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The Role of Breadfruit in Biocultural Restoration and Sustainability in Hawai'i

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Abstract: The Hawaiian Islands today are faced with a complex mix of sustainability challenges regarding food systems. After European arrival, there was a change of dietary customs and decline in traditional Hawaiian agriculture along with the cultural mechanisms which sustained them. Recently, there has been a resurgence for local food and culture alongside an enthusiasm for breadfruit (*Artocarpus altilis*)—a Polynesian staple crop. To investigate the role of breadfruit and biocultural restoration in Hawai'i, we conducted surveys and interviews with local breadfruit producers. Overall, we found that breadfruit has the potential to provide holistic, practical and appropriate solutions to key issues in Hawai'i, including food security, environmental degradation and public health, while simultaneously lending to the revival of cultural norms and social relationships. As breadfruit cultivation expands rapidly in Hawai'i, the opportunities for increased social and environmental benefits can be realized if appropriately encouraged.

Keywords: breadfruit; biocultural restoration; sustainability; food systems; Hawai'i; *Artocarpus altilis*

1. Introduction

Sustainability can be defined as improving the quality of human life while living within the carrying capacity of supporting ecosystems [1]. Common frameworks to sustainability may include dimensions of social, economic, environmental, cultural and political needs [2]. Some take the perspective that humans and environment are separate and therefore the major role humans play in the environment is destructive and extractive [3,4]. This sits in opposition to indigenous epistemology that views people as an integral part of the environment—a concept is that is captured in biocultural frameworks, in which we take into consideration relationships between biological and cultural systems in order to conceptualize the link between people and environment [5,6]. Biocultural refers to how human cultures are shaped by their surrounding ecosystems, which in turn, shapes culture itself [6]. This approach is not a new concept by any means but has implications for use today in terms of sustainable management practices. There is an "inextricable link" between cultural diversity and biodiversity and there has been insight on correlation between the two phenomena that illustrates their importance for the resilience of social-ecological systems that sustain life [3,6]. The preservation of cultures and the restoration or protection of the environment are therefore dependent on the other, not only in natural ecosystems but in human managed systems such as agriculture.

Including cultural aspects into environmental approaches is known to lead to sustainable management practices and more resilient systems [6]. Customary values and community capital in Hawai'i facilitate reciprocity and food sharing and the passing of knowledge which can help sustain

resources over time and provide effective natural resource management approaches [7]. Community involvement and cultural perpetuation of values is crucial to long term food security and can lead to greater chance of long term success in restoration [7,8]. These cultural perpetuations are likely tied, at least in part, to the key biological species through which biocultural relationships are formed. It terms of losing biocultural diversity, the globalization of food systems and unsustainable agriculture development are substantial contributors [6,9]. Hawai'i has been no exception, with plantation agriculture arguably being the largest driver to cultural displacement and loss over the past 200 years. However, within the last forty years, revitalization of traditional agriculture has increased, paralleling an increase in cultural revival. While there are several crops that hold importance in terms of Hawaiian culture, we focus on the role of breadfruit (*Artocarpus altilis*, (Parkinson, Fosberg)) within contemporary commercial agriculture to explore its broader applications for sustainability in Hawai'i. We argue that in Hawai'i, traditional agriculture plays a pivotal role in the connection between the socioeconomic and cultural aspects of sustainability and follow Barthel et al. [5] in arguing that supporting crops with biocultural importance is critical for long-term success of agriculture. Furthermore, the use and maintenance of such crops is essential for maintaining cultural values and practices, particularly within the modern socioeconomic landscape, and for the health of the environment.

1.1. Traditional Breadfruit Cultivation in Hawai'i

Breadfruit, or 'ulu in Hawaiian, is a tropical tree in the fig family [10] that produces a large (typically 1–3 kg) starchy fruit that tastes much like a potato, banana or plantain depending on the state of maturity (Figure 1). Breadfruit has been consumed as a staple crop throughout Oceania for millennia, appears in many aspects of traditional knowledge, has influenced sociopolitical environments and has multiple resource applications. A sterile, seedless variety of breadfruit was transported to Hawai'i at least 800 years before present [11,12].

Hawai'i, when compared to smaller and more ancient islands of the Pacific, expresses greater opportunities for agricultural development [13] and consequently, Native Hawaiian populations were heavily reliant on intensive cultivation of land [14]. This afforded the emergence of unique agricultural practices, such as mahi'ai—massive, intensive rainfed field systems Lincoln et al. [13] *in this issue*. Breadfruit grows well in marginal habitats and, throughout most of the Pacific, was an important staple crop, often seen as a "gift from the gods" and grown in semi-wild "food forests" with minimal active management [15]. However, in Hawai'i, where extensive cultivation of annual starches was possible, breadfruit assumed a complimentary role and was used to expand cultivable areas [16], increase resilience [17] and enhance place-adapted cropping systems [18]. While breadfruit trees maintained near households were managed much like elsewhere in the Pacific, large-scale breadfruit arboriculture took on a different form in Hawai'i. In addition to the semi-wild and largely unmanaged "food forests," Hawai'i developed breadfruit arboriculture that was well-spaced, highly managed and incorporated the intensive cultivation of multiple annual and perennial crops [11,16].

