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Revealing complex social-ecological interactions through participatory modeling to support ecosystem-based management in Hawai‘i

Rebecca J. Ingram[a,c,*], Kirsten L.L. Oleson[b], Jamison M. Gove[c]

[a] Joint Institute for Marine and Atmospheric Research, University of Hawai‘i at Mānoa, 1000 Pope Road, Marine Sciences Building 312, Honolulu, HI 96822, USA
[b] Department of Natural Resources and Environmental Management, University of Hawai‘i at Mānoa, 1910 East-West Road, Sherman Laboratory 101, Honolulu, HI 96822, USA
[c] Ecosystem Sciences Division, Pacific Islands Fisheries Science Center, 1845 Wasp Boulevard, Building 176, Honolulu, HI 96816, USA

ABSTRACT

The Hawaiian Islands are home to a complex and dynamic marine ecosystem that serves as a backbone to the state's economy and society's well-being. The marine ecosystem currently faces numerous threats that undermine ecosystem integrity and compromise socially valuable ecosystem services. The socio-economic and ecological complexity of the region invokes a clear need for ecosystem-based management (EBM) strategies. To support EBM development, participatory methods were used to gather expert and place-based knowledge from resource managers, scientists, and community members. Methods elicited local values, fostered diverse relationships, and increased community engagement in resource management. Using information collected, Conceptual ecosystemmodels were developed guided by the Driver-Pressure-State-Impact-Response framework that identify and quantify the strength of socio-economic and ecological interactions. The resulting models illustrate the complexity of system dynamics, highlighting connectivity between pressures and the ecosystem, with direct implications for ecosystem services. Importantly, many identified pressures occur at the local scale, presenting an opportunity for local resource management to directly affect ecosystem status. This study also found that many of the strongly impacted ecosystem services were cultural ecosystem services, which are critical to human well-being but lack integration into resource management. These models support an Integrated Ecosystem Assessment of the region by informing ecosystem-based strategies, facilitating the selection of ecosystem monitoring indicators, and emphasizing human dimensions.

1. Introduction

Society is inseparable from marine ecosystems [1], relying on numerous ecosystems services and benefits generated through complex social-ecological system interactions [2,3]. Despite this reliance, human activities such as overfishing, land-based pollution, and greenhouse gas emissions have degraded marine ecosystems globally [4–7], threatening food security, human health, and livelihoods.

Marine ecosystems in Hawai‘i contribute substantially to the economy and to society's well-being [8–10]. In 2015 alone, commercial and recreational fisheries grossed $933 million in sales (including direct sales of fish and sales related to fishing activity) [11]. In Hawai‘i, tourism is the largest industry, generating $15 billion dollars annually, and a significant portion of visitor activity is marine-based [12]. In addition to the marine ecosystem's contribution to the market economy, residents and tourists alike depend heavily on coral reefs in Hawai‘i for coastline protection, medicinal properties, and research and educational opportunities [10].

Marine ecosystems in Hawai‘i also play a significant role in sustaining culture, tradition, and social practices that are critical to human well-being [13]. While many definitions of human well-being exist, the Millennium Ecosystem Assessment defines human well-being as having access to necessary basic materials (e.g., food and water), human health, social relationships, a safe and secure environment, and freedom. This definition was also used to examine human well-being within marine social-ecological systems [8].

The societal dependence on the marine ecosystem in Hawai‘i makes recent declines in ecosystem status all the more alarming. The condition of coral reefs and fish populations in Hawai‘i has deteriorated over the past two decades [10,14]. Impacts of global climate change, including sea surface temperature rise, have led to back-to-back coral reef bleaching events in recent years [15]. Exacerbating these global stressors, a rapidly growing population is increasing coastal development, runoff, marine debris, and damaging forms of recreation (e.g., trampling of reefs) [10,16]. The societal importance of marine ecosystems in

* Corresponding author at: NOAA IRC NMFS/PIFSC/ESD 1845 Wasp Blvd, Building 176 Honolulu, HI 96818, USA.
E-mail addresses: ingramr@hawaii.edu (R.J. Ingram), koleson@hawaii.edu (K.L.L. Oleson), jamison.gove@noaa.gov (J.M. Gove).

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Hawai‘i, combined with threats of further degradation, creates a clear need for effective management strategies.

Marine resource management has historically focused on individual species or sectors, rather than ecosystems as a whole [17,18]. While an important piece of the process, focusing solely on one species/sector ignores other potentially affected aspects of the ecosystem, which can lead to system collapses and non-ideal management outcomes [19]. By contrast, Ecosystem-Based Management (EBM) is a holistic strategy seeking to understand the temporally and contextually fluid connections within a social-ecological system [20]. Understanding and describing these connections is fundamental to resource management [17,21], yet most studies do an inadequate job [8].

