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The *Moku* System: Managing Biocultural Resources for Abundance within Social-Ecological Regions in Hawai'i

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Abstract: Through research, restoration of agro-ecological sites, and a renaissance of cultural awareness in Hawai'i, there has been a growing recognition of the ingenuity of the Hawaiian biocultural resource management system. The contemporary term for this system, "the *ahupua'a* system", does not accurately convey the nuances of system function, and it inhibits an understanding about the complexity of the system's management. We examined six aspects of the Hawaiian biocultural resource management system to understand its framework for systematic management. Based on a more holistic understanding of this system's structure and function, we introduce the term, "the *moku* system", to describe the Hawaiian biocultural resource management system, which divided large islands into social-ecological regions and further into interrelated social-ecological communities. This system had several social-ecological zones running horizontally across each region, which divided individual communities vertically while connecting them to adjacent communities horizontally; and, thus, created a mosaic that contained forested landscapes, cultural landscapes, and seascapes, which synergistically harnessed a diversity of ecosystem services to facilitate an abundance of biocultural resources. "The *moku* system", is a term that is more conducive to large-scale biocultural restoration in the contemporary period, while being inclusive of the smaller-scale divisions that allowed for a highly functional system.

Keywords: Hawaii; biocultural resource management (BRM); ahupuaa; social-ecological community; social-ecological zone

1. Introduction

The small size of many Pacific Islands, coupled with the frequency of catastrophic natural events (i.e., hurricanes, tsunami, drought, flooding, lava flows, etc.) resulted in the development of social-ecological systems around the anticipation of and rapid recovery from environmental change. For this reason, Pacific Islands have been a focus of research into social-ecological system resilience, especially in light of global climate change [1–3]. Understanding traditional approaches to resource management has been a key component of such research. It is apparent that some Pacific Island cultures exceeded resource limits and exhausted their island's carrying capacity early on, while others adapted to resource limitations by adopting conservation measures and, therefore, persisted [4,5]. The Hawaiian archipelago in the era prior to European contact in 1778 (pre-contact era) is a prime example of the latter, making Hawaiian resource management in that era a particular topic of interest with global ramifications.

The "biocultural resource management" (BRM) approaches developed and employed by Hawaiians to manage an archipelago-scale social-ecological system—in the pre-contact era—sustained an abundance of resources for more than a millennium [6]. This state of biocultural resource abundance is known in the Hawaiian language as, "*ʻāina momona*", and is a term that was particularly attributed to lands that employed aquaculture technologies to increase fish biomass [7]. The word, "*ʻāina*", is a derivation from the word, "*ʻai*",which means, "food, or to eat", with the nominalizer "*na*" added to literally mean, "that which feeds" [8], but is generally used as a noun meaning, "Land, earth" [9]. The word, "*momona*", is an adjective meaning, "Fat; fertile, rich, as soil; fruitful...", [9]. Thus, the term *ʻāina momona* is commonly translated in the contemporary period as, "fat land", or, "abundant land", in the context of food production. *ʻĀina momona* was achieved and maintained through careful management on a landscape scale, which extended from the mountains to the sea [6,10].

Through research, restoration of agro-ecological systems, and a renaissance of cultural awareness in Hawaiʻi, there has been a growing recognition of the ingenuity of Hawaiian biocultural resource management systems. These systems effectively adapted to local conditions, while accumulating a body of knowledge in response to observed effects of management—both successes and failures—in order to sustain resource abundance over time. Researchers [11–16], policy makers, K-12 educators, and others, frequently refer to the Hawaiian system of biocultural resource management as, "the *ahupuaʻa* system." In this vein, *ahupuaʻa* are frequently described as self-sustaining units, and put forth as models for sustainability in Hawaiʻi today [17,18]. *Ahupuaʻa* have been equated with watersheds, and described as being in alignment with Western scientific management approaches such as "ridge to reef", and ecosystem-based management [19,20]. Our research indicates that while some of the notions aligning Western scientific approaches to resource management with Hawaiian approaches to biocultural resource management may be valid, attributing them to the *ahupuaʻa* scale does not stand up to scrutiny. For example, some key resources (e.g., adze for felling trees and carving canoes) did not naturally exist within each *ahupuaʻa*, and the population dynamics of key species managed for the survival of human populations were not confined to *ahupuaʻa* boundaries. In fact, there are many examples of biocultural resources that were often managed at the scale of larger land divisions. These nuances, discussed in more detail below, refute the notion that *ahupuaʻa* were self-sustaining. Furthermore, only 5% of *ahupuaʻa* have boundaries that actually corresponded with watershed boundaries [15], whereas other land-division scales more closely align with this concept (discussion below). There are also land-locked *ahupuaʻa*, which do not have boundaries that touch the ocean, and coastal *ahupuaʻa*, which do not have boundaries that extend to the mountains [15]. Therefore, the notion that *ahupuaʻa* were watershed-based, self-sustaining units is not supported. As such, limiting the contemporary application of Hawaiian biocultural resource management to the *ahupuaʻa* scale is not conducive to effective, large-scale restoration.

In recognition of knowledge gaps in the understanding of how Hawaiian biocultural resource management strategies functioned and adapted on a system level, this research aims to fill those gaps by synthesizing 21st century research on the topic and coupling that with contemporary understandings about population dynamics of key biocultural resource species. We aim to build a more nuanced understanding of the inner workings of the Hawaiian biocultural resource management system in the pre-contact era, and how it was able to foster long-term biocultural resource abundance. We do this through an examination of six aspects of biocultural resource management. We also aspire to use a more complete understanding to determine a more accurate term to describe this complex system as to be applicable in the contemporary period for large-scale (i.e., system level) biocultural restoration.

2. Methods

The authors of this paper operate in the realms of both biophysical and social science, and have a combined study of various aspects of the social-ecological system in Hawaiʻi that adds up to well over a century of work. The group includes multi-disciplinary ecologists, botanists, aquatic biologists, and geographers, along with scholars of Hawaiian resource management and governing policy. In this paper we draw upon our collective research that has employed various methods such as archival resource analysis (including maps, governing documents of the Hawaiian Kingdom, Hawaiian language newspapers, etc.), elder interviews, spatial modeling, remote sensing, and biological mapping/monitoring from the mountains to sea. Recent advances in our collective work include several inter-disciplinary projects in the biocultural realm, which have allowed us to synergistically engage with one another's research in the pursuit of better understanding the depth and the breadth of the Hawaiian biocultural resource management system. These collaborations have been key to the development of this article.

3. Results

Our research yielded information that can be grouped into six aspects of biocultural resource management that are relevant to what Winter et al. [21] referred to as the "Hawaiian social-ecological system".

Aspect 1: Nested land divisions provided the framework for systematic management of biocultural resources.

