A multi-decadal assessment of social thresholds and outcomes in marine social-ecological systems in Hawai‘i

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Abstract

Coastal communities and nearshore ecosystems comprise social-ecological systems (SESs) where ecological goods and services (EGS) help meet many social, economic, and cultural objectives. In an era of political and environmental change, acute and chronic stressors can induce regime shifts, transitioning systems from high-functioning states to less favorable ones with diminished EGS provisioning. Despite the inherent interdependence of human communities and resource ecosystems, and management’s ultimate goal to promote human well-being, social regime shifts within SESs are underexplored relative to ecological regime shifts. This case study uses social indicators to identify temporal trends and thresholds across fisheries, tourism, and coastal employment in the Hawaiian SES. Generalized Additive Models (GAM) identify periods of change and link them to regulatory and environmental drivers. Composite indices score social outcomes over time and across local communities using Data Envelopment Analysis (DEA). Trends and thresholds coincided with regulatory changes, economic conditions, and environmental perturbations. Together, threshold identification and outcome ranking assess social adaptability to resource changes and provide insight for adaptive management of regime shifts for marine ecosystems in Hawai‘i.

Keywords: Hawai‘i, thresholds, social regimes, social indicators, social-ecological systems, fisheries

1. Introduction

Marine management goals include both ecological and social well-being outcomes [1,2], yet management agencies have historically assessed ecosystem outcomes (e.g., stock assessments), rarely monitoring and measuring social outcomes (e.g., recreational engagement) [3]. Through management and resource use, social systems influence ecosystem outcomes. The ecological system, in turn, provides benefits to human systems through ecological goods and services (EGS)[4]. Social-ecological systems (SESs) are characterized by this mutual influence between humans and the environment [5]. While this connection is well-documented, analytical assessments of marine SESs tend to focus on ecological conditions and clear integration of social science in fisheries management remains rare. To address these linkages, an approach championed by NOAA Fisheries, the United States federal fisheries management agency, is ecosystem-based fisheries management (EBFM) [6]. EBFM embraces a holistic approach to fisheries management that aims to maintain healthy ecosystems and EGS provisioning, ultimately improving social as well as environmental outcomes [7].

To develop and achieve management objectives that integrate across ecological and social domains, adaptive EBFM requires understanding how ecological and regulatory drivers influence social outcomes [8], yet metrics for these drivers and outcomes are rarely assessed. Quantitative assessments of social conditions can deepen this understanding by measuring the effects of specific management actions on EGS provisioning. One such approach that has been gaining traction in SES research is the identification of social tipping points, or threshold moments that suggest the movement from one social state to another [9]. Such assessments can identify which social objectives are or are not being met and classify SESs into distinct regimes with different basic functions (e.g., high v. low fisheries productivity). This change in state is commonly referred to as a regime shift. Threshold analyses have frequently been used to describe environmental regime shifts but have rarely been extended to social regimes [10,11]. As a precursor to the present case study, a cross-regional comparison of social thresholds across six marine SESs in the United States was conducted as a proof-of-concept for a novel approach to identify and rank social regimes [12]. In this case study of the Hawaiian SES, we apply that approach at a finer scale, using social indicators to examine shifts in social benefits derived from marine EGS. This research builds on the cross-regional comparison by exploring (i) what social regime shifts (i.e., threshold crossings) occur in the Hawaiian SES (e.g., in fisheries or tourism indicators) and what are the potential drivers of these local shifts, and (ii) to what extent are shifts consistent across communities in Hawai‘i? Examining these concepts is essential for understanding and quantifying the social value derived from management of these ecosystems. In particular, a case study of a coral reef SES serves as a model system for conducting social threshold analyses and comprehending the potential social losses in systems prone to climate change as well as the potential gains from management actions.
The main Hawaiian Islands' ecological sensitivity and tightly linked SES make it particularly important to explore whether marine resource-dependent human communities exhibit social shifts due to ecological changes. The tropical Pacific region has consistently experienced climate extremes such as warmer temperatures and lower pH [13–15]. The past century has

been characterized by longer and more frequent marine heatwaves, shorter intervals between coral bleaching events, and unfavorable calcification conditions for reef-building corals [16–18]. Indicative of the sensitivity of tropical coral reefs to these extremes as well as increasing local anthropogenic stressors, studies have frequently demonstrated ecological regime shifts in these systems [19–21]. Climate projections predict increasingly severe ecological changes (e.g., in distribution and abundance of migratory species, reef structure and species composition), which may have cascading impacts for social objectives such as fisheries productivity, ocean recreation, tourism revenue, food provision, and cultural practices in Hawaiʻi [22–27].

1.1 Social thresholds in the Hawaiian social-ecological system

Social state refers to the economic and social conditions in which people are living and can be described by a set of social objectives (e.g., income, social cohesion, health outcomes, etc.) that measure various facets of human well-being [3,28]. As social objectives may be specific to local geography and context, (i.e., objectives that are high-priority in one region or for one group of people may be low priority in others), regional case studies are vital for evaluating local management priorities. Known for its nearshore coral reefs, the Hawaiian Islands are an SES in the tropical Pacific where benefits derived from marine resources permeate every aspect of daily life [29]. This study focuses on social indicators that measure these benefits from four prominent sectors: commercial fishing, recreational fishing, marine employment, and tourism (Fig. 1)[30]. Social state is also influenced by factors that are not dependent on marine resources and fall outside the scope of this study. In Hawaiʻi, fishing activities extend from the shore to the open ocean, and range from large commercial vessels to owner-operated small boat vessels (commercial and recreational), and shoreline fishing [31–33]. Commercial fishing contributes to human well-being by providing income, livelihoods, and job security [34,35]. Non-commercial fishing not only serves as a recreational activity, but also enhances social networks through catch sharing, provides food security through subsistence, and is an important cultural practice that promotes heritage and solidifies a sense of place for many fishers [25,27,36]. Non-commercial fishing engagement and productivity are measured as recreational fishing metrics (i.e., number of recreational trips, number of fish landed) and will be referred to as recreational fishing hereafter. The beaches and reefs of Hawaiʻi also contribute to the state's tourism industry, drawing domestic and international visitors who bring revenue to the state and supply jobs [37–39]. While these economic, social, and cultural benefits do not represent all elements of human well-being in Hawaiʻi, they represent key social objectives to which coastal EGS contribute.

Social indicators can evaluate the achievement of social objectives and track progress toward management goals [3]. Indicator levels will continuously fluctuate, but rapid and continued change in one direction may define a shift from one state to another (e.g., high to low fisheries productivity) [40,41]. After a shift, functions and attributes of the social state are markedly different, potentially signaling an improvement or decline in human well-being, or a different configuration of indicators where some increase while others decrease. Social regime shifts are of management interest because they can signal fundamental changes in social system functioning and are thus useful for understanding system sensitivity to external perturbations such as regulatory and environmental change. In a tropical SES like Hawaiʻi, regime shifts signaling deteriorating ecological conditions may lead to declining social outcomes through diminished EGS, which, in turn, may affect social resilience (Fig. 1) [42,43].

Identifying social trends and thresholds requires social data with temporal depth and spatial specificity that are challenging to develop and therefore rarely available. In Hawaiʻi, long-term monitoring programs yield metrics for commercial and recreational fishing, fisheries and seafood employment, as well as tourism. These metrics reflect the established emphasis of fisheries management on predominantly economic aspects of human well-being rather than the broader suite of human well-being domains that have been identified (e.g., see Breslow et al. 2017, Leong et al. 2019)[28,36]. However, they represent a synthesis of the best available data for trend analysis of EGS delivery in Hawaiʻi. This analytical foundation lays the groundwork for assessing social outcomes in Hawaiʻi and serves as a potential model for analysis of future longitudinal social and cultural datasets that may be collected. Social-ecological systems such as Hawaiʻi are also subject to influences external to their linked ecosystems; however, this research explores how marine management can shape social-ecological outcomes by narrowing the focus to social objectives with a demonstrated relationship to marine environmental conditions.

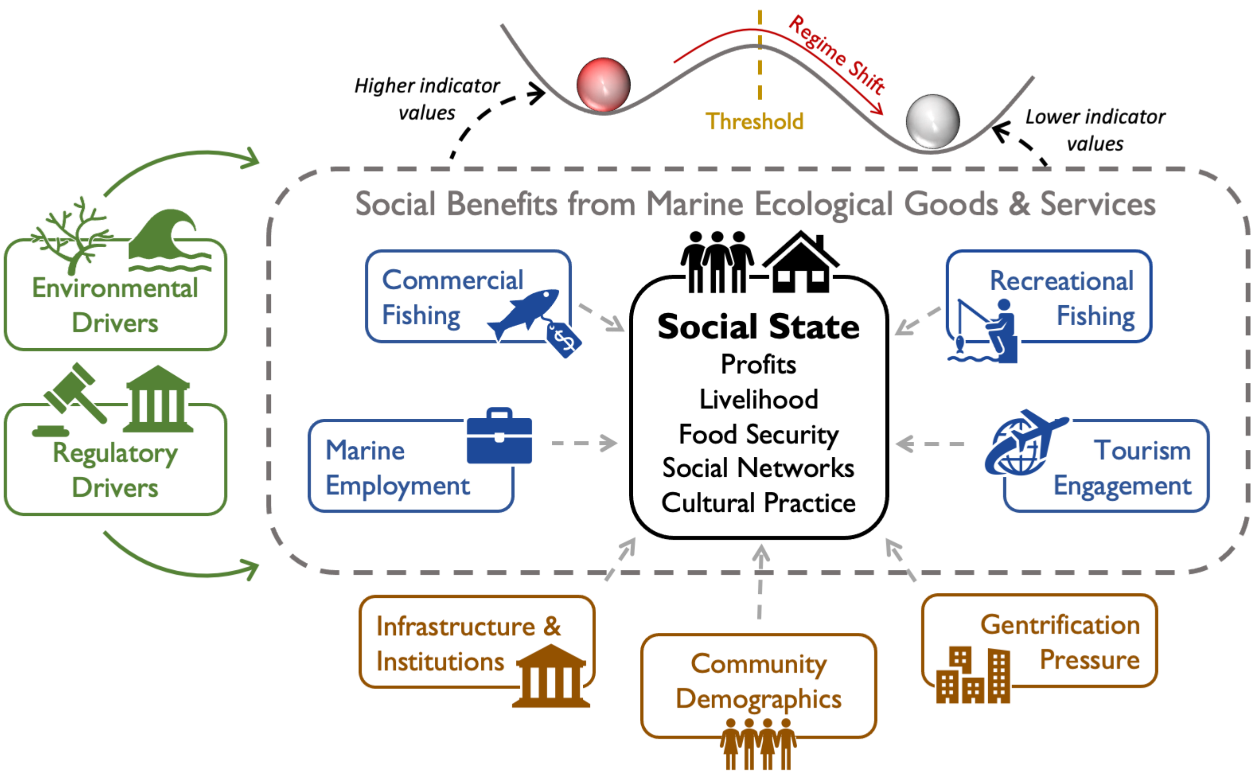

Figure 1. Conceptual diagram of the marine resource-based social-ecological system in Hawaiʻi. Environmental and regulatory drivers (left) directly influence the social benefits derived from marine ecological goods and services (larger gray dashed box), including fishing, marine employment, and tourism. These changes in benefits have direct consequences for social state, which is defined by objectives such as profits, livelihoods, food security, social networks and cultural practices (inner black box). The social system has the potential to undergo regime shifts

between states with distinct indicator value configurations (top curve graphic). Factors influencing social state that are not dependent on marine resources (bottom) fall outside the scope of this study.

