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Linking Land and Sea through Collaborative Research to Inform Contemporary applications of Traditional Resource Management in Hawai'i

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Abstract: Across the Pacific Islands, declining natural resources have contributed to a cultural renaissance of customary ridge-to-reef management approaches. These indigenous and community conserved areas (ICCA) are initiated by local communities to protect natural resources through customary laws. To support these efforts, managers require scientific tools that track land-sea linkages and evaluate how local management scenarios affect coral reefs. We established an interdisciplinary process and modeling framework to inform ridge-to-reef management in Hawai'i, given increasing coastal development, fishing and climate change related impacts. We applied our framework at opposite ends of the Hawaiian Archipelago, in Hā'ena and Ka'ūpūlehu, where local communities have implemented customary resource management approaches through government-recognized processes to perpetuate traditional food systems and cultural practices. We identified coral reefs vulnerable to groundwater-based nutrients and linked them to areas on land, where appropriate management of human-derived nutrients could prevent increases in benthic algae and promote coral recovery from bleaching. Our results demonstrate the value of interdisciplinary collaborations among researchers, managers and community members. We discuss the lessons learned from our culturally-grounded, inclusive research process and highlight critical aspects of collaboration necessary to develop tools that can inform placed-based solutions to local environmental threats and foster coral reef resilience.

Keywords: ridge-to-reef; groundwater; land-use; nutrients; bleaching; scenario; resilience; collaboration; scientific tools; management

1. Introduction

Pacific Islands are ideal systems to understand land-sea links in the context of social-ecological system resilience [1–3], defined as the capacity of the system to cope with disturbances without shifting to an alternative state while maintaining its functions and supporting human uses [4,5]. Around the Pacific Islands [6,7], local knowledge and associated management practices (e.g., agroforestry, fisheries management) have been recognized to play a key role in building resilience to disturbances [8–10]. These local ecological knowledge systems (henceforth LEK) are customary knowledge-practice-belief systems passed down orally over generations, through adaptive management [8]. This knowledge is formed through historical resource-use practices and long-term, qualitative observations over a restricted geographical area. LEK continues to be modified under rapidly changing social, economic and ecological contexts. Where indigenous peoples depend on local environments for resources, they have also adopted conservation practices, which in some cases can enhance abundance or/and biodiversity [11]. For instance, traditionally managed community fisheries in Hawaiʻi have exhibited equal or higher biomass than even no-take marine protected areas [9,12]. Because of the long-term and place-based understanding embodied in LEK systems, there is increasing recognition of the importance of integrating LEK into management strategies to build resilience [13–15], especially in Pacific Islands, where environments are unpredictable and highly vulnerable to climate change [16].

Awareness of natural resource decline has contributed to a cultural renaissance across the Pacific Islands, where local communities seek to revive local customary and place-based management approaches [17], such as customary *moku* (ridge-to-reef) management approaches [18,19], *kapu* (traditional closures) and *pono* (sustainable) practices to protect biocultural resources and foster social-ecological resilience [17,20]. These social-ecological systems can be defined as Indigenous and community conserved areas (ICCA), where "natural and/or modified ecosystems containing significant biodiversity values, ecological services and cultural values, are voluntarily conserved by indigenous, mobile and local communities, through customary laws and other effective means" [21]. In ICCAs, local people, who are intimately connected to the environment, culturally and/or through their livelihoods make decisions over how resources are used and have the capability to enforce regulations, which can lead to effective conservation outcomes (even if conservation is not the primary objective) [22,23]. Ridge-to-reef management systems that integrate LEK can enhance social-ecological resilience through reducing impact from climate disturbances and strengthening governance systems with capacity to quickly organize and act [2]. These types of ICCAs offer lessons in integrating traditional knowledge and management practices into sustainability and conservation planning but require national level legal and policy changes to accommodate and empower the ICCAs operating at the watershed-reef level [8,24]. The restoration of local management is challenging, because users have often grown in number and shifted in character from small, homogenous resident populations using resources for subsistence, to transient, global tourist populations using the same resources for recreation [25,26].

After nearly two centuries of decline of the Hawaiian biocultural resource management system, there has been a resurgence of interest—from within academia and the policy realm, as well as at the community level—in reviving that system to restore biocultural resource abundance [27]. This renaissance has inspired an attempt to align traditional Hawaiian biocultural resource management with contemporary frameworks of ecosystem-based management that re-establish the cohesive links between terrestrial and marine systems, encompassing integrated ecological and social processes from ridge-to-reef [28–30]. There has been a growing focus on a land-division scale known as *moku* to revive traditional resource management in a localized context as a means for communities to engage in biocultural restoration. *Ahupuaʻa* are social-ecological communities nested within *moku*, which are delineated as land-divisions that often extend from the mountains to the sea and exist within the context of the Hawaiian system of governance and biocultural resource management [27]. Motivations by Hawaiian communities to employ contemporary ICCAs include access to and restoration of biocultural resources, security of land and resource tenure, security from outside threats, financial benefit from resources or social-ecological system functions, participation in management, empowerment, capacity building and cultural identity and cohesiveness [8,11,31]. Perpetuating ancestral practices related to food systems provides roles for community members of all ages, while maintaining relationships and balance with the natural world in specific areas [32,33].

Despite management challenges, declining resource health and conflicts over access, two *ahupuaʻa* (social-ecological communities) embody this cultural renaissance [34]. Hāʻena on the windward side of Kauaʻi Island and Kaʻūpūlehu on the leeward side of Hawaiʻi Island have successfully maintained control of a critical component of their food system by enhancing the management of their coastal resources through the creation of innovative ICCA's (Figure 1). Both places have become the first, officially sanctioned ICCAs in the U.S. State of Hawaiʻi. Coral reef fish caught near shore with nets, pole and line, or spears, are a very important component of community food systems [6,35]. Therefore, both communities in this study initiated marine closures of different sizes to protect fishery species, many of which are also known to feed on algae (herbivorous fishes). Without these herbivorous species, algae blooms can cover the reef when excess nutrients flow into the sea from the land. By eating the algae, these protected fishes create space for new corals to settle and ensure the persistence or resilience of the reefs.