In Hawai'i, breadfruit likely started as part of individual garden plots near settlements, expanded into semi-wild food forests cultivated on colluvial valley slopes and culminated into the development of sizeable, systematic arboriculture [11,13,16]. Such arboricultural developments cultivated breadfruit within intercropped agroforestry systems planted with kukui (candlenut, *Aleurites moluccanus*), 'ōhi'a 'ai (mountain apple, *Syzygium malaccense*), 'uala (sweet potato, *Ipomoea batatas* L.), maia (banana, *Musa spp*), uhi (yam, *Dioscorea alata*), kalo (taro, *Colocasia esculenta*), kō (sugar cane, *Saccharum officinarum*), wauke (paper mulberry, *Broussonetia papyrifera*), 'olena (turmeric, *Curcuma longa*), pia (arrowroot, *Tacca leontopetaloides*), 'awa (kava, *Piper methysticum*), 'awapuhi (shampoo ginger, *Zingiber zerumbet*) and kī (tī, *Cordyline fruticosa*) [19–21]. These rainfed systems comprised a significant portion of the total agriculture [18,22], created habitat that allowed the optimal cultivation of some crops such as wauke [20] and produced a highly diverse set of food, resource and medicine crops [16].

Figure 1. The large fruit and leaves of the Hawaiian breadfruit tree.

1.2. Traditional Importance of Breadfruit in Hawai'i

Breadfruit has made substantial contributions to food production, health and nutrition, environmental quality and culture in the Hawai'i for centuries [11,15,23]. 'Ulu was a staple food source in addition to kalo, 'uala, uhi and mai'a, ranking third in importance for complex carbohydrates and serving as an essential crop in times of human and environmental disturbances [11,22,24]. The fruit is nutritious, especially when compared to contemporary starches such as rice, corn and wheat [25]. 'Ulu trees are relatively low maintenance but provide substantial yields, resulting in high surplus production after establishment. Breadfruit was seasonally abundant but unlike elsewhere in the Pacific, storage of breadfruit in underground pits appears to have been rare, while application as an animal feed appears to have been more extensive [15,26].

Breadfruit was also a valuable resource and medicine. A long list of uses for wood includes; housing and construction, canoes, surfboards, drums, cloth and poi (fermented taro with water) boards, all of which could be polished with its leaves that were used as an abrasive similar to sandpaper [11,15,27]. Virtually all parts of the plant are used medicinally–the leaves, bark, fruit, flowers and latex–to treat ailments including skin conditions, high blood pressure, cardiovascular disease; the flowers are commonly used to repel mosquitos; and the high-latex sap also has an array of applications, including caulking and bird snaring [11,15,27,28].

The development of tree resources, such as breadfruit, can be seen as investing into the land to develop long-term resources for future prosperity [29]. The development of large-scale arboriculture, such as the famous breadfruit groves of Kona and Lāhainā, took place during the "golden age" of Hawai'i in the 16th century [13,30], with the resulting surplus of production further empowering the development of sociopolitical complexity and hierarchy [31–33]. Due to the nature of political and

labor organization, extensive systems of agriculture were able to form over time, ensuring the ability for ancient Hawaiians to spend more time into shaping political dynamics. The groves of breadfruit acted as a significant resource that was driven by the desire to increase local economies, which in turn developed stronger political hierarchies (through taxes, military service, etc.) that could further invest into the landscape [16,17].

The seasonal surplus of breadfruit may have powered social dynamics and rituals, such as the emergence of the Makahiki—an extended period where work and certain religious ceremonies were suspended and corresponding to a time of increased recreation and tax collection [34,35]. During Makahiki, breadfruit served many ritualistic purposes including the shaking of the Maoloha net at the end of Makahiki; if the food dropped from the net, there would be no famine during next growing season [34]. The occurrence of the festival in October to January corresponds well with the surplus breadfruit season. The Makahiki developed out of Kona, which was famous for the "breadfruit belt" (expansive stretch of agroforestry largely consisting of breadfruit that crossed over several regional districts throughout the Kona Field System of Hawai'i Island) [14]. One could argue that such an extended period of ceremony could only be made possible by an extensive surplus. This would be similar to other Pacific Islands, where annual time periods that corresponded to religious and ceremonial occurrences aligns with the productive periods of breadfruit and other crops [15,36]. While speculative, that the most famous ceremony of abundance in ancient Hawai'i developed in a region famous for its breadfruit and coincided largely with the season of breadfruit productivity suggests a linkage between 'ulu and abundance.

The abundance from 'ulu also has an important place in Hawaiian cosmology. Stories include that of the god Kū who turned himself into an 'ulu tree to feed his starving wife and children [14]. Breadfruit was depicted in stories of embodiment, in which the gods would enter a breadfruit tree in supernatural form, signifying a close relationship and admiration of the natural world [11]. Many concepts of Hawaiian traditions and values are captured in a range of 'ōlelo nō'eau (Hawaiian proverbs, sayings or stories) that utilize 'ulu as a metaphor for wealth, success and planning. The reoccurring lessons utilize breadfruit to teach values on sharing and hospitality, warnings to be kind to travelers and making sacrifices for the prosperity and success of others [37,38].

1.3. Loss of Traditional Food Systems

The arrival of Europeans in the 18th century marked a decrease in the native Hawaiian population and greatly altered the path of Hawaiian agriculture. This shift resulted in the decline of traditional systems, the establishment of plantation agriculture, the marginalization of native peoples and reshaped the future of Hawai'i [1]. As with all traditional crops, the abundance of breadfruit in Hawai'i declined precipitously (see Kagawa-Viviani et al. *in this issue*).

Upon arrival, early European explorers reported seeing considerable breadfruit groves around all the islands, especially near villages and settlements, with vast arboricultural "belts" in several regions [11,13]. The Kona breadfruit belt was modeled to have consisted of more than 100,000 trees; it is now, however, reduced to a few hundred trees, often neglected and unwanted [16]. These traditional, intercropped systems once produced enough food to sustain the largest population in Polynesia and indeed supported a larger population on each island (excluding O'ahu) than exists today [39,40].

