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ʻĀina Momona, Honua Au Loli—Productive Lands, Changing World: Using the Hawaiian Footprint to Inform Biocultural Restoration and Future Sustainability in Hawai'i

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Abstract: Pre-Western-contact Hawaiʻi stands as a quintessential example of a large human population that practiced intensive agriculture, yet minimally affected native habitats that comprised the foundation of its vitality. An explicit geospatial footprint of human-transformed areas across the pre-contact Hawaiian archipelago comprised less than 15% of total land area, yet provided 100% of human needs, supporting a thriving Polynesian society. A post-contact history of disruption of traditional land use and its supplanting by Western land tenure and agriculture culminated in a landscape less than 250 years later in which over 50% of native habitats have been lost, while self-sufficiency has plummeted to 15% or less. Recapturing the *ʻāina momona* (productive lands) of ancient times through biocultural restoration can be accomplished through study of pre-contact agriculture, assessment of biological and ecological changes on Hawaiian social-ecological systems, and conscious planned efforts to increase self-sufficiency and reduce importation. Impediments include the current tourism-based economy, competition from habitat-modifying introduced species, a suite of agricultural pests severely limiting traditional agriculture, and climate changes rendering some pre-contact agricultural centers suboptimal. Modified methods will be required to counteract these limitations, enhance biosecurity, and diversify agriculture, without further degrading native habitats, and recapture a reciprocal Hawaiian human-nature relationship.

Keywords: human land use footprint; traditional ecological knowledge; biocultural restoration; social-ecological system; Hawaiian Islands; biocapacity; sustainability

1. Introduction

E Kāne-au-loli-ka-honua

Honu neʻe pū ka ʻāina

O Kāne-who-transforms-the-world

Like a sea-turtle crawling, so the land (changes)

The opening lines out of a traditional *pule* (prayer) for cultivation evokes a Hawaiian god who transforms the world, an acknowledgement of the dynamic nature of ecosystems. The second line is evocative of the nature of changes; occurring slowly over the course of generations, but, as a sea turtle's surges of movement upward from the shore towards her nesting site, sometimes more abrupt, noticeable, dramatic. The wisdom incorporated within oral traditions in Hawaiʻi (and elsewhere in the world) may be, at first blush, obscure and incomprehensible, but ultimately a huge wealth of information pertinent to today's challenges can be found within them. This paper describes how an effort to combine biological monitoring, archeological databases, and oral traditions created the first geospatially explicit rendering of the human land use footprint in the pre-contact Hawaiian archipelago.

While this geospatial footprint allowed for a variety of very useful extrapolations, including better estimates of the pre-contact human population in Hawai'i, not only for the entire archipelago, but per island, it also offered a milestone in the story of landscape changes in Hawai'i from those times to present, and can inform future strategies for biocultural restoration and sustainability.

Hawaiian biological diversity has seen losses and changes as a result of the presence of people and their biological introductions. So too has Hawaiian culture seen losses, in language, knowledge, and sovereignty; yet traditional knowledge provides some of our best sources directly describing the pre-contact world. Our efforts to understand the magnitude of changes to natural systems in Hawai'i led us, at about the turn of the millennium, to model the patterns of major ecosystems in Hawai'i, so that we have a fair idea of the pre-human ecological settings to contrast with the sometimes startling and staggering losses of our natural heritage in today's world.