2. Methods

This research synthesizes time series data from socioeconomic and coastal monitoring programs to detect trends and thresholds over time and across communities in Hawai‘i and link them to local environmental and regulatory drivers. Composite indices were constructed to rank social outcomes through quantifying the collective achievement of social objectives within distinct regimes. Together, the two analyses complement each other to explore how drivers affect individual indicators and collective outcomes. We use the combined threshold and outcome ranking methodology outlined in Perng et al. 2023 [12], which presents a cross-regional comparison of social regimes in fisheries across the United states. As a follow up to the cross-regional study, this case study explores social regimes at the finer regional scale using locally-relevant indicators and adds a spatial analysis across communities in Hawai‘i.

2.1 Indicators and data sources

This study describes the Hawaiian SES through the lens of marine management, with a focus on fisheries. Social objectives often are not explicitly defined, but can be inferred based on sectors largely related to the type of marine resource-dependent activity. This is reflected in publicly available datasets collected for commercial fishing, recreational fishing, tourism, employment, and environmental quality (Table 1). Potential social indicators available for each marine activity sector reflect the assumptions made by managers on the important marine resource-related data to collect longitudinally. For commercial fishing, fisheries management typically seeks to optimize catch and profitability, which are proxied by landings and revenue, respectively, for the purposes of this study. Additionally, diversity in both catch and revenue indicate higher adaptive potential and functional redundancy in the fishery through varied resource streams [44,45]. Similarly, recreational fishing objectives optimize for higher engagement (landings and effort) and greater diversity in catch, which is reflected in reported landings [46]. Tourism and marine-resource related employment also assume that increased revenue, jobs, and spending reflect good social conditions [47,48]. The ecological indicators selected represent environmental processes that have been shown to influence the chosen social indicators via effects on coastal and pelagic species in the Hawai‘i region. Specifically, greater secondary consumer biomass and a higher ratio of hard coral to fleshy and turf algae indicate good reef conditions, as they enhance biodiversity and stock abundance. Primary productivity measured by chlorophyll-a concentration can limit pelagic fisheries yield [49]. Sea surface temperature anomalies related to El Niño–Southern Oscillation events regulate target pelagic species in commercial fisheries in Hawai‘i, where warmer periods are associated with higher fish abundance [50,51].

Most data are available at the statewide scale and were used in both the threshold and outcome ranking analyses. The outcome ranking analysis included a statewide temporal and spatial analysis across local communities, which comprised distinct datasets that were collected at smaller geographical scales as part of a Community Social Vulnerability Indicator program [52,53]. For example, both outcome ranking analyses use recreational trips as an indicator, but the community data focus on for-hire recreational modes such as private charters. Nonetheless, the indicators used in the spatially sensitive outcome ranking analysis are thematically aligned with the indicators used in the statewide temporal analysis in their focus on commercial and recreational fishing in local communities across the main Hawaiian Islands.

Table. 1 Sources and descriptions of indicators used in threshold and outcome ranking analyses.

Marine Activity Sector	Source	Indicator	Definition and Units of Measurement
Commercial Fishing (1981 - 2019)	NOAA Fisheries; https://foss.nmfs.noaa.gov/apexfoss/f?p=215:200:6724777967495::NO::::://foss.nmfs.noaa.gov/apexfoss/f?p=215:200:6724777967495::NO:::	Commercial Landings	Millions of pounds landed
		Commercial Revenue	Millions of dollars in revenue from landings sold, deflated using US Bureau of Economic Analysis implicit price deflator (https://fred.stlouisfed.org/data/GDPDEF.txt)
		Landings Diversity	Shannon Diversity Index: calculated from species-specific pounds landed
		Revenue Diversity	Shannon Diversity Index: calculated from species-specific revenue
Recreational Fishing (1981 - 2019)	Marine Recreational Information Program; https://www.fisheries.noaa.gov/data-tools/recreational-fisheries-statistics-queries)	Recreational Landings	Millions of pounds landed
		Recreational Effort	Millions of angler trips
		Recreational Landings Diversity	Shannon Diversity Index: calculated from the recreational landings data
Tourism Engagement (2005 - 2016)	National Coral Reef Monitoring Program; https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0191513	Visitor Spending	Total visitor spending
		Number of Visitors	Total number of tourism arrivals
		Tourism GDP	Total GDP produced by the tourism industry
		Tourism Employment	Total number of individuals employed in the tourism industry
Marine Resource-Related Employment (BLS: 2001 - 2019; NES: 1997 - 2018)	US Bureau of Labor Statistics; https://data.bls.gov/cgi-bin/dsrv?en	Employment	Total number of individuals employed by establishments in marine resource-related sectors (fishing, seafood markets, seafood packaging, seafood wholesale)
		Earnings	Total wages paid to employees in the four marine resource-related sectors above

Marine Activity Sector	Source	Indicator	Definition and Units of Measurement
		Establishments	Number of establishments in the four marine resource-related sectors above
	US Census Bureau, Nonemployer Statistics; https://www.census.gov/programs-surveys/nonemployer-statistics/data/datasets.html	Self-Employment	Number of self-employed individuals in fishing, seafood markets, and seafood processing sectors
		Earnings (Self-Employed)	Millions of dollars in total receipts from self-employed individuals in the three sectors listed above
Environmental (2005 - 2016)	Donovan et al., 2018 [54]; Data hosted on Dryad database; https://datadryad.org/stash/dataset/doi:10.5061/dryad.rj083bv	Secondary Consumers	Biomass of secondary consumers (grams per m^2)
		Coral-Algae Ratio	Ratio of hard coral percent cover to fleshy macroalgae and turf algae percent cover
	Ocean Colour v 5.0; https://climate.esa.int/en/projects/ocean-colour/data/	Chlorophyll-a	Chlorophyll-a concentration (mg/m^3)
	NOAA NCEI; https://www.ncei.noaa.gov/access/monitoring/enso/sst	ENSO Sea Surface Temperature Anomalies	Niño 3.4 region sea surface temperature anomalies calculated using the Extended Reconstructed Sea Surface Temperature version 5
Local Community (2010 - 2018; Census County Division scale)	Community Social Vulnerability Indicators; Individual indicators and sources outlined in Jepson and Colburn, 2013 [52];	Commercial Landings	Pounds landed per thousand capita
		Commercial Revenue	Dollars in revenue from landings sold per thousand capita
		Number of Dealers	Number of fish dealers per thousand capita
		Number of Commercial Permits	Number of commercial permits per thousand capita
		Recreational Fishing Trips	Number of recreational trips per thousand capita
		Population Density	Population (thousands) km^2
		Total Water Area	Area of census tract area covered by water

2.2 Threshold analyses and multi-criteria outcome ranking

Following the methods outlined in Perng et al. 2023, we identified thresholds in the selected indicators (Table 1) and calculated composite indices from the suite of indicators to represent and rank social state. Non-linear Generalized Additive Models (GAM) were fit to indicators over time. Significant trends and thresholds were identified by calculating derivative functions of the fitted model with 95% simultaneous confidence intervals. The first derivative function measures slope and a significant trend occurs when the slope deviates significantly from zero. Positive and negative values signify increasing and decreasing trends, respectively. The second derivative function measures changes in slope and a threshold occurs when there is a rapid change in slope, interpreted as a change in sign in the second derivative. Thus, thresholds always occur within regions of significant trends, while trends may occur without thresholds.

To rank outcomes, we used Data Envelopment Analysis (DEA) to score system performance based on a suite of indicators. We constructed composite social-ecological indices that represent the collective achievement of social objectives, while accounting for environmental inputs that affect resource availability. These indices were used to evaluate social outcomes in a statewide temporal analysis and a spatial analysis across local communities. The two analyses used different datasets due to differing data availability at each spatial scale. Each analysis covered the entire time period of data overlap for all indicators used to create the indices. In the statewide analysis, commercial revenue, revenue diversity, recreational landings, total marine resource-related employment, and visitor spending were the outputs for our social index. For the ecological index, secondary consumer biomass and the ratio of corals to fleshy and turf algae were the inputs. In the spatial analysis of fishing communities, the social index used per capita values of commercial landings, commercial revenue, and number of dealers, commercial permits, and recreational angler trips across 41 communities in the main Hawaiian Islands (Local Community indicators; Table 1). Because indicators used to construct the input index can be considered as any measures that may regulate or limit output, [1]total water area and population density from the fishing community dataset were used as proxies for resource availability and usage capacity (Fig. 11)[55]. Mean-normalized observations were benchmarked to a reference point. We followed the common convention of setting the first observation in the dataset as the reference point, which was 2005 for the temporal analysis and Hilo, Hawaiʻi in 2010 for the spatial analysis.

By combining threshold analyses and outcome ranking, our approach assesses integrated system performance through the achievement of social objectives. The GAM identified temporal regime shifts with regards to the provision of benefits derived from the local marine ecosystem. The DEA scored regimes based on the indicators selected to represent delivery of ecological goods and services, while accounting for environmental conditions. We then linked identified shifts and system outcomes to management actions by identifying regulatory changes

[1] Total water area per community was used as a proxy for resource availability as it represents the area providing benefits from marine EGS (e.g., fish, recreational trips, marine tourism).

preceding thresholds. Together, the analyses complement each other to determine how the Hawaiian SES responds to ecological and regulatory drivers.

3. Results and Discussion

The threshold analysis showed that social thresholds, with regards to marine ecosystem service provisioning, do indeed exist and that regulatory changes throughout time are consistently correlated with these shifts. The outcome ranking analysis demonstrated linkages between ecological and social changes and spatial variation among local communities in Hawaiʻi. As a whole, the results display compensatory relationships between social indicators that appear to have tradeoffs (i.e., pelagic v. coral reef fishing) and fundamental integrative relationships among environmental, regulatory, and social changes in the marine SES in Hawaiʻi.