The genesis of landscape-scale biocultural resource management, within the social-ecological system of the Hawaiian archipelago, was born out of necessity when human-population growth began to put a strain on natural resources. Hawaiian historians of the 19th century, such as Kamakau [7] and Malo [22], recounted that at the height of human population in the *aliʻi* era, the land was divided into various scales—such as *moku*, *ʻokana*, *kalana*, *ahupuaʻa*, *ʻili*, *moʻo*, *pauku*, and further into various types of agricultural plots (Table 1). Of these land divisions, the *moku* and the *ahupuaʻa* were key political boundaries in the pre-contact system of governance, managed by positions in the ruling class known as *aliʻi ʻai moku* and *aliʻi ʻai ahupuaʻa* respectively. Land divisions below the *ahupuaʻa* (social-ecological community) level were primarily derived through kinship and cared for by specific extended families [23]. While biocultural resources were managed within the context of those scaled boundaries, there is insufficient understanding of the interplay between the nested land divisions within the biocultural resource management system.

Table 1. Categories of land divisions within an island documented in the 19th century by Kamakau [7] and Malo [22], with contemporary descriptions of the units they represented as interpreted by the authors.

Land Division Term	Unit within the System
moku	A social-ecological region
ʻokana/kalana	Intermediate category being either a group of *ahupuaʻa* within a *moku* that collectively compose a larger watershed; or a smaller watershed within a single, large *ahupuaʻa*
ahupuaʻa	A social-ecological community

Table 1. *Cont.*

Land Division Term	Unit within the System
ʻili	A division within an *ahupuaʻa*, often associated with an extended family
moʻo	A section of land within an *ʻili*
pauku	A strip of land within an *moʻo*
kīhāpai and others	Various types of cultivated plots

The first land division made to manage biocultural resources under the strain of a growing human population was that of *moku* (district or region), and continued population growth later necessitated the subdivision of *moku* into *ahupuaʻa* (a community-level division) for more localized resource management [6,7,24]. This approach to biocultural resource management was not standardized in a cookie cutter approach, but rather depended on biophysical aspects of the land- and sea-scape [16]. Historical maps and Hawaiian language records detail the proper names and boundaries of some units below the *ahupuaʻa* level, such as *ʻili.* While these place names have been mapped for some individual *ahupuaʻa* [14], comprehensive mapping of these land divisions for all the islands in the archipelago has yet to be completed.

Aside from the biophysical differences across islands, as well as the regions within them, land divisions varied over time, being shaped by the dynamic and varied needs of each island's human population, as well as the political structure needed to govern people and manage biocultural resources. It is not clear how many times *moku* were re-subdivided into *ahupuaʻa* in order to manage the needs of a growing human population. The names of some *ahupuaʻa* seem to indicate that they were at one time larger *ahupuaʻa* that were later subdivided into two. This is evident by the occasional occurrence of adjacent *ahupuaʻa* having binomial names that are differentiated only by the epithet, being descriptors of opposing characteristics; whereas all other *ahupuaʻa* names are monomials. For example, on Kauaʻi, Kalihi-wai (Kalihi of fresh water) is adjacent to Kalihi-kai (Kalihi of salt water), and Nuʻalolo-kai (Nuʻalolo of the sea) is adjacent to Nuʻalolo-ʻāina (Nuʻalolo of the land) [16]; and on Hawaiʻi Island, Pakini-nui (Pakini major) is adjacent to Pakini-iki (Pakini minor) [15]. This may be evidence that *ahupuaʻa* were subdivided to adjust to the needs of the people. A similar trend is observed in adjacent *moku* of similar aspect—such as Kona ʻĀkau and Kona Hema on Hawaiʻi Island, and Koʻolau Loa and Koʻolau Poko on Oʻahu—although it is unknown whether or not these are the result of a historical subdivision process for which records have been lost to time.

All of the Hawaiian terms for land divisions (Table 1), with the exception of two—*ʻokana and kalana*—were primarily political boundaries associated with governance and systematic biocultural resource management as discussed above [7,22]. Both of these terms are somewhat cryptic, intermediate level social-ecological divisions. Each has a unique definition, but both seem to be applied to the same situation in different places in the archipelago; and, therefore, we suspect that these two terms are synonyms. Synonymy has been documented between the varying classification systems utilized in the pre-contact era [25], including for terms used to classify land designations within the Hawaiian biocultural resource management system [16]. Such synonymy can lead to confusion, which is particularly true for terms that have fallen out of common usage in the contemporary period, and especially for classifications that—by their cryptic nature—do not fit well into tables developed by scholars.

Both *ʻokana* and *kalana* were units smaller than a *moku* that could have either contained several small *ahupuaʻa* [9,26], or were distinct areas within large *ahupuaʻa* [27]. The intermediary nature of this land division has led to confusion about what this unit was, exactly, and how this concept fits into contemporary restoration efforts. It is seemingly more related to biophysical realities and regional identity of the community rather than governance and resource management. "*ʻOkana*", is a contraction of, "*ʻoki,*" and "*ʻana*", meaning, "cutting off", [26] in reference to the partition of a larger land division into smaller units. While its synonym, "*kalana*", can be broken down into, "*kala*", and its nominalizing suffix, "*na*", to literally mean, "that which loosens, frees, releases, removes, unburdens" (translation by authors), in reference, perhaps, to a watershed. These divisions were based upon the biophysical characteristics of the area, rather than the political needs for governance.

There are a few known examples that can inform our contemporary understanding of these terms. The term *kalana* has been applied to the Hanalei region of northern Kaua'i, which includes the *ahupua'a* of Hanalei, Waioli, Waipā, and Waikoko [28]. This appears to reference lands that collectively release *wai* (fresh water) into Hanalei Bay. Other examples are observed on the dry leeward side Hawai'i Island, where the *moku* of Kona is divided into the *kalana* of Kekaha, Kona Kai'ōpua, and Kapalilua [29]. The *kalana* of Kekaha (a contraction of the term, "ke-kahawai-'ole", meaning, "land without streams") in the northern area of Kona is characterized by arid lands with neither streams nor abundant rainfall, but instead has subterranean freshwater flow. Kona Kai'ōpua (Kona of the puffy clouds above the ocean), in the middle section of Kona, is where the *'ōpua* (cumulus) clouds commonly rest in the field of vision in region just off shore. Kapalilua (the double cliff), in the southern region of Kona, is composed of several *ahupua'a* which encompass a region in Kona with a unique topography that is dominated by large sections of sea cliffs.

Uncertainties remain relating to the boundaries of various land divisions, as described above. This arises from several factors: (1) While Hawaiians quickly adopted paper-based mapping, after contact with Europeans, as a crucial means of documenting and asserting knowledge and rule over lands, they did not make such maps in the pre-contact era [30]; (2) several volcanic eruptions have modified or destroyed *ahupua'a* and/or *moku* boundaries; (3) boundaries were well established at the shoreline, but were more ambiguous offshore; (4) the conquest and unification of the islands destroyed sovereign boundaries established by prior dynasties; and (5) current boundaries set by various indigenous and historical authorities are sometimes in conflict [15]. More research into historic land divisions and how their boundaries shifted over time is needed.