1.1. The Rich Ecological Setting in the Hawaiian Islands

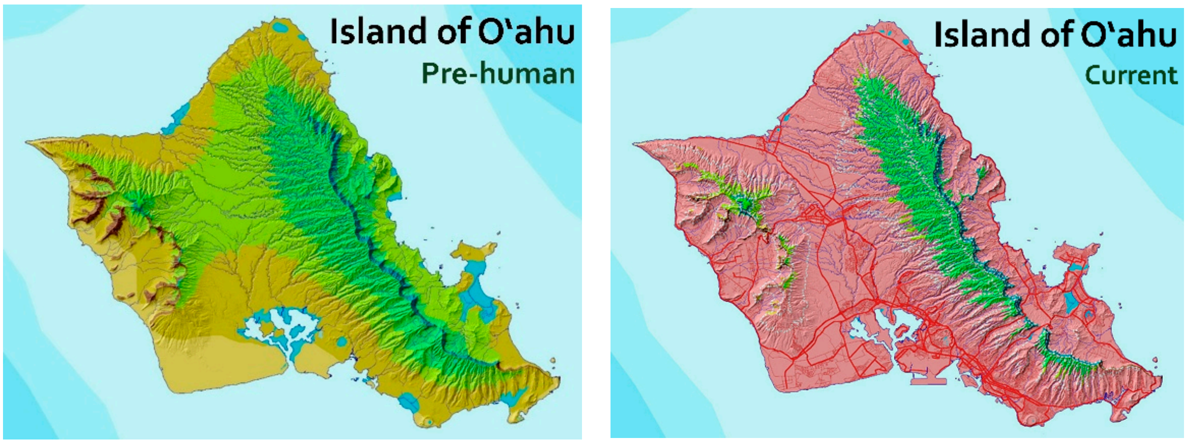
A variety of sources have documented the biotic richness of the Hawaiian Archipelago, recognizing it as a unique Biogeographic Ecoregion whose isolation has generated extremely high levels of endemism in both terrestrial and marine realms (e.g., ~90% endemism of native flowering plants; >98% endemism of native terrestrial invertebrates; 25% endemism of native reef fishes) [1,2]. An estimated 15,000 species are found nowhere else [3]. When a Holdridge Lifezone analysis [4] was conducted for the Hawaiian Islands by the U.S. Forest Service [5] it revealed that of the 38 lifezones defined in a system designed to cover the full range of terrestrial ecosystems on Earth, 27 could be found in the 17,400 sq km land area of the Hawaiian archipelago, making the archipelago the single most ecosystem-rich known on the planet [6]. This explains the many natural communities endemic to Hawai'i that comprise its broad native habitat zones.

Biocapacity, defined as the ability of an area of land or sea to provide for natural resources [7], is acknowledged as varying site by site according to a number of factors, including ecological richness. The extremely high diversity of biophysical conditions in Hawai'i suggests strongly that its biocapacity, although never formally determined numerically, is higher than the global average. This has probably facilitated both the prominent adaptive radiations of endemic Hawaiian species into a broad range of ecological niches, as well as the remarkably large pre-contact Hawaiian population supported by the archipelago. As a social-ecological territory, it was as close as possible to being an independent unit—relying on no external trade for survival.

1.2. The Current Loss of Major Terrestrial Native Habitats in Hawai'i

Recent mappings of the remaining native-dominated vegetation in Hawai'i have been conducted (e.g., Figure 1), and largely agree on the areal extent of remaining native-dominated habitats [8–11]. They point to major losses of certain broad categories of natural communities, such as the Lowland Dry Communities, which have been almost entirely lost on smaller islands, and have been reduced to 31% of their original extent on the largest island of Hawai'i. In contrast, certain zones, in large part much less suitable for human occupation or uses, have retained much larger percentages of their original cover, as seen in Table 1. Geospatial documentation of the remaining native-dominated areas have guided conservation efforts of both public (Federal and State) as well as private agencies and organizations, focusing efforts on the maintenance of intact areas, augmented by restoration of damaged or destroyed ecosystems [12].

It is apparent that the elevation and moisture zones most compatible with human residence and uses, such as agriculture, have resulted in a bias toward loss of lowland native ecosystems in Hawai'i. With few exceptions, areas below 600 meters elevation have been almost entirely displaced by a growing human footprint of land use, and by that of the non-native plant and animal introductions that have naturalized and spread, further displacing native species habitats [13].



(**a**) (**b**)

Figure 1. (**a**) Native habitats on Oʻahu before humans. (**b**) Current extent of native habitats (via [10]). Pink = human footprint. Over 80% of native habitat has been lost.

Table 1. Example remaining native habitat zones on Hawaiʻi Island, the largest island in Hawaiian archipelago.