3.1 Thresholds and Trends

3.1.1 Commercial fishing

Analysis of commercial data demonstrated a period of fisheries expansion at the beginning of the time series. Commercial landings and revenue have similar trends, with revenue exhibiting steeper slopes during periods of change (Figs. 2a-d). Total fisheries revenue (x) displayed a marked increase and regime shift in the 1980s, primarily driven by pelagic species (△). Functions of landings displayed similar shapes, but shallower slopes precluded detection of a significant trend or threshold in total landings. The time series began in 1981, a few years after the implementation of the Magnuson-Stevens Fishery Conservation and Management Act (MSA) in 1976, which is the primary law governing U.S. offshore commercial fisheries [56]. Growth of the pelagic fishery coincided with the creation of exclusive economic zones (EEZs) under the MSA, which provided new domestic fishing opportunities in areas that were previously international waters. Prior to the creation of EEZs, international fleets, particularly Japanese vessels, competed for tuna resources in the Pacific until the MSA pushed them 200 miles offshore from the Hawaiian Islands [57]. Increasing diversity in landings and revenue, especially in pelagic species, accompanied the increasing revenue (Figs. 2e, f). This suggests that new opportunities prompted local fishers to increase value landed by diversifying catch. In the 1980s, pelagic fisheries in Hawaiʻi transitioned from primarily pole and line fishing of skipjack tuna (aku) to a longline fishery dominated by bigeye tuna (ahi) and swordfish (aʻu; Fig. 3) [58]. Technological innovations introduced to Hawaiʻi in 1985, specifically modern longline vessels featuring a single monofilament mainline, facilitated this transition [59] and greatly improved fishery efficiency [60].

While early expansion also occurred in the bottomfish (deep; ▫) and lobster fisheries (✳), the initial growth was punctuated by rapid decline and closures. Deepwater species displayed significant increases in both landings and revenue in the early 1980s (Figs. 2c, d), possibly due to increasing demand, and contributed to fisheries expansion early in the time series [61]. The nascent lobster fishery of the Northwestern Hawaiian Islands (NWHI), which began in 1976, displayed a similar increasing trend, but this was not significant in our analyses. Following heavy extraction in the early 1980s, both fisheries experienced significant landings and revenue declines in the late 1980s through the 1990s and bottomfish experienced landings and revenue diversity declines [62,63]. This decline prompted the transfer of bottomfish and lobster fishing vessels to the growing pelagic longline fishery, further contributing to its expansion [58]. Bottomfish landings and revenue plateaued in the late 2000s, remaining at the lowest level for all species groups, while diversity of both decreased significantly in the 1990s. These trends were likely due in part to the establishment of 19 Bottomfish Restricted Fishing Areas (BRFAs) in 1998 that contracted available fishing grounds, followed by a 2007 revision that reduced the number to 12 BRFAs while expanding the area covered [64]. In 2009, the NWHI bottomfish fishery closed permanently, while the main Hawaiian Islands fishery continued to be managed under an annual catch limit program that began in 2007 [65].

The initial expansion of the pelagic fishery was followed by a period of contraction. In the mid-1990s, total revenue significantly decreased due to a combination of declining trends in pelagic and deepwater species, neither of which were significant on their own. Longline fishery expansion halted due to a series of increasingly strict regulatory measures. A limited-entry management plan in 1991 restricted entry of new vessels into the fishery [33] and federal observers were placed on longline vessels beginning in 1993 [66]. This marked the beginning of a transitional period of fishery closures and diversification to alternative stocks. In the late 1990s, concern over charismatic megafauna led to a series of regulations to address fishery interactions. For the already overexploited lobster fishery, fishery interactions with endangered monk seals contributed to its closure in 2000 [62]. Similarly for the shallow-set swordfish fishery, seabird interactions and turtle bycatch contributed to the fishery closure from 2001-2004, likely driving low landings and revenue in the early 2000s (Figs. 2a, 2b, 3) [67–69].

Records of jawed vertebrates (▽) dropped to near zero in 2000, while records began appearing for several newly recorded pelagic species (e.g., opah, marlin, wahoo) and reef (○) species (e.g., scad, green jobfish, surgeonfishes; Fig. 3). This is likely indicative of a change in species recording methods that resulted in the appearance of significantly increased reef landings and diversity as well as pelagic revenue. For the newly recorded reef species, the volume of landings started relatively high in 2000, accounting for the sudden increase in reef landings and diversity. Alternatively, landings for newly recorded pelagic species started low and increased rapidly. This gradual increase of newly recorded pelagic species suggests that landings of miscellaneous jawed vertebrates may have increased substantially, warranting disaggregation. As landings of these new species increased, landings of many historically important pelagic species decreased (e.g., skipjack tuna, swordfish, etc.). The concurrent increase in pelagic revenue suggests an efficient fishery transition to more valuable stocks, possibly due to fishers diversifying catch to alternative stocks after the lobster and swordfish fishery closures and virtual closure of the bottomfish fishery.

The appearance of these new stocks marked another period of expansion for the pelagic fishery in recent years, punctuated by a significant increase in pelagic revenue that extended to 2015. Aside from new stocks, this increase was primarily due to increased tuna landings and value (bigeye and yellowfin; Fig. 3), likely driven by increasing global demand for raw tuna [70].

Domestic demand for tuna also increased as tourism spiked in Hawai‘i after the great recession in 2007-2009 [71,72]. Opah, blue marlin, pomfrets, spearfish, and oilfish also increased during this time, but the aggregate volume was far lower than that of tuna and swordfish (Fig. 3). The mid-2010s halt in pelagic growth coincides with the 2015-2017 phased reduction in bigeye tuna catch limits [73]. The longline fishery closed each year when it hit annual catch limits; the longest closure occurred in 2016, with almost a third of the fishing year remaining [70]. Low landings and revenue in 2020, likely driven by COVID impacts on Hawaiian fisheries, may have further influenced the recent trend. A steep decline in tourism, which drives local seafood prices, as well as reduced seafood exports, may be responsible for those low values [74,75].

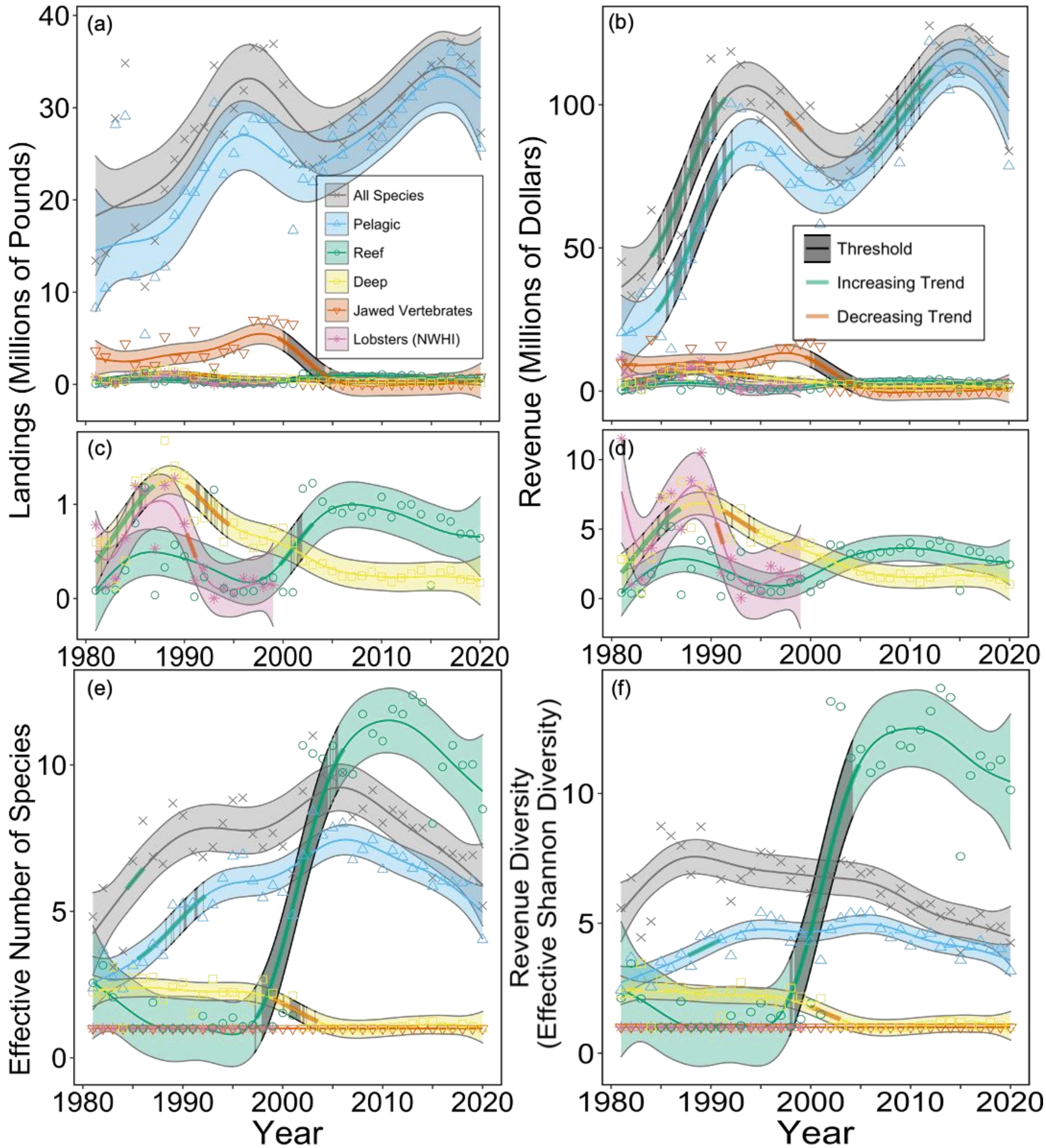

Figure 2. Generalized additive model (GAM) functions (±95% CI) of commercial fisheries (a) landings, (b) inflation-adjusted revenue (2020 value), (c, d) close-ups of (a) and (b), (e) diversity of landings, and (f) revenue diversity. Data are split by species groups: all species combined (x), pelagic species (△), reef and reef-associated species (○), deepwater species (□), jawed vertebrates (▽; landings not identified at species level, primarily pelagic and reef species), and lobsters (✳). Points represent raw data. Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds marking transitions from one regime to another are shaded in gray with black outlines.