Aspect 2: Designation of social-ecological zones (*wao*/*kai*) allowed for the management of population dynamics for key resource species across social-ecological regions (*moku*).

Terrestrial social-ecological zones (*wao*) within a social-ecological region (*moku*) were designated by a two-word term beginning with "*wao*" and followed by an epithet that described their primary purpose and indicated appropriate activities within each zone [16] (Table 2, Figures 1 and 2). Social-ecological zones in the marine environment (*kai*) have been historically documented within this system [7,29] (Table 3), but these have yet to be comprehensively examined or explored with spatial modeling. Both *wao* and *kai* spanned across the *moku*, which effectively divided each individual social-ecological community (*ahupua'a*) vertically, while connecting it horizontally to adjacent *ahupua'a* within a *moku* (Figure 1). The vertical divisions allowed for system-based management within each *ahupua'a*, while the horizontal connections between *ahupua'a* allowed for coordinated management of the population dynamics of key resource species between *ahupua'a* within each zone spanning a *moku*. This was achieved, in part, by a rotating system of harvest restrictions (described below), which ultimately facilitated management for maximum cumulative abundance and benefit of the entire system—a point that is elaborated below (Aspect 3).

Table 2. The five terrestrial social-ecological zones (*wao*) that appear to have been recognized on the island of Kaua'i. Management implications for each zone are provided (based on Table 3 in Winter and Lucas [16]).

Social-Ecological Zone	Translation	Management Implications
wao akua	Sacred forest	Primary function: Perpetual source population for endemic biodiversity. Designated as "sacred forest", making it a restricted forest zone for a native-only plant community, accessed only under strict protocols. Associated with montane cloud forest, elfin forest.

Table 2. *Cont.*

Social-Ecological Zone	Translation	Management Implications
wao kele	Wet forest	Primary function: Maximize aquifer recharge. An untended forest zone associated with core watershed areas (remote upland, wet forest below the clouds) which was left as a native-dominant plant community. Impractical for access except for transit-through via trails.
wao nāhele	Remote Forest	Primary function: Maximize habitat for native birds. A forest zone that was minimally-tended (generally remote upland, mesic forest) and left as a native-dominant plant community. Impractical for access except by bird catchers and feather gatherers.
wao lāʻau	Agro-forest	Primary function: Maximize the availability of timber and non-timber forest products. A zone allowing for the management of a highly-tended forest via an integrated agroforestry (native and introduced plants) regime: • Native and introduced hardwood timber • Introduced food trees • Native and introduced biofuel sources • Maximization of native biodiversity for non-timber forest products • Cordage and weaving material • Medicine and dyes • Ceremonial and adornment plants
wao kānaka	Habitation zone	Primary function: landscape-scale augmentation to maximize the availability of food, medicine, and housing. A zone allowing for (but not mandating) the conversion of forest to field agriculture, aquaculture, habitation, recreation, and/or temple worship. Native and introduced trees tended, individually or in groves, for regular and specific cultural services.

Table 3. An abridged list of select social-ecological zones (*kai*) within the marine environment as documented by Maly and Maly [29]. Translations of the meaning of these zones are provided by the authors.

Marine Social-Ecological Zone	Translation by Authors
ka poʻina nalu	Fringing reef with breaking waves (representing the seaward boundary of *ahupuaʻa*)
kai lūheʻe	Sea for fishing with octopus lures (outer reefs)
kai koholā	Sea frequented by humpback whales (*Megaptera novaeangliae*) (submerged volcanic shelves)
kai ʻele	Black sea (deep-sea area, possibly between volcanic shelves)
kai uli	Dark sea (deep-sea area, possibly beyond the islands' volcanic foundations)
kai pualena	Sea along the horizon that gets the first touch of the sun's light (deep-sea area)
kai pōpolohua-a-Kāne-i-kahiki	Distant, dark sea associated with the travels of Kāne (deep-sea area beyond sight of land)

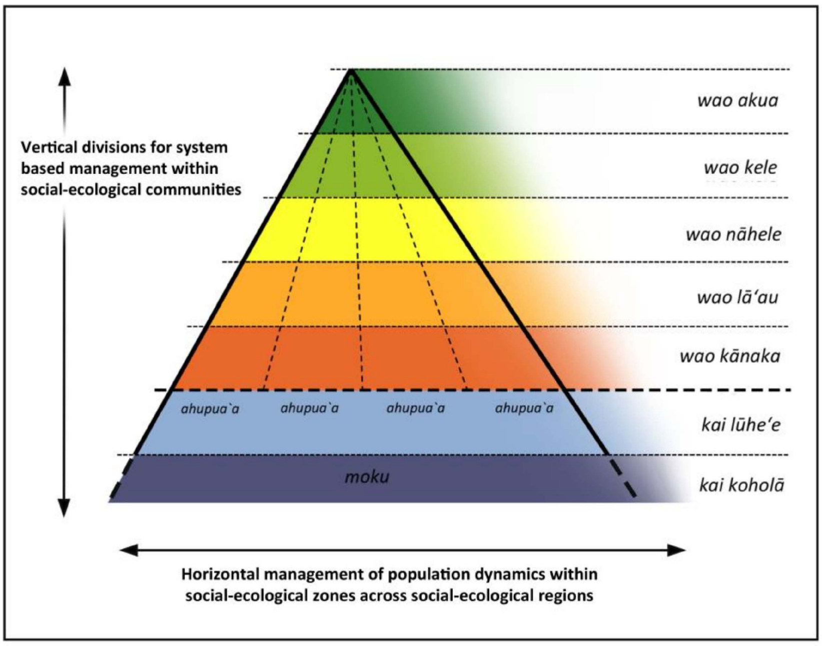

Figure 1. A schematic model depicting the layout of a single social-ecological region (*moku*) including the structure of both social-ecological zones (*wao* and *kai*, designated horizontally) and of social-ecological community boundaries (*ahupuaʻa*, designated vertically) to convey the framework for the biocultural resource management of the *moku* system in the Hawaiian archipelago in the pre-contact period. This framework provided for management in both the horizontal and vertical dimensions. Social-ecological zones are based on those identified from the island of Kauaʻi [16].

