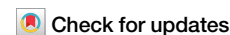


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Scaling biocultural initiatives can support nature, food, and culture from summit to sea



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Biocultural nature-based solutions provide many social, cultural, and ecological benefits. Yet, there has been little research on related land-sea societal benefits, hindering our ability to finance and scale these solutions. To help fill this gap, we evaluate the land-sea benefits of scaling biocultural restoration initiatives in Hawai'i, including multi-strata agroforestry and high-elevation silvopasture combined with native forest protection. We innovated and integrated a blue food production model into a land-sea modeling framework to illustrate the societal benefits of biocultural restoration efforts. Our results show that agroforestry transitions add value to forest protection by increasing sediment retention (30%) and nearshore fisheries production (10%) across all islands, while also supporting goals of biodiversity conservation, food production, and cultural connection to place. We demonstrate that the biocultural restoration of forests are nature-based solutions that provide a triple win for nature, people, and culture, and are critical to social-ecological resilience.

Nature-based solutions (NBS) are key strategies to achieve Sustainable Development Goals (SDG), biodiversity, and climate goals and targets¹. Defined as actions that protect, manage, and restore ecosystems while addressing societal challenges, NBS also provide benefits for human well-being and biodiversity^{2,3}. However, some NBS projects, including large-scale tree planting often fail without community buy-in and attention to local values and political-economic context⁴. Thus, NBS policies and practice now emphasize the need for equitable, inclusive approaches that incorporate Indigenous and other local community values, goals, and knowledge^{5–8}. Successful examples, like mangrove conservation in Indonesia, have improved livelihoods, reversed ecosystem loss, and offered climate adaptation benefits^{9,10}.

Biocultural approaches, which emphasize the reciprocal restoration of both ecology and culture^{11,12}, elevate and perpetuate Indigenous and local knowledge and rights, and align with the call for more just and equitable NBS^{13–15}. These approaches recognize that biodiversity and ecosystem restoration often depend on the perpetuation of traditional knowledge, practices, and cultural heritage, and that human well-being is linked to the health of the environment. In the Pacific Islands, biocultural approaches to restoration often center on ridge-to-reef frameworks, since Indigenous

resource management practices conceptualize land and sea as fundamentally interconnected^{16–18}. Pacific Islanders have practiced integrated land-sea management as a continuum with embedded forest protection and food production practices^{19–21}. Restoring these systems supports ecoscape restoration by regenerating habitats across land-sea boundaries and providing social, ecological, and cultural benefits^{16,17,22}. Biocultural approaches that restore local food production systems can enhance community health and well-being through increasing supply and access to culturally and nutritionally valuable foods^{1,17,23}. Gathering local food, on land and from the ocean, is essential for the perpetuation of traditional knowledge, as it preserves cultural practices, deepens ecological understanding, and strengthens community connections across generations. Traditional knowledge in the Pacific Islands is rooted in practices like crop diversity, soil replenishment, and rotational fishing grounds, which sustain food security²⁴.

Seafood, or “blue foods,” are vital for global food security²⁵ and the livelihoods of millions²⁶. Across the Indo-Pacific region, fish consumption averages 55–110 kg per person annually, compared to 18 kg globally²⁷. However, seafood's benefits are unevenly distributed across coastal communities, and assessing the benefits of seafood on a large scale can mask inequalities in the distribution of those benefits²⁸. Increasing reliance on

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imported foods in the Pacific, such as canned meats and sugary drinks, has worsened malnutrition and disease²⁹. Ensuring access to seafood and affordable options is crucial for sustaining and reviving traditional knowledge and improving health, which can feed back into sustainable ecosystem management.

In tropical and subtropical regions, sheetwash and hillslope erosion drive sediment budgets due to agriculture intensification or fallowing, overgrazed landscapes, and poor road planning, especially in dry areas prone to heavy rainfall^{30,31}. Mitigation is critical in regions with degraded vegetation, high rainfall and steep terrain, such as oceanic islands, which also face fire risk³² and grazing from feral ungulates or livestock, increasing sediment and nutrient flow to coastal waters^{33,34}. Empirical evidence has shown that coastal habitats and fisheries, vital for food security, are threatened by sedimentation, development, overfishing, and climate change through ocean warming and acidification^{22,35}. Ridge-to-reef management studies have demonstrated that land-based stressors vary spatially in their impact on the marine environment³⁶. Because terrestrial and marine processes occur across different temporal and spatial scales, resource management efforts require adaptable interventions for islands to achieve social-ecological benefits across land and sea^{37,38}.

Native Hawaiians (Kanaka 'Ōiwi) traditionally managed their islands from ridge-to-reef through land divisions (Moku subdivided into multiple ahupua'a). Mountain tops and associated forests were sacred and rarely accessed (kapu), while mid-watersheds supported gathering and diverse agriculture, including agroforestry, and lower watersheds were used for aquaculture and fishing^{18,39,40}. These systems fostered self-sustaining communities utilizing resources from mountains to sea (mauka to makai). The Moku system embodies ecological wisdom and social cohesion, concepts that remain relevant in modern discussions about sustainable resource management and cultural preservation in Hawai'i³⁹. European contact, beginning in 1778, colonization, and subsequent political-economic changes and introduced diseases led to Kanaka 'Ōiwi population decline, land dispossession, and the break-down of the Moku system^{39,41}. Following large-scale land privatization in the mid-1800s, sugar and pineapple plantations became dominant in Hawai'i. Today, much of the former plantation land is unmanaged, partly due to shifting economic forces, which has left nearly 40% of the state's agricultural land fallow and dominated by non-native and invasive species^{42,43}. In many areas, these unmanaged lands have become increasingly prone to erosion with the proliferation of non-native ungulates including goats (*Capra hircus*) and axis deer (*Axis axis*). At the same time, the fuel from unmanaged grasslands, in particular, pose an increasing fire risk, as seen in the devastating 2023 Maui fires^{44,32}. Bare soil from fire or overgrazing is then susceptible to runoff during heavy rain events, increasing sediment runoff impacts to marine ecosystems and societal benefits. Biocultural restoration that enhances sustainable food production while recognizing land-sea linkages is urgently needed.

Increasing calls and efforts to include biocultural restoration alongside native forest protection make Hawai'i a valuable case study for ridge-to-reef NBS. In 2015, the state committed to localized SDGs, including doubling local food production by 2030, protecting 30% of watersheds, developing a green workforce, and restoring community connections to place^{12,45}. Accomplishing these goals requires uplifting biocultural restoration^{46,47}. In high-elevation conservation areas (Wao Akua), watershed partnerships work to protect native forests, which have high ecological, hydrological, and biocultural value⁴⁸. In some high-elevation areas, multi-generational ranchers integrate native trees into pastures (i.e., silvopasture) to diversify ranching livelihoods while sustaining paniolo (local ranching) culture and support diverse societal benefits⁴⁹. In mid-elevations (Wao Kānaka), Kanaka 'Ōiwi, and Kama'āina (of Hawai'i) farmers and organizations are restoring land through Indigenous informed multi-strata agroforestry systems, integrating woody plants and crops, that were once abundant in Hawai'i^{50–53}. Biocultural marine restoration focuses on revitalizing traditional Hawaiian resource management systems and nearshore food abundance through practices like Community-Based Subsistence Fishing Areas (CBSFAs) and resting periods (Kapu days).

