial to the ecosystem productivity at the cost of diminished recreational catch and revenue relative to the Constant Effort scenario. These results are in line with a previous similar study for a small coastal area on the west coast of Hawaiʻi Island (Weijerman *et al.*, 2018). The catch CVs for these two reef-based scenarios were more stable than other management scenarios, but intangible benefits (dive enjoyment) were lower due to tropho-dynamic processes.

MPA removal under the assumption of increased resultant fishing effort led to increases in catch and revenue in the next 20 years at a cost of lowered bottomfish biomass. Under both MPA scenarios, the increase in biomass of charismatic megafauna may increase intangible benefits for wildlife viewing but also increase direct and indirect interactions in other fisheries. While the bottomfish fishery in Hawai‘i currently has no-take marine reserves, the assumptions we made about the post-MPA removal period with respect to fishing mortality, along with a lack of exploration of the sensitivity of those assumptions, bar any conclusions that are directly representative of bottomfish spatial management in Hawai‘i. Rather, we provided herein different ways to address spatial management tactics within a spatially aggregated ecosystem model.

Due to data limitations we were restricted to proxies for some of the indicators. For example, “Sustain marine revenues" is currently just measured by “total revenue”. The indicators “fishery-related employment”, “fishery profitability”, and “market access” could also be incorporated to get a more holistic view of the economic benefits (Symes and Phillipson, 2009). Other studies have identified important domains of human well-being and cultural ecosystem services for which data do not currently exist in our study area, such as sense of place and identity, equity, and justice (Breslow *et al.*, 2016; Leong *et al.*, 2019). Although our conceptual framework highlights the importance of reciprocal relationships between social and ecological state components, our ecosystem modeling results represent the one-way impacts of changes in ecological state components on the social state components due to model limitations and because these feedbacks are not yet quantified. Adding weightings to objectives and their associated indicators, when available, will improve the accuracy and relevance of ultimate trade-off decisions.

Our approach illustrates how modeling can support and inform implementing EBFM via its six guiding principles (NOAA Fisheries, 2016). We (1) *implemented ecosystem-level planning* by exploring policy documents and organizing a stakeholder workshop to identify management objectives and indicators related to marine resources. Engaging managers and stakeholders in development of models helps build trust, identify practical issues and concerns, and improves credibility in modelling (Wondolleck and Yaffee, 2017; Gray *et al.*, 2018). Through the use of a paired conceptual SES and ecosystem model, we (2) *advanced our understanding of ecosystem processes* by synthesizing both natural and social science principles to understand the complex system dynamics and cumulative impacts from anthropogenic stressors in order to (3) *prioritize vulnerabilities and risks to ecosystems and their components*. Additionally, having a calibrated end-to-end ecosystem model, we were able to (4) *explore and address trade-offs within an ecosystem*, as there are many interventions possible to reach a certain objective and some are likely to be more effective than others, thereby (5) *incorporating ecosystem considerations into management advice*. Lastly, the ability to make informed management decisions allows managers to be prepared for the likely time horizon of changes in social and natural state components to (6) *maintain resilient ecosystems*. In conclusion, this study shows the important role SES models can play to support the implementation of EBFM. It identifies data gaps, and despite the limited data available, the analysis gives a clear overview of the societal and ecological trade-offs of alternative management scenarios.

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## Supplementary material

The following supplementary information (SI) is available at ICESJMS online:
SI 1. A table of human dimension related objectives from agencies classified by category
SI 2. A description of the Ecopath with Ecosim (EwE) model development and validation
SI 3. A description of the EwE model skill assessment
SI 4. A description of the "Dive Enjoyment" indicator
SI 5. Results of EwE simulations of the reef-based fishery management scenarios with effort displacement
SI 6. Figures showing the percent change in biomass between end and start of the simulation across management scenarios for all functional groups

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## Data availability

The data underlying this article are available in the article and in its online supplementary material.