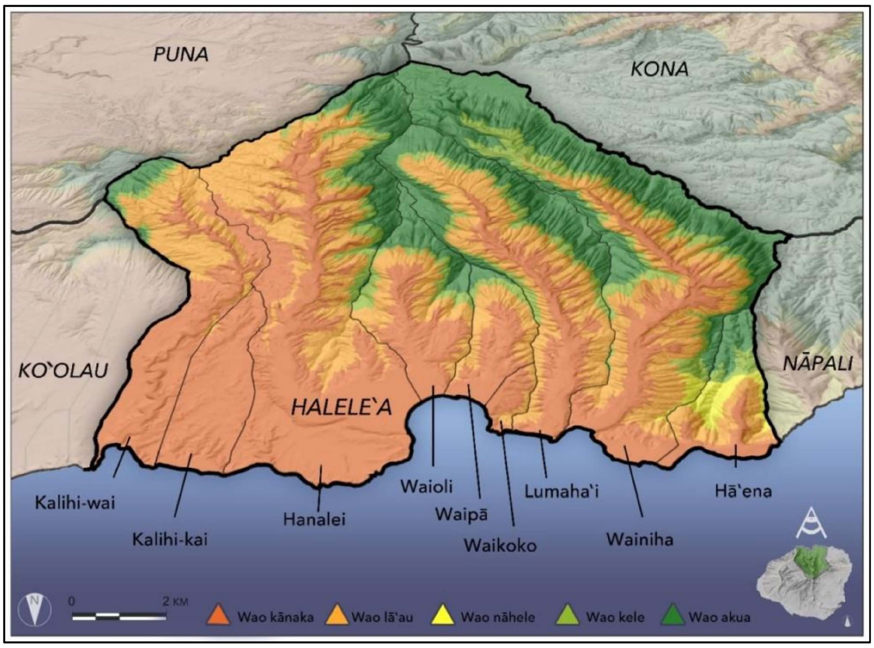

Figure 2. A spatial model depicting the layout for the social-ecological region (*moku*) of Haleleʻa on the island of Kauaʻi, including the social-ecological zones (*wao*) that dictated resource management in each social-ecological community (*ahupuaʻa*), as determined by Winter and Lucas [16]. Each *wao* is represented by a different color as indicated in the key. This *moku* contains nine *ahupuaʻa*, each of which are labeled here by name. Not all *ahupuaʻa* modeled here have all five *wao* documented from the island of Kauaʻi, which indicates that each *ahuapuaʻa* had varying levels of access to and amounts of biocultural resources.

Aspect 3: Population management of key biocultural resources operated on an ecoregion scale.

Moku provide ideal units for examining management systems for key resources [31]. While they are often understood as political boundaries, their alignment facilitated decentralized resource management under *ali'i 'ai moku*, the royal title for those who administered resources in a *moku*. *Moku* boundaries encompass land- and sea-scapes and are aligned with biophysical attributes of island ecosystems—such as landscape aspect, topography, climate regime, wave exposure, watershed classification, forest distribution, substrate type, and aquifer boundaries (Figures 3 and 4). In this regard, *moku* boundaries are more closely aligned with the scientific understanding of an archipelago-scale ecoregion than any other unit of land division recognized in pre-contact Hawai'i. Ecoregions are relatively large units of land containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change [32]. While usually referred to on a global scale, we use this term on an archipelago scale. This concept is explored in more detail below.

Owing to Hawai'i's orthographically driven climate patterns across the landscape and shoreline, bio-physical resources—such as sunlight, rainfall, temperature and wave energy [33,34]—ultimately drive natural resource abundance and the potential for cultivating biocultural resources via agro-ecological and aquaculture systems. While there are climatic similarities across *moku*, there are also key differences between *moku*. These differences can be seen with an RGB visualization of equalized temperature (°C), solar radiation (W/m^2), and rainfall (mm) [35,36] respectively (Figure 3). This can also be visualized in data distributions in histograms of climatic and landscape variables island wide, across *moku*, and within social-ecological zones (Figure 4). The overlay of *moku* boundaries in Figures 3 and 4 reveal clear patterns of climatic similarity within each *moku*. This suggests these divisions optimized land uses and had the potential to contain specialized biocultural resources. In particular, *wao kanaka* zones (including coastal areas) are primarily differentiated between *moku* by solar radiation, rainfall, temperature, and wave energy. This suggests that human interaction with the environment in these areas helped to further distinguish the *moku* from one another and inform appropriate uses. This is evident in the varying forms and intensification of agriculture associated with each *moku* [8], as well as coastal resource development or extraction [29]. This research does not assume that only these physical variables strictly dictated *moku* or *wao* boundaries while disregarding social and cultural drivers; however, an examination of the patterns of both similarities and differences across these spaces does suggest a logical grouping of resource uses as dictated or limited by some bio-physical constraints. *Moku* boundaries also correspond well with the population dynamics of key biocultural resources—such as fish, birds, invertebrates, and plants—that could be more effectively managed in the context of their natural ranges, and in their respective gene pools within ecoregions. Specific examples of key species in these life-form categories are given below.

Fresh-, brackish-, and salt-water vertebrate and invertebrate species were important components of traditional food systems in pre-contact Hawai'i [29]. At the local (*ahupua'a*) and district (*moku*) levels, fishing activities and catch distribution were strictly disciplined by a system of rules and regulations—born out of an understanding about the life cycles of various aquatic species—that were embedded in socio-political structures and religious systems (discussed below). Harvest management was not based on a specific amount of fish, but on identifying the specific times and places that fishing could occur so as not to disrupt basic life-cycle processes and habitats of important food resources [37]. Many of these laws provided protection for important species and allowed Hawaiians to derive sustenance from the ocean for centuries [38]. Knowledge about fish habitat needs, behaviors, and life cycles paved the way for the development of various aquaculture technologies that both increased and stabilized the production of fish biomass [29,39] in the social-ecological system.

Watersheds that contained perennial streams flowing from the mountains to the sea were provided with important vertical dimensions of instream food resources in the form of various species of native fish (*'O'opu*) and macroinvertebrates (*'Ōpae* and *Hīhīwai*) (Table 4). *'O'opu* were the most commonly-referenced fish listed as a traditional food source by native Hawaiians on islands with perennial streams in the middle of the 19th century, which alludes to the importance of these freshwater protein sources in that era [29]. This was particularly true for families living inland from the coast. Hawai'i's native stream species are all amphidromous [40] in that they move out to sea as larvae and return to freshwater as sub-adults to complete their juvenile and adult phases [41,42]. For '*O'opu*, eggs are laid and fertilized in nests, often close to stream mouths. Newly hatched larvae passively drift with stream currents into nearshore areas as marine plankton [43], then metamorphose and recruit into streams as juveniles [44]. The recruiting '*O'opu* are known in Hawaiian as *hinana*, which is the first size class recognized as edible [39]. Adults of each species predictably distribute themselves into high densities along elevational zones in the stream continuum [45], where they may be reliably collected seasonally. Given their amphidromous life histories, sustaining native '*O'opu*, '*Opae* (an ethnogenus comprising *Atyoida* and *Macrobrachium*), and *Hīhīwai* (*Neritina granosa*) larval production from streams within and among watersheds is important to replenish oceanic planktonic populations as cohorts mature to enter streams as juveniles. An ecoregional-scale of resource management, consisting of multiple adjacent streams combined into an ecoregion management unit (*moku*) would, therefore, serve to optimize larval production regionally and be beneficial in sustaining native food resources in streams on all islands.