Local economies, cuisines, cultural practices and the state of the environment shifted with the decline in traditional agriculture. Today, 80–90% of food is imported, making Hawai'i one of the most dependent states in the United States [41]. Recently, Hawai'i was assessed as the 48th worst state in terms of farming outlook [42]. Statewide dietary shifts to processed, imported foods have raised public health concerns. Hawaiians and other Pacific Islanders are especially vulnerable to dietary-based health issues, including obesity and diabetes, which have risen alarmingly fast, holding some of the highest rates in the world [25]. Furthermore, we see exceptionally negative environmental impacts that threaten soil, water, ecosystems and human health [43]; and the declining involvement in local food production greatly reduces the overall food security [1] of Hawai'i [44].

With the reduction of breadfruit and other crops, there are fewer opportunities for communities to engage with and learn about them. Furthermore, with decreased number of farms and the connection to cultural foods, there are fewer opportunities to connect with the land, learn cultural practices involving Hawaiian agriculture and to gather around Hawaiian food. It takes time for food to become cuisines and acquire symbolic meanings and once lost the efforts needed to restore those relationships are significant [24].

1.4. Resurgence for Local Food and Breadfruit in Hawai'i

In the 1970s, public awareness increased demands for local, fresh and healthy foods [1]. Coinciding with a growing interest for food self-sufficiency, a resurgence of Hawaiian culture, pride and practices also occurred in what is affectionately known as the "Hawaiian renaissance." These parallel movements coupled with research efforts regarding breadfruit, led to increased demand for fresh breadfruit in Hawai'i. Grassroots and institutional efforts partnered to conduct multiple campaigns to promote the cultivation, application and consumption of breadfruit in Hawai'i [45]. Such efforts included public education, festivals and tree-giveaways. Part of the challenge to popularize breadfruit was due to a social stigma that positioned breadfruit as a second class food in Hawai'i [46]. While outreach programs, marketing, availability, introduction of value-added products and presence in restaurant dishes has educated new users about breadfruit, the stigma was not as easy to overcome. Finding an appropriate role for breadfruit in cultural and agricultural contexts remains an ongoing challenge.

More recently, ecosystem-based management strategies are being promoted for agriculture and conservation [47]. The state government has recognized efforts to strengthen community-based conservation and set goals to have more sustainable and secure food systems in Hawai'i [44,47], while large landowners have similarly promoted improved practices to agricultural leaseholders. However, overall there has been a significant disconnect between stated goals and outcomes [48–50]. Breadfruit cultivation has the ability to contribute to these efforts and more.

2. Materials and Methods

We used a combination of surveys (Table A1), semi-structured interviews (Table A2) and onsite farm observations with 43 individuals and organizations engaged in breadfruit production (Figure 2). Of the 43 participants, 36 were bonafide agricultural producers, while the remaining were non-profit organizations growing breadfruit for preservation, cultural access and community food systems. Participants were initially recruited through open advertisement and targeted approach of well-known growers, with subsequent requests made using a "snowball" approach; all participants that expressed interests were included in the study. Participants represented a range of social and natural environments and included new and long-time farmers. Participants were selected by word of mouth, community connections, internet searches and qualified to participate if they cultivated at least ten breadfruit trees. The breadfruit farmers who engaged in the study are referred to as "participants". The participants varied in their experience of farming breadfruit but were all successful in growing trees that produced fruit and were therefore an expert subset of the general population. The study was conducted on various locations on the islands of Hawai'i (n = 19), O'ahu (n = 15), Kaua'i (n = 5) and Maui (n = 4). Interviews and surveys were conducted onsite beginning in March 2017 and finalized in May 2018, during the spring season (March-May) of each year.

Ethnographic data was collected in two forms; interviews and surveys. Informed consent was received for all participants and survey and interview scripts were granted IRB exemption for work with human subjects. The survey questions focused on the history of the farm and the trees, cultivation techniques, farming practices and tree care methods (Table A1). The interviews were semi-structured and probed the participants on their beliefs, concerns, lessons and ideas concerning breadfruit, contemporary culture and agriculture (Table A2). The interviews, in general, focused on the role breadfruit plays in the connection between culture and place and how those connections provide for the well-being of people and the environment of Hawai'i today. Interview duration was

variable, lasting between one-half hour and three hours depending on the individual's willingness and enthusiasm to share information. Quotations and activities reported from the interviews stem solely from the bona-fide agricultural producers and does not pull from the non-profit participants. Survey data was managed and organized in Excel 16.13 (Microsoft Corporation, Redman, WA, USA) and analyzed in SPSS 20.0 (IBM, Armock, NY, USA). Written notes from the interviews and on-site observations were pinned to survey results and coded for thematic descriptions by the authors. Often repeated themes were selected for emphasis and specific farm examples were pulled to demonstrate each theme.

