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Biocultural Restoration of Traditional Agriculture: Cultural, Environmental, and Economic Outcomes of Loʻi Kalo Restoration in Heʻeia, Oʻahu

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Abstract: There are growing efforts around the world to restore biocultural systems that produce food while also providing additional cultural and ecological benefits. Yet, there are few examples of integrated assessments of these efforts, impeding understanding of how they can contribute to multi-level sustainability goals. In this study, we collaborated with a community-based non-profit in Heʻeia, Oʻahu to evaluate future scenarios of traditional wetland and flooded field system agriculture (loʻi kalo; taro fields) restoration in terms of locally-relevant cultural, ecological, and economic outcomes as well as broader State of Hawaiʻi sustainability goals around food, energy, and water. Families participating in the biocultural restoration program described a suite of community and cultural benefits stemming from the process of restoration, including enhanced social connections, cultural (re)connections to place, and physical and mental well-being, which inspired their sustained participation. We also found benefits in terms of local food production that have the potential to provide economic returns and energy savings over time, particularly when carried out through a hybrid non-profit and family management model. These benefits were coupled with potential changes in sediment and nutrient retention with implications for water quality and the health of an important downstream fish pond (loko iʻa) and coral reef social-ecological system. Compared with the current land cover (primarily invasive grasses), results suggest that full restoration of loʻi kalo would decrease sediment export by ~38%, but triple nitrogen export due to organic fertilizer additions. However, compared with an urban scenario, there were clear benefits of agricultural restoration in terms of reduced nitrogen and sediment runoff. In combination, our results demonstrate that a biocultural approach can support the social and financial sustainability of agricultural systems that provide multiple benefits valued by the local community and non-profit while also contributing to statewide sustainability goals.

Keywords: biocultural restoration; food energy water; ecosystem services; cultural services; sustainable agriculture; Hawai'i; taro; wetland agriculture; flooded field systems; lo'i kalo; sediment; nutrients

1. Introduction

Across the globe, multiple factors have stimulated a growing interest in biocultural approaches to ecological restoration [1–5], including the strengthening of indigenous cultural revitalization movements [6,7], increasing acknowledgement among conservation and restoration professionals of the importance of social-ecological linkages [8–11], and growing recognition that restoration success often depends on community engagement [12–14]. Biocultural approaches to restoration focus on both ecological outcomes, such as biodiversity restoration and erosion control, as well as cultural outcomes, such as restoration of culturally important species and the traditions associated with them and community (re)connection to place [15–17]. Building on broader theories of social-ecological systems that emphasize the links between humans and the environment [18,19], biocultural approaches place further emphasis on a place-based approach and explicitly recognize that cultural and biological outcomes are interlinked and mutually reinforcing [20]. For example, the restoration of indigenous food production systems can strengthen cultural identity and improve nutrition and food self-sufficiency, while also restoring habitat for native plants and animals [2]. Restored habitats can then reinforce other cultural traditions that are linked to them [20]

Whereas industrial monocultures are often framed in terms of tradeoffs among food production and other outcomes such as water quality [21], traditional agricultural systems are typically characterized as potentially sustainable systems with synergies among desired ecological, cultural, and economic outcomes [22–24]. A social-ecological systems or biocultural approach to restoring traditional agriculture explicitly focuses on the links between the ecological and socio-cultural processes that underpin these systems [3]. Garnering broad support for biocultural restoration can be challenging, however, as short-term revenue is typically lower than monoculture agriculture or alternative land uses like urbanization, and conservation efforts often prefer complete restoration of 'natural' systems to maximize ecological benefits. While a growing body of literature points to a wide array of cultural and ecological benefits of biocultural restoration that can contribute to multi-level sustainability goals [7,16,20], there are few studies that evaluate these benefits (as well as tradeoffs) in a holistic and inclusive way. A framework for evaluating synergies amongst and tradeoffs across objectives of biocultural restoration could facilitate inclusion of these approaches in multi-scale restoration planning and facilitate adaptive management [9].

There are several existing approaches that can be adapted to guide an evaluation framework for biocultural restoration projects. Considering the environmental dimensions, the food-energy-water (FEW) nexus has emerged as an important framework for illuminating hidden synergies and tradeoffs in agriculture of great relevance to local, regional, and international sustainability initiatives [25], such as the United Nations Sustainable Development Goals (SDGs). While the FEW nexus has the potential to shed light on biocultural restoration approaches, it has generally focused on large-scale agriculture and largely ignores cultural aspects that can play critical roles in long-term societal sustainability and adaptive management. As an important complement to address cultural dimensions, a growing theory and emerging examples of inclusive valuation of land-use futures within the ecosystem services or "nature's contributions to people" literature sheds light on strategies to bring together diverse methodologies to assess benefits and tradeoffs in terms of locally relevant and linked ecological, cultural, and socio-economic concerns [16,26,27]. This work has been furthered by indigenous and place-based perspectives on cultural ecosystem services, often framed as reciprocal human-environment relationships well-aligned with biocultural restoration approaches [17,20]. We propose that combining and adapting the FEW nexus and ecosystem services (including place-based, indigenous cultural ecosystem services) frameworks has important potential to contribute to inclusive assessments of biocultural restoration.

Pacific islands can be considered as model systems to study biocultural restoration of traditional agriculture due to a combination of the socio-cultural significance of local food systems and their geographic isolation, which makes reduced dependence on imported food and energy sources an important part of building resilience. Pacific islands are also characterized by relatively small watersheds and tightly linked land-sea resources, making terrestrial agricultural practices and marine ecosystem health (also important for local food production) intricately linked [28,29]. In Hawaiʻi, elevated interest in the biocultural values of these traditional agricultural systems is demonstrated by a growing communities working to restore traditional terrestrial agriculture as well as nearshore aquaculture for linked cultural, economic, and environmental benefits [3,30]. The State of Hawaiʻi through the Aloha + challenge has also committed to interconnected sustainability goals around food, energy, and water (as well as links to local ecosystems and culture) and is recognized as an example of local implementation of the SDGs [31]. These commitments include: doubling food production in 20 years (Hawaiʻi currently imports nearly 90% of its food [32]); achieving 100% renewable energy by 2040; protecting watersheds and linked marine ecosystems; and facilitating re-connection to place and community-based management [31]. Achieving multiple sustainability goals simultaneously will require re-establishing community-based diversified agricultural systems with low energy requirements and few environmental tradeoffs. Yet, across the State, large tracts of agricultural land are currently fallow or used for high value export crops, largely due to the challenging economics of small-scale farming for local food production [33]. In this context, it is imperative to understand how biocultural approaches to traditional agricultural restoration can contribute towards achieving both local objectives and formal State of Hawaiʻi sustainability goals around food, energy, and water.

In order to contribute towards a better understanding of the multi-level outcomes of biocultural restoration projects, we collaborated with Kākoʻo ʻŌiwi, a community-based non-profit in Heʻeia on Oʻahu at the forefront of biocultural restoration of traditional agriculture, to evaluate the likely future benefits and tradeoffs of their vision around restoring a degraded and invaded wetland to loʻi kalo and native wetland plant communities. We specifically identified key ecological, cultural, and socio-economic outcomes of interest to Kākoʻo ʻŌiwi and the local community who participate in the biocultural restoration efforts, and assessed those in combination with the broader State of Hawaii's sustainability goals around food, energy, and water [31]. For evaluating the various outcomes we used mixed methods, including participatory methods using an indigenous cultural ecosystem service process and framework [17]; sediment and nutrient retention ecosystem service modeling [34,35]; and food, energy, and water tradeoff analysis [25,36–39].