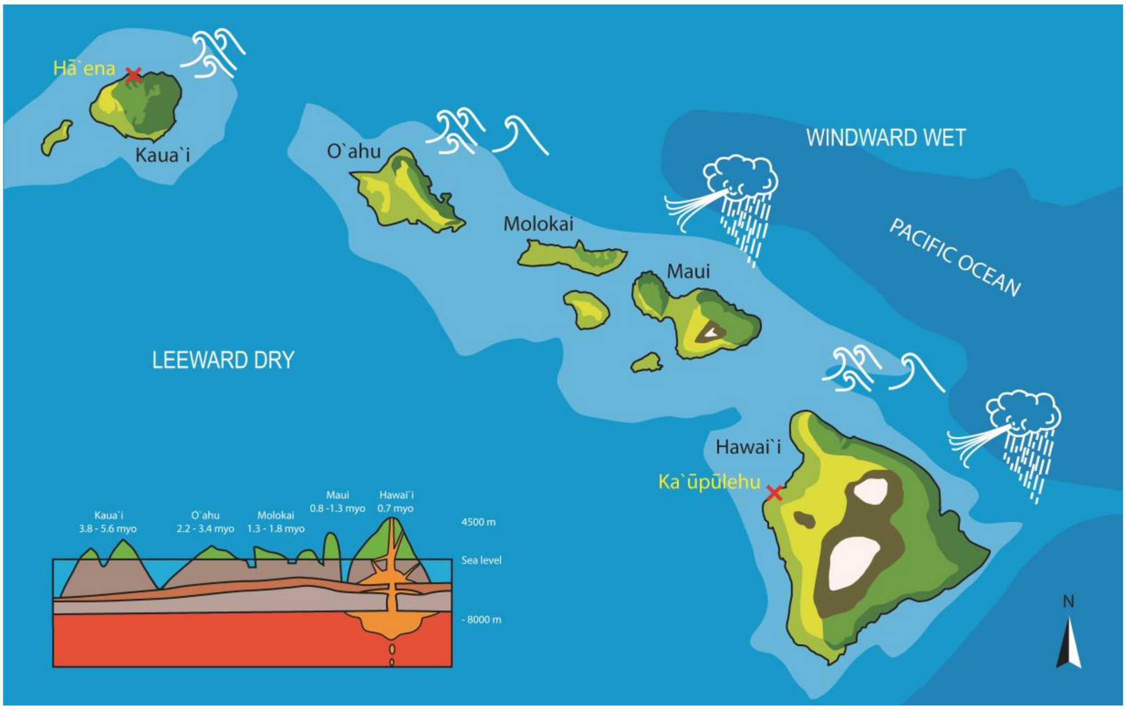

Figure 1. Locations of Hāʻena and Kaʻūpūlehu *ahupuaʻa* on Kauaʻi and Hawaiʻi along the main Hawaiian Island chain, with island age and the direction of the prevailing north-east trade winds and ocean swell indicated.

These local communities are also interested in reviving the *ahupuaʻa* approach by better understanding how land-based sources of pollutants from golf courses, lawns and cesspools affect their marine ecosystems to inform alternative land-use options [36]. Even with healthy herbivorous fish populations, these pollutants take a toll on coral reefs, especially with increases in ocean temperature and acidity as a result of climate change. Therefore, it is important to these communities and the health of all marine ecosystems, to ensure that future coastal planning takes land-based impacts into account. Effective ridge-to-reef management requires improved understanding of land-sea linkages and tools to evaluate the effects of land (e.g., nutrients carried through groundwater) and marine (e.g., wave power and reef topography) drivers on coral reefs to inform resilience management in the face of climate change. In response to these gaps, we adopted the traditional *ahupuaʻa* framework to study the effect of coastal development on coral reefs under projected climate impacts and identified place-based management actions that can boost system resilience. Here, we provide an overview of: (1) the renaissance of the traditional resource management system of Hawaiʻi, with a focus on two communities with ICCAs; (2) how applied collaborative science can support management; and (3) the development of decision support tools grounded in place-based management.

2. The Renaissance of Traditional Resource Management of Hawaiʻi

2.1. The Story of How Hāʻena Became a Marine ICCA

Recognizing the importance of customary Hawaiian management and subsistence fishing, Hawaiʻi enacted legislation in 1994 that allows the Department of Land and Natural Resources (DLNR) to designate community based subsistence fishing areas (CBSFAs) for "reaffirming and protecting fishing practices customarily and traditionally exercised for purposes of Native Hawaiian subsistence, culture and religion" [37]. This created a pathway to designate marine ICCA's in Hawaiʻi. Achieving a CBSFA designation allows community members to assist DLNR to develop and enforce place-specific management strategies/laws that regulate resources they depend on from the shoreline to one mile out to sea, or the edge of the coral reef, based on Native Hawaiian values and ancestral practices [37]. This designation allows residents to work with the state DLNR Division of Aquatic Resources (DAR) to develop and enforce laws (S.B. 2501, 23rd Leg., Reg. Sess. Hawaiʻi 2006) [6,25]. Through traditional Hawaiian values, the CBSFA designation emphasizes the connection between the environment and communities, whereby if you care for the environment, the environment will care for you. CBSFAs represent an agency-recognized avenue for local community groups to assert their indigenous rights by proposing management measures informed by customary fishing and management practices to sustain the health and abundance of marine resources for generations in the Hawaiian Islands [38].

Like many other places in Hawaiʻi, land privatization, along with coastal development of vacation and luxury homes, fragmented the land in the 1960s [39], which led many long-time families to move from the area [6]. Today, the rural *ahupuaʻa* is mostly owned by the State of Hawaiʻi and the non-profit organization, National Tropical Botanical Garden (NTBG), with ~140 private residences along the coast (Figure 2A). The NTBG, *Kānaka Maoli* (indigenous Hawaiian) and *kamaʻāina* (place-based community) of Hāʻena (henceforth Hāʻena community) persisted in the creation of rules guided by ancestral norms: *hōʻihi* (respectful reciprocity), *konohiki* (inviting ability) and *kuleana* (rights based on responsibilities) [33,40]. In 2006, the State of Hawaiʻi designated Hāʻena as its first CBSFA [25]. After this designation, the community was empowered to work with the state resource management agency to co-develop fishing regulations and secure their approval through the same onerous public process as any administrative rules promulgated by state government agencies [33].

In August 2015, after nearly ten years of planning and negotiation, over seventy meetings, fifteen rule drafts, three public hearings and multiple studies undertaken to document visitor impacts, user groups, fishery health and the importance of locally caught fish within and beyond the Hāʻena community, these rules became law [6,33] (Figure 2B). The community of Hāʻena managed to restore local-level management of their near-shore fishery by co-creating CBSFA rules to govern fishing and all coastal uses, including recreational activities based on customary practices and customary norms for the area [37]. The significance of this event cannot be understated. This was the first time in the state of Hawaiʻi that local-level fisheries management rules, based on indigenous Hawaiian practices, were recognized. Passage of these rules made Hāʻena the first coastal area in Hawaiʻi to be permanently governed by community developed, local-level rules based on ancestral knowledge and practices [33]. As the first site to work with DAR to co-create rules formally adopted as state law, Hāʻena set a precedent for at least 19 other Hawaiʻi communities pursuing co-management of local fisheries [37]. Many communities across Hawaiʻi view this effort as a larger community movement to increase self-sufficiency and restore formal local-level control over ocean resources as a food source [33].