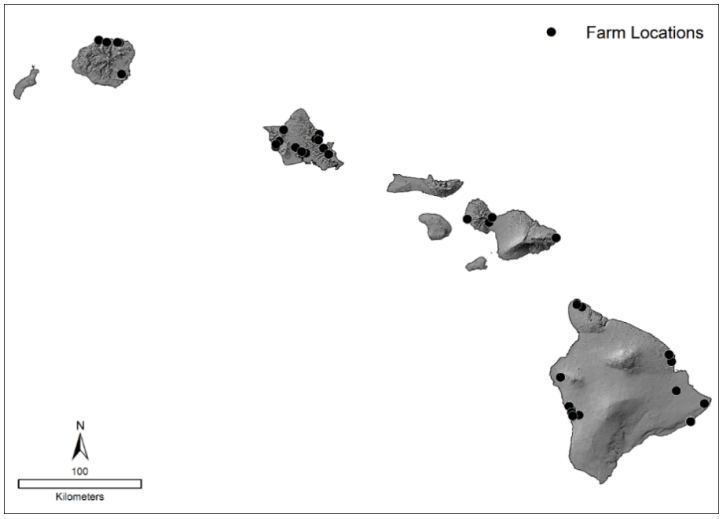

Figure 2. A map of the breadfruit producers that participated in the survey and interview portions of the study.

Participation included on-site sampling to assess soil and tree health at each site. Soil samples were retrieved from each site; composite soil samples were collected by mixing three soil cores taken 2 m from the trunk of the trees at a depth of 30 cm. Soils were assessed for pH and soil moisture in house, then dried, sieved, ground and packaged for analysis at Brookside Laboratory Inc. (New Bremen, OH, USA). Tree health was assessed through chlorophyll and photosynthetic measurements. Chlorophyll counts were measured using a SPAD 502 Plus Chlorophyll Meter (Spectrum Technologies, Aurora, IL, USA) and photosynthetic rates were measured using a miniPPM-100/150 Plant Photosynthesis Meter (EARS, Delft, The Neatherlands). Ten random, consecutive measurements were taken per leaf, with three leaves per tree and three trees per site analyzed (90 total measurements per site); the third leaf from the tip was used for measurement (Lincoln et al. in review). Measurements data was organized in Excel 16.13 and analyzed in JMP Pro 13 (SAS Institute, Cary, NC, USA).

3. Results

Participants were not surveyed for traditional demographic indicators (e.g., age, income, education) but were represented by statistics such as farm size and reliance on farming (Table 1). In these terms, participants overall agreed with statewide statistics [51,52] and previous surveys of farmers in Hawai'i [48,49]. Farmers represented a range of practices, goals, values and demographics. On one end of the spectrum, interviewees included the largest productive orchard in the state, growing over 500 trees in a monocropped section of a highly conventional agricultural operation. In contrast, we also saw smaller farms including Native Hawaiian homesteaders growing diversified agriculture mainly for subsistence purposes. Results included experiences of individuals, non-profit organizations, cooperative organizations and for-profit companies that operated on fee simple, lease and partnership lands (fee simple refers to leases privately owned land, partnership lands are less formal agreements that give access to land without ownership). The individuals we talked to represented Native

Hawaiians, plantation-era multi-generational families and new immigrants to Hawai'i. Despite these vast differences in motivations, backgrounds and structures, there were clear commonalities in the discussions with each as they related to and talked about breadfruit.

Table 1. Farm attributes of survey participants.

Attribute	Agricultural Producers			Non-Profits		
	n	Average	Std Err	n	Average	Std Err
Size of farm (acres)	36	27	10	7	409	339
Area in breadfruit	33	3.4	1.2	7	0.6	0.2
Number of trees	33	69	24	7	38	14
Age of trees	28	14	2.8	7	12	4.6
Production per tree (lbs.)	15	101	39	4	152	68

Analysis of interview notes resulted in the identification of five key themes: customary values, traditional agriculture, food security, ecological health and community (social) capital. Further organization indicated that each theme often overlapped and interacted with other themes, which lead to the development of a conceptual diagram of the themes in the framework of biocultural restoration and sustainability (Figure 3). Building upon this conceptual structure, results are presented within the five identified themes, utilizing data from the participant surveys and farm sampling, along with analysis and specific examples from the interviews. Results are further discussed within the frameworks of biocultural restoration and sustainability.

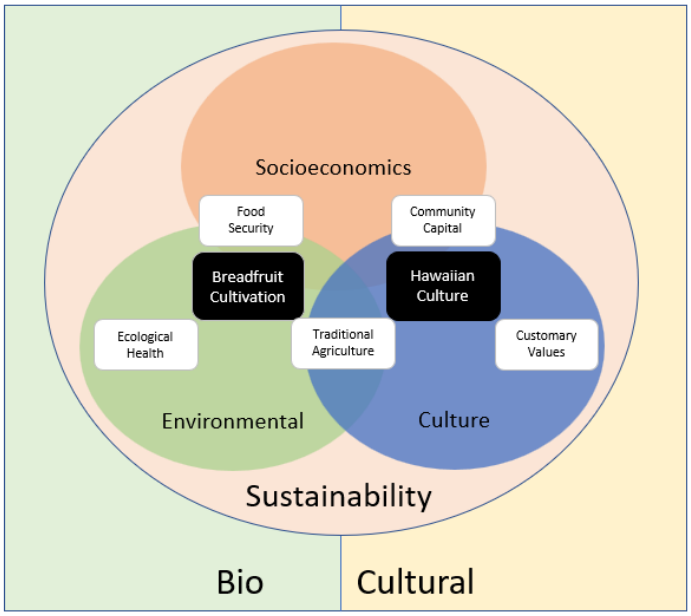

Figure 3. Conceptual diagram illustrating the relationship between the major themes that arose in the research and how they situate within the concepts of biocultural restoration and sustainability. The white boxes show the five themes identified from the interview data. The black boxes represent the basis of the biocultural relationship and the colored circles show common dimensions of sustainability.