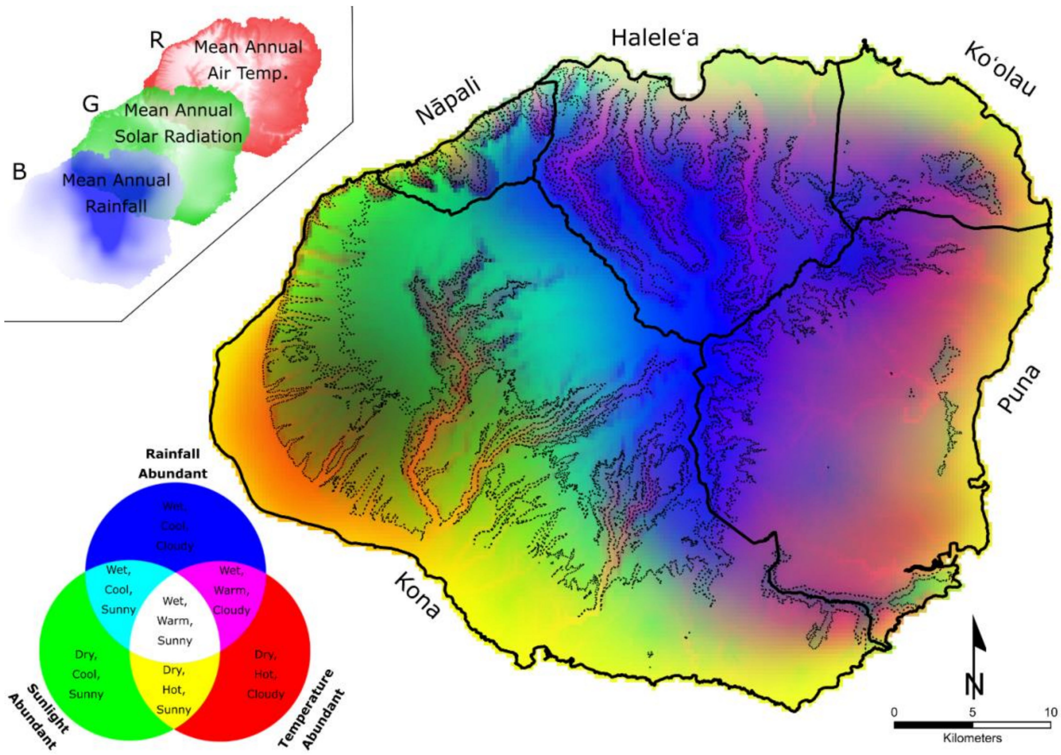

Figure 3. A visual interpretation of climate as delineated by histogram-normalized color combinations of red, green, and blue to simultaneously visualize gradients and combinations of temperature, solar radiation, and rainfall (red: mean annual temperature (°C); green: mean annual solar radiation (W/m^2); blue: mean annual rainfall (mm)). Social-ecological region (*moku*) boundaries (thick black lines), and social-ecological zone (*wao*) boundaries (thin dashed lines) representing the data produced by Winter and Lucas [16] are overlaid atop the island of Kaua'i. All climate data are from Giambelluca [35,36]. Areas with blue dominance represent relative rainfall abundance, areas of green dominance represent relative solar radiation abundance, and areas of red dominance represent relative warmer temperatures. This results in color mixes that demonstrate these climatic variables, with the Venn diagram providing a color key for visual interpretation of the mean annual climatic variability.

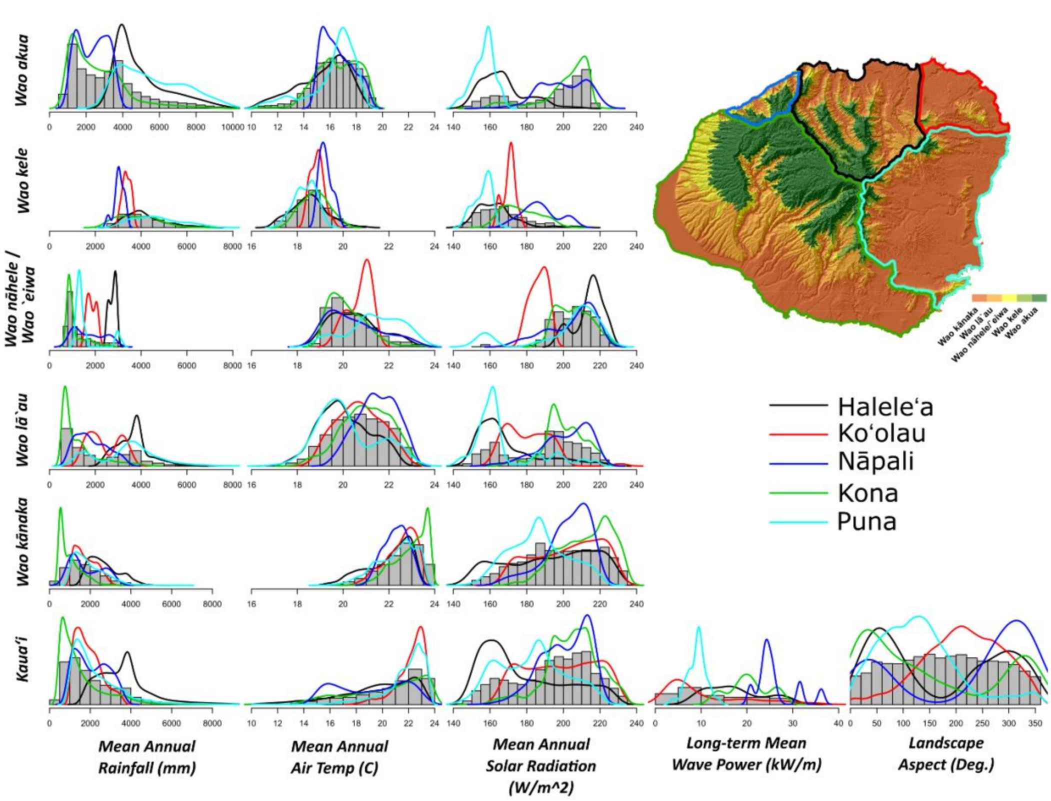

Figure 4. Histograms of climate and landscape variables (columns) for the example island of Kauaʻi. From left to right: mean annual rainfall (mm), mean annual temperature (°C), mean annual solar radiation (W/m^2), long-term wave power (Kw/m), and landscape aspect. Rows display island-wide data distribution (bottom) and subsets of socio-ecological zones. Grey histograms represent all data in the zone or island with color coordinated distribution lines display distribution of each according to *moku*. Base-layer image of Kauaʻi indicating social-ecological zones is from Winter and Lucas [16]. The boundaries of each of the five *moku* (Haleleʻa, Koʻolau, Nāpali, Kona, and Puna) for Kauaʻi are indicated in separate colors.