Figure 2. Ha'ēna study site. (**A**) Ha'ēna land use and community based subsistence fishing area (CBSFA) marine refuge boundaries and (**B**) The opening *pule* (prayer) prior to the public hearing in Hanalei for the Ha'ēna CBSFA package rules.

Traditional coastal management in Hā'ena relied on protecting key spawning and feeding areas for fishes [25,40]. One of the largest fringing reef systems in the main Hawaiian Islands is found in Hā'ena, where a large lagoon formed by the back-reef provides wave sheltered nursery habitat for culturally and economically important soft and hard bottom target fish species [3,33,41]. The reefs provide daily fish protein for many Hawaiian and other local families, as well as for *'aha'aina* (feasts commemorating events including weddings, birthdays, funerals and graduations) and other celebrations on Kaua'i [6]. Therefore, among these rules, a marine refuge (*Makua Pu'uhonua*) was designated in the sheltered lagoon of Makua to protect a key fish nursery area (see Figure 2A). By closing this area to fishing and all recreational use, the community successfully created a refuge grounded in indigenous practices and knowledge [11]. This closure protects culturally important fish species from being captured by fishers or disturbed by snorkelers, kite boarders, stand-up paddlers and others during vulnerable life stage (spawning) and behavior (feeding) [25].

2.2. The Story of How Ka'ūpūlehu Became a Marine ICCA

Ka'ūpūlehu is both commercially and residentially more developed than Hā'ena, with two large luxury resorts, a golf course and several private residences along the southern end of the coast (see

Figure 3A). Few lineal descendants and longtime residents of Ka'ūpūlehu live within the *ahupua'a* but many live nearby, maintaining strong connections to their ancestral lands [14,36]. The entire *ahupua'a* is owned by the largest private landowner in the state of Hawai'i, Kamehameha Schools (KS–an indigenous Hawaiian educational trust and the State of Hawaii's largest private landowner), which was established for the benefit of *Kānaka Maoli* [34,36]. KS seeks to balance multiple economic, educational, cultural and environmental goals [34,36,42,43]. Cultural and place-based values are of high priority for KS and *kama'āina* of Ka'ūpūlehu, (henceforth Ka'ūpūlehu community) are involved in resource management advisory councils, educational programs and cultural restoration projects in the *ahupua'a* [36]. Environmental outcomes, including groundwater recharge and restoring abundant nearshore fisheries, are also highly valued for cultural and economic purposes, as groundwater is the main water source statewide and fisheries are used for subsistence [44].

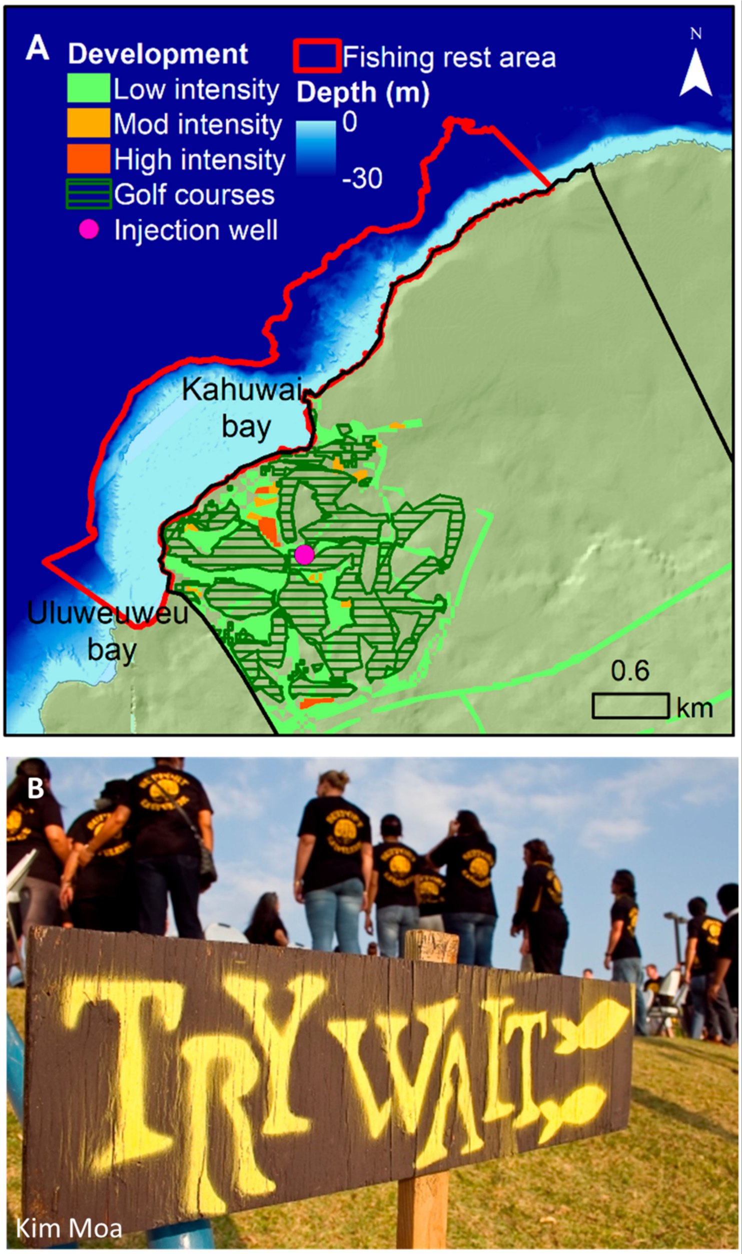

Figure 3. Ka'ūpūlehu study site. (**A**) Ka'ūpūlehu land use and marine reserve map; (**B**) Gathering for the opening *pule* prior to the public hearing for the 'Try Wait' fishing rest area in Ka'ūpūlehu.

Given that the scarcity of water resources limits agriculture, marine resources gathered historically from the ocean played a vital role in the diet of Kaʻūpūlehu families and their subsistence practices [45]. The families that lived (and live) in Kaʻūpūlehu were experts in their resources and knew how to survive within these rugged lands [45]. However the community has observed drastic declines in their coastal resources within the past 40 years, with the opening of the resort and the Kaʻahumanu Highway in 1975 thereby requiring and providing easier access to the isolated waters of Kaʻūpūlehu [45]. In response, the community sought to maintain and restore coastal and marine life health along with their interconnected traditions, before the system could no longer recover and all knowledge was forgotten. In 2015, after nearly ten years of planning and negotiation and over 350 community meetings and multiple studies undertaken to document fishing impacts and coral reef health, the community of Kaʻūpūlehu initiated a law implementing a 10-year fishing rest period known as 'Try Wait' (see Figure 3B), which adopted a term in the local pidgin language meaning, "Let's wait a moment." The protected area extends out to 120 feet deep (or 36.6 m) along a large portion of the coastline. This resulted in the protection of the entire fringing reef (see Figure 3A). Providing full protection of the nearshore reef for a 10 year period while the community develops their long-term management plan is a management strategy grounded in indigenous practices [11].