Native Habitat	Remaining Extent as of 2015
Montane Mesic	73%
Montane Dry	59%
Lowland Wet	45%
Lowland Mesic	28%
Lowland Dry	30%

The history of social-ecological landscape change in Hawaiʻi occurred over the course of about 1000 years, beginning with the initial migration of Polynesians from the nearest archipelagoes of Oceania, those of the Marquesas and Tahiti. For centuries, the human population grew and spread across the Hawaiian archipelago and developed a unique indigenous Hawaiian culture, marked by an epistemology that regarded the surrounding biotic community as familial and ancestral, thereby establishing a strongly biocultural society [14–18]. The rich ecosystems of the Hawaiian Islands generated an equally rich cultural system in the pre-contact society that developed within it.

Another major milestone occurred in 1778 when the Hawaiian Islands were encountered by Captain James Cook and this initial contact with the Western World resulted in increasing presence and influence of Western culture and land uses in the islands, establishing a different social-ecological context based on commodification of land and natural resources, culminating in the footprint of the early 21st Century. Although there have been discussions of the pre-contact and post-contact impacts of humans on the native biota and ecosystems of Hawaiʻi [19], there had been no geospatially-explicit reconstructions of landscape change offered specifically focusing on native habitat loss. Many of those early observations by Westerners were made from the ocean with limited geographic view plane and often by those with no familiarity with Hawaiian vegetation. Instead, we had only the reconstructions of the pre-human extent of terrestrial native-dominated vegetation zones in Hawaiʻi [20] to compare against the current extent (see example for Island of Oʻahu below). Oʻahu offers one of the more dramatic examples of the impacts that our human presence has wrought on native habitats.

However, for every "before and after" situation that spans centuries of time, it is instructive to provide intermediate stages that speak to the human factors, such as population growth, changes in religion, economic systems, and land tenure, and key introductions of both species and activities that influenced the trajectory, rate, and intensity of social-ecological change.

2. Materials and Methods

Mapping of the Human Land Use Footprint in Pre-Contact Hawai'i

Models of pre-Western contact agriculture in Hawai'i were combined with archeological and oral tradition to create an explicit geospatial footprint of human-occupied and transformed areas across the pre-contact Hawaiian archipelago. The goal was to determine the explicit geospatial areas that, by 1770 (the decade of Western contact), had been chronically occupied, directly manipulated, and significantly changed from pre-existing native ecosystem types into traditional Hawaiian uses: house sites, agricultural fields, fishponds, religious sites, major roads, and trails.

At the onset, we point out that this is not to be confused with the ecological footprint used in modern assessments of human sustainability [7,21,22], but is related to it because it describes explicitly the geospatial extent of human land uses related to elements of ecological assessments: agricultural use, resource areas utilized for shelter, energy, medicines, material resources, and other needs of a human population. It is also the inverse of the presence of pre-human ecosystems, and allows for assessments of impacts on ecosystem services and their historic decline in the course of increasing human modification and displacement of those native ecosystems. The Hawaiian social-ecological system of land management has been described as the *ahupua'a* system [23,24], and in this issue, as the *moku* system [18], based on units of land and sea that typically included a cross section of ecosystems from the summit of an island to the coast, and outward to include nearshore marine habitats. Nested within the *ahupua'a* were smaller units, while both clusters of *ahupua'a* and larger-scale units called *moku* comprised the major basis for Hawaiian social-ecological regions and management communities. Integration of human society and its processes with the endemic biota and a small set of transported Polynesian plant and animal introductions, shown in Appendix A, created a system in which biological resources were deeply woven via explicit genealogical ties, rendering them as biocultural relationships [25].

We recognized that Hawaiian management of *ahupua'a* and *moku* in the pre-contact era tended to minimize the human footprint by delineating portions of the landscape as *wao kanaka* (realm of human influence, typically in coastal and lowland areas) and designating sacred (typically upland) habitats such as the *wao akua* (realm of deities) [18,26].