Examples of integrated spatial assessments of watershed management's impact on marine societal benefits are sparse^{22,35} and often focus only on supply and biophysical metrics^{54–56}, overlooking the spatial variability in how people use and value these benefits. This limits our ability to evaluate investments and management priorities, coordinate across resource-managing entities, and reveal trade-offs amongst beneficiaries and ecosystems^{17,49,57}. Quantifying potential ridge-to-reef management benefits can attract financial support and community buy-in. In response, we assessed how combining existing native forest protection with transitions to agroforestry and silvopasture could benefit blue food production by increasing sediment retention across the Hawaiian archipelago. We addressed two questions: (Q1) Where do existing and planned native forest protection safeguard fisheries and seafood production through sediment retention? (Q2) How does scaling biocultural restoration on fallow agriculture and high-elevation pastureland through agroforestry add value to forest protection by boosting societal benefits from land to sea?

To address these questions, we created scenarios of biocultural forest restoration, including native forest protection and transitions to agroforestry. To quantify the benefits of native forest protection, we modeled forest loss with and without conservation action (i.e., fencing to remove invasive species and fire risk) in partnership with the State of Hawai'i Department of Land and Natural Resources, Hawai'i's Division of Forestry and Wildlife (DOFAW). For biocultural restoration on fallow agricultural lands, we drew on results of a statewide study of the motivations for and challenges to land use transitions to agroforestry in Hawai'i⁵³. In the study, interviews with agroforestry practitioners across Hawai'i, 50% of whom were Native Hawaiian, revealed that transitions to agroforestry most often occurred when practitioners gained access to former plantations lands, with practitioners primarily being motivated by their desire to restore relationships to 'āina (land), ancestors, and culture; strengthen local communities; and "reverse the damage of plantation agriculture and ranching"⁵³. We modeled where these systems are feasible today, based on land zoning, elevation, rainfall, and traditional agroforestry models⁵⁰. While there are many silvopasture options, we modeled a silvopasture system in high-elevation pastureland incorporating koa (*Acacia koa*), a native, culturally, and economically valuable timber tree, currently being implemented in pasture (>~915 m) in Hawai'i to diversify income streams and increase societal benefits. We expanded a spatially explicit land-sea modeling framework²² by nesting a novel yet simple blue food production model (Methods). Then we modeled the benefits of forest protection alone and combined with transitions to agroforestry on blue food production through changes in sediment retention and coastal Total Suspended Sediment (TSS). Our approach reveals locations where biocultural forest restoration NBS, can support island resilience and help meet SDG goals.

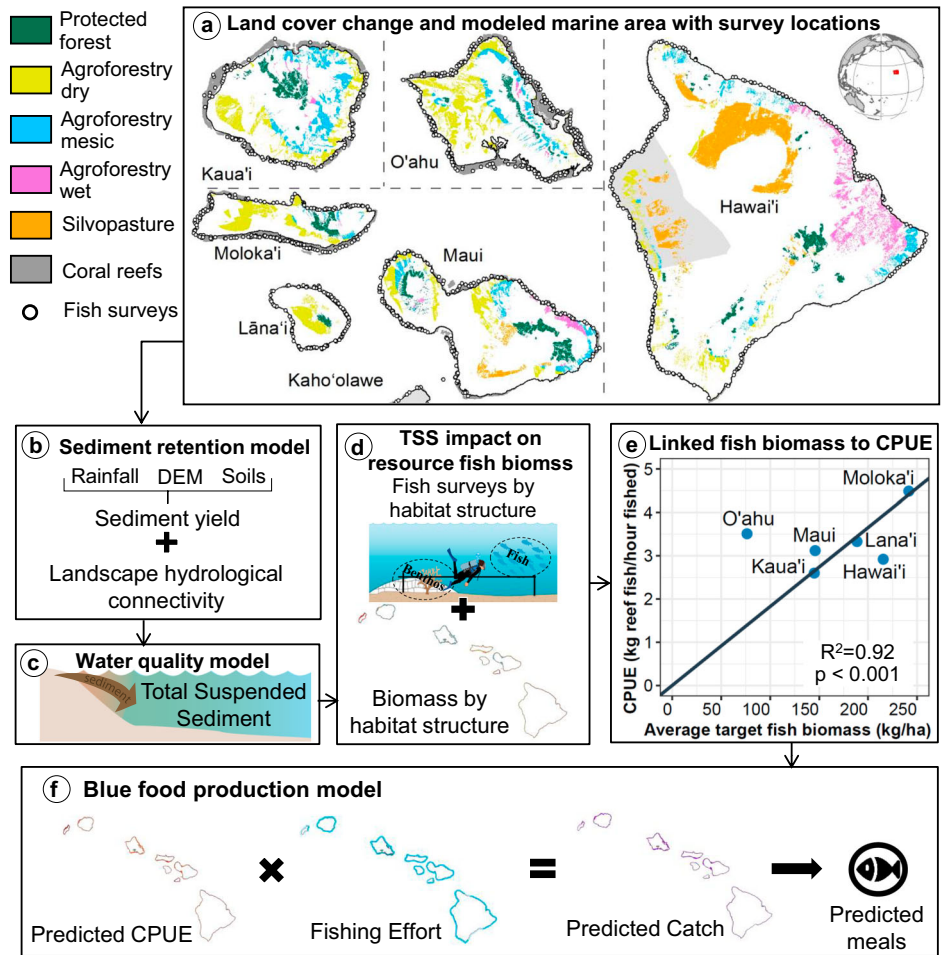
Results

Benefits from existing and planned forest protection throughout land and sea

Through collaboration with DOFAW, we mapped and modeled how existing and planned conservation fences protect existing native forests from fire risk, non-native ungulates (pigs, deer, goats), and the related expansion of non-native vegetation (Fig. 1a, Methods, Supplementary Fig 1). As a counterfactual, we ran a 30-year simulation of non-native forest and non-native grassland invasion based on observed expansion rates to estimate land cover change without protected areas (Methods). Using our expanded land-sea framework²², we tracked the effect of these watershed interventions on sediment retention, TSS, fisheries catch, and blue food production (Fig. 1). Forest protection efforts (fencing, ungulate removal, fire protection) help safeguard 400 km² (13%) of existing native forest and biodiversity across the state, including the potential to reduce fire-driven forest loss by 50% (Methods, Supplementary Figs 1 and 2).

Forest protection efforts are projected to retain almost 3500 tonnes of sediment annually across the island chain, with Maui and O'ahu benefiting the most from these interventions (Fig. 2a). Consequently, this helps maintain marine water quality and safeguard nearly 3000 kg of annual fish catch, equivalent to ~11,700 seafood meals annually (Fig. 2b). Sediment

Fig. 1 | Ridge to reef modeling framework. a Land cover maps showing the areas where watershed interventions are feasible given biophysical and zoning opportunities and constraints, including projected native forest protection within existing and planned fenced areas (forest green = native forest within protected areas) and potential agroforestry transition areas (yellow = dry multi-strata agroforestry; blue = mesic multi-strata agroforestry; pink = wet multi-strata agroforestry; orange = koa silvopasture) coupled with the modeled coral reef habitat area (grey) with survey locations used to parameterize the blue food model. The light grey represents the land areas that were not modeled due to no land use cover change (Kaho'olawe) and minimal surface runoff (West Hawai'i). b Sediment retention model, which incorporates rainfall, Digital Elevation Model (DEM), and soil characteristics, and land cover information to compute the annual sediment loads retained by vegetation and reaching the ocean (t/year). c A water quality model diffuses the change in annual sediment loads from the sediment retention model into the marine environment (Total Suspended Sediment [TSS]) as a function of wave energy, currents, and distance from river mouths. d The reef fish surveys are summarized by habitat type at the island scale to obtain the fish standing stock (g/m²) as a function of change in TSS. e The average fish standing stock by island is linked to the Standardized CPUE using a regression model (Supplementary Fig. 3). f The regression model is then used to predict CPUE at the reef pixel level and multiplied by total fishing effort to obtain total reef fish catch (kg by island) and number of seafood meals under different levels of watershed management.



retention per unit area of forest protection is the highest on O'ahu followed by Maui (Fig. 2c). Seafood production per unit area of forest protection is the highest on O'ahu followed by Hawai'i (Fig. 2d).