3.1. Customary Values

A key theme that emerged from participant interaction centered on customary Hawaiian values, regardless of participant ethnicity. Hawaiian values such as aloha (love or compassion), kuleana (reciprocal responsibility), ha'aha'a (humbleness), pono (righteousness) and ahonui (patience) were prominent in Hawaiian life [53]. One description of aloha from the early 19th century translates, "It was often said...Hawaiians...were full of love when they received visitors wherever they lived...[and]

people...were greatly taken by the hospitality (aloha) of the Hawaiians..." [53]. Expression of Hawaiian values was seen in direct statements by participants, as well as in descriptions of their activities. The importance of showing aloha to guests and between one another, to facilitate bonding and with it a sense of identity was expressed. This was further expressed through generosity, which may be thought of as an extension of aloha and living pono by ensuring comfort and sense of belonging between people.

Offering generous hospitality and food sharing were common themes during interaction with breadfruit farmers. The act of exchanging goods traditionally reaffirmed familial bonds and 'ohana (kinship, family) in ancient Hawai'i [54]. In contemporary times, food sharing is less relevant for food security but still remains a significant cultural tradition that strengthens social ties [55]. For example, a visit to "Farmer A's" farm included a sit-down dinner, food, wine and storytelling extending beyond the purpose of the visit. Another 'ulu farmer, "Farmer C," insists his guests will not leave without being well fed, "Farmer B" shared fruits and homemade products, while "Farmer D" sends visitors on the road with boxes of produce. Like many 'ulu farmers, "Farmer E," an agricultural producer and "Farmer F," a non-profit farmer, will both begin or end work visits with food potluck family-style. Of the 36 agricultural producers, 20 (56%) included food sharing with researchers. More instances of hospitality were demonstrated to the broader community. Of the producers, eight (22%) expressed that they regularly host community gatherings for the farming population where food and food exchange are a critical expression of community commitment and reciprocity. Foods shared among farmers at gatherings are locally grown and wholesome, emphasizing well-being and environmental health. "Farmer E" and "Farmer G" offer a place to stay for travelers and visitors and extend invitations to their community to gather, share stories and spend time together. We have found this to be very different than our previous experience with farmer surveys, in which less than 20% of farmers conducted food-sharing and gifts with the researchers [48,49]. Reciprocity extended beyond physical gifts, often aiding in neighboring farms or even providing direct financial support. Several farmers expressed the importance of supporting each other, with "Farmer E" voicing, "[It's] just the Hawaiian interest and value in me, if someone can do it, they should."

Breadfruit farmers also negotiate with their "customers," who are in reality our communities, which demonstrates a respect and appreciation for the well-being of all. Many 'ulu farmers meet customers halfway on pricing to be able to cover their needs and others provide affordable, local produce. This practice, surprisingly, was seen in both subsistence and commercially-driven producers. Within the interviews this practice was commonly expressed in terms of a "traditional" or "alternative" economy. These instances demonstrate the strong presence of Hawaiian values instilled and alive within the surrounding 'ulu farming communities and importantly, increase resiliency through reciprocity, increased self-reliance, social ties and community building [44,55].

While these values may be prevalent among farmers in general, breadfruit, which carries with it the traditional perspective of a "gift from the gods," seems exceptionally conducive to the customary values of giving. Compared to previous farmer surveys and interviews conducted by the author [48,49] expression of Hawaiian values was much higher among breadfruit cultivators. As "Farmer G" states, "the [breadfruit] trees give us so much for free. It is only right to share it with others."

3.2. Traditional Agricultural Practices

Multiple participating farms shared traditional agricultural practices that were passed down by family. Several farmers including "Farmer B," "Farmer C," "Farmer H," "Farmer I" and "Farmer J" cared for old, remnant breadfruit patches; they call the one large, eldest tree the "mother tree." New trees were then propagated using the keiki (child) root shoots or root cuttings. Similarly, we observed many farmers still using lou—the traditional harvesting tool, although the materials have changed [54]. Many producers (37%) use traditional planting and ground preparation methods, applying green mulch prior to planting. Three (8%) producers used the practice of placing a fish or octopus at the bottom of the planting hole and eight (22%) producers engaged in the ancient practice

of planting a placenta under a new tree. More than half (56%) the producers felt they engaged in some sort of cultural protocol when it came to their trees and expressed that these protocols enhanced the health and well-being of the land and plants. Several farmers utilized the traditional practice of planting in accordance with moon phases.

Importantly, participants primarily engaged in the traditional application of breadfruit cultivation within agroforestry systems. Of the farmers, only six (17%) had mono-cropped stands of breadfruit and of those four (11%) grew other crop species in adjacent plots. For the most part, breadfruit cultivation was integrated into diverse agricultural systems, somewhat sporadically interspersed within a variety of different crops or had breadfruit cultivation areas more systematically interplanted with other crops; intercropping included mai'a, kalo, niu, 'ōlena, 'awapuhi, coffee, papaya, ornamentals, citrus trees and leafy green vegetables. "Farmer H" was actively restoring the traditional Hawaiian breadfruit agroforestry system, while "Farmer G" has created a modern agroforestry system with a broad range of tree, shrub and annual crops. Agricultural producers and non-profits, such as "Farmer F," "Farmer K," "Farmer L," "Farmer M," incorporated breadfruit cultivation adjacent to lo'i (flooded terraced) cultivation of kalo. Growing breadfruit in diverse agricultural systems can be tied to cultural values and beliefs regarding the tree. At least three separate growers used the exact same phrase that "'ulu does not want to be alone" and although there is no agronomic evidence to support it, several farmers expressed that they felt breadfruit grew better in mixed agricultural settings rather than in isolation. Although we can likely expect and in fact already see, the development of more mono-cropped breadfruit as the industry continues to develop in Hawai'i (N.K. Lincoln unpublished data), current breadfruit cultivation is employed in mixed agroforestry agriculture that indicates its role in the revival of traditional agricultural practices and usage.