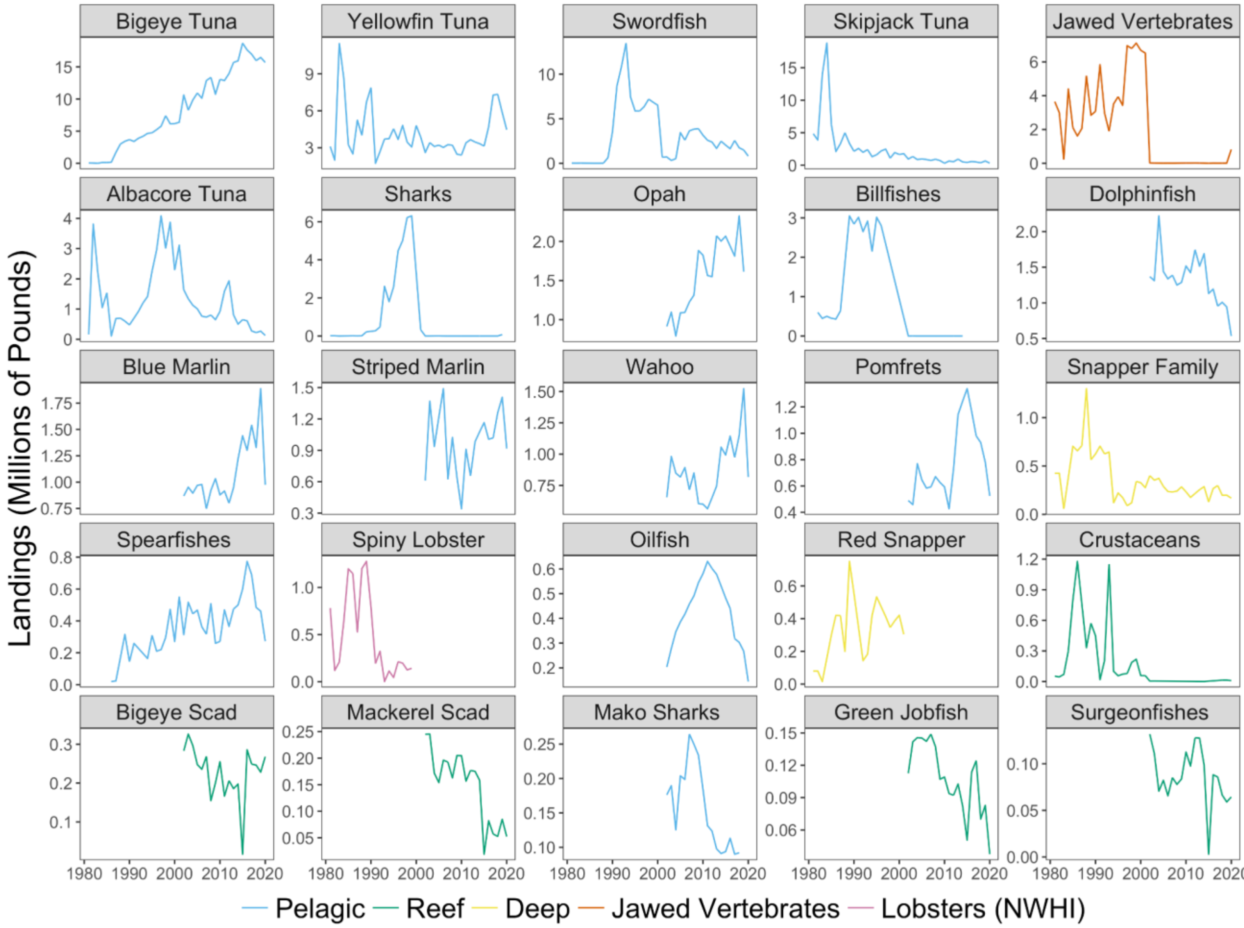

Figure 3. Commercial landings of the top 25 most landed species by volume. Plots are in rank order.

3.1.2 *Recreational fishing and tourism*

Recreational fishing patterns contrast the commercial patterns, with effort significantly increasing after 2015 and landings displaying a similar, but not significant, trend (Fig. 4). This indicates that increasing effort may have had diminishing returns. The mismatch between effort and landings also may have been influenced by a methodological change in data collection since 2018, as recent effort and catch-per-unit-effort values from which recreational landings are extrapolated were obtained from two different data streams. The increasing trend in recreational effort (Fig. 4e) opposes the commercial production trend (Figs. 2a, b), as increasing commercial productivity stopped after 2015. The post-2015 commercial trend appears to be decreasing, but continued data collection is needed to see if a significant trend establishes. This juxtaposition between trends in commercial and recreational effort potentially highlights fisher behavioral plasticity, demonstrating a possible tradeoff of fishers phasing toward recreational engagement in times of low commercial productivity. In Hawaiʻi, fishers often participate in both sectors simultaneously and recreational fishers may even sell a portion of their harvest to supplement their primary source of income [31]. These linkages between the two sectors suggest that integrated management of both sectors together is imperative to support effective ecosystem-based fisheries management.

There is also a noticeable divergence between recreational diversity in landings and commercial diversity. Unlike commercial fishing, recreational landings consist primarily of reef species (○) in terms of number of fish landed and is far more diverse (Figs. 2a, b, 5). Many recreational fishers fish for pleasure, subsistence, or cultural tradition and are likely to stay nearshore, within reef bounds, explaining the bias towards reef fish [27]. Coral reefs are the most biodiverse habitat type in the marine environment, likely contributing to high diversity in landings of reef fish [76,77]. Reef fish hold cultural significance in Hawaiʻi and fishing is a culturally important practice. Thus, in addition to economic objectives, high recreational engagement also contributes to sociocultural objectives, including community cohesion, cultural practice, and food security [25,27,36], although these contributions are not yet measured systematically. One of the top species landed in the recreational sector is the native striped mullet (ʻamaʻama) , a species that was highly coveted by Hawaiian royalty and was once cultivated in fishponds (◇; Fig. 5)[78]. Recreational fishing also contributes to other sectors of the economy through expenditures such as vessel and equipment purchase and maintenance [67,79,80].

Tourism also provides important economic benefits to Hawaiʻi. Coral reefs and the marine environment as a whole are instrumental in attracting tourism and its associated revenue. Visitors travel from all over the world to participate in marine-related activities, such as diving and snorkeling, eating fresh fish, and enjoying beaches [39,81]. Tourism stimulates the local economy, supplying hundreds of thousands of jobs paying billions of dollars in annual wages and generating more than twice that in visitor expenditures (Fig. 6). Tourism trends dipped significantly around 2009, accompanied by thresholds, signaling a temporary regime shift to low tourism and a return to prior levels. This coincides with the great recession, a global economic downturn that lasted from 2007 to 2009 [71]. Apart from the temporary decline, there is an overall significant increasing trend in tourism GDP and employment, as well the number of visitors. However, the initial decrease in visitor spending after 2007 outweighs the subsequent increase after 2009, suggesting that more tourists are visiting Hawaiʻi but are reducing trip expenditures. This has negative implications for the state, as tourism has been correlated with environmental degradation and displacement of local residents and Native Hawaiians [72,82]. With individual visitors reducing their spending, the economic benefits may cease to outweigh the environmental and sociocultural costs. If these trends continue, a management response may be necessary to ensure that the benefits of tourism remain greater than the costs.

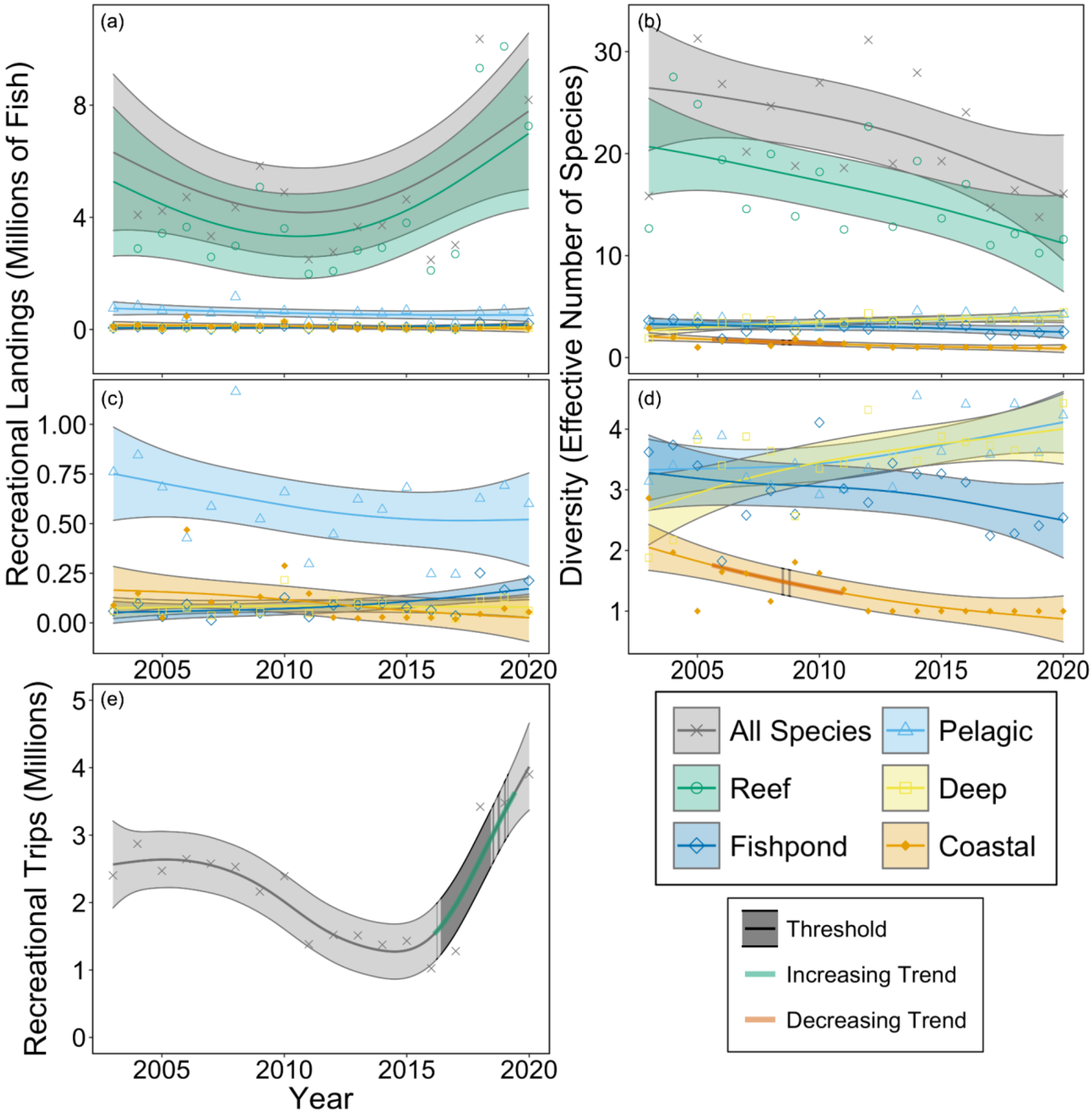

Figure 4. Generalized additive model (GAM) functions (±95% CI) representing recreational fisheries (a) landings, (b) diversity of landings, (c, d) close-ups of (a) and (b), and (e) effort. Landings and diversity are split by species groups: all species combined (x), pelagic species (△), reef and reef-associated species (○), deepwater species (□), fishpond species (◇), and coastal species (●). Points represent raw data. Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in gray with black outlines.