Spatially, the watersheds with higher sediment retention benefits correspond to the windward sides of the islands, where rainfall is abundant combined with areas with older substrate ages, such as the north shore of Kaua'i, Central O'ahu, and East Maui (Fig. 3). Some key areas on the leeward side of the islands also benefit from forest protection, including West Kaua'i, South O'ahu, and West Maui, areas where losing native forest could result in increased sediment export (Fig. 3). Consequently, native forest protection helps safeguard seafood production on both the leeward and windward side of the older islands, with the greatest benefits (up to 1800 kg/year in catch equivalent to 7100 meals/year) along East Hawai'i, followed by up to 380 kg/year in catch equivalent to 1500 meals/year on north shore O'ahu, West and East Maui (Fig. 3, Supplementary Table 1).

Added benefits throughout land and sea from transitioning fallow agricultural land to agroforestry

Through interviews with agroforestry practitioners⁵³, we identified two main agroforestry transitions: multi-strata agroforestry and silvopasture. First, 'Ōiwi (Native Hawaiian), local organizations, and farmers are converting fallow agricultural lands into multi-strata agroforestry, using a mix of understory, midstory, and canopy native and non-native, culturally important plants that are tended and harvested^{53,58}. We modeled where these transitions were possible based on land zoning and land use (fallow-zoned agricultural land and conservation land dominated by non-native species), elevation, rainfall, slope, and previous modeling of historical Native Hawaiian agriculture^{50,58} (Methods). We identified about 1650 km² of

suitable land for 354 km² of wet, 421 km² of mesic, and 875 km² of dry agroforestry (Supplementary Fig. 2). Second, ranchers are planting koa (*Acacia koa*) in high elevation pasture (>914 m), where there is less disease risk for koa from koa wilt (*Fusarium oxysporum*), to diversify income streams and increase societal benefits⁴⁹. We identified 800 km² of pasture suitable for high-elevation koa silvopasture (Methods, Supplementary Figs. 1 and 2).

Our land-sea models revealed that combining forest protection with agroforestry (including multi-strata and silvopasture) can increase annual sediment retention by 53,000 tonnes (30%) (Fig. 4a). The sediment retention benefits from transitions to agroforestry can increase annual fish catch by ~110,000 kg (10%), equivalent to 420,000 seafood meals per year (Fig. 4b). Sediment retention per unit area of agroforestry transitions is the highest on O'ahu followed by Kaua'i (Fig. 4c). Seafood production per unit area of agroforestry transitions is the highest on Maui followed by O'ahu (Fig. 4d). This is partly due to East Maui supporting healthier fish stocks given lower fishing pressure (Supplementary Fig. 4).

Sediment retention benefits are found throughout all the islands with the largest benefits in areas where multi-strata agroforestry is restored on un-managed non-native grassland areas, primarily West Kaua'i and O'ahu and East Hawai'i (Fig. 5). The primary exception is the central part of West Hawai'i where there is no surface water flow. Consequently, agroforestry has the potential to increase blue food production around all the islands and by up to 24,000 kg in catch or 95,000 meals annually in West Kaua'i and East Hawai'i as well as West Maui and leeward Moloka'i (Fig. 5). In addition, blue food production is increased by up to 600 kg in catch or 24,000 meals around O'ahu and in North Maui (Fig. 5, Supplementary Table 1).

Fig. 2 | Forest protection benefits at the island scale. Forest protection provides (a) annual sediment retention benefits (t/year) and (b) annual reef fish catch (kg/year) and seafood meals (number/year) by island, with (c) sediment retention benefits (t/year/km²) and (d) seafood meals per unit area of forest protection by island.

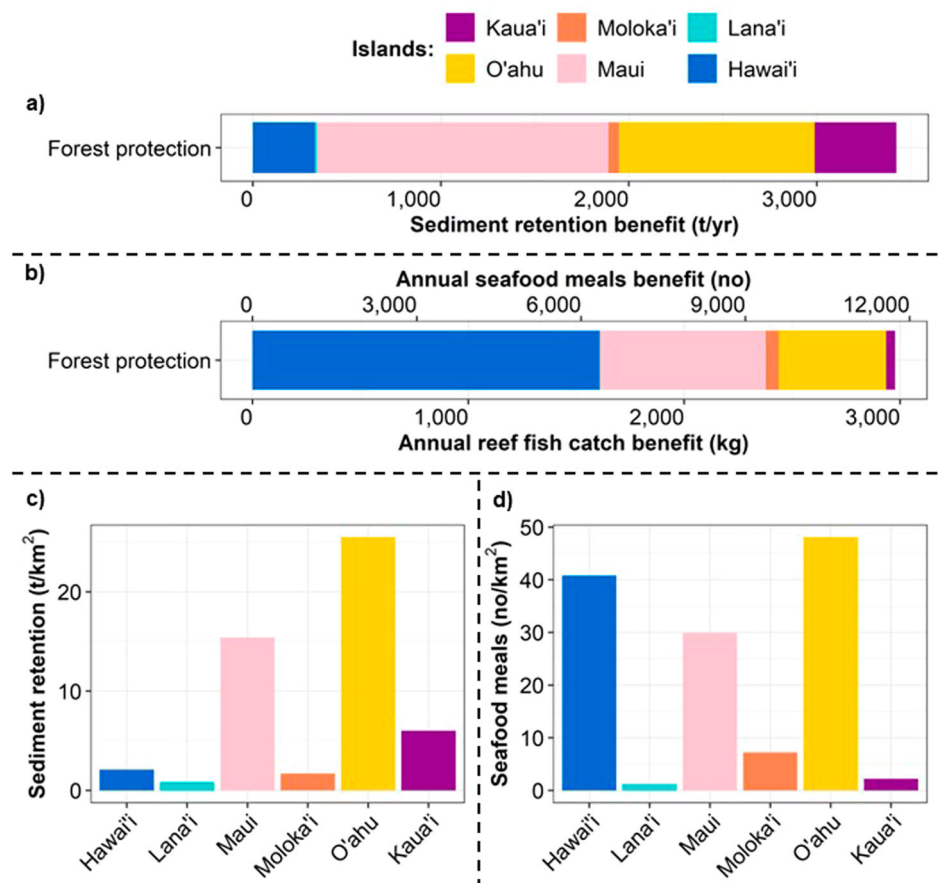
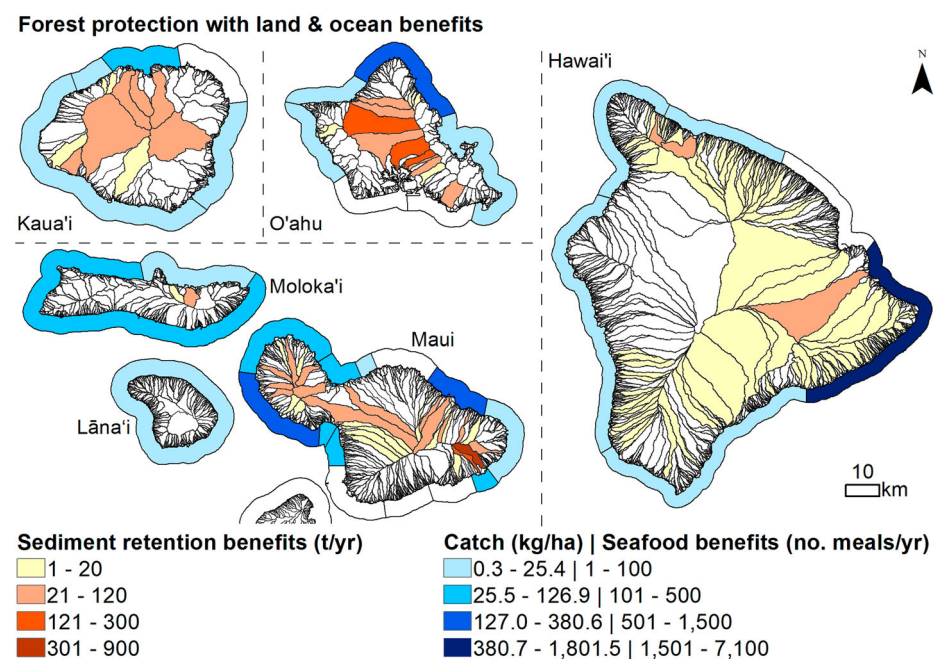


Fig. 3 | Forest protection benefits at the watershed and moku scales. Spatial variation in sediment retention (t/year) benefit by watershed and fisheries catch (kg/year) and seafood meals (number/year) benefits by moku provided by forest protection.