3. Developing Scientific Tools through Collaboration Grounded in a Hawaiian Approach

Collaborative research among scientists and local communities has the potential to overcome limitations of often-practiced 'expert' driven, narrowly focused scientific research. Collaborative research incorporates the dynamic interactions between people and nature, rather than viewing people only as "managers" or "stressors" [26], and positive outcomes for social-ecological management have been documented (e.g., [46]). Processes to define research questions and objectives based on collaborative approaches can also empower indigenous people and communities [26] and generate possibilities for complementary use of scientific and traditional knowledge [13,15,26]. This type of research requires understanding linkages and feedback loops between nature and people to inform local management in those particular places [26].

Our research process included five main steps and involved managers, scientists and the stewards of the land at different stages: (1) Problem formulation; (2) scenario design; (3) conceptual and model development; (4) scenario modeling and analysis; and (5) informing land-sea planning (Figure 4 and Table 1). Both communities were interested in restoring a ridge-to-reef approach to address contemporary environmental issues, including coastal development and fishing pressure impacts on coral reefs combined with bleaching from climate change. In collaboration with local landowners and communities, we developed a decision support framework grounded in Native Hawaiian culture by adopting the traditional *ahupuaʻa* lens to assess the impact of coral reefs under projected land use and climate change scenarios, combined with the marine closures. Key collaborators included local community members (e.g., landowners, care takers and active nonprofits), managers with jurisdiction across the ridge-to-reef ecological unit and local experts and scientists. Through local leaders (e.g., K.B.W. and M.B-.V. at Hāʻena, who are co-authors on this paper) and previous work with community members, we identified environmental concerns, ground-truthed models and identified solutions to mitigate local threats. Managers at the state level included the Hawaiʻi Department of Health (HDOH), which manages water quality from ridge-to-reef and ensures compliance with the Clean Water Act. Scientists and local experts from multiple disciplines, including terrestrial and marine ecologists, social scientists, economists, modelers, hydrogeologists and geographers were involved at different stages of the process to identify and link all the key processes and components that are important in the decision-making process spanning the top of the mountains to the sea and the community in between.

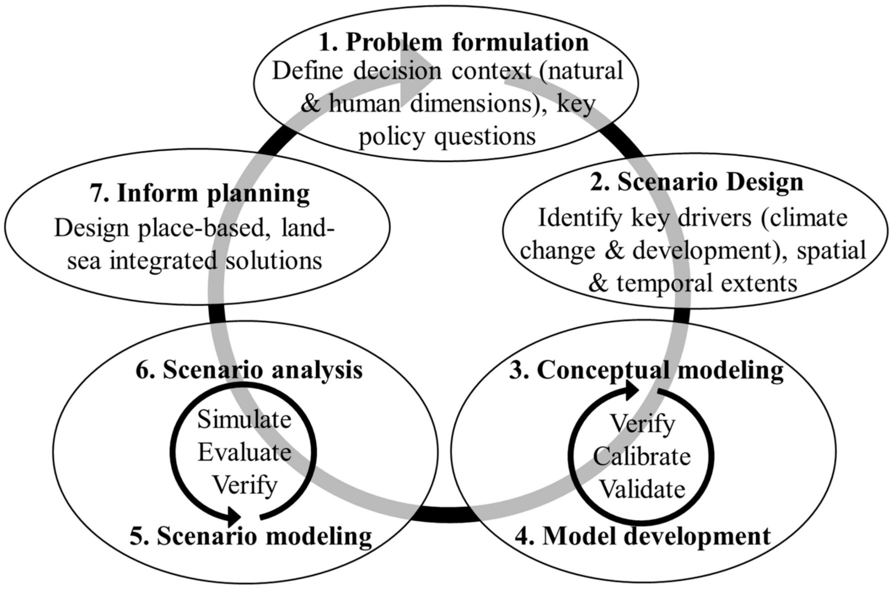

Figure 4. Collaborative science process. The collaborative science process involves stewards/care takers, managers and scientists, or a combination at multiple stages (see Table 1 for roles fulfilled by each group of actors).

Table 1. Roles of multiple actors in a collaborative science process. Stewards/care takers, resource managers and scientists, or a combination play multiple roles at multiple stages.

Stages	Actors	Roles
1. Problem formulation	Stewards/care takers	Community members, land owners and non-profits
	Scientists	Geographer, ecologist, hydro-geologist & planners
	Resource managers	Hawai'i Department of Health
2. Scenario design	Stewards/care takers	Preferences, vision & concerns
	Scientists	Compile data & map scenarios
	Resource managers	Share data
3. Conceptual modeling	Stewards/care takers	Determine key system components, indicators and processes
	Scientists	
	Resource managers	
4. Model development	Scientists	Measure indicators, design & build models, develop user friendly outputs
5. Scenario modeling	Scientists	Model indicator changes per scenario
	Resource managers	Assess & ground-truth outputs
	Stewards/care takers	
6. Scenario analysis	Scientists	Perform indicator analysis & assess potential risk for each scenario
7. Inform planning	Stewards/care takers	Guide place-based management
	Scientists	Synthesize & communicate scenario results
	Resource managers	Guide policy-making

First, we formulated the problem and key policy questions by consulting community members (e.g., landowners, caretakers and active nonprofits), managers with jurisdiction across the ridge-to-reef ecological unit and local experts and scientists to define the decision contexts. Second, we designed scenarios in partnership with local communities to capture their concerns, which included increases in coastal development and climate change impacts on coral reef habitat (e.g., corals and turf) and associated culturally important fisheries (e.g., surgeonfishes, parrotfishes and jacks) and the potential recovery from the recently enacted marine closures. We reviewed zoning documents produced by the County of Kauaʻi of Hawaiʻi and the Office of Planning related to coastal zone planning to determine where coastal development was allowable and feasible to project future land-use change. At the same time, we compiled all the existing data at both sites to calibrate the land-sea models. The database from the HDOH was used to inform the calibration of land-use nutrient loadings rates (e.g., the wastewater injection well loading rate). A local non-profit (The Nature Conservancy) and research group at the University of Hawaiʻi (Fisheries Ecology & Research Lab) provided empirical data to calibrate the coral reef models at Kaʻūpūlehu and Hāʻena, respectively. Wedetermined the impact of co-occurring human drivers on coral reefs by coupling the human driver scenario analysis (climate change, coastal development and marine closures) with the development of a novel linked land-sea modeling framework for Hāʻena and Kaʻūpūlehu *ahupuaʻa*. Local ecological and expert knowledge about the coral reef benthic habitat and key fish distributions was used to ground-truth our coral reef indicator maps under present conditions, resulting from the model development phase. For example, the first version of the models provided some outputs that were not consistent with local observations, which led to revisions of the modeling framework until consistency was reached. Subsequently, the downstream fate of nutrients from upstream sources was modeled and projected impacts on coral reefs was assessed under the different scenarios to identify areas on land where managing human-derived nutrients can promote coral reef resilience [3,47]. The modeled scenario outputs were evaluated against the local communities' observations about the location of re-occurring algae blooms and bleaching impacts. Based on the community and managers' feedback, our findings are currently being used to shape place-based management solutions grounded in a ridge-to-reef approach and the indicators can be monitored to track the policy effectiveness. The HDOH also funded the dissemination of these research findings through a statewide conference in 2018 (July–August).