In addition to the physical practices, value-based practices were commonly described by participants discussing their tree management. The most commonly mentioned practice was of kilo (observation of one's surrounding). Farmers often planned their schedules around cycles, weather patterns and observations. For example, "Farmer C" will only water trees according to observing his trees for signs of water deficiency. Similarly, "Farmer F" and "Farmer G" utilize observations of their tree health to determine the best co-crops and "Farmer B" selected individual planting sites based on nuances of microclimates on the farm. Utilization of intuitive management practices guides input adjustment resulting in conservative resource use. This method is reliable and profitable, demonstrated by "Farmer C" having one of the highest yields per tree. Types of local knowledge such as this are thought to have broader implications for restoration projects [8]. It is also important to note that knowledge gained from biocultural relationships typically is formed on small farms [5].

3.3. Community (Social) Capital

Many of the 'ulu farmers leverage their farm to enhance relationships between people, land and plants within their communities by serving as educational and cultural centers. "Farmer F" has regular work days for volunteers and students to participate in traditional farming methods, while "Farmer H" opens her farm to agroecology tours and farmer training to teach about agroforestry, traditional agriculture and dryland agriculture. "Farmer L," one of the largest agricultural producers that participated, has conducted several workshops on breadfruit production, including the promotion of diversified agroforestry despite the fact that he largely employs industrial, monocropping practices. As was often expressed, the education is not only about the food and the plant but the place and the people. "Farmer K" stated, "We really want to get the kids in the area out here to learn about the place where they live. A lot of them do not know the place names of where they live. They do not know what ahupua'a (traditional land division) they are in and I want to teach them that." Linking agriculture, cultural learning and land preservation is not a new concept but is currently being reinforced by 'ulu farmers. In such ways, knowledge and professional development skills are passed on through local and culturally appropriate methods. It is argued that cultural education increases resiliency of food

systems because memories and lessons that teach people to be stewards of their land allow them to adapt and reorganize [5].

Growers also commented on how they themselves were educated through engagement with ‘ulu. Rebuilding his farm from scratch, “Farmer F” recounted how he learned much of his farming through trial and error; while there were elders who taught him kalo farming, knowledge was not passed to him about growing ‘ulu. He was now excited to share what he learned with others and discussed the importance of knowledge exchange between farmers and the younger generation. This was a common theme amongst the breadfruit farmers, who dominantly indicated that working with the crop has been a rewarding learning experience. Their learning experiences are critical in particular because, unlike other crops, breadfruit has not been well studied from an agronomic perspective and especially regarding the vastly different growing conditions that Hawai‘i represents. As such, the accumulated knowledge from growers represents a significant knowledge source to share amongst themselves and others.

3.4. Food Security

Breadfruit makes significant contributions to food security and improved health in Hawai‘i. Some farmers share breadfruit in the customary sense between familial ties but in general, the practice is broader. One farmer, “Farmer N,” does not sell his fruit through any conventional economic pathway but only to friends, family, church members and the broader community, often trading or even giving it away. Every participant, even the most commercial agricultural producers, indicated that they give away fruit or reserve part of their harvest for friends, family, or community. This regard for others before profits is unique when compared to other farmer surveys in Hawai‘i (e.g., [48,49]). When “Farmer G” was pressed as to why breadfruit was given away, she indicated that breadfruit was going to be essential for Hawai‘i’s food security in the future and so that “people need to get ma’a (accustomed to) it now.” Similarly, “Farmer H” indicated that breadfruit was traditionally a food that signified wealth and abundance and that “there is no greater wealth than to be able to feed your community.” “Farmer H,” “Farmer F,” “Farmer C,” “Farmer M” and others all regularly donated fruit to local schools, food baskets and other non-profit organizations simply to engage in the practice of feeding their communities.

Due to the short shelf-life of the fruit and lack of processing facilities for breadfruit in Hawai‘i, a negligible amount of breadfruit is currently exported from the state. Despite supplying a purely local market, breadfruit has seen a dramatic rise in production (Figure 4). Based on our surveys the growth of breadfruit plantings statewide has grown exponentially, from fewer than 500 commercial tree plantings 20 years ago, to over 3000 trees today, with more than a doubling of plantings expected within the next five years. Considering that ‘ulu farms are located on all the main Hawaiian Islands (Figure 1) in multiple locations, it has potential to feed multiple communities around the state.

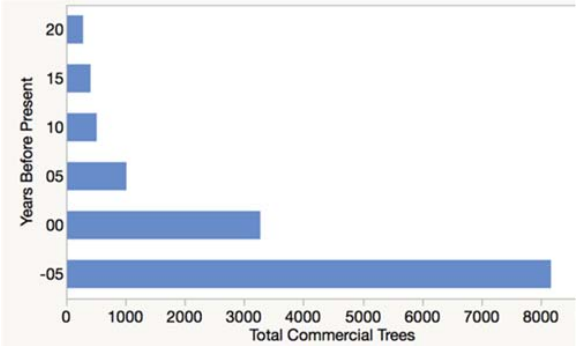

Figure 4. Cumulative number of commercial breadfruit tree plantings identified in Hawai‘i in 2017. The negative five-year category represents trees producers have indicated they plan on planting within the next five years.