Pertinent to the impacts of intensive agriculture on this social-ecological system, we incorporated the work of Ladefoged et al. [27] who created a geospatial model expressing the optimal conditions for the cultivation of the two major staple crops in Hawai'i: *kalo* (taro, *Colocasia esculenta*) and *'uala* (sweet potato, *Ipomoea batatas*). It was tested and refined via comparison to known archeological complexes associated with agriculture [27,28]. Because practically all of the lands of greatest potential for agriculture had been developed for agriculture (as seen by high congruence of agricultural archeology with the agriculture models), applying formulae for deriving human population estimates from agricultural area for Pacific Island nations yielded a pre-contact Hawaiian population of 400,000 to 800,000, with the largest populations on the islands of Hawai'i, Maui, O'ahu and Kaua'i [27]. For this paper we explicitly derived population estimates for the eight main islands by applying the island footprint percentages to a total population of 500,000. The uneven populations of the islands were further discussed in Kirch 2011 [29] in terms of the population basis of the great Hawaiian chiefdoms of the four most populous islands, supported by their exceptional agricultural and biocultural potential. Such highly productive agricultural lands, the basis for not only political power but cultural proliferation, were called *'āina momona*, sweet/productive lands [30,31]—the most important lands for maintaining biocultural vitality and biocapacity in those times, and an important focus for restoration of social-ecological systems and biocultural revitalization today.

From 2009 to 2012, working in cooperation with the research staff of the Office of Hawaiian Affairs (OHA), we expanded on the agricultural model by mapping known *loko iʻa* (estuarine walled fishponds, a major source of protein foods), and continuing the reviews of archeological geospatial databases compiled by the State of Hawaiʻi Historic Preservation Division (SHPD) [28] of the Department of Land and Natural Resources (DLNR), as well as historical maps from the Department of Accounting and General Services (DAGS).

Major compilations of oral history out of a variety of sources in both English and Hawaiian were gleaned for further information on *wahi pana* (storied localities), terrestrial trail systems, religious sites, including *heiau* (temples) and *koʻa* (shrines), to set against the emerging geospatial depiction of areas of habitation, agriculture, or other traditional uses listed in Appendix B. Because the oral traditional accounts were extremely place-specific, and because current land boundaries retained the *ahupuaʻa* designations largely intact from pre-contact times [32], descriptions of places in oral accounts were readily placed geospatially, to corroborate models and archeological mappings. It is becoming apparent that in terms of indigenous knowledge archives in written form, the millions of pages of Hawaiian language newspapers represent the single largest of such first-peoples archives known in the world [33]. Appendix B offers an overview of some of the major sources that were consulted.

We applied the agricultural model, augmented by documentation of the historical trails and fishponds, locations of *heiau* and other archeological geospatial data, and corroborated this with traditional accounts of the chiefly centers of governance and famous population centers. We unified all the layers, buffered them, and created the Hawaiian footprint.

3. Results

What emerged from this multidisciplinary combination of sources was the first geospatially explicit footprint of pre-contact human activity that modified or displaced the original native terrestrial habitats in the Hawaiian Islands, as seen in Figures 2–7. It was coined "the Hawaiian Footprint Project". This process was applied to all of the eight main Hawaiian Islands, and an example is available for public scrutiny online [34], with GIS layers provided by request via The Nature Conservancy of Hawaiʻi.

We demonstrated that the footprint affected pre-existing native ecosystems in an uneven manner, with the largest impacts in wetlands that were converted into *loʻi kalo* (flooded field system) agriculture and *loko iʻa* (estuarine walled fishponds), in lowland dry and mesic areas, where wood was collected for houses, cooking fires, tools, and other needs, and land was cleared for habitation, with regular fires set to promote pili grass fields for thatching. Other native ecosystems at higher elevations were negligibly affected.

A similar analysis of land uses one century later, applied to the Island of Hawaiʻi, documented greatly increased disruption of native vegetation [35]. Table 2 lists selected extents of habitats displaced by the 1870 human footprint and their current status. The geospatial depiction comparing these same pre- and post-contact situations, seen in Figure 7, clearly demonstrates the greatly accelerated rate of social-ecological disruption and loss of the original biocultural landscape.

Table 2. Extensive native habitat loss on the Island of Hawaiʻi in the first 100 years after Western contact by 1870 was driven primarily by large-scale ranching and the advent of sugarcane monoculture.