4. A Novel Linked Land-Sea Decision Support Tool for Local Management

The framework links land to sea through groundwater and tracks changes in abundance and distribution of multiple benthic and fish indicators under each scenario (Figure 5) (see [3] for more details). For each site, natural driver data, including topography and bathymetry, and rainfall and wave patterns, were included in the ridge-to-reef modeling framework to represent the natural disturbance regimes specific to each place (Figure 5A). The terrestrial drivers modeled included groundwater flow and nutrient fluxes, incorporating natural and human-derived nutrient flux. The marine drivers characterized the marine habitat conditions and were derived from the SWAN wave model and LiDAR bathymetry data with GIS-based models (Figure 5F). The coral reef predictive models were calibrated on local coral reef survey data [41,48]. To measure proxies of ecological resilience, which also represented important cultural resources to the local communities, the coral reef models focused on four benthic groups, known to change under land-based runoff and bleaching impacts, and four fish indicator groups subject to fishing pressure. The benthic groups were crustose coralline algae (CCA), hard corals, turf and macroalgae (Figure 5G). CCA and corals are active reef builders which provide habitat for reef fishes. CCA also stabilize the reef in high-wave environments. Abundant benthic algae can be a sign of high nutrients and/or low numbers of herbivorous fish, and can harm coral health through competition for space. Herbivorous and piscivorous fish identified as important by the communities (e.g., surgeonfishes, parrotfishes and jacks) were modeled based on their feeding modes and ecological role: (1) browsers; (2) grazers; and (3) scrapers; along with (4) piscivores, which are key fishery species and indicators of fishing pressure [49] (Figure 5H).

The human driver scenarios included coral bleaching, coastal development and marine closures [50]. Two future coastal development scenarios were based on current land zoning from the Hawaiʻi State Office of Planning and utilized the three commonly used types of wastewater treatment systems in Hawaiʻi (cesspools, septic tanks and injection wells) (Figure 5B). Nitrogen and phosphorus fluxes were modeled under each coastal development scenario and diffused in the ocean using a GIS-based coastal discharge model (Figure 5E). Two coral bleaching scenarios were derived from projected coral bleaching impacts for the region (Figure 5C). The marine closure scenario assumed removal of fishing pressure within the marine closure boundaries (Figure 5D) [38,44]. The climate change scenarios were applied in combination with the coastal development and marine closure scenarios [51,52]. Under each scenario, our land-sea models predicted the change in nutrient flux and associated abundance of the coral reef indicators (Figure 5G,H). Based on predicted changes, this approach informs place-based solutions rooted in the *ahupua'a* approach, by identifying priority areas on land where management can promote coral reef resilience to climate change (Figure 5I). The development of this new technology necessitated a collaborative process, which leveraged both scientific and local knowledge by involving scientists, community members and resource managers.

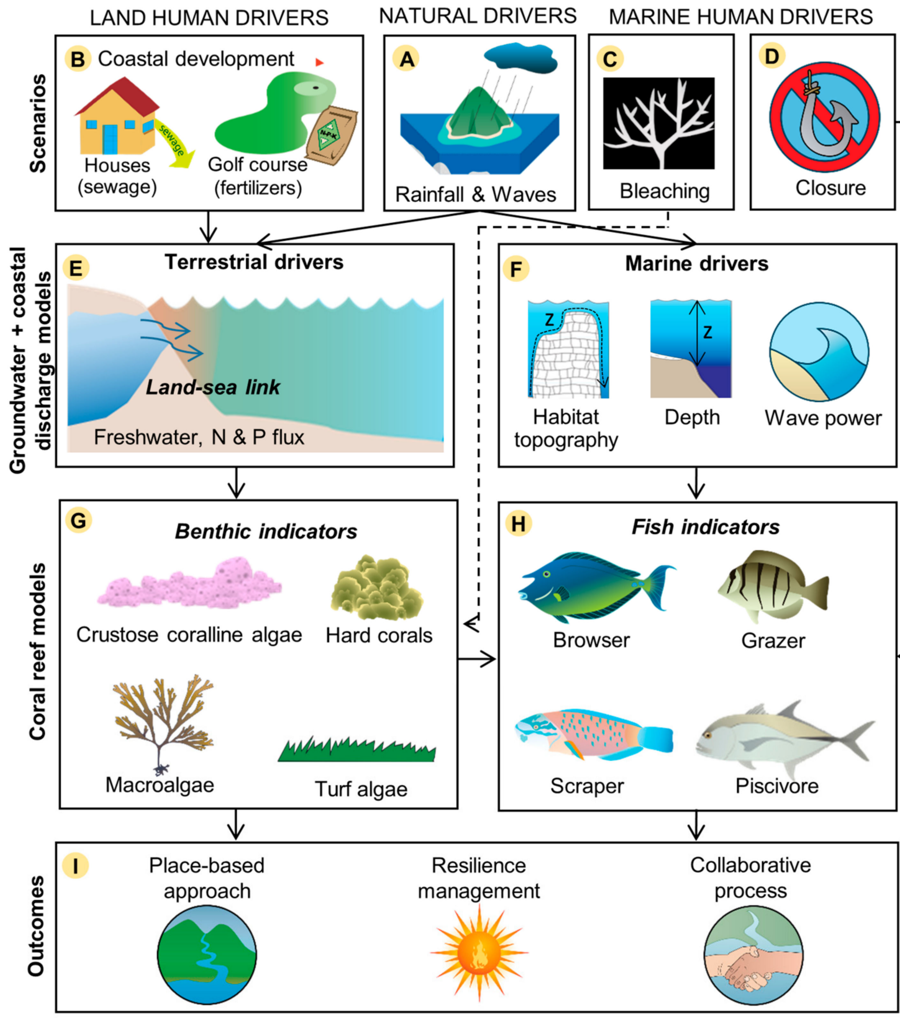

Figure 5. Linked land-sea modeling framework. The framework accounted for (**A**) natural and human drivers of coral reefs. Human drivers consisted of (**B**) land-based (coastal development) and (**C**,**D**) marine-based (bleaching and closure) scenarios. (**E**) The terrestrial drivers included submarine groundwater and nutrient discharge. (**F**) The marine drivers characterized the marine habitats. Under each scenario, coral reef models track changes in (**G**) benthic and (**H**) fish indicator abundance. This approach identified (**I**) priority areas on land where management can promote coral reef resilience to climate change through a collaborative process. Adapted from [3,47,53].