Some organizations, such as that of "Farmer O" and "Farmer P" have evolved into major community hubs for community food security. Children, community members and farmers participate and learn about local and traditional foods that support good public health. Meetings held at "Farmer P's" farm afford individuals to learn about these foods and make learned decisions about diet. Teaching, for example, that traditional starches, such as breadfruit with its moderate glycemic index, is predicted to greatly reduce diabetes if re-adopted [25]. Similarly, workshops and tree sales by "Farmer H" educate the community on growing backyard trees and the impact that it can make on a family's health, economics and food security.

3.5. Ecological Health

Contemporary 'ulu farmers demonstrate the ability to cultivate breadfruit in a way that protects the environment while remaining profitable. The majority of breadfruit farmers do not use fertilizers, herbicides, or irrigation, with a mere 7% of growers using pesticides (Table 2). Among the users of chemical and water inputs, only two had regular schedules, while the majority of growers applied fertilizers rarely with application times based on tree observations.

Table 2. Rates of various management practices associated with breadfruit cultivation among survey participants.

Practice (n = 38)	% Apply
Fertilizer	25%
Compost	44%
Mulch	54%
Cover Crops	5%
Intercropped	67%
Pesticides	7%
Herbicides	21%
Irrigation	28%

As mentioned previously, most 'ulu farmers surveyed intercropped their breadfruit trees. The diversification of crops in agroforestry systems increases the value of production, enhances profitability of traditional farms and reduces production costs due to a decreased need for inputs such as water, chemicals and energy [56]. Despite low inputs, farmers reported a 97% average success rate for all sapling establishment on average. When farmers added care to their trees, they largely chose environmentally friendly inputs such as recycled or green waste materials for mulch (e.g., clippings, woodchips, leaves, cardboard), organic or homemade fertilizers (e.g., fish emulsion, chicken manure) and natural compost (food scraps, mixed garden waste, human waste from composting toilets). "Farmer C" farmed without chemical inputs and only organic material as fertilizer yet reported exceptionally high yields. "Farmer H," utilized no inputs, also reported high yields and her tree's measurements showed the highest rates of photosynthesis of any producer measured. That breadfruit is highly productive without excessive inputs is captured by agricultural producer, "Farmer L," who said of his trees,

> "Is it a superfood?! It's definitely a tree of abundance. I always joke around it's like a tree of life. Hundreds of pounds. With really minimal [inputs], I fertilize them once in a while but other than that they just go. It's definitely a tree that gives plenty. It's suited for here. I learned to not quite force anything. There's so many trees I've tried to make grow on a farm. It's the ones from here that can endure."

While we did not investigate the role of biodiversity, several farmers made mention of their breadfruit trees being home to the 'io (the Hawaiian hawk, *Buteo solitarius*) and the 'ōpe'ape'a (the Hawaiian hoary bat, *Lasiurus cinereus semotus*), an iconic, endemic and federally endangered species. While this is not an adequate proxy for biodiversity, the presence of these two rare

animals nesting within breadfruit agroforestry clearly establishes the potential of increased habitat. Preserving biodiversity is an important concept for biocultural restoration, especially in agricultural development where the loss of biodiversity and environmental destruction are attributed to conventional agriculture methods such as monocropping [4].

Ultimately, breadfruit cultivation provides multiple environmental benefits under current production practices. Tree crops in general have shown to have multiple benefits and those impacts are enhanced in agroforestry settings. Forests are valuable systems needed to carry out ecosystem services essential to sustain the natural resource needs of society [5]. Agroforestry has the ability to replenish litter layer to the soil, increase and maintains soil quality, retain soil nutrients and prevent soil erosion [56,57]. For example, growers had, on average, very high levels of soil organic matter (mean 15.25%, standard error 1.38). These same functions improve water filtration and retention rates, increase water availability, reduce runoff and evapotranspiration, collectively improving water quality [56,57]. The shade and presence of multiple tree species also provide habitat, wind protection and essential microclimates that assure cooler summers and warmer winters [57]. The incorporation of increased biodiversity into farming systems at different trophic levels increases crop yields, wood production, yield stability, presence of natural pollinators and encourages weed and pest suppression [58]. The combination of low inputs, low labor, high productivity and ecosystem services benefits showcase the importance of breadfruit as a sustainable crop.

4. Conclusions

Breadfruit holds a unique position in the concept of biocultural restoration in Hawai'i by contributing to the five key themes described above. As a productive, low maintenance crop, 'ulu has the ability to be grown sustainably, which offers the dual role of food production and ecosystem restoration. Increasing availability of healthy foods in the market and through food sharing contributes to greater food security. The continued cultivation of breadfruit is reliant on the continuation of biocultural relationships, or passing knowledge on its growing needs and its importance as a food. Through these cycles, the cultivation of breadfruit in Hawai'i is supported by Hawaiian culture and Hawaiian culture is supported through breadfruit cultivation, where the restoration of one can affect the other (Figure 2).

Although we presented some of the key findings organized within reoccurring themes, these themes clearly overlap and interact with each other. The revival of customary values, for instance, brings forward practices that contribute to the development of community capital, which in turn provides direct benefits to food security through multiple direct and indirect effects. These interactive effects demonstrate, among other things, the intertwined nature of biocultural systems, in which the growth of one necessitates and requires the growth of the other. In multiple examples, we see both the positive and negative reinforcement that occurs within these systems. In a destructive loop, "Farmer F" was not able to receive cultural knowledge regarding breadfruit because the tree itself was not present in his mentors' lives. Conversely, through growing the tree he has recognized how it has contributed to the growth of his culture and identity within himself. As breadfruit cultivation continues to expand its inseverable connection to the Hawaiian culture will continue to fuel the growth of associated value systems. Scaling up, there is evidence that relatively small farms that practice diversified agriculture could increase food production globally, while simultaneously addressing sustainability issues regionally. Referring to Figure 2, traditional agriculture in Hawai'i is a major mediator between biological and cultural components and at the intersection of the three concepts of sustainability. This is where agriculture is significant in regard to sustainable socioecological systems. Breadfruit cultivation through traditional agriculture methods supports the needs of sustainable agriculture and can provide valuable ecosystem services while simultaneously producing food. From the social and cultural side, breadfruit is present in traditional practices that are necessary to sustain its cultivation long term.