Nearshore fish species were also important as a protein source, particularly for people living along the coast, and were managed on an archipelago-based ecoregion scale for abundance [29]. Management tools included the use of temporal and seasonal closures, a practice widely used in traditional Pacific marine tenure systems. Such closures most often applied to reduce intensive harvest of spawning fish or aggregations that occurred during lunar, seasonal, or annual cycles [4,46]. A number of pelagic and migratory species were heavily relied on as food sources, and effective management of their populations was more appropriately addressed at the *moku* level. An example of such management is evident in the ancient fishing regulation of *ʻŌpelu* (mackerel scad, *Decapterus* spp.)—in the *moku* of Kona Hema, Hawaiʻi Island, which happened beyond the seaward boundary of the *ahupuaʻa* in that ecoregion. This regulation mandated that *ʻŌpelu* be actively fed (*hānai ʻia*) in their natural aggregation areas (*koʻa*) during the restricted (*kapu*) season, which was associated with their spawning period. Each fishing family had a designated *koʻa* to *hānai* during the *kapu* season. If they fulfilled that responsibility they were allowed to fish within any of the *koʻa* during the unrestricted (*noa*) season, after first harvesting from the one they tended. If, however, a family did not fulfill their responsibility to *hānai* their designated *koʻa* in the *kapu* season, they then lost their privilege of fishing for *ʻŌpelu* in the following *noa* season. This is recalled in the proverb, "*Hānai a ʻai*", [29] that roughly translates to, "Feed [the fish], and [you may] eat", (translation by authors). Regulations that restricted the fishing of key species during their spawning season and calling for the active feeding of them during this period likely increased the fecundity of key resource fish species for the entire *moku*. The six-month *kapu* season for *'Ōpelu* was the *noa* season for *Aku* (skipjack tuna, *Katsuwonus pelamis*), a predator of juvenile *'Ōpelu* [29], therefore this restriction/feeding season for *'Ōpelu* corresponded with a shifted dietary reliance of Hawaiians to top-predator species as a protein source. As such, in addition to limiting pressure on key lower trophic level fish species, harvesting their predators reduced their natural mortality. When the *kapu* was lifted for *'Ōpelu* fishing, the six-month *kapu* for *Aku* fishing commenced [7,29,39], thus allowing for population recovery of that species. The rotating *kapu*/*noa*, *noa*/*kapu* seasons alternated between these two species on an annual basis. Another important nearshore fish, *'Anae holo* (striped mullet, *Mugil cephalus*), was a prized species that migrates along coastal areas and into estuaries within an archipelago-scale ecoregion, and was a focal species in aquaculture systems. Not only were *'Anae holo* fished for as they passed through the coastline of an *ahupua'a*, they were also attracted into aquaculture systems, which were designed to create or enhance habitat for key resource species in a contained area. This included six classes of fishponds [29,39]. The replenishment of fishponds was dependent on the spawning success of this and other species, which happens on a scale that is more closely aligned with *moku* boundaries than any other scale of land division in ancient Hawai'i.

Birds—including forest birds, waterfowl, seabirds, and other migratory species—were another key biocultural resource group as a source of both food for sustenance, and feathers for adornment. As with pelagic and migratory fish, the population dynamics of native birds extended beyond *ahupua'a* boundaries. Hawaiian honeycreepers (Fringillidae: Drepanidinae), a highly diverse passerine group relied upon for their feathers, can have home ranges of up to 12 ha [47]. In the context of inland forest at or near the apex of *ahupua'a* home ranges of native honeycreepers could most certainly go beyond *ahupua'a* boundaries, while staying well within the social-ecological zones (Figure 2) that spanned multiple *ahupua'a*—such as the *wao akua* and the *wao nāhele* in the case of forest birds. The *Koloa* (Hawaiian duck, *Anas wyvilliana*), once an important source of food associated with the *wao kānaka* zone [8], has been documented to fly between wetland systems in the same *moku* [48]. Ground-nesting seabird colonies—such as those of the *'Ua'u* (Hawaiian petrel, *Pterodroma sandwichensis*), which was another food source when abundant—encompass the upland forest of entire *moku.* An example of this is the colony at Honoonāpali [49]—the region of montane cloud forest encompassing the entire *wao akua* zone in the *moku* of Nāpali on the island of Kaua'i. Therefore, given that key resource birds have home ranges and population dynamics, which existed in social-ecological zones that spanned across many *ahupua'a* yet remained within *moku* boundaries, managing their populations for abundance would have been more effective if done at the *moku* scale.

Species ranges and population dynamics of native plants—as opposed to cultivated crops—were also not limited to *ahupua'a* boundaries. Native plants co-evolved with three natural vectors of dispersal—wind, birds (either internally or externally), and ocean currents. Coastal plants tend to be distributed by ocean currents, whereas inland species tend to be distributed by wind or wing [50]. *'Ōhi'a lehua* (*Metrosideros polymorpha*), the native tree with the highest biocultural value [51], has wind-born seeds that can be dispersed great distances. As for culturally-important trees with fleshy fruits—such as *Māmaki* (*Pipturus* spp.), *'Alahe'e* (*Psydrax odorata*), and many others—avian dispersers are critically important, and such birds are responsible for the structure and diversity of forests in Hawai'i [52]. Therefore, diversity of culturally-important native plants, as well as the structure of forests depended on physical and ecological factors that existed on a scale more closely aligned with those of the *moku* than any other scale of land division in ancient Hawai'i.

The abundance of biocultural resources, needed by stewards of the *ahupua'a* for their sustenance and well-being, depended on ecological factors, including life cycles of key resource species, that operated on scales larger than that associated with *ahupua'a* boundaries. This makes the larger *moku* a more practical unit for management.

Aspect 4: Ensuring high levels of biodiversity resulted in resilient food systems.

Hawaiians in the pre-contact era used taxonomy to attribute names to specific units of biodiversity in their social-ecological system [25], which provided a means to manage the components at the foundation of a diverse range of sociocultural traditions. The management of biocultural diversity has been identified as an important aspect of maintaining—and potentially restoring—the structure, function, and resilience of social-ecological systems [21]. The same concept can be applied to food systems. There is a word in the Hawaiian language for famine—*wī* [9]—which indicates that food was not perpetually abundant in all areas. Periods of famine are noted to have followed natural disasters, such as hurricanes, or climatic shifts which resulted in extended periods of drought [53]. This evidence suggests occasional short-term declines in food abundance, yet points to the importance of biodiversity for resilience of the food system. Some species of plants are referred to as "famine foods" [8,54], and the same is true for some species of marine life [39]. Resource managers had to maintain high levels of biodiversity (Table 4) throughout the social-ecological system as a means to facilitate resilience in the food system. Resource managers had tools to maintain abundance and biodiversity in the food system. These tools included various types of *kapu*, or harvest/access restrictions, to allow for the recovery of populations of key species [29]. When certain species had *kapu* placed upon them, many others in the system could be relied upon as substitutes—as indicated in the alternating *kapu* between ʻ*Ōpelu* and *Aku* (discussed above). The high levels of redundancy in wild food sources is indicative of a resilient food system, one that identified food sources that were relied on primarily in periods of scarcity.