Understanding how society benefits from and ultimately influences ecosystem services is central to EBM [1,22]. This study defines ecosystem services as the goods and benefits that people obtain from an ecosystem and the associated values and beliefs assigned by people to each service [23,24]. Ecosystem services are traditionally divided into categories: provisioning (i.e., materials provided by ecosystems), regulating (i.e., regulation of natural processes), supporting (i.e., supports production/maintenance of all other services), and cultural (i.e., nonmaterial benefits or values) [3,25]. Services derived from ecosystems are numerous and complex, and a given good or service may cross categories and represent multiple values [26]. For example, in Hawai‘i, fishing is not only a means for income and subsistence, but also holds immense socio-cultural value related to traditional practices and cultural heritage [8].

Despite their importance to human well-being, ecosystem services are not widely accounted for in management strategies [27], partially due to limited understanding of the social-ecological relationships that both produce and limit them [23]. This omission is especially true for cultural ecosystem services, likely due to a combination of factors, including their intangible nature, the propensity for individuals to ascribe values differently, and the difficulty or appropriateness in assigning monetary value [26,28]. Perhaps due to their recognized significance, cultural services are a stated management responsibility in Hawai‘i [29], yet there are few existing management policies in place to conserve or protect them [30].

Although a wide acknowledgement of the need for EBM exists, transitioning from theory to practice has been slow [20]. Many challenges restrict implementation of EBM, including limited data availability, conflicting governing agencies, and timeline or financial restraints [31]. While limited, successful examples of EBM begin by employing participatory methods to build a consensus of complex social and ecological system structure and function [19,31–33].

EBM has not been widely adopted in Hawai‘i; however, coastal resource managers across the state of Hawai‘i recently identified whole ecosystems (as opposed to individual species or habitats) and culturally important resources as their primary management responsibilities [29]. Nevertheless, few federal, state, or local EBM policies exist that support this more holistic management approach [34]. This study responded to the need for EBM in Hawai‘i with a participatory process that identified social-ecological connections along the west coast of Hawai‘i Island. Through an investigation of how human activities are affecting the nearshore marine ecosystem and how society benefits from that region, participants identified key pressures that influence both the ecosystem state and ecosystem services.

1.1. Using conceptual ecosystem models within an Integrated Ecosystem Assessment

The National Oceanic and Atmospheric Administration developed the Integrated Ecosystem Assessment (IEA) Program to inform and facilitate EBM [22]. IEAs commonly use conceptual ecosystem models (CEMs), a method of diagramming social-ecological system elements, to discover, integrate, and communicate relationships that exist amongst habitats, species, and social aspects of a system [18,35]. CEMs identify knowledge gaps, inform research needs, and represent a hypothesis of system structure and processes [36,37].

CEMs benefit from participatory methods, such as collaborative workshops with scientists, resource managers, and community members [21]. Participatory methods have multiple advantages: they capture place-based knowledge, incorporate regionally specific needs, build community trust in management programs, and build social cohesion [37–39]. Participatory methods also render the decision-making process more democratic [39].

CEMs are frequently structured using the Driver-Pressure-State-Impact-Response (DPSIR) framework [18,21,33,40–42]. DPSIR is valuable in identifying cause-and-effect relationships between society and the ecosystem [43,44], and joining scientific and place-based knowledge [45]. DPSIR can also integrate information regarding intensities of identified relationships [18,46,47]. Many variations of the framework exist. In this study, *Drivers* are natural or societal events that create *Pressures* on the ecosystem's *State*, leading to *Impacts* in ecosystem service delivery that may generate a *Response* from society or management [18,40].

2. Methods

2.1. Study Site: West Hawai‘i Island

The west coast of Hawai‘i Island, commonly referred to as West Hawai‘i (Fig. 1), is home to an ecologically dynamic nearshore marine ecosystem with a diverse assemblage of species [48]. The productivity of the region provides socio-economic value to residents through numerous ecosystem services, such as commercial, recreational, and subsistence fishing, as well as intangible services, such as cultural and traditional practices [13]. However, coral and fish communities across the region have suffered recent declines [10,49,50] suggesting deteriorating underlying ecosystem functions and processes [48]. A rapidly growing population, coastal development, marine-based tourism, and land-based pollution are partially to blame for the recent changes in marine ecosystem status [51–54]. Adding to these local impacts are the effects of global climate change. For example, elevated ocean temperatures in 2014 and 2015 led to the most destructive coral reef bleaching event ever recorded in this region [55,56]. Ultimately, these threats compromise the ability of the marine ecosystem to provide the numerous goods, services, and benefits that society depends upon for its well-being [13].