This study integrates diverse theories into a practical framework for evaluating biocultural restoration initiatives, with the aim of facilitating their on-the-ground planning, adaptive management, and assessment. Our research team built strong relationships with community members and non-profit staff to develop and apply the framework, ensuring that evaluation outcomes and approaches are reflective of local concerns while also linking to broader statewide sustainability objectives. Applying the framework collaboratively, we addressed the following research questions: (i) what are the locally-relevant cultural, environmental, and economic outcomes of biocultural restoration of loʻi kalo in Heʻeia, Hawaiʻi?; (ii) to what extent can biocultural restoration of loʻi kalo in Heʻeia, Hawaiʻi contribute to statewide sustainability goals around food, energy, and water?; and (iii) what are the synergies and tradeoffs among these outcomes and how can this inform design of biocultural restoration projects in Heʻeia and beyond?

2. Methods

2.1. Site Description

Our study site Heʻeia, Oʻahu is an ahupuaʻa (traditional Hawaiian political-ecological boundary), where several NGOs are committed to a biocultural approach of restoring traditional social-ecological systems from mauka to makai (land-to-sea), which include wetland and marine fish ponds (loko iʻa), upland agroforestry, and loʻi kalo. The area has recently been designated a Natural Estuarine Research Reserve, and the first of such reserves to explicitly focus on restoration for socio-cultural benefits [40]. The full Heʻeia watershed (11.5 km^2) spans from the top of the Koʻolau mountain range to Paepae o Heʻeia (traditional fish pond) and then to Kāneʻohe Bay, a 45 km^2 sheltered bay and highly valued conservation and subsistence and commercial fishing area. Average rainfall is 3020 mm at the summit and 1205 mm at the coast [41]. The watershed has two smaller basins, Haʻiku and ʻIolekaʻa, that contribute to streamflow in Heʻeia stream (Figure 1).

We focus on a ~800,000 m^2 wetland managed by the community-based non-profit Kākoʻo ʻŌiwi who seek to restore the now primarily invasive vegetation to the loʻi kalo systems present until the 1930s. The mission of Kākoʻo ʻŌiwi is to "perpetuate the cultural and spiritual practices of Native Hawaiians," of which restoring loʻi kalo through a biocultural approach is a central part. They have worked to restore loʻi kalo since 2008 and with the help of volunteers and a family program have successfully restored ~7,500 m^2 of loʻi alongside other managed areas, and seek to restore another ~500,000 m^2 to loʻi and other intercropped species (see below) in the next 20 years alongside a series of other restoration activities, including restoration of native wetland plant communities and agroforestry [42] (See SI Methods). They also aim to restore an additional ~100,000 m^2 of the area as retention basins (including areas restored to loko iʻa (fish ponds) and native wetland plant communities) with the remaining area including, streams, channels, access roads and small buildings, such as a commercial kitchen, poi (a traditional Hawaiian food made from mashed taro corms) mill, and community gathering place [42].

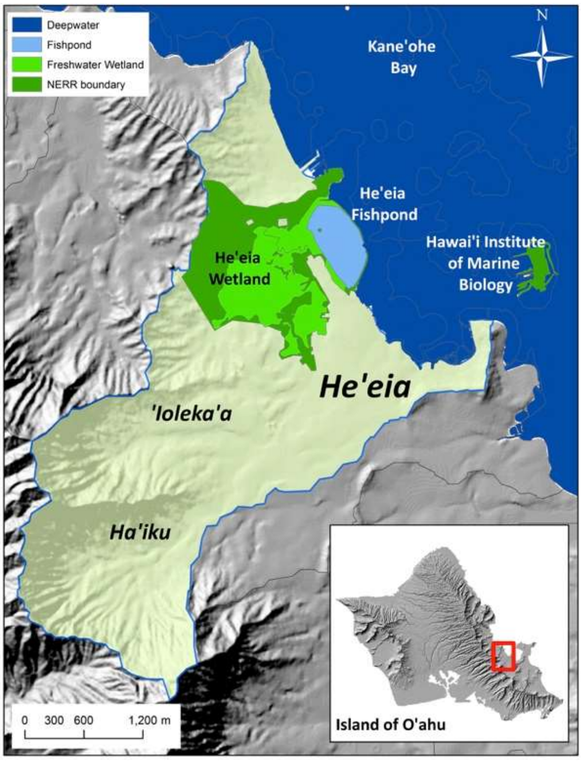

Figure 1. Location of Heʻeia wetland within the Heʻeia watershed, Oʻahu. NERR = National Estuarine Research Reserve.

2.2. Outcomes Evaluated

Emerging theory on biocultural restoration suggests that evaluations of biocultural projects should include place-based outcomes and indicators defined by and relevant to local actors [20,43]. At the same time, for biocultural approaches to gain traction in broader land-use planning initiatives, demonstrating their value to broader state, regional, and global sustainability goals and objectives is important [9,43] In the context of this study, we defined key outcomes of importance to Kākoʻo ʻŌiwi's and the local community [42] as well to the achievement of statewide sustainability goals around food, energy, and water [31] (Table 1). An important *first* goal of Kākoʻo ʻŌiwi is to build capacity of farmers and provide local families with the opportunity to learn to farm and care for loʻi kalo and (re)connect to the land. Among several initiatives to achieve this (see SI Methods), the organization began a family or ʻohana program where local families care for and maintain loʻi. There are currently 11 families participating in the project and scaling this program is an important part of the non-profit's growth strategy. *Second*, in line with the State's goal to double local food production, Kākoʻo ʻŌiwi strives to produce traditional and diversified food crops. While financial return is not a central goal, the organization sees financial sustainability as an important part of their ability to sustain food production. *Third*, in line with the State of Hawaiʻi's goal to be 100% renewable by 2045, the organization seeks to understand how renewable energy could be incorporated into their long-term plans and how traditional agriculture can reduce energy inputs associated with food production and imports. *Fourth*, in line with the State's goal of protecting watersheds and marine ecosystems, there is a strong interest in understanding how loʻi kalo and broader wetland restoration influences the sediment and nutrient retention functions of the wetland given links to the downstream fish pond and critical coral reef habitat of Kāneʻohe Bay, which both have high ecological, economic, and cultural value (Table 1).

Table 1. Outcomes of interest to Kākoʻo ʻŌiwi and to the broader State of Hawaiʻi Aloha + Challenge sustainabilty goals [31].

Outcome	Why Important?
Community and cultural outcomes	Central to Kākoʻo ʻŌiwi's mission and important for local community members
Traditional and diversified crop production	Traditional food production a key management goal of Kākoʻo ʻŌiwi; economic returns important for long-term restoration success; contributes to statewide sustainability goal to double local food production by 2030;
Energy savings	Potential cost savings for Kākoʻo ʻŌiwi with renewable energy; contributes to statewide sustainability goal to be 100% renewable by 2040
Sediment and nutrient retention (water quality)	Important for broader Heʻeia social-ecological system and food production downstream; contributes to statewide sustainability goals around watershed and marine conservation.