Discussion

Our land-sea assessment of biocultural NBS for watersheds can help inform the design of equitable and effective NBS to build island resiliency while advancing Hawai'i's 30×30 and SDG goals. Building on prior spatial watershed assessments linking land and sea health^{22,54,55}, we extended them

to illustrate the value of biocultural forest restoration on oceanic islands. Our methodology coupled a novel blue food habitat-based production model with a land-sea modeling framework to investigate the social-ecological benefits of multiple land stewardship scenarios. Combining forest protection in upper watersheds (Wao Akua) with transitions to agroforestry in

Fig. 4 | Agroforestry restoration benefits at the island scale. Agroforestry restoration provides (a) annual sediment retention benefits (t/year) and (b) annual reef fish catch (kg/year) and seafood meals (number/year) by island, with (c) sediment retention benefits (t/year/km²) and (d) seafood meals per unit area of agroforestry restoration by island.

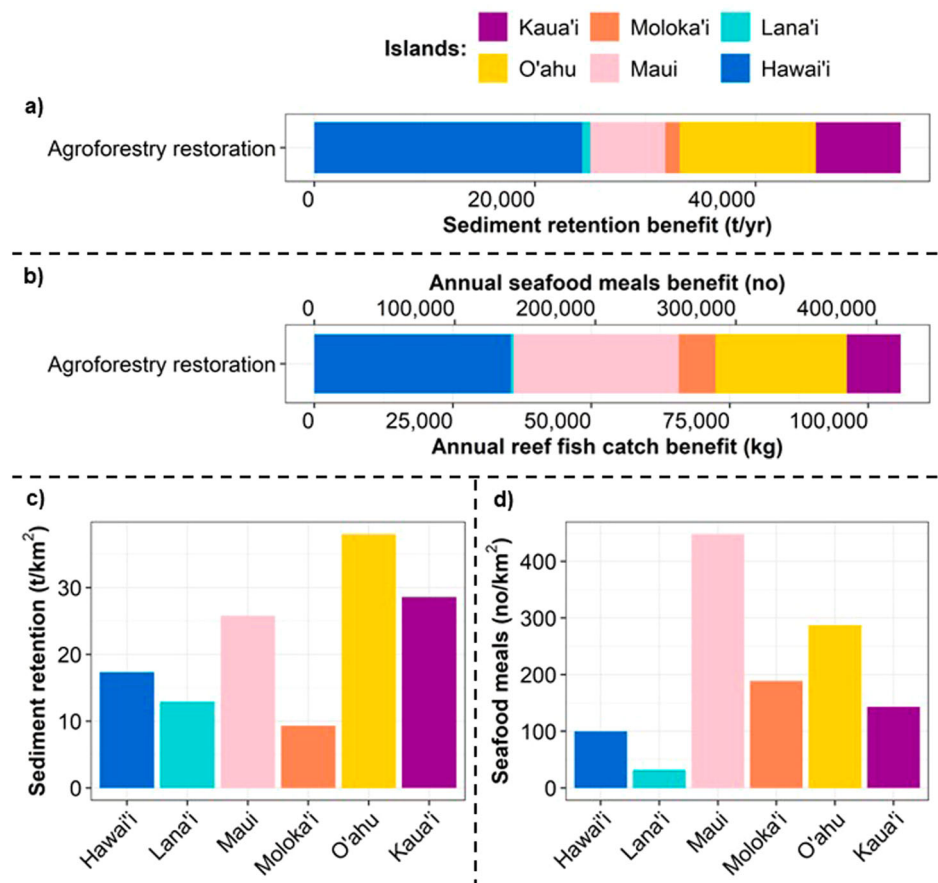
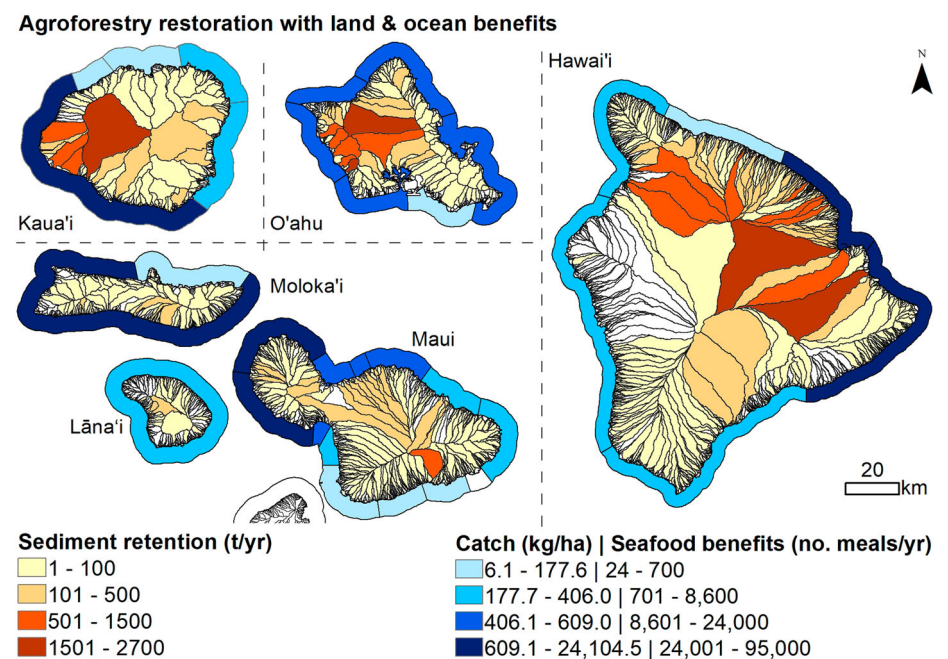


Fig. 5 | Agroforestry restoration benefits at the watershed and moku scales. Spatial variation in sediment retention (t/year) benefit by watershed and fisheries catch (kg/year) and seafood meals (number/year) benefits by moku provided by agroforestry restoration.



mid-elevations (Wao Kānaka) is essential to secure native biodiversity and restore culturally important species, food sovereignty, and multiple biocultural values. We found that biocultural forest restoration from summit to sea can, on average, enhance blue food production by 10% through increasing sediment retention by 30% at the archipelago scale. By quantifying these societal benefits spatially, we identified areas where prioritizing

investments and resources can generate greater benefits and could be the focus of further investigation. For instance, East Kaua'i, South shore of Moloka'i, West Maui, and East Hawai'i are places with high land-sea benefits where annual catch has the potential to increase by up to 600–24,100 kg with biocultural forest restoration. Our research highlights how restoring biocultural approaches can provide multiple wins for local

communities, through food production and natural ecosystem health from summit to sea.