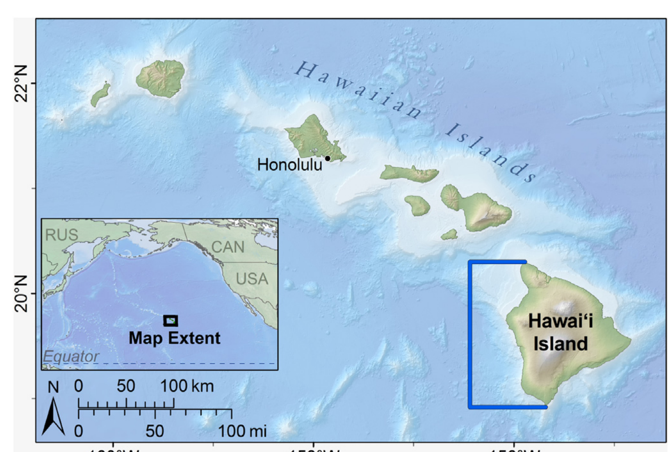

Fig. 1. Map of Hawai‘i Island within the Main Hawaiian Islands. The geographic boundary of the West Hawai‘i IEA are demarcated in blue.

2.2. Identifying and quantifying social-ecological interactions in West Hawaiʻi

Two participatory workshops and one electronic survey gathered scientific and place-based knowledge on socio-economic, biophysical, and ecological aspects of West Hawaiʻi. Invitations to participate in workshops were distributed via word-of-mouth and email to known scientists, resource managers, and community members within the conservation community of West Hawaiʻi. Invitations also encouraged participants to invite others who may be interested. Participant affiliations included local, state, and federal resource management agencies, tourism companies, and marine-related scientific organizations. Out of 54 total participants in this process, 23 were also West Hawaiʻi residents who provided important regional details that would have otherwise been unattainable (Appendix A).

The first workshop was held on September 4, 2014, during NOAA's Symposium on West Hawaiʻi's Marine Ecosystem, in Kailua-Kona, Hawaiʻi. The symposium and workshop were open attendance, advertised via electronic fliers emailed to private, state, and government institutions in related fields. Attendees of this Symposium are primarily active marine conservationists who study, work, and/or live in West Hawaiʻi. There were 32 workshop participants, including 14 West Hawaiʻi residents. During this workshop, participants self-selected into break out groups focused on a geographic location (North or South West Hawaiʻi), resulting in two North groups and three South groups. Each group was asked to identify and map drivers and pressures that influence coral reefs along the coast of West Hawaiʻi. Information was recorded directly on large, printed maps of the region and by designated facilitators within each group. One participant within each group was asked to record discussion notes, which were used to support analysis of information recorded on maps.

The second workshop took place on August 3, 2015, at the Hawaiʻi Conservation Conference (HCC), held at the University of Hawaiʻi at Hilo, Hawaiʻi. The workshop was advertised conference-wide, emailed to private, state, and government institutions in related fields, and to participants of the first workshop. Attendees of this conference are historically those involved in natural resource stewardship and conservation within Hawaiʻi. Additionally, since HCC 2015 was held on Hawaiʻi Island (as opposed to the normal venue on the island of Oahu), many people from West Hawaiʻi were expected to attend. There were 24 participants at the second workshop (three had also attended the first workshop) and nine were West Hawaiʻi residents. The second workshop included a list of drivers, pressures, and ecosystem services derived from a combination of the first workshop, an extensive literature review, and expert opinion. Participants were asked to verify and/or edit this list as they saw necessary. This workshop concentrated on four constituent components of the West Hawaiʻi marine ecosystem: corals, reef fishes, pelagic fishes, and water quality. These components were selected due to high regional ecological and socio-economic significance [9,10,48]. Each component is recognized to have a state (e.g., degraded, intact, etc.), and, when taken together, the state of these individual components reflects the state of the overall nearshore ecosystem. Participants self-selected into groups based on these four components and completed identification of system interactions.

During the second workshop, participants quantified the relative strengths of identified pressure-state and state-service interactions. Pressure-state relationships were quantified because they are more amenable to local resource management than underlying drivers, which are frequently outside of the spatial and/or temporal range of local management. Within their self-selected groups (described above), participants answered the following question for each interaction, based on Cook, Fletcher and Kelble [57]: *On a scale of 0 (no effect) to 5 (strongest effect), what is the direct effect of X on Y (representing the effect of a pressure on an ecosystem component's state; or the effect of an ecosystem component's state on an ecosystem service)?* Each group reached a consensus for individual interaction scores. Cumulative effect strengths were then calculated by summing scores. At the end of this workshop, participants were offered a voluntary questionnaire to assess whether they deemed the workshop useful (Appendix B).

In order to capture more system interactions, an electronic survey was built using Qualtrics, a licensed online survey platform (https://Qualtrics.com). The survey was emailed to 34 workshop participants who had self-identified as an expert in a marine related field on workshop sign-in sheets. The initial email invitation and two reminder emails were sent to all participants resulting in 10 completed surveys.