2.3. Assessment Methods

We provide a brief overview of methods used to assess each outcome listed in Table 1. Detailed methods can be found in the Supplementary Information.

2.3.1. Community and Cultural Outcomes

To understand participant families' perspectives and experiences with the family or ʻohana program to date, we conducted semi-structured, in-depth interviews with 8 of 11 families in the pilot project following an informal gathering between the researchers, participants, and Kākoʻo ʻŌiwi staff. Interviews were conducted while working with the families in the loʻi for 2–3 hours, which helped to build relationships and facilitate conversations (see SI Methods for guiding questions and further methods).

Our interview approach and analysis adapted an existing process and framework developed by Pascua et al. [17] to assess cultural ecosystem services from an indigenous Hawaiian perspective. This framework was developed through participatory methods within other indigenous Hawaiian communities and proved to be a more appropriate classification for cultural services than western frameworks such as the Millenium Ecosystem Assessment cultural ecosystem service categories [44]. Rather than framing cultural ecosystem services as uni-directional benefits from nature to people, Pascua et al. [17] focus on reciprocal relationships between people and ʻāina (land, literally that which feeds), which resonated with the place-based, indigenous and local communities with whom she worked. The cultural service categories encompass the Hawaiian language that contain nuanced meaning not reflected within their English translations. As such, it was important to use a Hawaiʻi-based categorization method to document the results and maintain the authenticity of outcomes mentioned within each interview.

Interview quotes and themes were coded according to Pascua et al. [17]'s Hawaiʻi-based cultural ecosystem service framework that includes four main categories: ʻIke (knowledge); Mana (spiritual landscapes); Pilina Kānaka (social connections); and Ola Mau (physical and mental well-being) as well as subsets of those categories. Where themes did not fit into existing categories, a new category was created (see Table 4 and SI Methods).

2.3.2. Future Scenario Analyses

In order evaluate ecological and economic outcomes important both to Kākoʻo ʻŌiwi and of relevance to State of Hawaiʻi sustainability goals around food, energy, and water, we developed a spatially explicit future agricultural restoration scenario based on Kākoʻo ʻŌiwi's conceptual plan and input from the farm manager and executive director (Figure 2; Table 2; SI Methods). The scenario is over a 20-year period (2018–2037) in line with the timeline of Kākoʻo ʻŌiwi's conceptual plan [42]. As a point of comparison for the sediment and nutrient retention analyses only, we included an urban scenario based on development patterns of neighboring urban areas (Table 2; SI Methods).

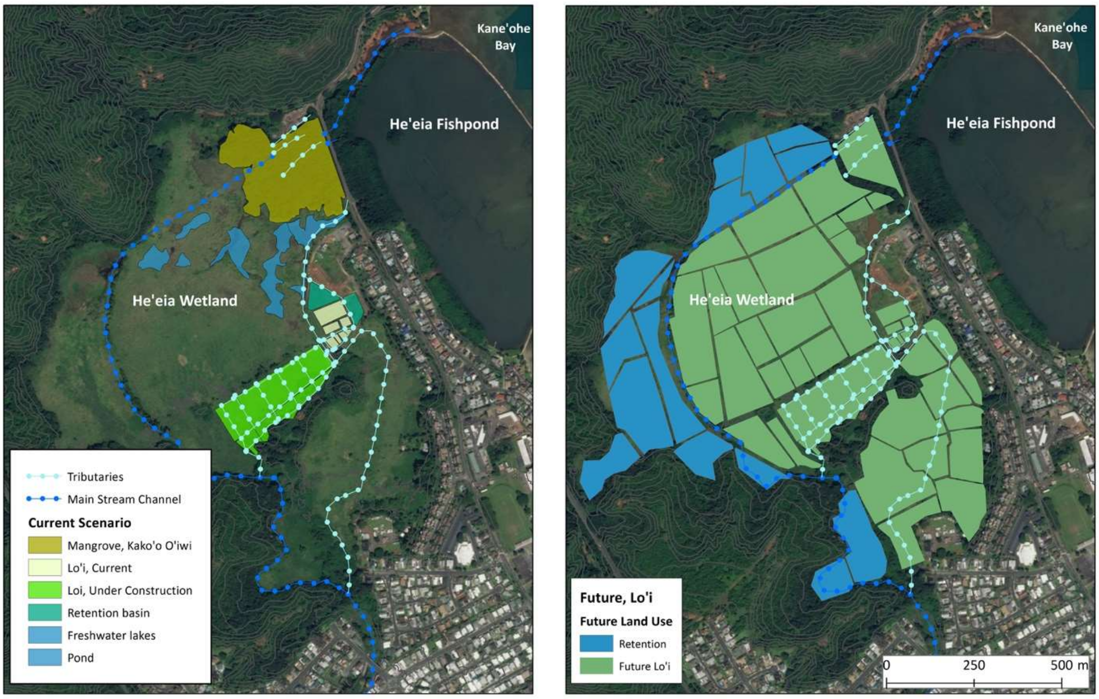

Figure 2. (**left**) Current land cover in Heʻeia wetland. Note that mangroves (an invasive species in Hawaiʻi) are currently being removed, but that the effect of mangrove removal was not considered in this study; (**right**) restored agriculture scenario in Heʻeia wetland. Retention areas are re-planted with wetland native plants or restored to loko iʻa (fish ponds).

Table 2. Descriptions of current, restored agriculture, and urban scenarios of He'eia wetland.

Scenario	Description
Current land use	Wetland area (~800,000 m^2) mainly dominated by invasive guinea grass (*Megathyrsus maximus*) and Job's tears (*Coix lacryma-jobi*); 7300 m^2 of lo'i kalo already restored
Restored agriculture	~500,000 m^2 restored to mix of kalo (taro; *Colocasia esculenta*), ulu (breadfruit; *Artocarpusaltilis altilis*) and mai'a (banana; *musa sp.*); ~100,000 m^2 to retention basins including loko i'a (fish ponds) and native wetland plants; additional areas for waterways, roads, educational and community buildings, and other infrastructure
Urban	The full 1,600,000 m^2 parcel managed by Kāko'o 'Ōiwi is converted to mid-intensity urban development. On-site disposal systems, similar to the surrounding communities are assumed to be dominant.

2.3.3. Traditional and diversified crop production and economic returns

We estimated potential crop production (local food production) and economic returns (total revenues, total costs, and total profits) over the future agricultural restoration scenario under varying assumptions of banana (*musa* sp.), breadfruit (*Artocarpusaltilis altilis)*, and taro (*Colocasia esculenta*) productivity [45–53], with the percent area of each crop defined by Kāko'o 'Ōiwi staff. (Table 3; SI Methods). While kalo (taro) is the dominant crop, we included additional crops as Kāko'o 'Ōiwi's production model includes diversified cropping systems (Table 2).

Table 3. Assumptions underlying estimation of economic returns from food production.