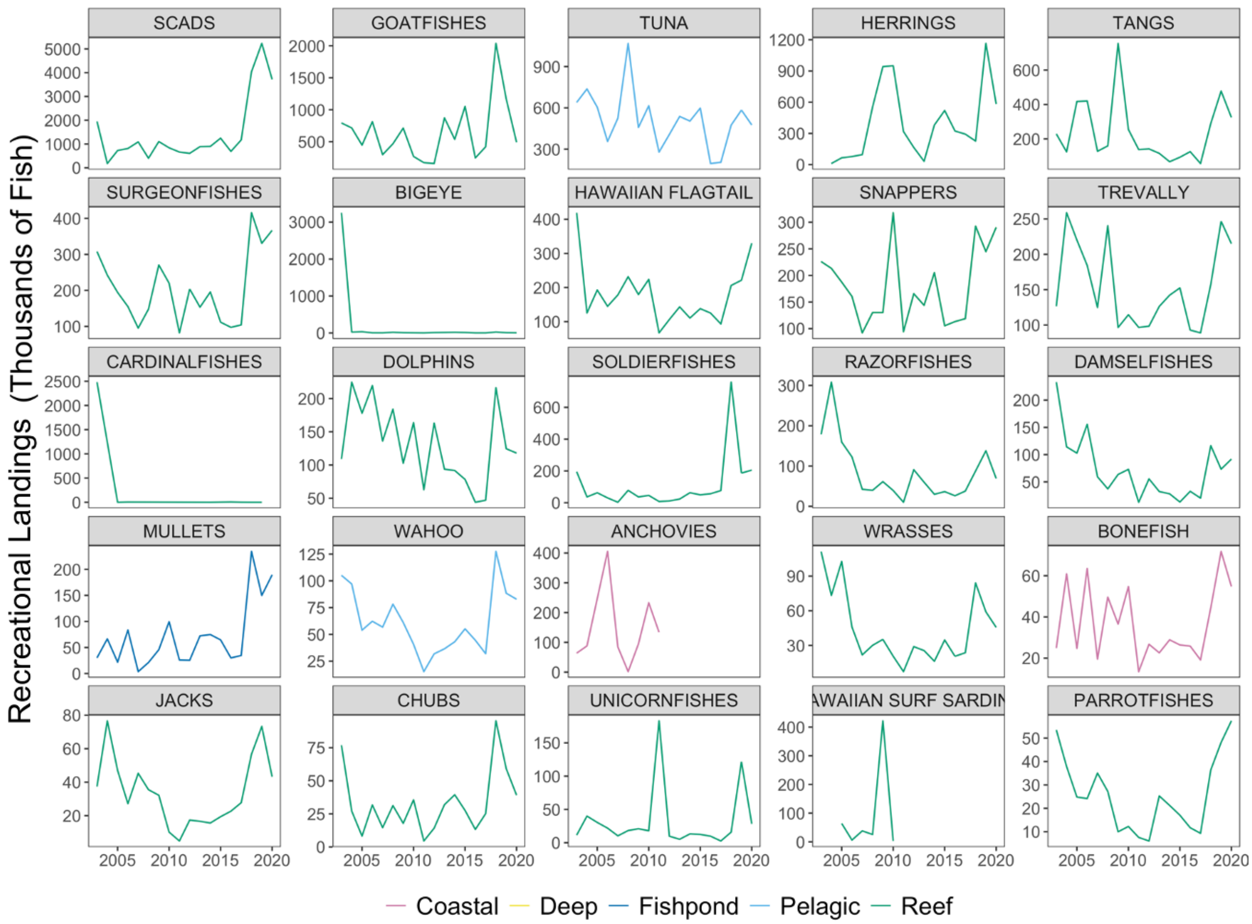

Figure 5. Recreational landings of the top 25 most landed species by quantity. Plots are in rank order.

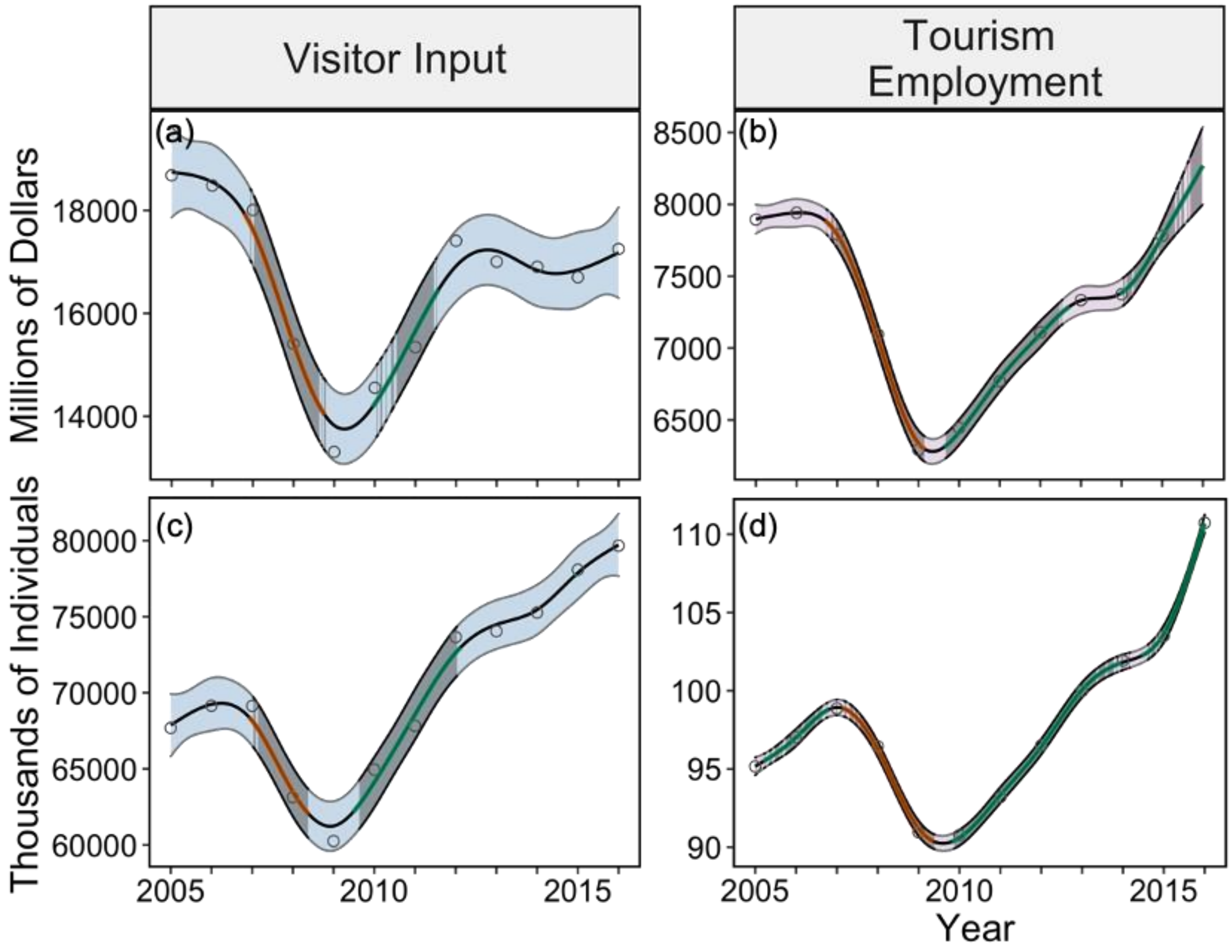

Figure 6. Generalized additive model (GAM) functions (±95% CI) representing (a) visitor spending, (b) tourism GDP, (c) number of visitors, and (d) tourism employment. Points represent raw data. Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in gray with black outlines.

3.1.3 *Marine resource-related employment*

Employment trends in fishing and seafood sectors demonstrate a significant downturn and regime shift across all employment statistics from 2001 to 2005 (Fig. 7). This shift was driven by declines in fishing (○) and seafood wholesale (△) and coincides with the swordfish fishery closure from 2001-2004. Following the closure, a substantial proportion of vessels that targeted swordfish moved to California [67]. Additionally, because the bulk of swordfish landings are exported to the U.S. mainland due to low local demand, wholesalers saw employment and wages decrease post-closure. The wholesale sector rebounded after 2010, significantly driving up marine-related employment and wages (Fig. 7a, b) and signaled a regime shift in marine employment. The shift aligns with upward commercial revenue trends, which were driven by increased values of bigeye and yellowfin tuna (Fig. 2). High prices of tuna were likely a result of increased demand by tourists in Hawaiʻi after the great recession [72] and increased exports to high value Japanese markets in the early 2010s [83,84]. In contrast to employment and wages, establishments significantly decreased over the entire time period across all sectors (Fig. 7c). This multi-sectoral decline in establishments signaled a regime shift, as evidenced by identified thresholds. This regime shift demonstrated consolidation, as employment increased while establishments decreased (Fig. 7a).

Employment trends vary between Bureau of Labor Statistics (BLS) and Nonemployer Statistics (NES) with regards to sector distributions (Fig 7). For BLS data, seafood wholesale and seafood markets (□) are the two foremost sectors of marine employment and display opposing trends early in the time series (Fig. 7a, b). At this time, the two sectors may have been in direct competition over freshly harvested fish. In Hawaiʻi, fishers have the option of selling fresh fish directly to wholesalers and retailers or through local auctions (e.g., Honolulu Fish Auction on Oʻahu, Suisan Fish Market on Hawaiʻi Island) where dealers may bid on same-day harvest [85]. Post-2008, employment and wages plateaued for seafood markets but increased for wholesale, likely due to an increase in tourism and domestic seafood demand. Additionally, wholesale dealers may have shifted towards direct transactions with latters and reduced the capacity of markets as an intermediate. Although fishing accounts for the lowest proportion of BLS employment, it comprises the bulk of NES employment (Figs. 7d, e), indicating that owner-operators dominate the commercial sector. The prevalence of owner-operators, who demonstrate higher efficiency than hired captains, may improve fishery efficiency [86]. Fishing employment also demonstrated an overall declining trend. Decreased employment coupled with increased harvest revenues also supports a narrative of increasing fishery efficiency.