4.1. Place-Based Models

Due to direct exposure to the prevailing trade winds, Hā'ena *ahupua'a* receives very high rainfall (4040 mm·year^{-1}), resulting in large fluvial and groundwater inputs [54] (see Figure 6A). Dominated by steep cliffs, the Hā'ena *ahupua'a* is 7.3 km^2 and spans 1006 m elevation from the summit of Ali'inui Mountain to the sea, with two flowing perennial streams in the Limahuli and Mānoa valleys. On the other hand, Ka'ūpūlehu *ahupua'a* receives much less precipitation (ranging from 1350 to 260 mm·year^{-1} from ridge-to-reef) due to its location in the rain shadows of Mauna Loa and Mauna Kea mountains [55]. Geologically young, the surface is less eroded with poorly developed ephemeral stream channels and groundwater seeping along the coast [56] (see Figure 6B). The *ahupua'a* covers 104 km^2 and spans 2518 m elevation from the summit of Hualalai Mountain to the sea. High rainfall in Hā'ena results in nearly three times more groundwater discharge (10,279 m^3/year/m) compared to Ka'ūpūlehu (3085 m^3/year/m), which also means that nutrients are more diluted (less concentrated) than Ka'ūpūlehu, which is much drier. Our groundwater models showed that groundwater in Ka'ūpūlehu has higher levels of nitrogen from natural sources (38,900 kg/year or 7.08 kg/m/year) compared to Hā'ena (29,200 kg/year or 6.02 kg/m/year). Hā'ena is rural with limited development and agriculture, so most of the nutrients come from natural processes, with the exception of land areas to the east of the *ahupua'a* where nutrients are largely human-derived (human-derived nutrients: N: 7.8% and P: 5.5%), compared to more developed Ka'ūpūlehu (human-derived nutrients: N: 24% and P: 35%). The key sources of human-derived nutrients were wastewater from houses on cesspools at Hā'ena and the golf course and wastewater from the injection well at Ka'ūpūlehu.

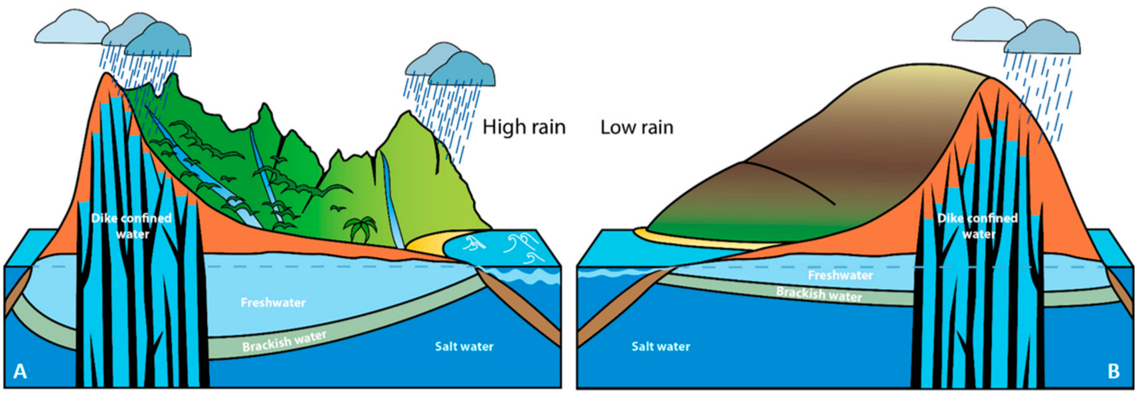

Figure 6. Illustration of the groundwater system at Hā'ena and Ka'ūpūlehu. (**A**) Hā'ena is located on old, wet, wave exposed coast of Kaua'I; (**B**) Ka'ūpūlehu is young, dry and wave sheltered.

Due to its older geological age and exposure to marine erosion from oceanic swells at Hā'ena (nearly one order of magnitude higher than Ka'ūpūlehu) has over time carved wider and shallower reef flats and produced shallow lagoons protected from the swell by well-developed reef crests [57]. The back-reef areas form lagoons that are protected from wave power by well-developed reef crests and support a benthic community dominated by corals and macroalgae [41]. The benthic community on the wave-exposed fore-reef is dominated by crustose coralline algae (CCA) and turf algae [58,59]. Our coral reef models showed that high wave power at Hā'ena has shaped the living community of the reefs, which are dominated by CCA and turf algae with many grazers and less scrapers (see Figure 7A). The Makua lagoon area is an exception where corals are able to grow, sheltered from powerful waves by a well-developed reef crest. In comparison, the coral reefs of Ka'ūpūlehu are younger and form a relatively narrow fringe on the steep slope of that island [57]. Because the reef is sheltered from large winter waves, its slopes are dominated by corals and have high habitat complexity, which supports higher fish biomass, particularly scrapers, while the shallow reef flats are dominated by turf algae with some CCA and support lower fish biomass (see Figure 7B) [48]. Browser abundance was low at both sites. Our coral reef models also showed that land-based nutrients from groundwater can increase benthic algae, suppress coral and CCA and decrease numbers of locally important fish at both sites.