A CEM was developed following each stage of this process (one CEM for each group within both workshops, and one CEM for the electronic survey) using activity notes, observations, photographs, and participant responses. Each CEM followed the DPSIR structure. The final CEM combines all identified relationships. CEMs included in this paper were built using an online network-modeling platform (https://kumu.io).

3. Results

3.1. Conceptual ecosystem model of West Hawaiʻi

Participants of the workshops and electronic survey identified 596 unique interactions within West Hawaiʻi (Fig. 2). For individual ecosystem components, participants identified the greatest number of interactions for reef fishes (341), followed by corals (320), water quality (190), and pelagic fishes (113). In total, participants identified 24 drivers creating 32 pressures, which affect four ecosystem components, and impact 27 ecosystem services.

Throughout the participatory process, participants both validated and expanded upon the lists of drivers, pressures, and ecosystem services included in this study. All elements are included in the West Hawaiʻi CEM (Fig. 2).

3.2. Quantifying identified social-ecological interactions: Pressure-to-State

Participants quantified a total of 73 pressure-to-state interactions (Table 1). The strongest reported pressures on the ecosystem included extraction of fish (cumulative effect = 18 out of a possible 20, min-max score = 3–5), nutrient input (17, 3 − 5), habitat destruction (17, 3 − 5), and ocean temperature (17, 3 − 5). Extraction of fish was perceived to have the strongest possible effect (score = 5) on corals, reef fishes, and pelagic fishes. Nutrient input was perceived to have the strongest effect on corals and water quality. Habitat destruction was perceived to have the strongest effect on corals and reef fishes. Ocean temperature was perceived to have the strongest effect on corals and pelagic fishes. The perceived weakest pressures in West Hawaiʻi were wind (4, 0 − 2), sea level rise (3, 0 − 2), precipitation (2, 0 − 2), and lava (1, 0 − 1).

Collectively, pressures were perceived to have a stronger impact on corals and water quality than reef and pelagic fishes (Table 1). Eight pressures received effect scores of five on coral reefs and seven received effect scores of 5 on water quality. Only two pressures received effect scores of five on reef fishes and pelagic fishes.

3.3. Quantifying identified social-ecological interactions: state-to-ecosystem service

Participants quantified a total of 81 state-to-ecosystem service interactions (Fig. 2). Biodiversity, biological interactions, and four cultural services (spiritual value, heritage value, Hawaiian cultural value, and non-extractive recreation) were scored as the most affected ecosystem services (cumulative effect strength = 20 out of a possible 20, min-max = 5–5) Fig. 3. Cultural services in particular were seen to be strongly affected by the state of the ecosystem. Seven of the ten ecosystem services with highest scores (19 or above) were cultural services. Additionally, nearly all cultural services (91%) scored above 17. The services seen to be least affected by the overall ecosystem's state were climate regulation (7, 0–5; driven largely by water quality) and atmospheric regulation (6, 0–5; same driver).