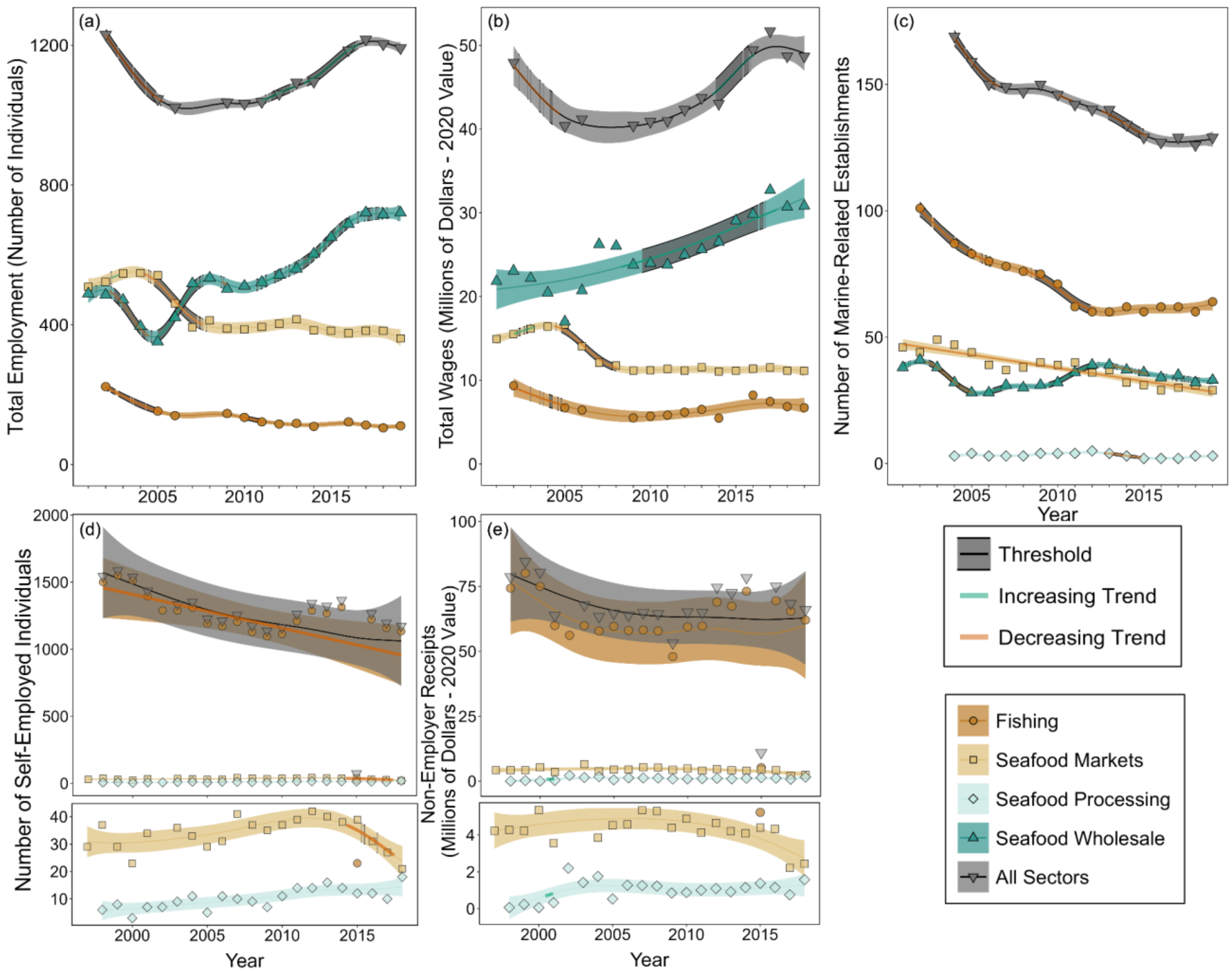

Figure 7. (Color printed) GAM functions (±95% CI) representing (a) total employment, (b) total wages, (c) number of establishments, (d) self-employment, and (e) nonemployer receipts in marine resource-related industries. Bottom panels of (d) and (e) display zoomed-in plots of seafood markets and seafood packaging. Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds marking transitions from one regime to another are shaded in gray with black outlines.

3.1.4 *Management implications of identified thresholds and trends*

The combined insights from commercial fishing, recreational fishing, tourism, and marine employment results reveal threshold responses to local regulatory actions (e.g., fishery closures, catch limits) and broader economic pressures (i.e., the great recession). The contrasting commercial and recreational trends underscore the delicate balance required in fisheries management, as concentrated stewardship efforts on one sector has the potential to undermine the other. Notably, the commercial emphasis on pelagic species and the recreational focus on reef species hold profound implications for the social benefits that may be derived from future seas. Shifts in the commercial fishery are likely to manifest as range shifts of pelagic species, potentially resulting in increased travel distances for fishers, changes in the species they target, or even relocation from the region altogether [87–89]. For the recreational fishery, projected climate change may lead to fishery decline as rising temperatures and ocean acidification impact reef-building corals [18,90]. These environmental impacts, coupled with recreational fishing pressure, threaten coral reefs in Hawaiʻi and the benefits they provide to coastal communities. Thus, addressing recreational fishing in management may be vital to sustaining ongoing reef fisheries productivity and human well-being in Hawaiʻi.

Management effectiveness hinges on scientific evaluations, which are inherently constrained by data collected through monitoring programs. These programs predominantly capture economic aspects, typically collecting little to no data that directly measure many other important social or cultural objectives (e.g., social cohesion, culturally appropriate food systems, sense of place). Additionally, the historical context of colonialism in Hawaiʻi skews data collection efforts towards objectives prioritized by governmental management agencies, such as economic profitability, rather than those important to local residents and native or indigenous groups [91]. Tensions between local residents and managers, as well as between disparate stakeholder groups, regarding resource use priorities complicate efforts to holistically assess social regimes. Further, data that measure local cultural objectives such as spirituality and sense of place would contribute to a more well-rounded analysis of social state [25,36]. Therefore, enhancing the responsiveness of marine management may be achieved by expanding monitoring programs to include the assessment of these sociocultural objectives that are currently not thoroughly examined.

3.2 Multi-Criteria Outcome Ranking

3.2.1 *Temporal analysis of statewide indicators*

The social index measuring social benefits (outputs) and the ecological index measuring resource inputs display similar shapes, with the ecological index exhibiting larger fluctuations (Fig. 8). Although the relationship between the two indices is not one-to-one, as demonstrated by a fluctuating social-ecological index, they display similar peaks and valleys, demonstrating the expected association between ecological condition and social state. Smaller fluctuations in social state suggest that it may be robust to short-term changes in environmental conditions due to human behavioral plasticity. This plasticity allows the maintenance of service provisioning in years of low ecological index values. The social-ecological (productivity) composite index, which is the ratio of the social index to the ecological index, displayed three spikes: 2006, 2010, and 2013 (Fig. 8). These spikes reflect low points in the ecological input index driven by low secondary consumer abundance. Despite lower resource values, the social index only experienced a relatively small decrease, suggesting potential resilience and adaptability. For instance, fishers in Hawaiʻi commonly use multiple fishing modes, allowing them to adapt to changing resource conditions [31]. Fisher flexibility and the engagement of some individuals in both recreational and commercial sectors suggests that future ecosystem-based management efforts may benefit from directly addressing system outcomes, rather than applying sector-specific regulations.

In addition to behavioral plasticity, there are also external drivers, such as economic conditions, that may affect the social response to environmental resource changes. The social index was highest in 2009 and 2012, corresponding to peaks in recreational landings and commercial revenue, respectively. Thus, success in either the commercial or recreational sector may contribute to high social indices, but tradeoffs between the two may differentially affect individuals. While these peaks coincide with higher ecological index values that reflect peaks in sea surface temperature anomalies, secondary consumers, and coral to algae ratio, the relatively small magnitude of change suggests external drivers at play. High recreational engagement in 2009 coincided with the end of the Great Recession, and dropped steeply soon thereafter [71], suggesting that fishers may have increased their recreational fishing engagement during the economic lull. The 2012 spike in commercial revenue, despite steady landings (Fig. 2), coincides with peak tourism visits post-recession (Fig. 6) and may be another example of economic influence (i.e., booming tourism driving up fish prices). The spikes and dips of the temporal analysis demonstrate that regimes fluctuated regularly within the assessed time period and that high social index scores, in terms of marine EGS provisioning, are tied to fisheries productivity and seafood markets. Overall, there appears to be a shallow increasing trend in social state quantified through indicators related to ocean EGS, demonstrating a continued reliance on ocean resources in the Hawaiian SES.

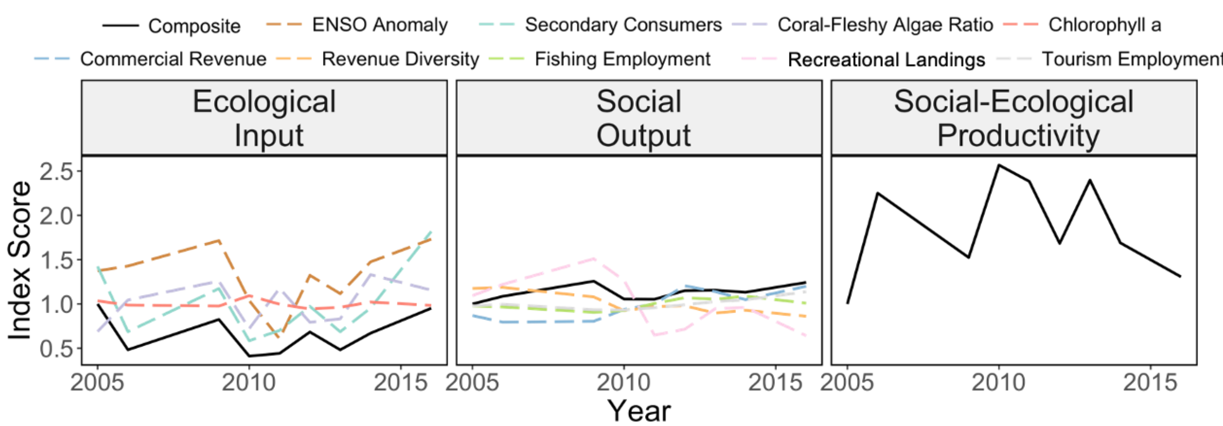

Figure 8. Plots of ecological (input), social (output), and social-ecological (productivity) indices from 2005 to 2017. Dotted lines represent mean-normalized values of individual indicators.