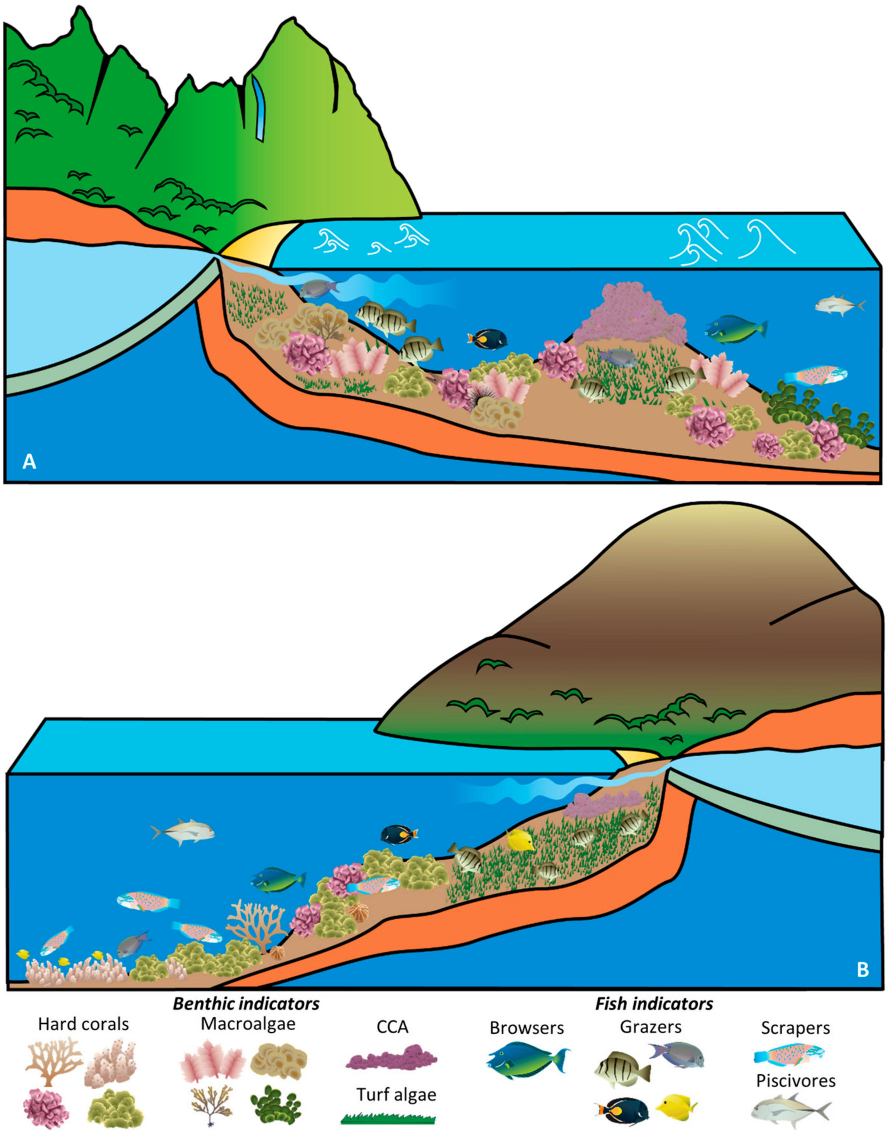

Figure 7. Illustrations of the coral reefs. (**A**) Coral reefs in Hāʻena are characterized by a reef crest dominated by crustose coralline algae (CCA) and turf algae and back reef with abundant corals and macroalgae with many grazers and less scrapers and (**B**) Coral reefs in Kaʻūpūlehu are dominated by corals on the slopes and turf algae on the reef flats with many scrapers.

4.2. Place-Based Solutions

Using this framework, we located coral reefs vulnerable to local and global human stressors and linked them to areas on land where limiting sources of human-derived nutrients could prevent increases in benthic algae and promote chances of coral recovery from bleaching. Under the high coastal development scenario, most of the total nutrient increase (>2000 kg) occurs to the east and center of the *ahupuaʻa*, where flushing and mixing from waves is limited by the reef crests of Makua and Puʻukahua reefs. Some of these areas that contribute high levels of human-nutrients lie upstream from the protected reef fish nursery at Makua. Coral reefs in Hāʻena may appear less susceptible to nutrient inputs from coastal development because they benefit from dilution and mixing from high freshwater and wave power. However, we showed that the back-reef of Makua is vulnerable to algae blooms (habitat area loss: 8.2%; shift in fish biomass composition, marked in pink in Figure 8A) and coral bleaching (habitat area loss: 13%, coral percent cover loss: 0–9%, fish biomass loss: −3.3%; marked in yellow in Figure 8A) due to the nearness of human-derived nutrient sources, limited mixing due to shallow depths and low wave power, and abundant corals and algae. Under the high coastal development scenario at Kaʻūpūlehu, most of the nutrient increase (>8000 kg) occurs to the north of the *ahupuaʻa*, downstream from the proposed development. On the other hand, coral reefs appear more vulnerable to nutrient inputs from more coastal development, combined with higher levels of background nitrogen in the groundwater and limited dilution and mixing from low rainfall and wave power (habitat area loss: 14%, fish biomass loss: 0.6%; marked in pink in Figure 8B). Additionally, Kaʻūpūlehu's plentiful coral cover is prone to coral bleaching (habitat area loss: 13%, coral cover loss 0–13%, fish biomass loss: −1.5%; in yellow in Figure 8B).

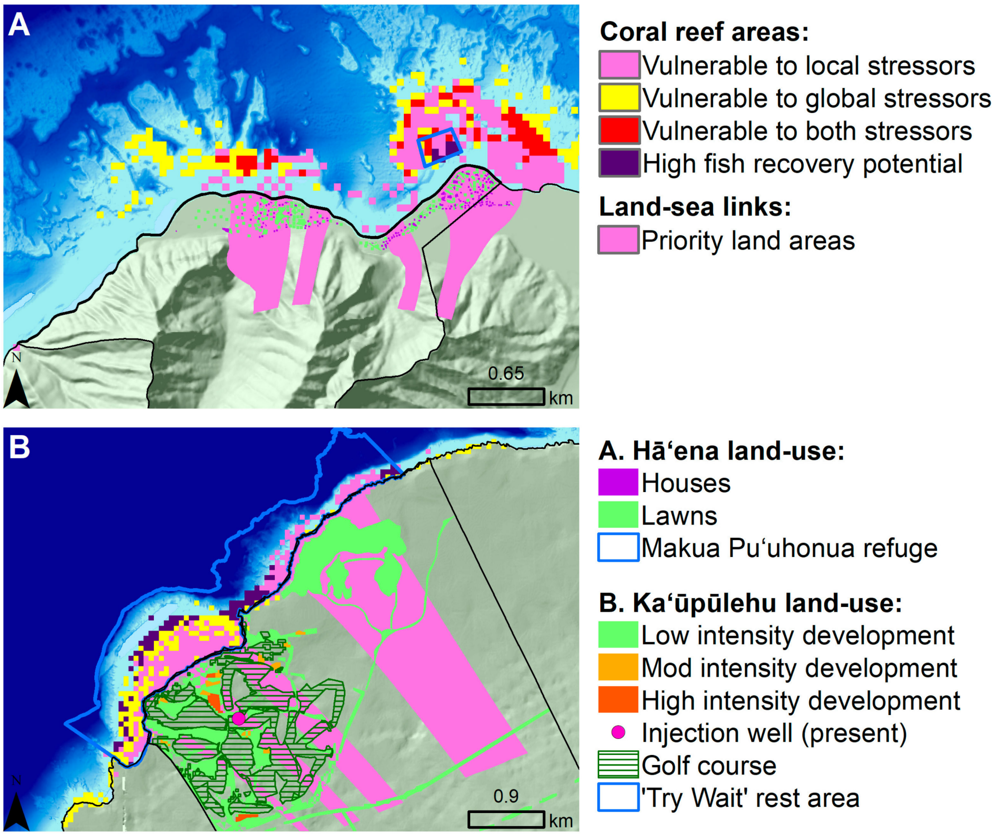

Figure 8. Coral reef areas vulnerable to local and global human stressors (i.e., nutrients and bleaching), coral reef areas with high fish recovery potential and priority land areas for management. Coral reef areas vulnerable to local and global human stressors (i.e., nutrients and bleaching), coral reef areas with high fish recovery potential and priority land areas, where local management actions can target wastewater and fertilizer practices at (**A**) Hāʻena and (**B**) Kaʻūpūlehu. Projected high coastal development land use/cover and marine closure/fishing rest areas are also shown.