Crop	Area Added Annually (m^2)	Area in Production by Year 20 (m^2)	Area in Year 20 as % of Total Farm Area	Yield (kg/m^2)	Farm Price ($/kg)	Production cost ($/kg)
Banana	2428	50,181	10%	0.58–2.39	2.34	1.50
Breadfruit	4856	50,181	10%	0.20–2.43	2.58	0.32–0.83
Taro	6475	125,453	25%	1.12–1.79	5.51–10.34	6.33–10.14

2.3.4. Energy Savings

In order to understand how utilizing solar power could increase Kāko'o 'Ōiwi's financial returns while contributing to the State's goal to be 100% renewable by 2045, we evaluated the use of renewable energy for food production as well as avoided energy use for food imports in the restored agriculture scenario (SI Methods).

On-farm Solar Energy for Food Processing

Kāko'o 'Ō'iwi is hoping to realize cost savings over the long run by operating the proposed taro processing facility using solar power. Commercial poi production is similar to wet milling of other starches. Assuming that energy requirements for wet milling corn are comparable to those for poi production, we calculated the required daily energy and corresponding photovoltaic (PV) system power capacity to produce poi for taro production scenarios 1 and 2 [54,55]. PV installation costs were then estimated assuming a cost of $3.01 per watt [56]. Utility bill savings and revenue from solar energy sales back to the grid were estimated using Hawaiian Electric Company's (HECO) Schedule 'G' General Service rate of $0.27/kWh and the HECO Customer Grid-Supply rate of $0.15/kWh (SI Methods).

Avoided Energy Inputs

One of the main reasons for higher energy efficiency in the case of organic farming is the lack of input of synthetic nitrogen (N) fertilizers, which require high energy consumption for production and transport. Kāko'o 'Ō'iwi currently applies 151 kg ha^{-1} of organic fishmeal N-fertilizer for taro production and would continue this practice under both future scenarios. Indirect energy savings—i.e., fossil fuel energy inputs that would have been required to synthetically produce the required amount of N-fertilizer—were calculated for the 20-year management period [57].

We also estimated the fuel needed to ship taro to Hawai'i as a conservative estimate of the energy offset from locally produced taro (SI Methods).

Sediment and Nutrient Retention

Sediment and nitrogen retention (accumulation) within the wetland and export from He'eia stream were estimated for the current, restored agriculture, and urban scenarios. These are important metrics of success for Kāko'o 'Ōiwi as changes in water quality through sediment and nutrients directly links wetland management to the fish pond and coral reef which have high socio-economic, cultural, and ecological significance for the broader He'eia system. For both parameters, we estimated the input and export based on existing data or model estimates to determine the amount retained by the restoration area.

The calculation for sediment retention in the current scenario employed a simple box model (retention equals sediment input minus export) based on data from the United States Geological Survey (USGS) for import into the wetland [58] and Hawai'i Department of Health (HDOH) [59] and USGS [60] for export out of the wetland (see SI Methods for further details). Sediment retention in the restored agriculture scenario was estimated through literature values of annual retention rates of rice paddies (a similar system to lo'i) [61]. Total sediment retained in the restored scenario was estimated by multiplying annual retention rate (kg m^{-2}) by the retention area. Sediment export from the restored agriculture scenario was estimated as the net current input [58] from above the wetland less the total retained. To estimate sediment export from He'eia wetland in the urban scenario, we used the InVEST Sediment Delivery Ratio model [34,62] (See SI Methods).

We used a box model approach to estimate the amount of nitrogen input to and export from the wetland. We modeled nutrient input into the wetland from the broader He'eia watershed with the InVEST Nutrient Delivery Model (InVEST NDR) [34] (see SI Methods). For the current scenario, we calculated nitrogen retention in the wetland using USGS discharge data [60] and HDOH average nutrient concentrations at the He'eia stream mouth [59] (SI Methods). For the restored agriculture scenario, we conservatively estimated fertilizer rates within the restored lo'i areas as approximately 15 g m^{-2} based on manager input and plant (taro) uptake at 23% of fertilizer N applied [63]. For the urban scenario we assumed there was no retention capacity within the wetland. Given that there are no centralized wastewater treatment options, we estimated a similar input of N (as from the surrounding neighborhoods) in wastewater from on-site sewage disposal systems [64] (SI Methods).

3. Results

3.1. Community and Cultural Benefits

The families participating in the 'ohana program spoke of motivations for participation that went far beyond the direct benefit of producing kalo, spanning all inter-related categories of Pascua et al. [17]'s framework ('Ike—knowledge; Mana—spiritual landscapes; Pilina Kānaka—social connections; and Ola Mau—mental and physical well-being) and beyond (see Table 4 for examples and quotes). Families consistently mentioned that they most value the intangible benefits gained from the opportunity to maintain their own lo'i such as developing a reciprocal relationship between and among kānaka (Indigenous Hawaiians) and 'āina (land):

> *"My family gets to eat, mentally, physically, spiritually. The place that we're working at becomes more abundant and healthier and restored. The thriving factor increases as we work not only for my own family but for the place."*

Families talked of an ability to connect with landscape or experience a sense of "feeling the living, breathing, 'āina" while working in the place (Mana; Table 4). Many spoke of the opportunity to mālama

Hāloa, referencing the kin relationship between kānaka and kalo (taro) with roots in creation described in the Hawaiian creation chant, the Kumulipo (Table 4). In many cases, the program was their first opportunity to have access to land and water that allowed them to fulfill this kuleana (responsibility) to their ancestors by following in their footsteps and perpetuating the traditional practice (Table 4).

Social connections (Pilina kānaka; Table 4) were also an important motivation and perceived benefit of the program. Goods produced through the traditional agricultural practice were primarily discussed in the context of having kalo to take home or share. They valued building an ʻohana through common experience with like-minded individuals, sharing of the work, and establishing trusting relationships and aloha for each other over all else (Table 4). There was also strong interest in passing down knowledge, passions, and environmental knowledge to new generations, keiki (children), and other families that may enter the program (Table 4).

While participants emphasized that kalo, per se, was not their primary motivation for participation, they pointed to the importance of beliefs and cultural practices around food cultivation and preparation:

> *"I think most of us in our hui have experience with food and we know that if you're working around food and you're working around something you're going to eat later on, you've got to have good thoughts and say good words and put good intentions into something you're going to put into your own body later."*

They emphasized that the program helps to build a sense of pride and accomplishment, creating a sense of belonging (safe space), and providing the opportunity to progress as kānaka (Hawaiians). They gain a sense of pride, accomplishment, and mental healing from coming to the loʻi, putting in the work, and watching their kalo progress. In the words of a participant:

> *"Just creating this safe space where people can feel like they're okay and they don't have to be judged. They can just come here and feel aloha. Creating a sense of belonging and that they belong to something bigger, and something healthy and something that's aloha."*

However, there was also concern about how to deal with potential changes to the current positive atmosphere as the program grows; the trusting relationships, the heart of the ʻohana, may dissipate with a larger number of families and loʻi:

> *"The one thing that I think about as we see all these families here is that we really have to continue to create this space of positivity, so that we don't have to deal with the things like stealing or...you know what I mean? As you get hundreds and hundreds, as organizations get big, they tend to make these operational rules and that's when people start to get...when attitudes change. And so on..."*

Table 4. Cultural outcomes discussed by community participants in the ʻOhana program categorized by Pascua et al. [17]'s cultural ecosystem service framework developed through participatory methods with several indigenous and local communities in Hawaiʻi.