3.2.2 *Spatial analysis by fishing communities*

To delve deeper into local conditions, central tendencies and variation in social-ecological productivity across local communities were compared. Kaua‘i has the highest social-ecological productivity overall (Fig. 9). Two things could be driving this result. First, Kaua‘i has the second lowest population of all counties, contributing to high per capita values of many indicators in the composite index (Fig.10). Secondly, Kauai‘i is the least developed county, and less disturbed stocks may have led to higher productivity.

Our results highlight inter-county differences with regards to which ecological goods and services are most important for each county. The index scores highly vary across fishing communities within each county, but certain communities stand out largely because fisheries activities are concentrated there (Figs. 9, 11). In Kauaʻi, Līhuʻe has the highest index, likely because it is the population and economic hub of the island where the majority of the county's boats are moored [92]. In Honolulu County, which covers Oʻahu, Honolulu has the highest index and is the home base of the pelagic longline fleet, which conducts most of the state's commercial fishing activities [93]. In Maui County, Hana and Spreckelsville have the highest indices. Spreckelsville has a very small population, and the high value is likely an artifact of using per capita values. Hana is a rural area on east Maui where population is also low and residents frequently engage in fishing [53,94]. Maui has the lowest commercial production of all four counties but has proportionally high recreational fishing values (Fig. 10). Due to low interharbor competition and location in a tourist hub, Maui's charter fleet is highly profitable, boasting the highest charter fees and per trip revenues in the state [92]. High productivity was also found in Lahaina community in Maui from where most charter trips originate. In Hawaiʻi county, North and South Kona on west Hawaiʻi Island had the highest indices. This is likely due to high commercial engagement driven by the aquarium fishery as well as recreational sportfishing [95]. West Hawaiʻi houses the largest contiguous reef in the main Hawaiian Islands and was the predominant collection area for aquarium fishers in the state until the 2018 aquarium fishing moratorium that eventually transitioned to a statewide ban in 2021 [96–98]. Additionally, the harbor with the largest concentration of charter fishing operations is located in Kona, where avid sportfishers, both domestic and international, travel to attend renowned billfishing tournaments [92,99]. These spatial differences suggest that environmental and regulatory changes will not be evenly distributed across counties and communities.

3.2.3 *Linking index trends across geographic scales*

The temporal and spatial analyses demonstrate linkages between community and statewide trends. There was a spike in commercial landings and revenue in 2012 across counties (Fig. 10), which aligns with the high social output index value in the statewide analysis (Fig. 8). Some individual communities demonstrated discernible peaks in 2012 (e.g., Kekaha-Waimea, Lahaina), likely contributing to the 2012 spike (Fig. 12). All counties demonstrate declining commercial landings and revenue after 2015 (Fig.10), suggesting that the effect of the recent commercial fishing lull was consistent across counties. This trend was accompanied by a shallower decline in commercial permits and no discernible change in the number of dealers, suggesting that seafood vending industries remained valuable. The employment results support this inference, as seafood wholesale employment and revenues continued to rise after 2014 (Fig. 7). Recreational trips were relatively consistent until 2015, when a decline for Honolulu County began, followed by low values for Kauaʻi and Hawaiʻi County in 2016 and Maui County in 2017 (Fig. 10). This is reflected in the statewide data (Fig. 4) and comes on the heels of a large-scale marine heatwave that resulted in severe coral bleaching events in the Hawaiian Islands [16,100].

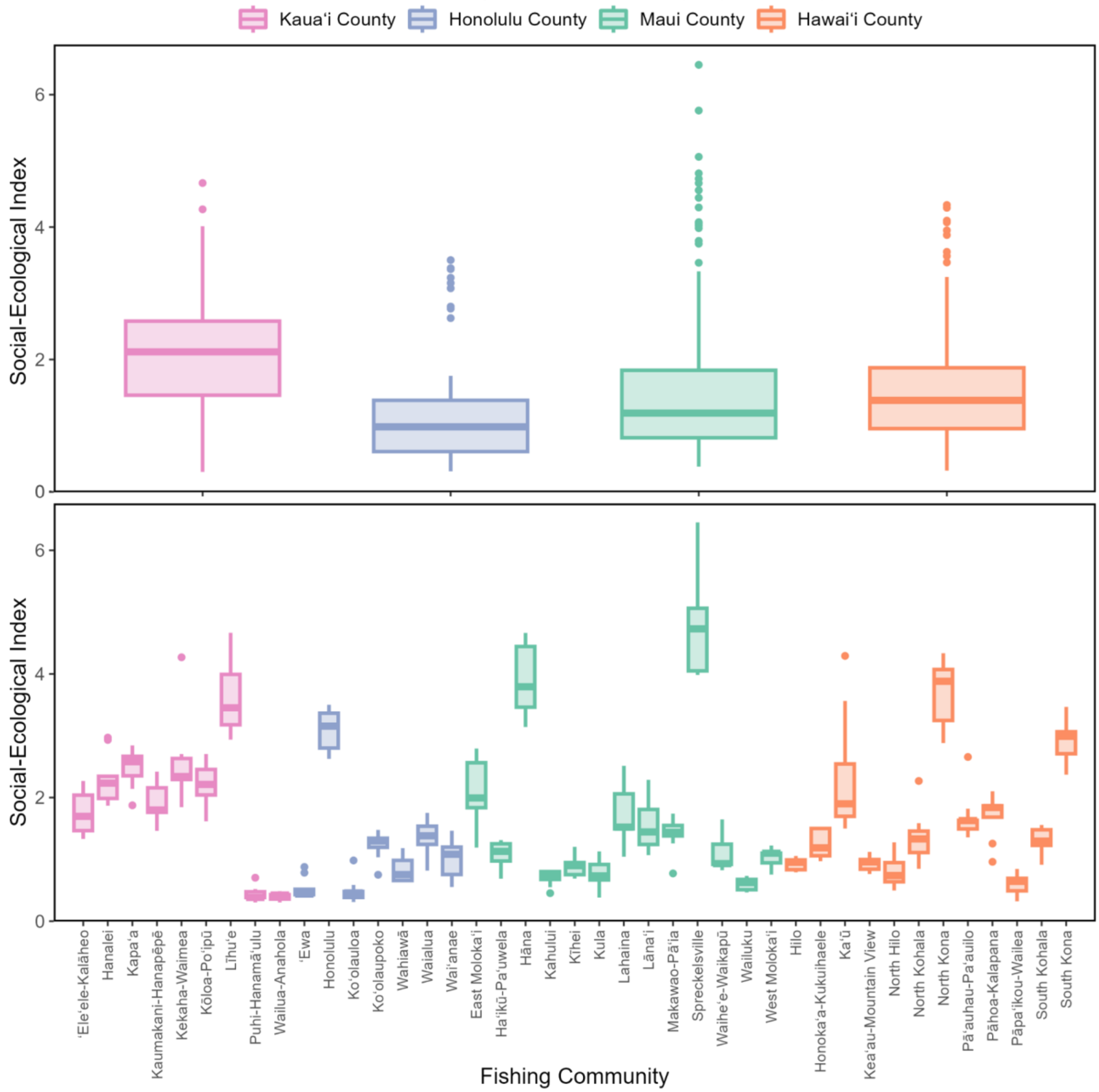

Figure 9. Medians and variabilities of social-ecological (productivity) indices across 2010-2018 summarized by counties (top) and fishing communities (bottom).

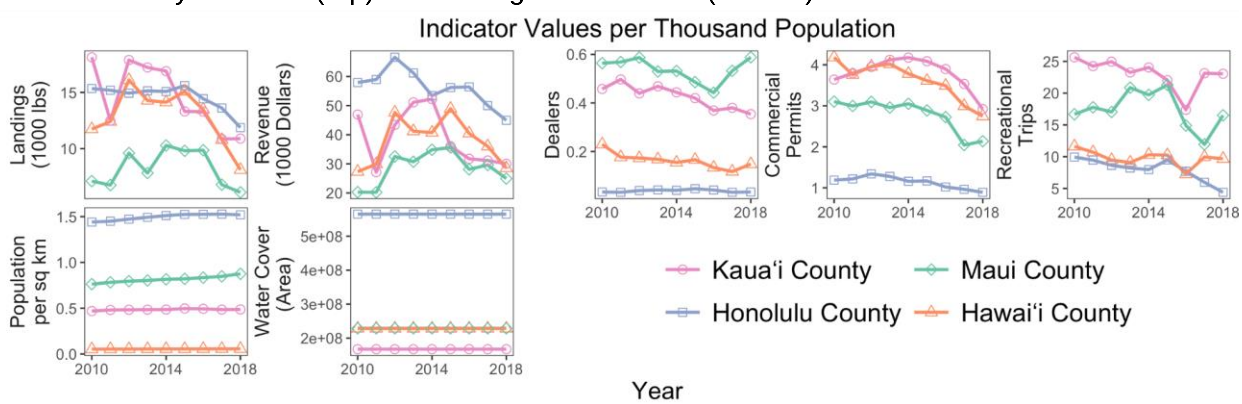

Figure 10. County means of social output (top) and ecological input (bottom) indicator values from 2010-2018. Social output indicators are presented as per thousand capita values.