Most watershed management efforts currently focus on biodiversity and groundwater recharge in relatively intact upper elevation areas (Wao Akua) where invasive species are the primary threat to Hawai'i's native and endemic species^{59,60}. Our analysis shows that current and planned fencing can protect 400 km² (13%) of native habitat on mountain ridges, enhancing sediment retention and blue food production, particularly on Maui and O'ahu. On O'ahu, key watersheds for sediment retention discharge in Pearl Harbor, an important fishing ground but largely inaccessible due to military control (Fig. 2a). Previous studies show that protecting forests through high-water-use invasive canopy species protects groundwater recharge⁴⁸, maintains forest canopy integrity which reduces fire risk^{61,62}, and support biodiversity^{63,64}.

The middle-elevation lands (Wao Kānaka) receive less conservation focus than either higher forests or marine areas, but our analysis reveals that agroforestry transitions offer meaningful social-ecological benefits and a powerful pathway to ecoscape restoration. Converting fallow grasslands to multi-strata agroforestry can enhance sediment retention, increase local food production, and provide culturally important resources, like medicinal plants and materials for ceremonies. Those land-sea benefits are particularly notable on the leeward side of the older islands (Kaua'i, Moloka'i, and Maui), all around O'ahu, and on the windward side of Hawai'i, likely due to larger sediment retention rates from converting grasslands to multi-strata agroforestry. Multistoried cropping and pasture systems help with fire mitigation⁵³ and may offer carbon finance benefits⁵⁸. Transitions to agroforestry conserve biodiversity through a mix of native and culturally important plant species that can support other native organisms⁶⁵, without impacting current crop or livestock production, since our modeling limited agroforestry transitions to fallow lands and silvopasture areas where grazing could continue. Our results highlight the need to elevate community-led efforts to restore middle-elevation forests through transitions to agroforestry for island resilience and local food sovereignty⁵⁰.

Building on studies on sediment impacts on coral reef fisheries and their importance to Hawai'i's food security^{66–71}, we show that watershed restoration across the Hawaiian Islands can boost coral reef fisheries in some regions by up to 60%, providing thousands of additional seafood meals annually (Supplementary Table 1). Our innovative blue food production model can be integrated into a land-sea framework to inform watershed management or be used independently to assess and guide nearshore fisheries management, even in data-poor regions. Nearshore fisheries are vital for global subsistence and yet methods to value them are lacking or limited to data-rich species-specific fisheries. This approach enables mapping, quantifying, and valuing blue foods using available data on effort, catch-per-unit effort, and habitat maps that are typically available for tropical environments.

Equally important, protecting habitats and restoring Indigenous food systems offer biocultural benefits, including perpetuating knowledge and practices ('Ike), social networks (Pilina), spirituality (Mana), and well-being (Ola Mau)⁴⁶. Silvopasture can sustain paniolo (local ranching) culture while restoring biodiversity, sediment retention, and providing financial returns⁴⁹. Healthy resources, like nearshore fishes and cultural crops, enable traditional practices to be passed down through generations. In the Pacific, producing and sharing local food strengthens social networks^{70,72–74}. Other studies found that food systems can also increase people's resilience in the face of market shocks, like COVID-19, through increasing food access and security when supply chains break down and borders close⁷⁵. Agroforestry and local fisheries provide benefits that extend beyond where the food is gathered and provide opportunities for that perpetuation.

Modeling involves simplifying assumptions and working with data limitations. One key challenge is linking static models to dynamic management scenarios, as watershed interventions may take 10–30 years to fully function as sediment traps⁴⁸ and benefit nearshore ecosystems and seafood production⁷⁶ (Methods). There is also a need for empirical measurements of erosion under the various land covers modeled in this study as, due to a

paucity of local data, we used available information from other locations to parameterize the sediment model. We did not measure the benefits of sediment retention on benthic habitats, which can create more positive outcomes for fisheries^{76,77}. The sediment retention and blue food production models simplify complex ecological and social processes (Methods). Although we did not validate the InVEST SDR model in this study, it has been validated for Hawai'i in previous research⁷⁸. We minimized uncertainty by validating fish biomass with reef survey data⁷⁹ and scaling catch values by island to align with empirical catch data⁶⁹ (Methods). We report marginal changes and relative spatial differences, rather than absolute modeled values, which are recommended when InVEST SDR is not validated⁸⁰. These results are a 'screening' tool, requiring further investigation and empirical studies to inform the design and implementation of NBS²².

For the decision-maker community, accounting for these sources of uncertainty and implications on management outcomes is important when communicating these results. For the scientific community, our methodology calls for more frequent land use and benthic habitat health mapping, better attribution of management interventions to ecosystem dynamics, and open access research and empirical data sharing. This will help integrated tools like this to be able to reflect the latest conditions of the resources, predict land-sea management outcomes more accurately, center people's values, and promote holistic management. Advancing research on mapping beneficiaries of ecosystem benefits and empirical studies on how change in marine water quality impacts fisheries is key to more accurately predicting the outcomes of land-sea management.

The spatial insights generated across the entire group of islands (pae 'āina) can help large landowners and agencies that have responsibility (kuleana) at landscape scales prioritize watershed interventions. Currently, DOFAW's 30×30 initiative focuses on fencing priority watersheds (mauka), while the Department of Aquatic Resources' Holomua Marine Initiative manages nearshore resources. Our findings can inform the Holomua Marine Initiative by modeling mauka interventions, and addressing gaps in current approaches. For instance, Hawai'i Monitoring and Reporting Collaborative (HIMARC), who provide scientific support to Holomua, use land-based pollution models (like nutrients from cesspools) but do not account for marine outcomes from watershed actions, which is often what communities call for. Incorporating land-sea processes in 30 × 30 and resilience planning will provide a clearer understanding of how sediment impacts marine environments, which have not explicitly been considered in Hawai'i and across the Pacific. This study can foster collaboration among agencies and landowners to unify land and ocean care, supporting island resilience equitably via biodiversity, food production, and biocultural benefits.

Mobilizing resources to prioritize transitions to agroforestry in Hawai'i offers a triple win for people, nature, and culture; however, large-scale investment in these transitions is lacking. Many agroforestry efforts are small-scale and rely on their ability to self-fund, write grants, and recruit volunteer and in-kind donations to be economically viable⁵³. Yet, agroforestry has more revenue potential than forest protection alone and could create over 165,000 green jobs, assuming one full-time employee per hectare (No'eau Peralto PhD, personal communication, May 15, 2024) and 1650 km² of agroforestry restored. This value does not account for the large numbers of volunteer hours spent at existing sites, which could greatly increase this number (No'eau Peralto, PhD, personal communication, May 15, 2024) and highlights that people value caring for the land. Many rural communities on islands are losing their workforce as youth seek job opportunities elsewhere, in industries such as tourism, which can be volatile as shown by COVID-19⁸¹. Investing in biocultural forest restoration can create a green workforce dedicated to nurturing nature and generate positive externalities like fisheries and higher water quality for recreation. Financial support, including through public and private financing, is essential to sustain these societal interventions.

Future climate projections for Hawai'i show rising temperatures⁸² and more extreme rainfall, leading to increased wildfire risk⁶¹ and sediment runoff. Fallow agricultural lands are near urban areas and pose an unprecedented fire risk⁸³ as shown by the devastating 2023 Maui fires. Land use changes have a

greater impact on fire risk than climate change⁸³, suggesting that transitions from fallow agricultural land to agroforestry may be a key opportunity for enhancing public safety. On the marine side, local fisheries management is just as crucial for seafood production as climate change in island contexts^{84,85}. Without improved management, Hawai'i's growing population could reduce local coral reef systems' ability to meet seafood demand by 40%⁶⁷. Given that reefs currently contribute 7 million meals annually⁶⁸, it is pivotal to identify more resource management measures that could enhance this food source (and explicitly link agroforestry footprints to food production). To this end, we used island-specific catch-per-unit-effort (CPUE) scaled to coral reef habitats, and fish biomass, and modeled sediment projections to estimate reef fish catches under different watershed management scenarios.