ʻIke (knowledge)	
Ma ka Hana ka ʻike (learn place-based practices by actually doing them)	
• Learning mahiʻai kalo (wetland taro farming). • Experience builds on previous knowledge/experience and adapting practices to a particular landscape. • Practice promotes other place-based cultural practices such as kuʻiʻai (traditionally pounding poi with a board and stone).	*"The number one thing I value about this experience is, just the opportunity and just the fact that I was asked to participate and given the opportunity to be a part of it and to bring my family along with me . . . this opportunity is unique because it was like 'Okay, go take care of a particular loʻi by yourself, with our families..we'll give you guys some tools, we'll give you guys some direction, but go...go at it. You're going to help us increase the abundance of this area."*

Table 4. *Cont.*

Nānā i ke Kumu (observe familiar natural processes and seasonal occurrences)	
• Observation of rain intensity, stream flow, etc. and learning corresponding responses in the lo'i. • Understanding of physical aspects of the landscape needed to maintain lo'i (soil, water flow, different types of mud, nutrient cycles, etc.). • Expansion of ecological knowledge and interactions within the ecosystem (presence of different animals with different seasons). • Learning of human impacts on landscape. • Ability to observe how natural processes influence each other on an ahupua'a scale.	*"It's definitely personal growth out here because you're learning science and you've got to learn the moons. You've got to know when it's going to rain too hard. We live in Kāne'ohe, so when we have heavy rain it's like 'Uh oh'...we're thinking about the lo'i. We've had it when the water was up to here, on my hips, but I think we're kind of getting smart about adjusting the water and water flow. With these (lo'i), the makawai go this way so we have to be careful. We're at the top so it feeds into the next one and the next one."*
Hālau 'Ike (diverse formal and informal learning)	
• 'Āina-based/culture-based education for keiki. • Informal learning through working in the place and alongside other people. • Opportunities for teaching moments for communities and the broader world about cultural practice. • Enhancement of environmental awareness and sustainability. • Ability to draw links between technology and scientific study to place-based observations. • Gaining perspective of environmental processes operating on a wider scale. • Learning how people fits into the broader picture of the environment (reciprocal relationships between kanaka and 'āina, being part of the solution).	*"They appreciate it a lot more … They understand the kuleana. And I like that about … this opportunity, the fact that we have our own place and we have the ability to come and take the kids and do this with them. Eventually, I'm going to lose that, my kids are going to go to sports on Saturdays; it's just good to have this time with them. You know, and it's not a chore to try to get them to do this. I have two daughters so my youngest daughter is like, 'I don't want to get muddy dad...' but once she gets in, she has fun."*
Mana *(Spiritual landscapes)*	
Ho'omana/Mauli Ola (spiritual beliefs and practices allowing people to interact with mana of a landscape)	
• Physical connections with the landscape facilitate mental connections (feeling the living, breathing 'āina); and cultural identity. • Gaining an awareness of sacredness of landscape. • Fulfillment of a kuleana. • Connections with ancestral presence by following in their footsteps with cultural practice.	*"So there's that saying I always go back to, 'you don't grow the kalo, the kalo grows you.' And what I've gained is just a different perspective in the different aspects of life really. From the relationship side of how man fits into the larger picture of the environment and the 'āina and seeing the 'āina as an actual living breathing thing, because when you come out here on Sundays and it's just you and it's quiet like this, you can actually hear and feel and see how it's moving. You can see all the life in the water, you can almost feel and hear the 'āina speaking to you, too."*
Wahi Pana (appropriate access to, and understanding of place-specific practices associated with storied landscapes)	
• Promoting an understanding of and respect for the value of the practice within the place. • Learning of the stories of the landscape. • Understanding the meanings of place/weather event names. • Opportunity and access to engage in cultural practice within the place. Access to place to mālama hāloa.	*"That's another thing that's changed for me too, is we notice that we're so excited to talk about the different stories … . And the kids are starting to talk about it too and for us it's like 'oh, this is great, I'm hearing the children talk about Keahiakahoe' and there's so much. This is like an open classroom because there's always something to learn*

Table 4. *Cont.*

ʻAumakua/Kinolau (presence/recognition of familial gods/ancestors)	
• Deepened connection with Hāloa; recognizing kalo as a family member. • Presence and significance of names of rain, winds, etc., to various aspects of the landscape.	*"Something so fundamental, from who we are as kanaka, what are we supposed to do? We're supposed to mālama Hāloa, we're supposed to mālama our older brother. 'You have a chance to mālama Hāloa? Awesome!' Because I don't know how many of us would love to have a plot of land and water where we could potentially do that. That's so many Hawaiian families' dream."*
Hōʻailona (presence of environmental signs/indicators and the ability to recognize them)	
• Ability to recognize different species of plants and animals indicating different states of the loʻi and different seasons. • Ability to recognize bioindicators of various cycles within the ahupuaʻa system. • Listening to omens from weather dictating when to/ not to work (during heavy rainfall, difficult conditions, etc.).	*"It just feels really comfortable there and there's some real specific things . . . .that you get to know all the sounds of the birds that are going to be around and you're working and you're like 'oh, you can hear the aeʻo.' You don't even have to look up but you know exactly and you can picture where they must be because you can hear their direction. You know the buzzing of the pinao when they're around, it's just a lot of specifics. You even get a sense of what's normal weather for that time of morning and what's unusual. Things are shifting, it's a different season. You're so much more present with the environmental setting there than I know I am at other places."*
Pilina Kānaka *(social interactions)*	
Hoʻolako (perpetuation of practices/skills allowing individuals to provide for their families)	
• Kalo for the home/family. • Kalo for community and sharing.	*"We're part of the family program, but my intentions for this particular one, is mainly for our school and also for my family because this is more than enough kalo to go around. So we can be a part of the family program and also be able to provide 'school' with whatever kalo they need. Families can come and eat better, learn about how and why what foods work and which ones don't, and try to get Hawaiians back to what they ate before."*
ʻIke Aku, ʻIke Mai (share traditional/local knowledge and values)	
• Passing down knowledge and passions to new generations and keiki. • Creating an ono (taste) for the traditional practice. • Setting/shifting/sharing an awareness, intention, and purpose while working in the landscape; cultural continuity in life. • Promoting new, young leaders. • Ways to connect mindsets to entire ahupuaʻa.	*"We have so much to teach, not only our own keiki but other communities. If you look at how our island is a microcosm for the entire planet, hopefully it can be used on a global level. With Hawaiians, and kilo, and the way they would be so in tune that when one thing is blossoming they know which fish are running. And the wet and dry season, there was just so much detail. And when you're that in tune and everything, you're actively engaging all those nodes of connectivity between the different aspects of life. Especially when you name things, that's such a Hawaiian thing to do. Or just labeling something wind, or something rain. If you look at Hawaiian culture and Hawaiian language, there's thousands of names for rain and names are descriptive, same thing with winds, clouds."*
Kōkua Aku, Kōkua Mai (presence of strong social ties/social networks)	
• Establishing of trusting relationships and aloha for each other. • Building community. • Building an ʻohana through common experience with like-minded individuals. • Sharing of the work. • Expanding social networks. • Facilitation of goods exchanges not within monetary means.	*"It's a prioritization of our relationships with that ʻāina and with each other. If that's the driving force, then, people aren't caring about who got how much and when and what and all that stuff. Among our hui, and I'm sure others as well are similar this way, there is a genuine wanting to take care of each other and take care of that place. If that stays the priority, I don't think there would be any problems."*