Although the extent to which nutrient levels interact with elevated SST to affect the outcome of bleaching events remains poorly understood, it is increasingly recognized that water quality plays a complex role in the fate of nearshore coral reefs under climate change [60–62]. This seems to be the case since excess nutrients have been shown to impact coral reefs by promoting benthic algae growth and reducing coral's ability to recover from bleaching impacts [63,64]. When combining the effects of future coastal development and climate change on coral reefs, the impact worsens at both sites. Coral reefs vulnerable to both (coral reef areas marked in red in Figure 8A,B) do not overlap at Kaʻūpūlehu (habitat area loss: 20.8%, fish biomass loss: −1.6%), while the shallow back-reef of Makua at Hāʻena is vulnerable to both stressors due to limited wave mixing (habitat area loss: 21.1%, fish biomass loss: −3.3%).

Given that climate change and coastal development occur simultaneously, these results suggest that adopting local management can benefit both places. Land-based management can improve the benthic habitat conditions by preventing increases in benthic algae, which promotes coral recovery from bleaching within & outside the marine closures (habitat gain: 8% at both sites). Therefore, to promote coral reef resilience to climate change, the Hāʻena community may benefit from upgrading cesspools in the priority areas we identified, located upstream from Makua (located in pink zone in Figure 8A). Based on our findings, the Kaʻūpūlehu community could focus on minimizing phosphorus inputs from the wastewater injection well by increasing the nutrient removal through treatment (located in the pink zone below the injection well in Figure 8B) to reduce the vulnerability of coral reefs located downstream. In addition, the community could help foster resilience of their coral reefs by ensuring that environmentally sound practices are continued when fertilizing the golf course, particularly in the land areas located upstream from Uluweuweu bay and Kahuwai bay (located in pink zone in Figure 8B). This may also help to protect the water quality of a culturally important groundwater spring (*Wai a Kāne*) that was identified by the Kaʻūpūlehu community in Kahuwai bay (Figure 3B). While marine-based management increases the herbivore population within the reserves, which can supplement adjacent reef through spillover (fish biomass gain within the marine closure boundaries: +13% at Hāʻena and +2.6% at Kaʻūpūlehu). Overall, this research supports the communities' concerns and provides evidence that more coastal development can potentially negatively impact culturally important fisheries at both sites.

4.3. Application and Transferability

Ridge-to-reef management that integrates LEK has been widely advocated because it can improve social-ecological resilience. Watershed units have commonly defined the ecological systems in traditional management systems, which have been found in the Pacific north west, Asia, Africa and Oceania [65]. Among the richest set of ridge-to-reef, social-ecological system approaches to natural resources management is found in Oceania [8,65]. Examples include the *tambak* in Indonesia [66], the *puava* in the Solomon Islands, the *tabinau* in Yap, the *vanua* in Fiji [67] and the *moku* in Hawaiʻi [27]. Through this research, we show that place-based solutions that integrate land and sea processes are critical for addressing local environmental threats. We demonstrate that culturally grounded and inclusive research can guide management actions with multiple benefits such as improved groundwater and coastal water quality and foster the resilience of coral reefs, which are important food production systems for local communities. The lessons learned from this process highlight the critical aspects of collaboration necessary to develop scientific tools that can inform these practical and appropriate management actions. Managing ICCAs requires taking into account interests at all levels, evaluating trade-offs and finding win-win solutions [23].

There is a strong need for planning tools that can prioritize local management actions at relevant spatial scales for decision makers, which are simple to interpret and implement [68,69]. These decision support tools can easily be updated as more data becomes available, or model components of the framework can be substituted or added based on management objectives. For example, in another application, we substituted the groundwater models with the open source Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) spatially-explicit Sediment Delivery Ratio Model (SDR version 3.2) [70] to model the impact of sediment runoff on coral reefs in Fiji [71]. To support Fijian communities currently working with government, NGOs and the private sector to design and implement Integrated Coastal Management plans [72], we applied the modified land-sea modeling framework with scenario planning in Kubulau District (Fiji), where logging and commercial agriculture expansion competes with forest conservation and potentially fisheries livelihoods, to identify where forest conservation or restoration actions could benefit coral reefs [71]. In addition to fostering collaboration, this approach offers a flexible, transferable, data-driven, place-based model that is spatially-explicit and relies on increasingly available free remote sensing imagery and bathymetry data (i.e., Worldview III, GEBCO).

5. Conclusions

These research findings suggest that different environmental conditions make place-based solutions essential [23], because one-size-fits-all kinds of management ignore issues of place and scale [26]. Rodgers et al. [73] provided the first quantitative statewide evidence that watershed and adjacent coral reef health are significantly interconnected in Hawai'i, with the exception of ridge-to-reef systems on the windward side due to exposure to high rainfall and wave power, implying that reefs in these locales are less vulnerable to land-based activities. Consistent with Rodgers et al. [73], our impact assessment showed that Ka'ūpūlehu is vulnerable to local land-use change, as well as climate change impacts. Our findings also revealed that coral reefs on the windward side are vulnerable to local land-use change at the local-scale, especially back-reef systems, like Makua back-reef. In addition, our results show that managing local human drivers can foster coral reef resilience to global human drivers. Although the marine closures can promote reef recovery, they are not always able to offset the impacts from coastal development and other land-based activities on coral reefs, especially beyond their boundaries. Due to the risk that coastal development can undermine local marine conservation efforts, it is essential to manage upstream land-use change.

Therefore, local-scale and place-based solutions are particularly important in Hawai'i, where locally sourced food is socially and culturally important and food systems are vulnerable to coastal development and climate change impacts [18,33]. Our research provides place-based case studies of the interaction of researchers, community members, resource managers and policy makers to inform future planning. ICCAs, such as Hā'ena and Ka'ūpūlehu, can help redefine co-management and the role of local communities and institutions throughout Hawai'i. Although this management approach may be more suited for communities with strong ancestral ties to the place, as larger and more heterogeneous communities, such as Maunalua Bay on East O'ahu, will require early onset and more efforts to build consensus [74] and necessitate creative strategies to engage the various members [75]. However, this type of research can help coordinate and facilitate reaching agreements across different community groups by testing policies prior to implementation and bridging gaps between managers and communities by visualizing synergies and trade-offs on maps.

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