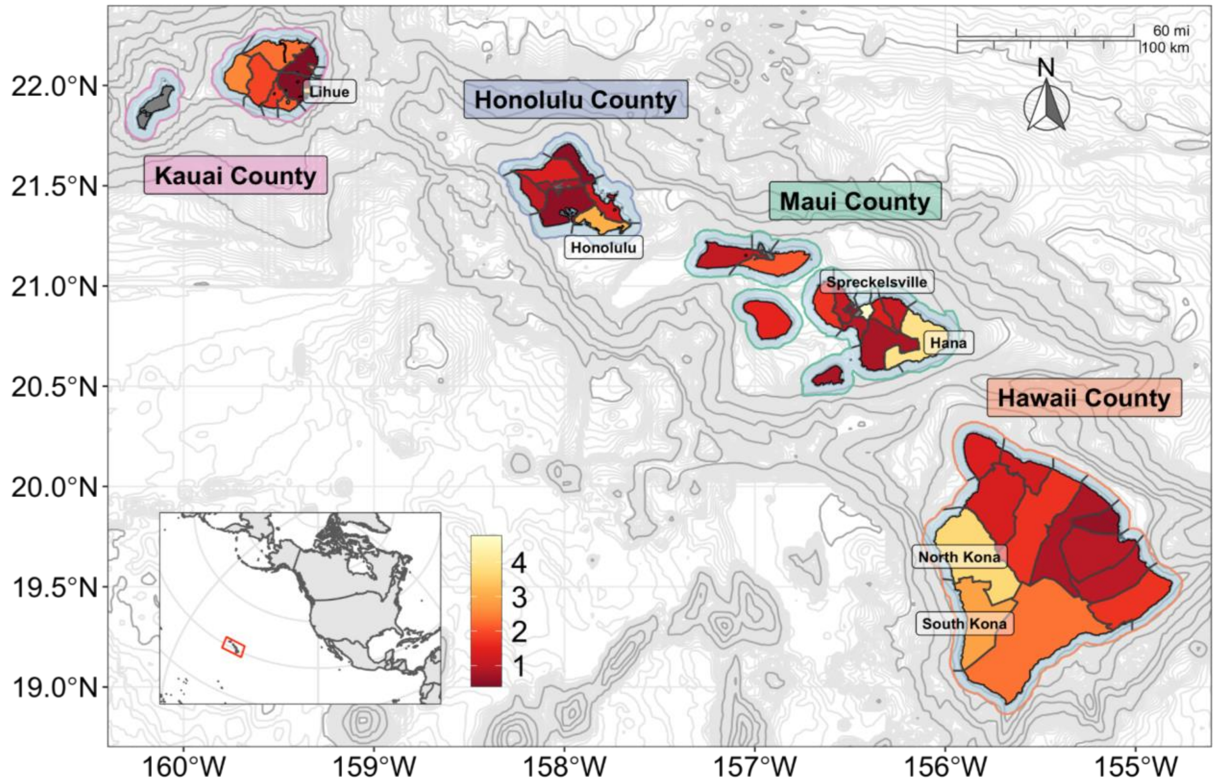

Figure 11. Map of communities in Hawaiʻi (census county divisions) depicting mean social-ecological index values over the assessed time period. Higher index values (brighter colors) represent higher fishing engagement and productivity. Water regions, encompassed by color-coded county outlines, represent the water area for each fishing community, and are represented by the total water area indicator. The 6 communities with the highest indices are labeled in transparent white boxes on the map. No indicator data were available for Kalawao County (shaded in gray) on Molokai.

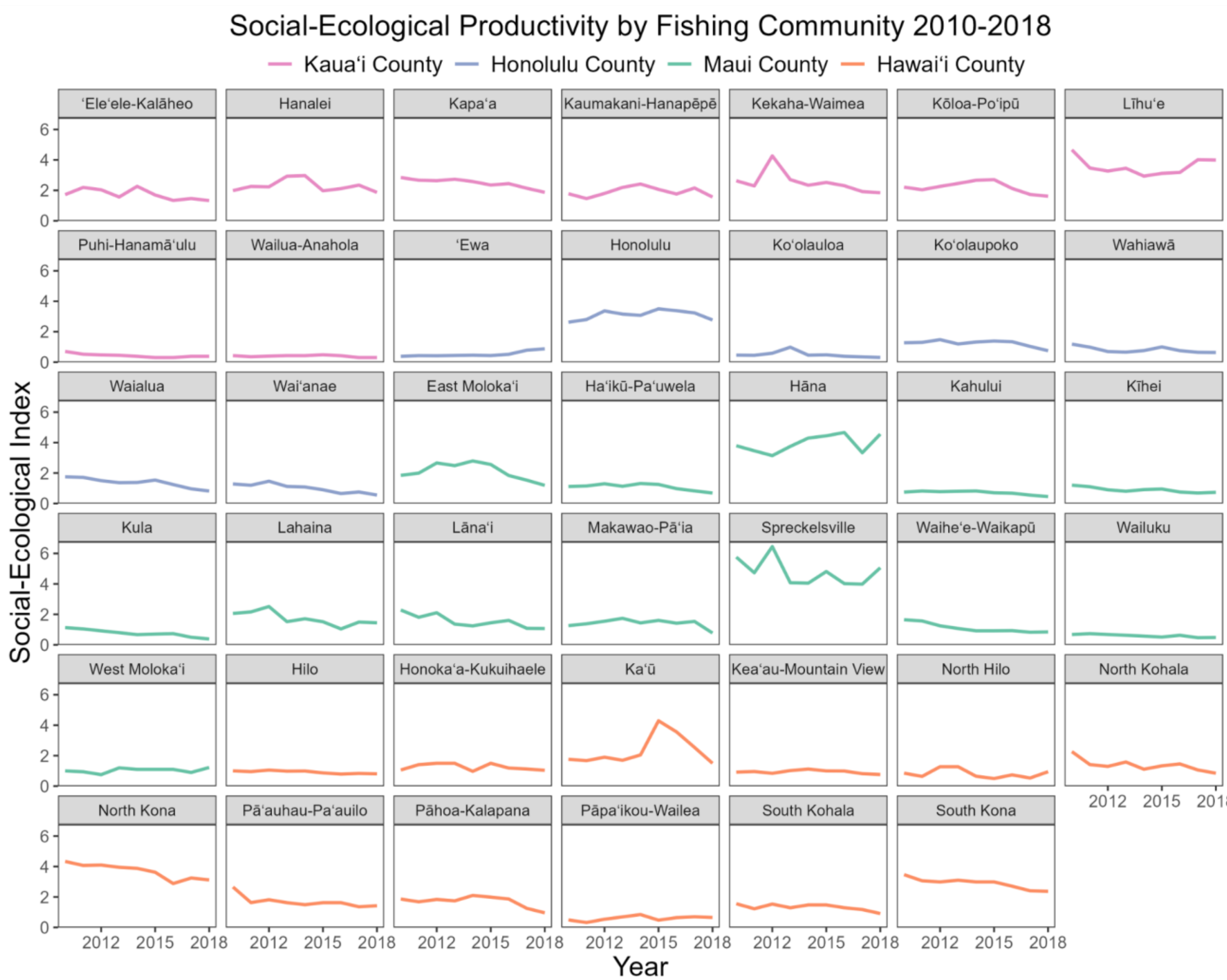

Figure 12. Social-ecological (productivity) indices for individual fishing communities from 2010-2018.

3.2.4 Management implications of index trends

The outcome ranking results demonstrate that geographic scale affects observed index trends. Low variation in index scores at the county scale demonstrates that coarser data aggregation in assessments can mask local community differences. Thus, social-ecological assessments, as well as data collection, at finer geographic scales are likely to provide more appropriate insights for local management. These results also demonstrate a correlation between environmental and social indices, and that human behavioral plasticity has the capacity to mitigate the negative effects of some environmental fluctuations. However, climate disturbances may have stronger impacts on the SES if conditions worsen. Within the assessed time frame, heat stress on reef-building corals may have negatively affected reef fish and therefore recreational fishing, which targets predominantly reef species [101–103]. Extreme weather events may become more common, as evidenced by the recent fires impacting Maui, and projected climate change effects may outpace the behavioral plasticity that allows for short-term adaptations.

4. Conclusions

Using quantitative social indicator data, we formulated a comprehensive profile of changes that defined recent decades of marine resource use in Hawai‘i. This work represents a follow-up case study that extends and refines a broader cross-regional analysis by assessing a locally-relevant suite of indicators in Hawai’i [12]. While prior ecologically centered studies have focused on environmental factors as systems constraints, these complementary studies integrate social influences, elucidating fisheries regulations, conservation actions, and economic conditions as drivers of resource-based regime shifts. The longline fishery continues to be a valuable fishery with reliable harvest and profitability after over a century of exploitation, possibly due to early implementation of conservation strategies, such as limited-entry or catch limits [73]. Additionally, the pelagic fishery is managed under internationally set quotas, and multiple regions are jointly responsible for keeping total harvests under a sustainable yield. Conversely, bottomfish fishery regulations were implemented only after stocks were over-exploited, leading to a slower recovery and long-term closures of large fishing areas that are only recently reopening. Fishery interactions and bycatch were also a common motivation for fishery closures, such as in the case of the lobster fishery and the temporary closure of the swordfish fishery [62,67].

By coupling our threshold analyses with outcome ranking, this study demonstrated tradeoffs and potential lateral movement between the commercial and recreational fishing sectors. It also highlighted the importance of acknowledging local fisheries characteristics by identifying species-specific contributions to shifts in these sectors. Target species (e.g., bigeye tuna and swordfish), are more prone to overexploitation [33,70] and may strongly impact the social-ecological system (SES) in Hawai’i if unexpected changes in their abundance or distribution occur. The spatial analysis underscored regional differences within the state, emphasizing that different counties rely on local factors to drive the collective achievement of local social objectives. For example, longline fishing drove commercial indicators in Honolulu County, while aquarium fishing and recreational sportfishing likely drove fisheries engagement in Hawai‘i County. Such local differences may obscure the effects of broad scale ecological drivers (e.g., sea surface temperature anomalies), with local drivers determining social-ecological outcomes at finer geographic scales in the short term. However, over longer time scales, climate effects may become more apparent. Trends and potential thresholds that occur at a finer scale may not be detected on a larger scale and state-level data may require longer temporal coverage to express discernible patterns. Our findings highlight the pivotal role of scale in trend and threshold detection, echoing the call for a more place-based approach by West Hawai‘i community members in Leong et al. 2019 [36]. To understand community impacts, SES research will need to operate at finer scales than the broader ecological or management scales typically considered in Ecosystem-Based Fisheries Management (EBFM) assessments. Recognizing and addressing these scale-related intricacies is vital for comprehensive and effective management strategies that consider both ecological and social dimensions.

This study describes the marine SES in Hawai‘i from an ecosystem service perspective that highlights social benefits from fisheries and tourism. We illustrate substantial contributions of the pelagic environment to commercial fishing, high recreational engagement in reef fishing, and economic dependence on reef-related tourism. This resource dependence and the sensitivity of marine ecosystems, reefs in particular, to temperature and seawater carbon chemistry suggest that forecasted climate change may precipitate an era of declining delivery of ecological goods and services (EGS) and deteriorating social state in Hawai‘i [90,104]. Notably, reliance on reef species makes recreational fishing particularly vulnerable to climate impacts. As a result, climate change elevates the risk of losing important cultural and social benefits associated with recreational fishing. Sustaining EGS that humans derive from natural resource systems will require integrated SES management that addresses interacting environmental and social factors. This research represents a vital step in investigating these social-ecological linkages from a resource management lens. However, the analyses were limited by the availability of indicators and the demographic aggregation of data, which reflect the assumptions of current fisheries management that focus heavily on economic outcomes. Social indicators representing additional benefits from fishing (e.g., food security, social cohesion, and cultural continuity) and the impacts of socioeconomic stratification on resource access play an important role in community resilience but could not be assessed. These concepts are particularly relevant in Hawai‘i, a region with strong cultural ties to the natural environment and substantial socioeconomic disparities [25,105]. Future social data collection for cultural and resource equity indicators would allow for the construction of more representative indices of social state.

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