Table 4. *Cont.*

Ola Mau *(Physical and mental wellbeing)*	
Lako/Momona (availability and access to subsistence resources rich enough for people to thrive)	
• Access/presence of water; water coming up from below creating potential for lo'i. • Adequate stream flow processes and nutrient cycling, weather, mud, etc. • Presence of ae'o and pinao. • Access to restoration of whole ahupua'a.	*"I've always wanted to do this. But I just didn't have the resources. So once this came about, it was perfect, honestly to me. The water is the main thing; the water was the source of life for Hawaiians. "Water is life" without the water, you can't do anything."*
Ho'oikaika Kino (active lifestyle to support the physical demands of specialized practices)	
• Building strength from work. • Opportunities for self, family, keiki to be outdoors from time required to do the work. • Encourages appreciation and patience for the work.	*"It's more than just a lo'i, it's like being on a big farm, being outside, and stepping on sleeping grass, getting little cuts and scrapes and bruises, those are all wins for me. Those are all little victories in our family because those are the kinds of memories that I have as a kid growing up so, it just makes me feel good that I'm able to pass those kinds of experiences on to my kids."*
'Oihana (engaging in family roles and occupations)	
• Perpetuation of the practice for passing to new generations of kalo farmers. • Preservation of mahi'ai kalo occupation. • Presence of strong family role models. • Encouragement of future mahi'ai kalo. • Roles within the mahi'ai kalo process. • Mahi'ai roles as providers.	*"It's been a bit of an adjustment not fully being in control of the amount of water coming in, or the taro that we plant, the types and variety of kalo that we plant, or the planting style. It's okay to kind of sit back and do it the Kāko'o way. I've been more focused on building relationships and just getting our kids outside and having them develop more of that relationship to 'āina, has been more of the gem for me . . . Usually I'd be in more control of what I'd want to see, but I'm kind of okay in not being in control and just putting my hands in and just doing the work."*
Personal and mental wellbeing	
• Provides a physical and mental sanctuary (place to recharge). • Strengthening sense of or reconnection with cultural identity (becoming pa'a. • Sense of belonging (safe space). • Cultivates a sense of pride and accomplishment; opportunity to aloha or mālama something. • Brings about a sense of awareness of intention, purpose, and mindset within the landscape. • Building a reciprocal relationship with land (kalo grows you). • Encourages an appreciation and patience for the practice. • Sense of joy in the family.	*"It's a sense of pride, just enjoying and getting enjoyment. The luana of this place is maika'i. Just creating this safe space where people can feel like they're okay and they don't have to be judged. They can just come here and feel aloha. Creating a sense of belonging and that they belong to something bigger, and something healthy and something that's aloha. And strengthening their sense of identity as a Hawaiian, living in Hawai'i. Those two things, I think, create confidence . . . like I said, you make decisions for the greater good."*

3.2. Traditional and Diversified Crop Production and Economic Returns

Over the 20-year management period (2018–2037), the range of estimated profit for breadfruit and banana was positive (Table 5). Profit from raw taro (without sales of additional products) was negative for both scenarios. However, including additional taro products such as poi increased profits, as did allowing for volunteer family effort (15% reduction in costs), although the lower bound of the estimated profit range remained negative (see Figures S1–S4). When considering the three crops collectively and assuming no volunteer effort, combined profit ranged from –$6.33 million to $14.22 million (Figure 3). Under the family program, the estimated range of profits increased to –$4.09 to $16.46 million (Figure 3).

Table 5. Estimated total production and profits over 20 years for banana, breadfruit, and taro.

Crop	Total Production over 20 Years (Million kg)	Total Profit over 20 Years (Million $)
Banana	0.31–1.26	0.26–1.06
Breadfruit	0.14–1.65	0.24–3.68
Taro	1.48–2.36	–6.84–9.48
Taro (with family program)	1.48–2.36	–4.59–11.72
All crops	1.93–5.57	–6.33–14.22
All crops (with family program)	1.93–5.57	–4.09–16.46

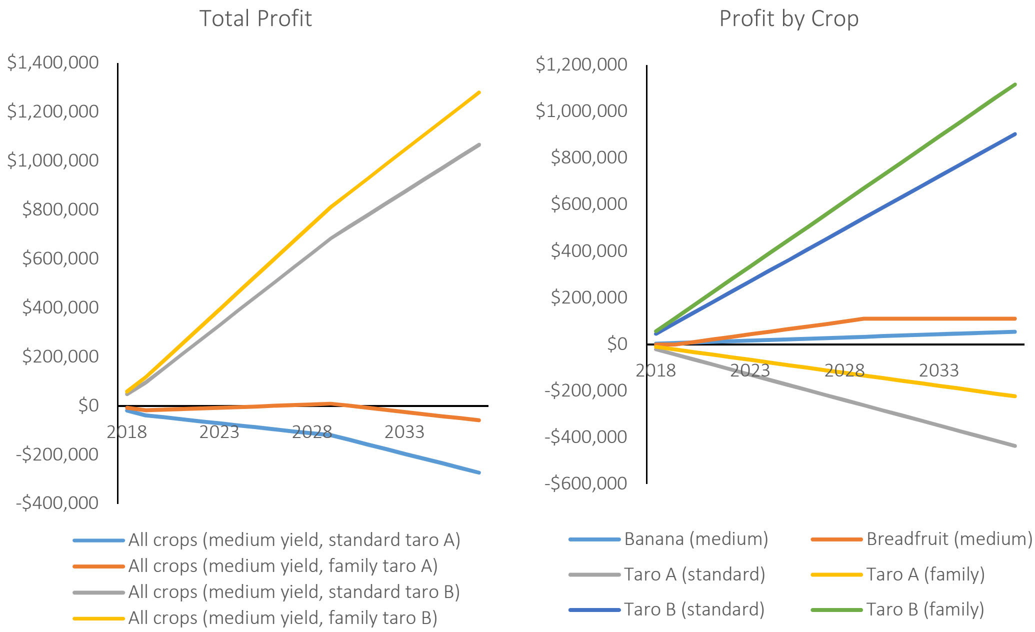

Figure 3. Total profits in different crop scenarios (**left**) and profit by crop type (**right**). Note that *taro A* and *B* are used to differentiate the two yield-cost-price scenarios developed in collaboration with Kākoʻo ʻŌiwi (see SI Methods for details) and *family* denotes implementation of the family volunteer farming program.

3.3. Energy Savings

Estimated annual energy savings, owing to the use of organic N-fertilizer in place of synthetic N-fertilizer in taro production, ranged from 0.16 to 0.25 kWh/m^2. Over the 20-year management period, this amounted to a cumulative energy savings in the range of 0.20–0.33 million kWh. In terms of energy offsets, the low taro yield scenario would offset 46–48 tons of heavy fuel oil, while the high yield scenario would offset 115–120 tons over the 20-year project time horizon. This is equivalent to 5.3 million kWh (low) to 13.6 million kWh (high).