Our results suggest that biocultural NBS, rooted in local culture, can co-produce social-ecological benefits and help us thrive amidst change. There are, however, key barriers that must be overcome to facilitate the biocultural transitions outlined in this paper. Achieving resilient Indigenous food systems and land care will require political and economic shifts to remove barriers that marginalize Pacific Islanders and other local communities from engaging in land care. Amplifying and (re) valuing Indigenous principles like kinship, relationship to land, and reciprocity through public and private investments necessary to support these transitions will require substantial increases in existing funds for land management. Future work will usefully explore the economic resources needed to support these transitions and explore practical ways to fund these transitions given the broad societal benefits they provide. Restoring land-sea connectivity, integrating Indigenous knowledge, and securing financial support for these interventions can build resilience, meet SDGs, and address climate challenges.

Methods

Modeling approach

Our approach to quantify the societal benefits provided by combining native forest protection with the restoration of multiple habitats to multi-strata agroforestry from summit-to-sea consists of four key components: (1) land cover transition scenarios (Supplementary Fig. 1), (2) the open source InVEST Sediment Delivery Ratio (SDR) (version 3.14.1)⁸⁶ to quantify the change in sediment export to the coast based on topography, soil erodibility, and rainfall erosivity (Supplementary Table 3), (3) a marine water quality model incorporating wave energy and currents to estimate TSS⁵⁵ (Supplementary Table 3), and (4) a blue food production model combining fishing effort^{71,87}, CPUE⁶⁹, benthic habitat structure⁸⁸, and fish surveys⁷⁹. We conducted this workflow on each land stewardship transition independently and then computed the relative change in societal benefits.

Land stewardship design

The land stewardship strategies illustrate a mid-century timeline (30 years from now) without predicted rainfall change under climate change. See Supplementary Table 3 for all data sources.

Constant land cover types

The 2015 Carbon Assessment Hawai'i Land Cover Map (CAH)⁸⁹ was chosen as the most updated land cover map that integrated components from previous land cover and land use mapping efforts with LANDSAT TM imagery at 30 m × 30-meter resolution, resulting in 48 detailed land cover units. This base map provides detailed attention to vegetated areas, describing general species assemblages in forests, shrublands, wetlands, and grasslands across the state. Descriptors of urban or agricultural lands are less detailed, encouraging use with the Hawai'i Statewide Agricultural Land Use Baseline layer (ALUB)⁹⁰. The ALUB was created to show contemporary commercial agricultural land use activity across the state, made using WorldView-2 satellite imagery (2011–2013). Aerial analysis was combined with State and County datasets including County Real Property Tax and Agriculture. Water Use data. Combined, these state-wide datasets provide detailed data on both vegetation classification as well as increased understanding of how these areas are used. For example, CAH allows us to see the array of vegetation on a parcel while ALUB allows us to understand land cover in use. So we combined both

layers using ArcGIS 10.8.2⁹¹. Finally, to ensure that we didn't overestimate sediment erosion in the younger islands, we overwrote vegetation types with the spatial extent of the lava rock from the 2020 land fire cover map⁹².

Forest protection land cover transition

DOFAW provided a GIS shapefile showing the location of existing and proposed fenced units. In the first scenario, we assumed no reduction in fire-driven forest loss and unrestricted spread of non-native forests at a 2% annual rate of expansion⁴⁸. We compared this to a scenario that includes existing and planned fencing in the next 30 years, where we assumed that non-native forests does not spread into the protected areas and there is a 50% reduction in fire-driven forest loss within protected areas. Where non-native species do not spread and fire-driven forest loss does not occur, we assumed no change from the baseline conditions. Last, we computed the area (km²) of native forest that gets protected by those fences by the island.

Multi-strata agroforestry land cover transition

We developed a multi-strata agroforestry transition suitable for dry (550–1500 mm/yr), mesic (1500–3000 mm/yr), and wet (>3000 mm/yr) rainfall zones based on interviews with agroforestry practitioners from 30 sites in Hawai'i^{53,58}. Multi-strata agroforestry systems in Hawai'i are site-specific and diverse relative to other agriculture in Hawai'i; they include both native and non-native, culturally important understory, mid-story, and canopy plants integrated together in mixed systems of over 10 species per site⁵⁸. We identified the average annual rainfall of each site based on their location on the Hawai'i Rainfall Atlas⁹³ and categorized sites as dry, mesic, and wet systems according to the rainfall zones in Price & Jacobi⁹⁴.

While each multi-strata agroforestry system has a unique and diverse mix of species, some common species of dry systems include koa (*Acacia koa*, native), 'ulu (*Artocarpus altilis*, canoe plant), citrus trees (*Citrus* sp.), and cacao (*Theobroma cacao*) with native understory plants like 'ipu (*Lagenaria siceraria*, native), 'uhaloa (*Waltheria indica*, native), and 'ilima (*Sida fallax*, native), sweet Potato (*Ipomoea batatas*, canoe plant), and Cassava (*Manihot esculenta*)⁵³. Mesic systems often include 'ulu, koa, niu (*Cocos nucifera*, canoe plant), Papaya (*Carica papaya*), Avocado (*Persea americana*), Mango (*Mangifera indica*), Citrus trees, and mai'a (*Musa* sp., canoe plant) with culturally important plants like māmaki (*Pipturus albidus*, endemic), kalo (*Colocasia esculenta*, canoe plant), Ginger (*Zingiber officinale*), and ti (*Cordyline fruticosa*, canoe plant) in the mid- and understory^{53,65}. Wet systems frequently incorporate 'ōhi'a (*Metrosideros polymorpha*, endemic) and kukui (*Aleurites moluccanus*, canoe plant) in the overstory with 'Ōlena (*Curcuma longa*), māmaki and 'awa (*Piper methysticum*, canoe plant) in the mid- and understory^{53,95}. Based on the characteristics of transitions described in the interviews and practitioners' common motivations of biocultural restoration, we assumed that multi-strata agroforestry transitions could occur on environmentally feasible land that was either: (1) zoned agriculture, but not used currently for agriculture (i.e., fallow or unmanaged); (2) zoned conservation, but considered low priority given a dominance of non-native species; (3) zoned urban, but undeveloped.

To determine unmanaged or fallow agricultural lands, we used a combination of the 2020 State of Hawai'i Agricultural Baseline⁹⁰, which identified areas in active agricultural production, and state land use district boundaries map, which delimits agricultural zoned land⁹⁶. Those lands zoned agriculture, but were not in production in 2020 were considered unmanaged agricultural lands. Within these areas, we excluded any areas classified as developed or as native vegetation in the CAH land cover map⁸⁹ and young lava flows⁹². Following the Kurashima et al.⁵⁰ spatial models of colluvial agriculture (agroforestry) systems, we constrained the scenarios from sea level to 855 meters in line with crop growth restrictions and excluded areas with slopes over 30 degrees. We assumed multi-strata agroforestry would not occur in areas with less than 550 mm rainfall per year, since long-term irrigation is often cost-prohibitive for agroforestry practitioners⁵⁰. In addition to fallow agricultural lands, we also considered

undeveloped urban and rural zoned areas as well as non-native dominated conservation zoned lands, which overlap with projections of suitable area for historical Indigenous colluvial agriculture (agroforestry)⁵⁰. This aligns with several examples of agroforestry transitions on conservation lands dominated by invasive species⁵³, and on urban, but not developed lands.