Many ecosystem services (57%) received cumulative interaction strengths

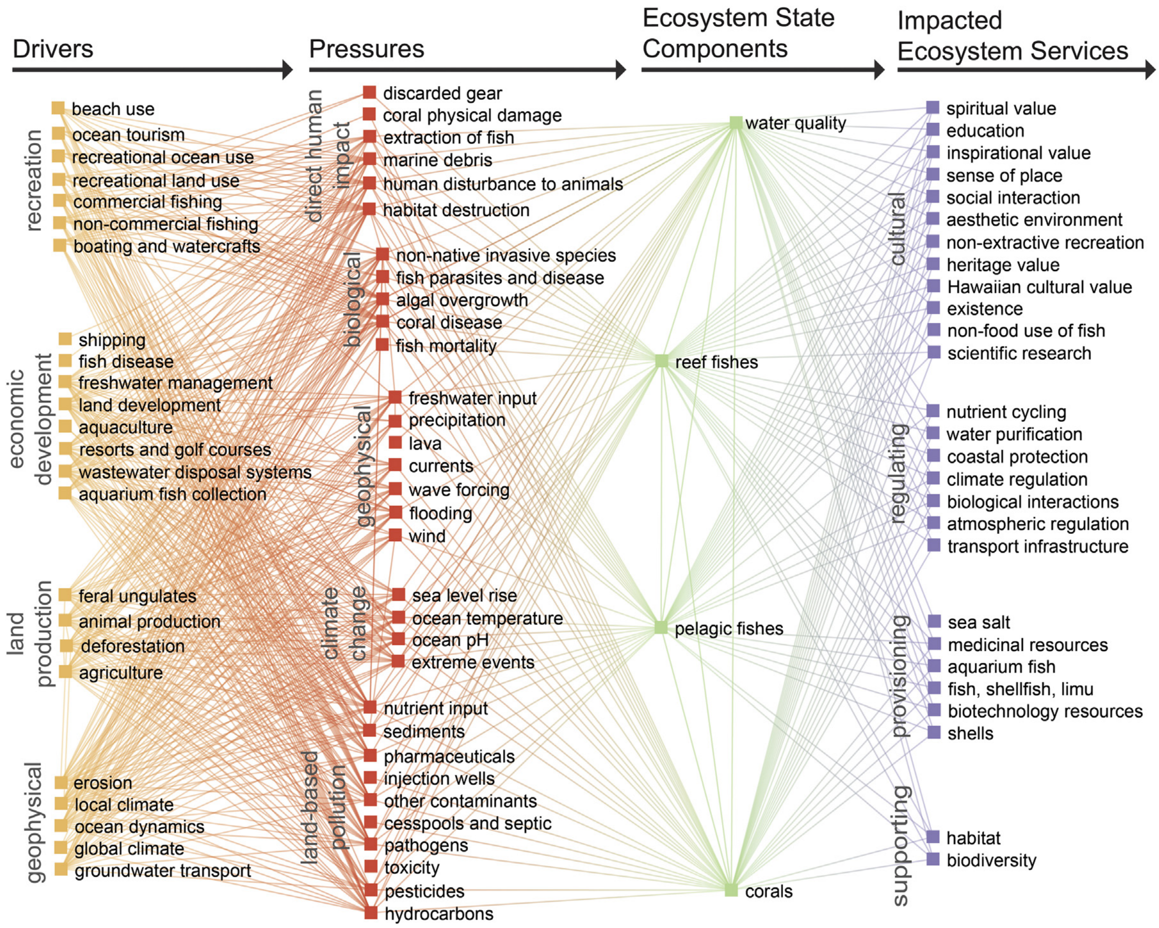

Fig. 2. Conceptual Ecosystem Model of the West Hawai‘i social-ecological system displaying interactions between pressures (red) created by drivers (orange) that alter the state of ecosystem components (green) that comprise the overall ecosystem. Changes in the state of these components lead to impacts on ecosystem services (purple). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

over 15, reflecting the perception of workshop participants that these ecosystem components have a critical role in the delivery of ecosystem goods, services, and benefits. Collectively, corals and water quality were scored as having the strongest effect on the delivery of ecosystem services, compared to reef and pelagic fishes. All ecosystem services were perceived to be impacted by multiple ecosystem components, and a majority (65%) were perceived to be directly affected by all four ecosystem components, highlighting the importance of the functioning of the entire social-ecological system on ecosystem service delivery [19].

Participants in the water quality group recorded the strongest strength (5) for the direct effect of water quality on every ecosystem service, deeming water quality critical to delivery of all services. It is possible that the water quality group interpreted the question differently than other groups; however, no confusion or ambiguity exists in group notes or facilitator recollections. Furthermore, the relative ranking based on cumulative effect does not change if water quality values are removed.

4. Discussion

4.1. Identification of locally manageable pressures changing the ecosystem's state

West Hawai‘i CEMs reveal complex system dynamics and provide an understanding of human-ecosystem interactions, which can guide targeted management action and offer important information for EBM [58]. This study contributes to a growing body of literature highlighting the importance of participatory conceptual modeling in EBM implementation [18,33,59]. West Hawai‘i CEMs also serve as a foundation for further analysis of specific system interactions and indicator development.

While mitigating global climate impacts is critical for long-term conservation, there is evidence supporting the efficacy of immediate local responses in improving coral reef condition [60,61]. Reducing local human pressures, such as fishing and pollution, can directly improve coral reef ecosystems, as well as increase resiliency to global impacts [62,63]. By disentangling complex social and ecological interactions, managers can identify the strongest pressures to the ecosystem, informing prioritization of management strategies [57,58]. To more concretely guide strategies in West Hawai‘i, pressures amenable to management at a local level were identified (Fig. 4). In West Hawai‘i, management has an opportunity to directly address half of the identified pressures and three of the strongest pressures, aiming to mitigate effects of pressures and enhance ecosystem service delivery.

Participants reported that extraction of fish (i.e., any method of fishing, including net, line, or spear from boat or shoreline), nutrient input, habitat destruction, and rising ocean temperature were the strongest pressures in West Hawai‘i (Table 1). Regional studies support that these identified pressures are in fact substantially affecting the marine ecosystem of West Hawai‘i [15,48,52], lending support to the credibility of input produced by this group of participants.