Aside from interest in supporting the State's renewable energy goals, Kākoʻo ʻŌiwi is interested in becoming more self-sufficient in their on-farm energy use to increase the profitability of their programs. The energy required for poi milling in taro production scenario A (1.12 kg/m^2 yield) totaled 37,361 kWh over 20 years. Powering this process with solar energy would require a 3410-watt PV system at an installation cost of $10,327. Cumulative utility bill savings of $9908 combined with $5094 in revenue from selling excess energy back to the grid resulted in a payback period of 15 years. For taro production scenario B (1.79 kg/m^2 yield), energy input totaled 59,778 kWh over 20 years. The higher input would require a larger (5450-watt) PV system at an installation cost of $16,523. This resulted in cumulative utility bill savings and revenue from grid supply sales equal $15,853 and $8151 respectively. The payback period remained unchanged at 15 years.

3.4. Sediment and Nutrient Retention

Overall, we found that the full agriculture restoration scenario decreased sediment export by 38% compared with the current scenario, but that nutrient export could increase by as much as 240% due to fertilizer inputs. However, nutrient export in the restored agriculture scenario was still less than half of export in the urban development scenario (Figure 4). Specifically, sediment exported to Kāneʻohe bay from the wetland was estimated at 1070, 668 and 2365 tons year^{-1} for the current, agriculture restoration and urban scenarios, respectively (Table 2). Nutrient export was 2500, 8515, and 17,995 kg year^{-1} for the current, agriculture restoration, and urban scenarios.

Sediment export at He'eia stream mouth during baseflow for the current scenario was based on average TSS concentration exported from the wetland (18.5 mg L^{-1} from 2013 to 2017; [59]) and combined mean daily discharge of Haʻiku and ʻIolekaʻa streams (1.8 2.87 cfs; [60]), translating to approximately 75 tons year^{-1} of sediment. We assumed this was 7% of the sediment budget given that much of export is not associated with baseflow [65], which translated into a total current export of 1070 tons year^{-1}. Thus current net input and export (2335 tons input and 1070 tons export), translated to an accumulation of 1265 tons of sediment in the wetland per year (see SI Methods).

For the restored agricultural scenario, Slaets et al. [61]'s accumulation rate for loʻi retention in the agricultural restoration scenario translated to a future accumulation of 1670 tons of sediment per year (for the ~600,000 m^2 of retention space available in this scenario). Sediment retention was null in the urban scenario and conversion of the upland areas within Kākoʻo ʻŌiwi from non-native vegetation to urban also increased sediment export by 31 tons year^{-1}.

Nitrogen

Predicted N export from upper Heʻeia watershed into the wetland using the InVEST NDR model under the current scenario was 4990 kg year^{-1}. Using the Department of Health [59] average N concentrations and baseflow estimates, we calculated that 2500 kg year^{-1} of this import is currently retained by the wetland, resulting in an export of ~2500 kg year^{-1}.

For the restored agriculture scenario, we estimated that an additional 6015 kg year^{-1} of N (from fertilizer) would be added to the system that may not be taken up by crops (based on 23% uptake by plants), resulting in an export of 8515 kg year^{-1}. Urban development contributed a wastewater derived nitrogen load of 12,960 kg year^{-1} in addition to the current predicted export, resulting in a total export of 17,955 kg year^{-1} (Figure 4).

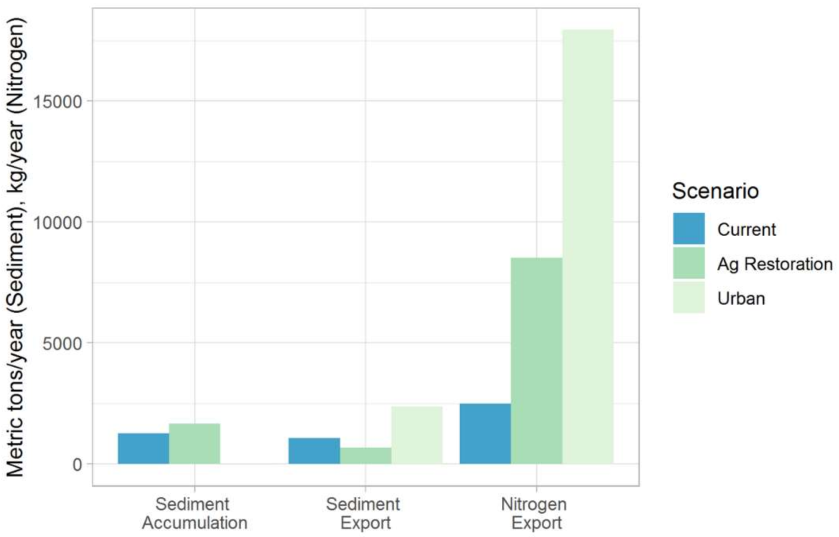

Figure 4. Summary results of sediment accumulation (tons/year), sediment export (tons/year) and nitrogen export (kg/year) under the current, restored agriculture, and urban scenarios.

4. Discussion

Interest in biocultural approaches to restoration are growing across the world [2,9,20,43], and Hawai'i is emerging as a hotspot for biocultural restoration of traditional agriculture [7,15]. This can be attributed to an indigenous Hawaiian cultural renaissance around food and ahupua'a and broader moku (district or region) management [3,66] coupled with the State of Hawai'i's recent commitment to doubling local food production [31]. Statewide efforts to increase local food while also moving towards renewable energy, watershed and marine ecosystem protection, and local (re) connection to place situate these systems-level biocultural restoration efforts as transformative projects for sustainability and resilience at multiple scales.

A defining principle of biocultural approaches to conservation and restoration is the need to start from a cultural, place-based approach while also acknowledging diverse actors and multiple goals across spatial scales [9,43]. In this study we set out to assess future scenarios of restoration in terms of outcomes valued by the local community and a community-based non-profit as well as the State of Hawai'i as formalized in sustainability goals around food, water, and energy [31]. In the context of biocultural restoration of lo'i kalo in He'eia, O'ahu, we identified a diverse set of locally relevant environmental, cultural, and economic goals, many of which align with statewide sustainability goals (see Table 1). We found a number of benefits, including those stemming from the biocultural restoration process, as well as key challenges facing this and similar biocultural restoration projects as they begin to scale.

From the perspective of participating families in the 'ohana program, the most important benefits associated with cultivating kalo were associated with the *process* of restoring lo'i kalo rather than just the cultural or economic benefits of the end product. In particular, families valued the opportunity to (re)connect to important biocultural landscapes and build social connections among like-minded people. That cultural benefits emerge from the process of restoring reciprocal relationships to place rather than just the end products of biocultural restoration has been noted elsewhere [7,20,67]. The attention to restoring ritual and the cultural protocols alongside ecological systems is an important theme emerging from this study and other articles in this issue [7,20]. While work on "relational values" [68] and to some extent "nature's contribution to people" [27] has acknowledged this, the vast majority of literature in ecosystem services has focused on the value of the end state rather than the process of getting there.