Silvopasture land cover transition

We combined the multi-strata agroforestry land use transition with a transition from ranching to silvopasture, another form of agroforestry that integrates trees into pastureland. We discussed and co-developed the silvopasture system with several ranches and a state department, which manages ranch land. In particular, one ranch is developing a high elevation (>914 m; 3000 ft) silvopasture system that integrates the native tree koa (*Acacia koa*) with cattle and is considered a model by some other ranches. The goals of this work are to maintain the cultural practice of ranching while also producing revenue from koa harvesting over a 40-year time horizon and enhancing societal benefits of rangelands⁴⁹, including by increasing carbon storage and augmenting fog interception. We focus on this silvopasture system because it has the potential for large-scale implementation and a wide range of desired co-benefits.

Spatially, silvopasture was considered feasible only on existing pasture lands and alien grasslands located in agriculture zones above 914 m (3000 ft) with rainfall of at least 550 mm. Due to the elevation restriction, silvopasture is only feasible on Maui and Hawai'i Island and because research and development of wilt-resistant genotypes for lower elevations is still ongoing. In addition, we only focused on areas where growing Koa is suitable⁹⁷.

To determine the sediment erosion factor, we assumed that a 66% tree cover per hectare approximately corresponds to 16 trees per hectare. This assumption was based on information provided by a ranch, corroborated by USDA, where mature koa, can account for 70% of crown cover, and reach heights of 20 m in 40 years, with crown widths of >20 m. With Koa corresponding to mesic native forest type, we did a weighted average of erosion factors for native mesic forest (66%) and 34% of pasture (Supplementary Table 4).

Land-sea modeling framework and sub-ecosystem services models

We adapted an existing land-sea modeling framework developed to prioritize wastewater management in Hawai'i and forest management in Fiji in order to promote coral reefs habitat health and targeted fish biomass benefits^{54,98}. This framework was then scaled to the archipelago of Vanuatu⁵⁵ and the Mesoamerican Reef region to inform the design of watershed-based NBS that can support coastal and marine societal benefits²².

Using this land-sea framework, we mapped and quantified when feasible the effects of native forest protection and agroforestry transitions on four social-ecological benefits from summit to sea: (1) Native forest protected area (km², a proxy for biodiversity that we derived from the forest protection land cover transition described above), (2) Agroforestry restored area (km²) for wet, mesic, dry climate region (a proxy for biocultural values), (3) sediment retention (tonnes/year), (4) nearshore fisheries production (kg of catch) and associated blue food production (# of seafood meals).

We report the change in listed metrics above, relative to the status quo (native forest protection). We applied three ecosystem services models to understand the effect of watershed management on blue food production: (1) InVEST Sediment Delivery Ratio model (sediment retention benefit); (2) marine water quality model (TSS loads/year); and (3) habitat-based blue food production model. We used information from interviews with local community members to compute the other societal benefits metrics (ha of agroforestry restorable, # jobs creation potential, biocultural value, and food production).

InVEST Sediment retention model

The Sediment Delivery Ratio model is from the open-source and spatially-explicit suite of InVEST models are designed to map and measure the flow of

nature's benefits to people⁸⁶. The SDR model incorporates the influence of precipitation, soil properties, topography, and vegetation cover, which can be modified by land stewardship transition option^{80,86}. For each watershed management scenario, the SDR model calculates (1) the annual soil erosion at the pixel scale (30 m) using the Revised Universal Soil Loss Equation (RUSLE) and the ability of downslope vegetation to retain sediment, (2) the sediment delivery ratio (i.e., proportion of soil eroded from a given area) that will travel to the stream mouth at the shoreline, and (3) summarizes the sediment export pixel values at the watershed scale⁹⁹. The output metric reported for this service is a change in tonnes of sediment retention per watershed per year, relative to the status quo/forest protection. We assumed no sediment runoff for Keauhou, Kealakakua, and Kiholo (West Hawai'i) based on the lack of streams and soils in the area¹⁰⁰.

To estimate the sediment retention (t.yr⁻¹) and, indirectly, the change in sediment export to the coast by watershed, InVEST SDR model (version 3.14.1)⁹⁹ operates at the DEM resolution (10 m × 10 m, aggregated to 30 m × 30 m) obtained from USGS¹⁰¹. After testing a range of streamflow accumulation thresholds on the DEM, we selected the following values for each island to delineate stream network and watershed boundaries using ArcHydro: (1) Kaua'i = 1000, (2) O'ahu = 3000, (3) Moloka'i = 2000, (4) Lana'i = 2000, (5) Maui = 5000, (6) Hawai'i = 5000. The connectivity of SDR and the watershed boundaries were verified by comparing predicted stream pourpoints at the coast to the available DAR stream map and local watershed maps. At the pixel-scale, SDR computes the amount of sediment erosion using the Revised Universal Soil Loss Equation (RUSLE) (Eq. 1)⁹⁹. The RUSLE equation estimates the overland gross erosion per pixel (see Eq. 1 and Supplementary Table 3 for data sources):

$$\text{Soil loss} = R \times K \times LS \times C \times P \quad (1)$$

Where R = rainfall erosivity factor (MJ.mm.ha⁻¹.hr⁻¹), represent the ability of rainfall to cause erosion and was derived using historical annual precipitation (P)⁹³ and the equation from Bols 1978: $R = 2.5 P / [100(0.073 P + 0.73)]^{102}$, K = soil erodibility factor (tons-ha-h-(ha-MJ-mm)⁻¹) represent the rate of soil loss per rainfall erosion index unit, obtained from SSURGO database, with no data assumed to be 0.01 and converted to SI by $K = [K_{\text{factRF}}] \times 0.1317^{103}$, LS = slope-length and gradient factor, C = Cover management factors (C-factor) represent the ratio of soil loss for different land cover types compared to the soil loss from well-tilled and continuous fallow land, assuming the same soil, slope, and rainfall conditions^{104,105} and P = Conservation practice factors (P-factors) represent the impact of management practices on soil erosion rates. C-factors and P-factors were assigned to each land cover use type and derived from peer-reviewed and white literature where possible containing comparable land uses and geographies (Supplementary Table 4). SDR uses local topography from the DEM to model sediment transport across the landscape and determine the ratio reaching the shoreline⁸⁶. Sediment retention is then aggregated at the watershed scale. Although the modeling results were not validated against local datasets for this study, this approach allows us to explore the relative change between management interventions⁸⁰. We may underestimate sediment retention due to erosion processes not accounted for by SDR, such as landslides and stream bank erosion⁸⁶. We recommend fieldwork to collect TSS measurements at catchment outlets and compare them to SDR outputs.

When parametrizing SDR on the land cover types we made 4 key assumptions: (1) Canopy is less dense and understory cover is denser in dry forest and shrublands than in their wet counterparts and we ignored the variation in the understory. (2) Most remaining native species are fenced, which results in removal of non-native ungulates, we assumed a denser understory than in invasive species cover types^{63,64}. (3) Mesic forest, shrublands, and grasslands erosion factors are somewhere in between dry and wet but research on those is lacking, so we assumed a weighted average of wet and dry erosion factor values. We note that those values for shrubland and grassland would depend a lot on the management, such as well managed pasture, unmanaged, over-grazed/intensive. (4) Multi-strata agroforestry is

similar to natural forests with more people trafficking around for care, so we assumed a little more erosion on those relative to native forests.