Table 4. The amount of native biodiversity functionally relied upon as food sources in the pre-contact era Hawaiʻi.

Life Form	Edible Species	Source
Freshwater vertebrates	5	Maly and Maly 2003 [27]
Freshwater invertebrates	4	Maly and Maly 2003 [27]
Ocean vertebrates	231	Maly and Maly 2003 [27]
Ocean invertebrates	57	Maly and Maly 2003 [27]
Macro-algae	29	Abbott 1996 [55]
Birds	38	Keauokalani 1859–1860 [56]

Aspect 5: Rotations of harvest restrictions were tools to manage for abundance of biocultural resources.

Maly and Maly [29] comprehensively documented Hawaiian fishing traditions from the pre-contact era, through the Kingdom period, and into the territorial period—based on a compilation of historical records and oral histories. They documented rotating harvest restrictions (*kapu*) that were placed and lifted (making an area *noa* or free from restriction) on either a regular or intermittent basis. The Hawaiian biocultural resource management system employed various kinds of harvest and access restrictions (*kapu*). The punishment for breaking a *kapu* was swift and severe [7,22]. A summary of the types of *kapu* employed in Hawaiian biocultural resource management strategies is described below (Table 5). These various kinds of *kapu* were employed in concert with each other—on both a temporal and spatial scale—to manage for the long-term abundance of key biocultural resources, while at the same time ensuring that local communities could access resources for their daily survival and well-being. The process for deciding which kind of *kapu* to employ and when, with the goal of managing population dynamics within a *moku*, was done by implementing a multi-criteria decision-making process—such as that which is described below (Aspect 6).

Table 5. A list of various types of *kapu* (restriction) along with associated descriptions compiled from Maly and Maly [29] and examples for each.

Kapu Type	Description of *kapu*	Examples
Seasonal harvest restriction associated with spawning periods	Placed an annual ban on the harvest of key fish species during their spawning season, which helped to ensure healthy populations for future fishing seasons.	Annual six-month *kapu* on *'Ōpelu* (*Decapterus* spp.)
Monthly harvest restriction associated with particular moon phases	Regulated either specific harvest practices or harvest of particular species on named moon phases, which effectively staggered harvesting pressure throughout the month and protected spawning events occurring on certain moons.	No fishing allowed on the 27th phase of the moon (*Kāne*).
Occasional access restriction, associated with particular areas	Intermittently imposed to restrict human access into areas that needed immediate recovery, or in areas being saved for a planned large harvest in the foreseeable future.	Lāwa'i (an *ahupua'a* in Kona, Kaua'i) is a place-name commemorating the lifting of a *kapu* over the entire bay fronting that *ahupua'a.*
Occasional harvest restriction, associated with a particular taxa	Intermittently imposed to temporarily rest harvest of specific taxa observed to be in decline as a means to facilitate population recovery.	*Kapu* placed on *'Ula* (lobster, *Panulirus marginatus*) when population observed to be in decline.
Occasional harvest restriction, associated with a particular life-stage of a specific taxa	Prevented harvest of particular species at key stages in their life cycles, as a means to manage population demographics of that species and enhance reproduction. These restrictions only protected certain life stages while other life stages of that same species could be harvested.	*Kapu* placed on *Moi li'i* (juvenile threadfin, *Polydactylus sexfilis*) only, while allowing for the harvest of other life stages of the same species.

Aspect 6: Systematic approaches towards holistic evaluation of solutions to biocultural resource problems.

In resource management, solutions born out of a narrow view of a problem have the potential to unintentionally create new problems in other areas of a system. Multi-criteria decision-making processes can be used as a tool to determine the best possible solution to a complex problem [57]. Hawaiians employed such tools in the approach of managing biocultural resources to attain abundance (*'āina momona*) in their social-ecological system.

Knowledge of an evaluation process relating to the system-level management of biocultural resources has been documented from the island of Moloka'i—as developed in the pre-*ali'i* era prior to the voyage of Pā'ao to Hawai'i (approximately 800 years BCE). This evaluation process operated on both the temporal and spatial planes, and in the spiritual realm. It was utilized as a tool by decision-making councils that were composed of recognized experts who were valued for their unique skills and experience—whether that be in agro-ecology, aquaculture, hydrology, meteorology, phenology, etc. The councils operated along certain guiding principles, and themselves guided resource management to ensure the health and integrity of eight resource realms [6,58]. The council's decision-making process entailed consideration of the impact of a proposed solution on each of the eight realms (i.e., the spatial scale, Table 6) as to arrive at solutions that addressed the problems of a specific realm without causing harm to any of the other realms. Once a decision was arrived at, it was implemented by the people in a manner that honored the ancestral past while addressing present needs, and establishing more abundance for future generations (i.e., the temporal scale) [6,58].

Table 6. The eight main components of the systematic evaluation process that was developed on the island of Molokaʻi to ensure abundance in all resource realms of the social-ecological system [6,58], with descriptions and contextual interpretations provided by the authors.

Component of Decision Matrix	Component Description and Contextual Interpretation
moana-nui-ākea	The sea from the shoreline to the horizon, as seen from the highest vantage point in the area; and all associated biota.
kahakaipepeiao	The area extending from the place where the ocean meets the land to the place where soil exists. This includes the splash zone where algae, crabs, and other shellfish may be located; sands where turtles nest; dunes where seabirds nest and coastal strand vegetation exists; sea cliffs; and all associated biota.
mauka	The area from where soil begins, extending all the way to the mountaintops; and all associated biota.
nāmuliwai	All the sources of fresh water—artesian springs, streams (including coastal springs that create brackish-water and contribute to healthy and productive estuarine environments); and all associated biota.
kalewalani	The realm inclusive of everything above the land—the air, winds, sky, clouds, rain, rainbows, birds, atmosphere, sun, moon, planets, and stars. This encompasses all the elements and celestial bodies that influence the tides and ocean currents, which directed traditional navigation and guided fishing and planting seasons.
kānakahōnua	The needs of the people. This included the *kānāwai* (laws) that governed behaviors and ensured a functioning society which contributed to the people's health and well-being.
papahelōlona	The intellect and cumulative knowledge built up over generations. This is the knowledge of *kahuna* (keepers of priestly knowledge), knowledge about the connections across the social-ecological system and the correlations between the cycles of nature, and knowledge of expert practitioners in astronomy, healing, and other schools of knowledge.
keʻihiʻihi	The spiritual realm and the ceremonies needed to maintain *pono* (balance) in the *ʻāina*. These included elements of nature, ancestral deities, and religious protocols needed to maintain sanctity in the landscape.