In regards to the process of restoration, we found a suite of benefits across all categories in the indigenous Hawaiian cultural ecosystem services framework of Pascua et al. [17], as well as some extensions. This included benefits classified as 'ike (knowledge): families particularly valued the chance for place-based experiential learning of how to grow kalo and provide opportunities for their children to be in and learn in these environments. There was also substantial reference to themes related to mana (spiritual landscapes) as families described the work as a cultural practice linked to ancestral practices and the Kumulipo (legend of Hawaiian origin), and to pilina kānaka (social connections) as the program was discussed as strengthening connections between and among families. Participants also pointed to physical and mental health benefits (ola mau), with many references to the lo'i as a place of individual and collective mental renewal as well as physical health benefits. This connection created a deeper understanding of kuleana (responsibility) to the land and of cultural identity as kānaka (indigenous Hawaiians). The site became a place of healing, love, and self-reflection, providing a higher purpose for the people working to restore the area. Participants described a sense of pride and accomplishment, a sense of belonging (safe space), and valued the opportunity to progress as kānaka (indigenous Hawaiians).

While attention to process is key, an important cultural as well as economic benefit of the restoration is also clearly the production of traditional crops, an outcome highly valued by Kāko'o 'Ōiwi and aligned with the State's goal of doubling local food production. Even in the lowest return scenario, there are still 339 tons of bananas (mai'a), 151 tons of breadfruit (ulu), and 1628 tons of taro (kalo) produced. The food produced would represent an important step towards the State's goal of doubling local food production and would increase the total area dedicated to taro production across the State by 50% [31].

The focus on organic production methods and renewable energy as part of the broader biocultural approach, also produced important energy savings benefits that align with the State's renewable energy goals. In comparison to energy use that would have occurred with the use of industrial fertilizer and oil for electricity, organic fertilizer and solar power also saved 0.87–1.41 million MJ. Adding in potential savings through avoided food imports, this saving is substantial and clearly demonstrates the potential of biocultural restoration of traditional agricultural systems to produce food in a way that also provides synergies for energy sustainability goals.

Our finding that the most financially beneficial model included diversified crop production utilizing a "hybrid" production model that includes the family program also points to important potential synergies between local community and cultural benefits and the program's financial sustainability. Our economic analysis suggests that if the family program were to go to scale, it could roughly increase returns by $2 million USD, which would help to sustain a project that provides many benefits locally and more broadly. However, to go to scale the number of families must increase substantially. While Kākoʻo ʻŌiwi is committed to providing these opportunities and "growing farmers," families interviewed also expressed concern that some of the greatest components of the project (close social connections and a sense of sanctuary) could change as more families get involved. Managing scaling in the context of the cultural significance of the quality of the process of restoration is critical to the long-term success of the project.

Finally, our results suggest that biocultural restoration of loʻi kalo in Heʻeia can provide benefits in terms of the broader social-ecological system including downstream fishpond (managed by Paepae of Heʻeia) and the Kāneʻohe Bay coral reef ecosystem. In elevated concentrations, both nitrogen and sediment can have adverse impacts on coral reefs and fisheries and likely make these systems less resilient to climate change [65,69,70]. When compared to a hypothetical urban scenario (which was once the fate of Heʻeia wetland and could be in the future if sustainable models are not developed), we found important benefits of loʻi kalo restoration in terms of reduced nitrogen and sediment loads to these nearshore environments. This aligns with previous research in the Pacific showing that taro fields retain sediment [71], as well as studies of sediment retention in similar rice paddy systems [72]. Loʻi kalo and similar systems have also been shown to have a high capacity to store water compared with invasive wetland grasses [73] and urban environments [74], suggesting that these systems retain and slow more water because of their construction as basins and, therefore, more sediment than alternative land uses addressed in our study. The approach presented in this article accounted for baseflow and small storm conditions; further research is needed to understand how the conversion back to loʻi would be affected by larger storm events.

Within the restored agriculture scenario, however, we found an important tradeoff between enhanced sediment retention (and reduced sediment export to the bay) and increased nitrogen export (due to fertilizer inputs). While the nutrient loads are much lower than they would be with urban expansion or with other forms of conventional agriculture, they are higher than current land cover, and could have impacts on important downstream systems. However, the model used did not directly consider nutrient uptake of drainage channels or by complex microbial and wetland plant communities, and thus can be considered conservative [75]. Careful design of loʻi and the wetland system could mitigate some of the nutrient tradeoffs while also increasing sediment retention of the system. Field design insights from natural and constructed wetlands used to treat waste discharge sites could also be incorporated into loʻi kalo design to further reduce nutrient export [76].

While addressing this potential nitrogen tradeoff is paramount, leaving the area as invasive grasses provides no economic and little to no direct cultural or community benefit and would likely leave the area more susceptible to urban development pressures. The current plant community also provides little to no ecological habitat value, whereas the restored system (including loʻi kalo as well as native wetland restoration) is expected to increase habitat for native fish (e.g., ʻoʻopu akupa;

Eleotris sandwicensis), insects (e.g., *Pantala flavescens*), plants (e.g., neke; *Cyclosorus interruptus*, 'ahu'awa; *Cyperus javanicus)* and birds, including the endangered Hawaiian stilt (aeʻo; *Himantopus mexicanus knudseni*). Overall, our research suggests that the restored system would substantially contribute to prioritized local cultural, economic, and ecological goals while also helping to meet the State of Hawaiʻi's sustainability goals around food, water, and energy. Thus, the project thus represents a locally viable and beneficial opportunity to meet broad societal environmental objectives, which provides broad lessons for the worldwide challenge of local implementation of the SDGs, in an equitable and effective way.

5. Conclusions

Biocultural approaches to conservation and restoration explicitly recognize the interconnection between biological and cultural diversity and between social and ecological systems that have often been obscured in Western-based conservation efforts. While not a new concept, theories of biocultural restoration that emphasize cultural and place-based perspectives, knowledge, and values are emerging in a context of contemporary conservation and restoration efforts [2,29,43]. Here we demonstrated how existing frameworks of evaluation of synergies and tradeoffs in land management from the food-energy-water and ecosystem services frameworks can be adapted to illuminate potential synergies and tradeoffs among multiple cultural, environmental, and economic goals associated with biocultural restoration projects. An important contribution of such an integrated assessment is that it highlights the potential of biocultural restoration to both achieve locally-relevant cultural, economic, and ecological goals while also contributing meaningfully to broader sustainability goals defined by formal policies.

Kākoʻo ʻŌiwi is at the center stage of biocultural restoration of social-ecological systems in Hawaiʻi. Our collaborative case study from Heʻeia, Hawaiʻi suggests that biocultural restoration of traditional agriculture has the potential to simultaneously meet multiple community and statewide sustainability goals, including increasing local food production, reducing energy consumption, increasing cultural connection to place, and decreasing sediment delivery to downstream coastal systems. Yet, there are important tradeoffs to consider in the form of nutrient export, which will be much less than alternate land uses (like urban and conventional agriculture), but still likely an increase from the current fallow, degraded system. By understanding and adapting in light of potential tradeoffs, it is clear that the process of (re)connecting to place inherent in a biocultural approach provides a suite of community and cultural benefits that are essential to the long-term social and financial sustainability of this multi-benefit system.

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