Marine water quality model

The sediment model connects to the fisheries model by diffusing the sediment load from all the watersheds into the nearshore waters from a pourpoint for forest protection and agroforestry transitions, separately. The pourpoints along the shoreline are proxies for stream mouths. Using google satellite imagery from 2021 and a local stream map¹⁰⁶ to determine their location whenever feasible. To represent the impedance of sediment moving through water from their source, we created a diffusion factor surface layer (c) using the sum of two marine variables rescaled from 0–10 using equal intervals, known to affect sediment diffusion: wave power (kW)¹⁰⁷ and currents (m/second)¹⁰⁸. The sediment then spread into coastal waters is modeled for each pour point by applying a non-linear decay function over the diffusion factor surface layer pertaining to each watershed until a maximum distance of 1.5–2 km from the shoreline is reached (see Eq. 2) (see Supplementary Table 3 for model inputs data sources):

$$TSS = \sum_{(n=1)}^{412} s_p \times e^{-c^2/D_c} \quad (2)$$

where TSS = Total Suspended Sediment per grid cell value (t/yr), s_p = Sediment load (t/yr) at each pourpoint of watershed i (obtained from SDR InVEST), c = diffusion factor surface (unitless) represents the impedance of moving planimetrically through each cell from each pourpoint using a composite of two oceanographic drivers known to affect sediment dispersion: wave power (kW)¹⁰⁷ and current (degree and seconds)^{55,108,109}, D_c = diffusion threshold. The distance from the shore for each decayed sediment plume per watershed was set to not exceed 1.7 km from the shoreline. This threshold was based on field studies that tested the influence of land-based source pollutants in Hawai'i^{110,111} and modeled studies⁸⁷. This model does not account for tidal or longshore transport influence, which may impact the dispersion of TSS along the coastline by over- or under-estimating the TSS deposited on the bottom of the ocean. Future investigations can compare modeled water quality to local observations, satellite imagery, and/or in-situ data available for specific areas.

Blue food production model

We linked the effect of watershed management to fisheries through the impact of total suspended sediment on resource fishes. Fish taxa, identified as important for subsistence and commercial fisheries by local Hawaiian communities (Hā'ena and Ka'upulehu)⁹⁸ (resource fishes) and aligned with McCoy et al.⁶⁹: Acanthuridae (15 spp), Carangidae (4 spp), Fistulariidae (1 spp), Kyphosidae (3 spp), Labridae (6 spp), Lethrinidae (1 spp), Lutjanidae (4 spp), Mullidae (7 spp), Scaridae (8 spp), Serranidae (1 spp) were considered. We modeled total resource fish biomass (kg/ha) as a function of habitat structure and TSS. We derived the empirical resource fish biomass (g/m²) from reef survey data collected by NOAA⁷⁹, which comprised 1162 survey locations, collected between 2010–2016. We omitted Kaho'olawe and Ni'ihau from the analysis because there was no land use transition due to a lack of climate data⁹³ and no CPUE data⁶⁹.

We derived the in-situ resource fish biomass by assigning averaged values by habitat strata for each island (with Hawai'i split into leeward and windward). We used a subset of 10 NOAA habitat structure classes including a variety of hard-bottom habitats as well as a sand habitat type⁸⁸. The rubble and mud classes were removed. The 'unknown' habitat class was included within 1 km of the shoreline, under the assumption that there are suitable habitats for fishes given the presence of surveys (which normally focus on hard-bottom habitats) but cloud cover and oceanographic conditions precluded habitat mapping using satellite imagery. The empirical fish biomass values from each site were assigned to each habitat strata and averaged. When there was no empirical data available for a stratum, we assigned the value from a similar habitat class (Supplementary Table 4). For instance, for Aggregated Patch Reef and Individual Patch Reef, we used fish

biomass values from aggregate reefs. Similarly, for Scattered Coral/Rock, we used values from Rocks/boulders.

A study by Wakawella et al.⁷⁷ in Palau found that herbivore biomass declined linearly with increasing total sedimentation rate (GAMM, $p < 0.001$, $\chi^2 = 37.29$, d.f. = 2) from a 45.5 g/m² at low sediment sites to 1.4 g/m² at high sediment sites, equivalent to a 95% reduction. The study defined high sediment regimes as areas with TSS greater than 21.9 tonnes/ha/year and low sediment regimes as areas with less than 21.9 tonnes/ha/year. Using those breaks, we reclassified the TSS plumes for forest protection and agroforestry transitions and intersected this layer with the nearshore habitat map by island, so portions of each habitat were either exposed to low or high sediment regimes. Then, we decreased the standing fish biomass from transect averaged values by 95% based on the high sediment regime for each land use transition. The shapefiles were then converted into raster grids for the fisheries model (100 m × 100 m).

We fitted a linear regression for average in situ target fish biomass (g/m²) to standardized catch per unit effort (sCPUE) at the island scale⁶⁹. The sCPUE by island combines the CPUE from all the gear types (boat- and shore-based fishing using line, net, or spear), resulting in the following sCPUE values: Kaho'olawe and Ni'ihau (no data), Kaua'i (2.6), O'ahu (3.51), Moloka'i (4.49), Maui (3.12), Lana'i (3.33), Hawai'i (2.92). The intercept was set to zero assuming that zero biomass results in zero sCPUE. We then predicted CPUE spatially as a function of standing fish biomass per pixel using this linear regression equation (Supplementary Fig. 4).

We computed the nearshore catch at the pixel level (100 m × 100 m) by multiplying spatially explicit sCPUE with total fishing effort (boat and shoreline fishing for spear, net, and line fishing gears)⁷¹ (Supplementary Fig. 4) and summarize the total modeled catch in kg by island. We then derived scaling factors by dividing the total modeled catch by island under the current land cover by the reconstructed total catch from McCoy et al.⁶⁹. Then we calculated the relative difference in catch for each land cover transition and applied the same scaling factors for each island: Hawai'i (7.2), Kaua'i (6.5), Lana'i (3.1), Maui (3), Moloka'i (3.4), O'ahu (3.1).

To convert nearshore catch to seafood production, we applied conversion factors derived from interviews with Native Hawaiians from the community of Kiholo, Hawai'i on how they prepare fish for cooking to calculate edible weight and meals⁷⁰. A conversion factor of 0.67 was applied to all the modeled species and the number of meals was calculated from edible weight by using a standard seafood portion size of 0.17 kg (6 oz) derived from interviews with local restaurant owners⁷⁰. Finally, we summarized the change in catch (kg/year) and seafood meals production (count/year) by Moku (traditional management divisions). To do this, we applied *Moku* marine boundaries, created by the State of Hawaii Division of Aquatic Resources to group and summarize ridge-to-reef datasets, which are based on the traditional *Moku* land divisions that extended seaward to reef edges and beyond.

Data availability

No datasets were generated or analyzed during the current study.

Code availability

Links for downloading the InVEST open-source software are available at naturalcapitalproject.stanford.edu. The source code is available at <https://github.com/natcap/invest>¹¹². Statistical analyses were performed using the software packages R (www.r-project.org) v.4.0.2 and are available at https://github.com/jade-md/r2r_hawaiian_archipelago.git¹¹³ and ArcGIS Desktop (www.esri.com) v.10.8 with Advanced licensing and extensions Spatial Analyst and Geostatistical Analyst.

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All authors were involved in the conceptualization and contributed to reviewing and editing the manuscript. J.M.S.D., K.A.S., G.M., N.D., C.T., Z.H.S., L.L.B. conducted formal analysis. J.M.S.D. led the writing of the original draft. J.M.S.D., K.A.S. and N.D. developed computer code and software for the ecosystem service models. J.M.S.D., K.A.S., L.L.B., G.M., N.D., C.T., T.T., Z.H.S., N.K. provided data and inputs on the design and implementation of the land use transitions and ecosystem service models.

Competing interests

The authors declare no competing interests.

Additional information

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