Our findings suggest the support of breadfruit production has the potential to be a pivotal solution to sustainability issues in Hawai'i. Evaluating the experiences and lessons learned from discussions

with farmers, we saw that breadfruit is making significant contributions to reconnecting people with place, revitalizing traditional agriculture and Hawaiian culture and that this phenomenon has practical implications for the future. While we cannot say if breadfruit itself promotes these activities or if individuals who engage in these practices are more prone to grow breadfruit, the biocultural restoration of breadfruit can be strongly linked to the furthering of a sustainable socioecological system regardless.

As stated by "Farmer H,"

> "We have started calling breadfruit a 'solutionary' food. There are so many problems with our food system. I mean there is the health and nutrition, there are the environmental issues, there is food justice and food security. And there is just the loss of identity and enjoyment of food. So many issues that need to be fixed. We need a revolution of the way we deal with food. What is amazing about breadfruit is that it hits all of these. I mean, more than any other food I can think of. That it is a tree. That it is embedded in the culture. That it is a nutritious staple. It really has the potential to be a solution to many problems in our food system. So, it is the revolutionary solution that we need...'solutionary.' Get it?"

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Appendix A

Table A1. List of survey question reported on in this paper as administered to 43 successful breadfruit cultivators in Hawai'i.

1.	What is the size of your farm in acres?
2.	What is the number of acres in breadfruit?
3.	What is the number of trees on your property?
4.	What immediately surrounds your breadfruit trees?
5.	What surrounds your farm?
6.	What type of breadfruit varieties do you grow?
7.	Where are your trees from?
8.	How were your trees propagated?
9.	What form did you get your trees?
10.	Describe the planting method used for your trees.
11.	Do you use other methods to ensure the success of a young plant?
12.	Did you use wind and/or sun protection when establishing your orchard?
13.	What was the survival rate of your plantings?
14.	What is the planting pattern of your trees?
15.	Can you describe the spacing?
16.	How many trees are you growing of each variety?

Table A1. *Cont.*

17.	Do you prune your trees?
18.	At what height do you prune your trees?
19.	What time of year do you prune your trees?
20.	Anything else you'd like to share about how you prune your trees?
21.	How much sunlight did your trees get at establishment?
22.	How much sunlight did your trees get now?
23.	Can you estimate production as pounds per month in pounds or percent annual production?
24.	What was your most productive month?
25.	Can you describe your production seasonally?
26.	What was your production (in pounds) per tree annually in: 2014, 2015, 2016?
27.	Anything else you'd like to share about your production?
28.	Do you use any of the following to assess tree health: Immature Fruit Drop, Leaf Color, Leaf Amounts, Other?
29.	How do you know when you need to do the following or do you follow a schedule for Irrigation, Fertilization, Pruning?
30.	Do you fertilize?
31.	What type/brand?
32.	How often and what time(s) of year?
33.	How much?
34.	Do you use compost?
35.	How often?
36.	How much?
37.	What time(s) of year?
38.	Do you mulch?
39.	What type?
40.	How often and what time of year?
41.	How much?
42.	Do you use soil amendments?
43.	Have you had soil tests done for fertility?
44.	Have you had tissue testing done for nutrients?
45.	Do you use additional nutrient management practices? Please describe.
46.	Do you irrigate?
47.	If yes, why?
48.	How much?
48.	How often?
50.	What time of day?
51.	If no, why not?
52.	Do you use additional water management strategies? Please explain.
53.	Have you noticed any pests?
54.	If yes, what kind?
55.	Do you use insecticides?
56.	What type?
57.	How often?
58.	How much?
59.	Do you use other methods to control pests?
60.	Have you notice any of the following diseases?
61.	Do you use herbicides?
62.	What type?
63.	How often?
64.	How much?
65.	Do you use string trimmers, mowing or ground cover?
66.	Do you use cover crops?
67.	If yes, what types?
68.	Do you regularly remove fallen branches, fallen fruit and fallen leaves?
69.	Do you use additional weed or pest management practices?

Table A2. List of general interview topics that were explored with willing participants.

Interview Questions
1. What were your motivations to grow breadfruit?
2. What do you think about the production of breadfruit throughout the state?
3. How do you cook and eat breadfruit?
4. Who do you sell to/share your breadfruit with?
5. Have you seen more or less breadfruit production and consumption throughout Hawai'i in your life?
6. Would you recommend other farmers to grow breadfruit? If yes, why, if no, why not?
7. What are the benefits and challenges of growing breadfruit?
8. What, if any, additional practices did you or do you use to grow and care for your breadfruit trees?
9. What support would be most beneficial as a farmer to receive from
a. research in agricultural development for breadfruit?
b. from government bodies?
c. your community?
10. What obstacles, if any, do you face producing breadfruit from a
a. Growers standpoint and
b. Market stand point?
11. What cultural significance, if any, does breadfruit hold for you?
12. Are you involved in community activities outside of farming that involve breadfruit such as;
a. Education
b. Farmers unions
c. Farmers markets
d. Community potlucks
e. Food donations
f. Agricultural workshops/collaborations with researchers

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