Participants identified extraction of fish as the strongest pressure affecting the overall ecosystem state. In West Hawai‘i, the biomass of target fish species (i.e., species caught as a food resource) is declining more rapidly than other fish species, providing firm evidence that the immediate cause of the decline is fishing, and not different or aggregated pressures [14,64]. While fishing in and of itself represents an important ecosystem service [26], heavily fished coastal environments may not provide a diversity of ecosystem services that support human well-being, such as recreation and cultural value [8]. These types of competing objectives commonly arise with the use of an ecosystem,

Table 1
Participant identified pressure to ecosystem state interaction effect scores. Values represent a scale of 0 (no effect) to 5 (strong effect). *CUMULATIVE EFFECT* is the sum of the strength of a single pressure across all four components of the ecosystem. *TOTAL PRESSURES* is the count of pressures impacting a single component. *CUMULATIVE IMPACT* is the sum of interaction scores impacting each ecosystem state component. Pressures highlighted in red are amenable to local management.

Ecosystem Pressures → Ecosystem State Components	Corals	Reef Fishes	Pelagic Fishes	Water Quality	Cumulative Effect Strength
Extraction of Fish	5	5	5	3	18
Ocean Temperature	5	3	5	4	17
Nutrient Input	5	4	3	5	17
Habitat Destruction	5	5	4	3	17
Extreme Weather Events	4	3	2	5	14
Pesticides	5	0	3	5	13
Sediments	3	4	2	3	12
Ocean pH	2	2	4	3	11
Marine Debris	4	1	3	3	11
Freshwater Input	1	2	2	5	10
Human Disturbance to Animals	5	1	3	1	10
Hydrocarbons	3	0	1	5	9
Algal Overgrowth	5	2	1	0	8
Non-native Invasive Species	3	1	1	3	8
Coral Disease	5	1	1	0	7
Pathogens	0	1	1	5	7
Flooding	3	3	0	0	6
Pharmaceuticals	0	0	1	5	6
Wave Forcing	5	0	0	0	5
Other Contaminants	1	0	1	3	5
Wind	2	0	2	0	4
Sea Level Rise	1	0	0	2	3
Precipitation	0	0	0	2	2
Lava	0	0	0	1	1
Locally Manageable Pressures	20	15	19	19	TOTAL PRESSURES
Non-locally Manageable Pressures	72	38	45	66	CUMULATIVE IMPACT

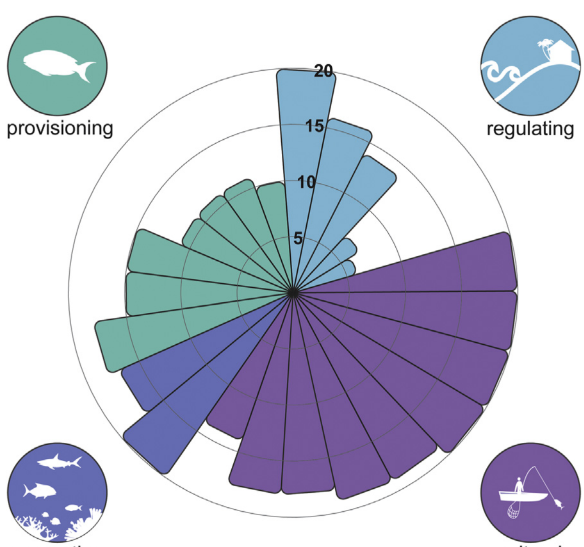

Fig. 3. Participant identified cumulative effect strengths of the overall ecosystem state (comprised of four ecosystem components) on individual ecosystem services. Each plot segment represents a single ecosystem service; segment colors represent ecosystem service category (provisioning, regulating, supporting, and cultural). Effect strength is weaker towards the center and increases outwards.

therefore an inclusive and participatory process, such as the one described here, helps highlight conflicting stakeholder preferences and the many tradeoffs that managers must consider.

Nutrient input and habitat destruction were both identified by participants to be among the second strongest pressures affecting the overall ecosystem state in West Hawai‘i. Coastal development, land-based sources of pollution, and on-site waste disposal systems (e.g., cesspools and septic systems, the predominate form of waste disposal in West Hawai‘i) have increased nutrient contents in nearshore waters of West Hawai‘i [51,52,65], resulting in declines in coral cover and water quality in some coral reefs in West Hawai‘i [66]. Nutrient input has also been linked to increased algal growth and coral disease, as well as threatening human health due to the presence of infection causing pathogens in untreated sewage [67].

Participants also identified ocean temperature among the second strongest pressures affecting the overall ecosystem state. Rising ocean temperature often leads to bleaching events and depressed growth rates of coral skeletons [68,69]. Massive bleaching occurred in reefs along West Hawai‘i during 2014–2015, resulting in an average of 49.7% mortality in reef building corals [56]. Although some studies are pessimistic of local management's ability to prevent further temperature-driven degradation of coral reef ecosystems [70–73], existing evidence suggests that local strategies can successfully mitigate some of the impacts of climate change [60–62,74]. Because coral reefs provide such a massive amount of ecosystem services to society [10], mitigating climate change impacts to coral reefs is critical. In Hawai‘i, statewide plans are in development to increase coral reef resilience to rising ocean temperatures [15].