The implementation of biocultural resource management tools, such as the coordination of various types of *kapu* (harvest restrictions) across the *moku* (as discussed above), were the kind of issues decided upon by systematic evaluations of both problems and potential solutions. The unilateral placement of *kapu* on the scale of a single *ahupuaʻa* would not be as effective as collaborative and coordinated efforts between multiple adjacent *ahupuaʻa*. Various types of rotating *kapu* were employed in concert—between *ahupuaʻa* within the context of the *moku*—to synergistically yield long-term abundance of key biocultural resources. For example, when a key species was closed in one *ahupuaʻa*, it might be open in the adjacent *ahupuaʻa*, with shared harvest rights across both, so that residents could continue to access that resource even while it was rested and rejuvenating in their own home area. The designation of social-ecological zones, which maintained horizontal connections between *ahupuaʻa* facilitated this management approach, and allowed for the continual replenishment of key species in the archipelago-scale ecoregion without compromising the ability of *ahupuaʻa* tenants to feed themselves. This was true for key biocultural resources in oceans, estuaries, streams, wetlands, and forested areas. Similar evaluation processes were likely employed in the *aliʻi* era—between the arrival of Pāʻao from Tahiti and the arrival of Europeans in 1778—although records of this are not known to exist.

4. Discussion

An analysis of various aspects of managing biocultural resources on a system level has provided some insight into the pathways that pre-contact Hawaiians followed to attain the state of abundance known in the Hawaiian language as *ʻāina momona.* However, an abandonment of traditional resource management practices in the post-contact era led to a decline in biocultural resources. A good example of this can be seen by the loss of *kapu* (restrictions) as resource management tools.

Kapu were born out of and engrained in the ancient Hawaiian religion in the pre-contact era. These restrictions regulated many aspects of society and human behavior, not just use and management of biocultural resources [7,22,59]. When the ancient Hawaiian religion was abolished in 1819—forty years after Western contact—the *kapu* system was dissolved. With it went a system of regulations for resource extraction, and the authority to enforce violations [29]. Regulations and enforcement were key tools used to manage for long-term abundance of biocultural resources. Loss of the *kapu* system left valuable species unprotected as Hawai'i, an important stop on shipping routes across the Pacific, entered the global trade economy of the 19th century. The massive over-harvesting of *'Iliahi* (Sandalwood, *Santalum* spp.) for export to China contributed to the near extinction of these trees [60]. The example of *'Iliahi* shows how not only key species, but entire ecosystems, were vulnerable to the pressures of capitalism without the *kapu* system in place to protect biocultural resources. After the word "*kapu*" took on a negative connotation in the Christian era—due to its association with the ancient religion—some forms of resource extraction regulations continued under a different term, "*ho'omalu*", which means, "to rest;" and were codified into law during the Kingdom Era. This was applied locally within *ahupua'a* to particular species or areas, as needed and identified by the designated *konohiki* [29].

The abolishment of the *kapu* system was just one of many changes that undermined the Hawaiian system of biocultural resource management during the 19th century. Depopulation from introduced diseases in the century following European contact was a major contributing factor to the abandonment of agro-ecological systems [61]. Changes in land tenure from the 1840s through the overthrow of the monarchy in 1893 created private ownership in place of communal land holdings [14,30,62,63]. Nearshore fisheries, and local rights to harvest and manage them, were gradually condemned, starting with the Act that annexed Hawai'i as a territory in 1900. This opened fisheries to public access and shifted resource management authority from the *ahupua'a* level to centralized bureaucracies under the territorial and then state governments, and decoupled nearshore resource management from land-based resource management [64,65]. However, in spite of all the change, some *ahupua'a* tenants continued modified forms of biocultural resource management tools into the 20th century, such as the continued practice of designating species and areas for protection (*ho'omalu*). These informal "rests" were designated by respected elders, but were not codified or enforceable except by social pressures [37]. Andrade [14] documents some specific examples of informal community agreements to rest certain areas, or to rotate harvest in the *ahupua'a* of Hā'ena (Halele'a, Kaua'i). Hā'ena is just one of many Hawaiian communities that found novel ways of adapting to continue traditional resource management practices well into the 20th century.

5. Conclusions

Of all the scales of land division in ancient Hawai'i, the *moku* unit is the scale most closely aligned with archipelago-scale ecoregions that encompass population dynamics of key biocultural resources—such as fish, birds, and plants. Biocultural resource management on this scale involved spatial management in both the horizontal and the vertical planes via the designation of social-ecological zones, as well as the concentric scaling of nested land divisions. All of this was done in concert with knowledge about temporal patterns associated with the cycles of lunar months and solar years, which were correlated with life cycles and population dynamics of key resource species. Given the success of this traditional resource management system in ancient Hawai'i, a return to this approach would be an essential component of large-scale biocultural restoration in the 21st century.

We introduce the term "the *moku* system" to describe the Hawaiian biocultural resource management system, practiced in the pre-contact era, which divided large islands into social-ecological regions (*moku*) and further into interrelated social-ecological communities (*ahupua'a*)—each of which contained a network of scaled kinship-derived sections (*'ili*, *mo'o*, etc.) nested within them. Each *moku* had several social-ecological zones (e.g., *wao* and *kai*) running horizontally as belts across the region. These *wao* divided individual *ahupua'a* vertically while connecting them to adjacent *ahupua'a* horizontally, allowing for holistic management of biocultural resources across human communities. These delineated social-ecological zones created a mosaic that contained forested landscapes, cultural landscapes [66], and seascapes which synergistically harnessed a diversity of ecosystem services to facilitate an abundance of biocultural resources. The richest (*waiwai*) *ahupua'a* cycled enough fresh water (*wai*) through them to allow for aquaculture via various classes of fresh- and/or brackish-water fishponds. Such *ahupua'a* were labeled with the term "*'āina momona*' (abundant lands) due to the amount of food and other biocultural resources they were able to sustainably produce over successive generations.

The contemporary trend of framing biocultural conservation efforts around the scale of *ahupua'a* can be effective in some localized instances, such as the creation of Indigenous and Community Conserved Areas (ICCAs). Successful examples of these in the contemporary period include the Hā'ena Community-based Subsistence Fishing Area (CBSFA) on the island of Kaua'i, and the Ka'ūpūlehu Fish Replenishment Area on Hawai'i Island, which employs marine management rules and regulations (e.g., closed areas, closed seasons, size restrictions, restricted entry), within single *ahupua'a*, that have been used for thousands of years by Pacific Islanders [67]. However, limiting discussions of biocultural resource management to the *ahupua'a* scale may not be conducive for the success of large-scale efforts to restore and maintain biocultural resource abundance. While the scale of *ahupua'a* is key, there are multiple additional scales of divisions within *moku* boundaries (*'okana/kalana*, *ahupua'a*, *'ili*, *mo'o*, *pauku*) that need to be considered. More research is needed to understand the interplay between these divisions, the organization of human communities in ancient Hawai'i, and to allow for further insight into the historic management of biocultural resources as a means to inform contemporary restoration efforts.

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