The overlap between participant input and regional studies highlights the

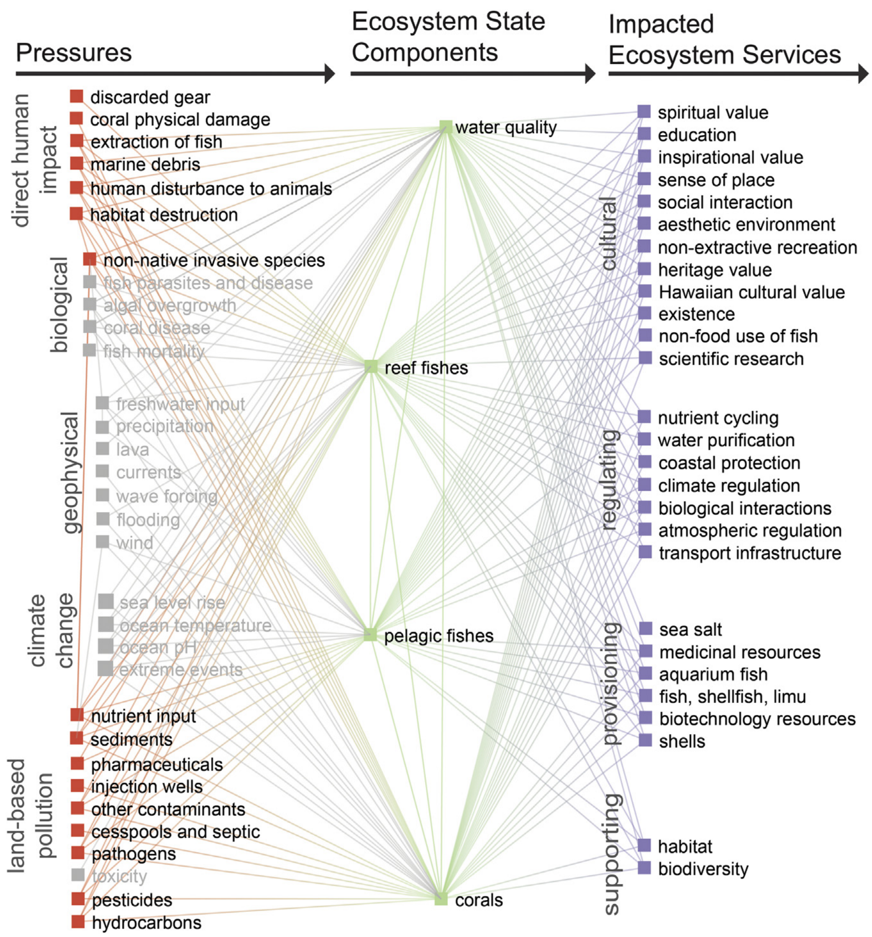

Fig. 4. Conceptual Ecosystem Model of the West Hawaiʻi social-ecological system, highlighting locally manageable pressures (red) over non-locally manageable pressures (grey). Pressures alter the state of ecosystem components (green) that comprise the ecosystem, leading to impacts on ecosystem services (purple) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

importance of creating management strategies alongside a community. Those who study and live in this region were able to provide nuanced information regarding strong ecosystem pressures, and additional information on system complexity and connections.

4.2. Importance of cultural services in resource management

Quantifying ecosystem impact onto ecosystem services can provide insight on production and delivery. The ecosystem services with multiple, highly scored linkages to ecosystem components are the most susceptible to declines in ecosystem state [57]. West Hawaiʻi CEMs reveal that at least three ecosystem components affected 87% (20/23) of ecosystem services. These results parallel similar studies [57,58,75] and highlight the fact that ecosystem service delivery relies on the functioning of a whole, integrated ecosystem [3].

Our results uncovered that cultural services were perceived to be the most impacted type of service in West Hawaiʻi (Fig. 3). Cultural services are generally non-material, intangible benefits provided by ecosystems, and are commonly as or more important to people than associated material services (e.g., the act of fishing may be more valuable to a person than the fish caught) [26]. Similar studies have also found cultural services to be the most impacted services, either directly or indirectly [57,58], which could result in negative ramifications due to the importance of cultural services to society.

In Hawaiʻi, cultural identity and connection to place are recognized as direct contributors to human well-being, and to diminish cultural services would substantially impair human well-being [30,76]. The significance of cultural services in conjunction with these findings underscores the importance of including such services in resource management strategies.

In some coastal and marine regions, management has begun to incorporate cultural services through the use of ecosystem indicators [77–79]. Indicators measure attributes of social-ecological systems to determine current trajectories within a community, and can inform management strategies aimed at addressing degraded attributes [78,80]. The West Hawaiʻi IEA used results from this research to aid in identifying indicators as a first step toward capturing the full range of ecosystem services provided to this community [48]. These results, particularly the impacts to cultural ecosystem services, have led the West Hawaiʻi IEA to prioritize expanding the current list of indicators to incorporate more human dimensions and cultural services indicators.

4.3. Using a participatory processes to characterize the marine social-ecological system

Reaching a consensus on system structure through a collaborative and open process can have benefits beyond final information obtained. Local stakeholders generally possess a deeper understanding of regional goals, needs, and complexities that may be otherwise left out of a model [37]. The process of participatory modeling captures this place-based knowledge, identifies gaps in current regional understanding, and fosters a collaborative relationship between all involved [37].

Community engagement is an effective way to gather information on local areas and resource use, particularly nuanced or conditional details [38]. Inviting everyone into the same room enabled communication, knowledge sharing, and enhanced trust in the management process [38]. While this is not something this study directly measured, a voluntary workshop questionnaire showed an increased awareness of system dynamics, management strategy development, and regional understanding (Appendix B). Overall, participants appreciated the collaborative opportunity provided by the workshop, and expressed a desire to continue this process in the future.

During this process, participants suggested system connections that workshop activities did not directly ask for, such as feedbacks and nonlinear relationships. For example, during the second workshop one group identified pressures that were caused by changes in ecosystem state. Since no other groups discussed this, it is not possible to uniformly include the information in the models. However, the inclusion of this information has helped to discover this potential research gap, and the need to identify key feedbacks in the social-ecological system.

Participatory processes gather knowledge that may be otherwise unattainable. It is important to note, however, that while this process is crucial for collecting information, participants may suffer from cognitive biases during workshops (e.g., they may be heavily influenced by current events or other readily available information). For example, the second workshop took place while West Hawaiʻi ocean temperatures were uncharacteristically warm, causing widespread and severe coral bleaching. This event may have influenced participants to record ocean temperature as a stronger pressure than during non-bleaching years. Though this presents a potential temporal bias, these are still important temporal regional details. Furthermore, since EBM and the IEA are intended to be cyclical, biases can be addressed through future process iterations.

5. Conclusion

Marine ecosystems face global and local pressures, compromising ecosystem services that are socially valuable and sustain local economies. Our CEMs reveal the complexity and connectivity of socio-economic and ecological aspects of West Hawaiʻi, an economically important region that is ecologically unique within the state of Hawaiʻi. Numerous existing linkages corroborate the need for a holistic management approach, as single sector strategies will result in unforeseen impacts on connected elements within the system. These results highlight that some of the strongest perceived pressures influencing the West Hawaiʻi marine ecosystem can be managed at local scales, thus emphasizing management interest in developing strategies that address local pressures to increase ecosystem resiliency. Further, these findings suggest consideration for a much stronger role of cultural ecosystem services into management strategies as they are both socially important and perceived to be strongly impacted by numerous ecosystem pressures. These results should be used to inform current and future resource management decisions in West Hawaiʻi to create community-supported strategies. Ultimately, this will help to facilitate EBM and the conservation of valuable marine ecosystems and the services they provide to society.

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Declaration of interest

None.

Appendix A

See Appendix Table A1

Table A1
Total number of participants involved in process.

	Workshop 1	Workshop 2	Workshop 2: Survey	Electronic Survey
Total Participants	32	24	21	10
West Hawaiʻi Residents	14	9	Not Recorded	Not Recorded

Appendix B

See Appendix Table B1

Table B1
Workshop 2 survey.

Hawaiʻi Conservation Conference 2015 Voluntary Participant Survey
What best describes you?
State/Federal Agency Staff (8)
Resource Manager (3)
Community Member (7)
Other: (3)
I increased my knowledge or gained a new skill from today's workshop.
(1: do not agree at all; 10: agree very much) *Average = 7.05*
I plan on using information that I learned today in my work.
(1: do not agree at all; 10: agree very much) *Average = 7.29*
I plan on using information that I learned today in my daily life.
(1: do not agree at all; 10: agree very much) *Average = 5.35**
*this question was not answered by one participant
I changed how I think about land-sea management based on today's workshop.
(1: do not agree at all; 10: agree very much) Average = 5.67
I think the DPSIR model and process is useful for resource management in Hawaii.
(1: do not agree at all; 10: agree very much) *Average = 8.24*

Participants were encouraged to list examples/additional comments after each question and at the end of the survey. Such answers are not included here, as that would jeopardize the anonymity of participant responses.

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