Native Habitat Loss	1770 (ha)	% Lost	1870 (ha)	% Lost	2015 (ha)	% Lost
Lowland Mesic	14,400	21%	29,900	44%	48,800	72%
Lowland Dry	42,200	19%	93,100	43%	151,300	70%
Lowland Wet	20,700	9%	27,500	12%	124,600	55%
Montane Dry	2100	1.4%	55,400	37%	61,000	41%
Montane Mesic	800	1%	12,900	17%	19,400	26%
Alpine/Subalpine	1300	<1%	13,600	6%	18,700	9%

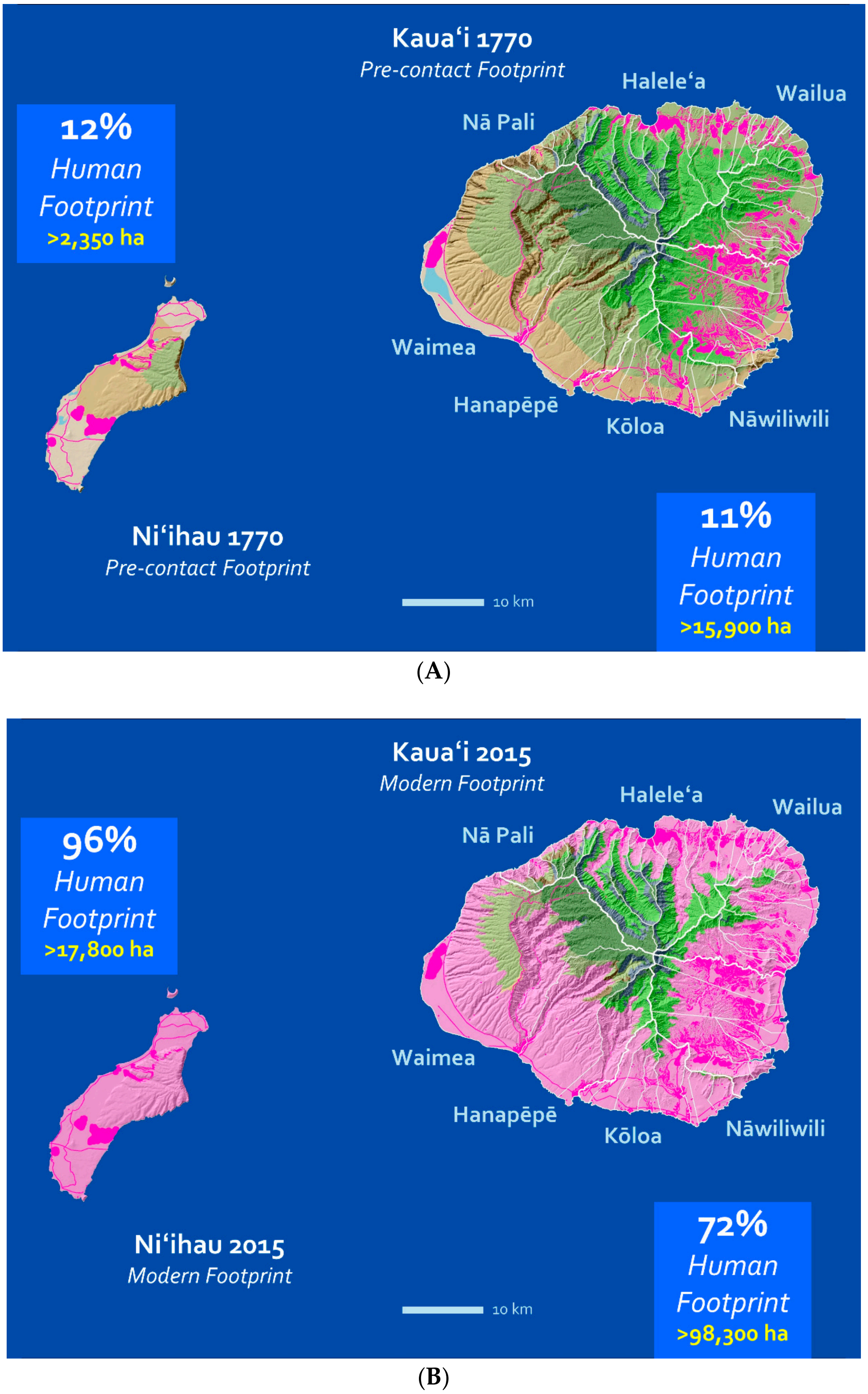
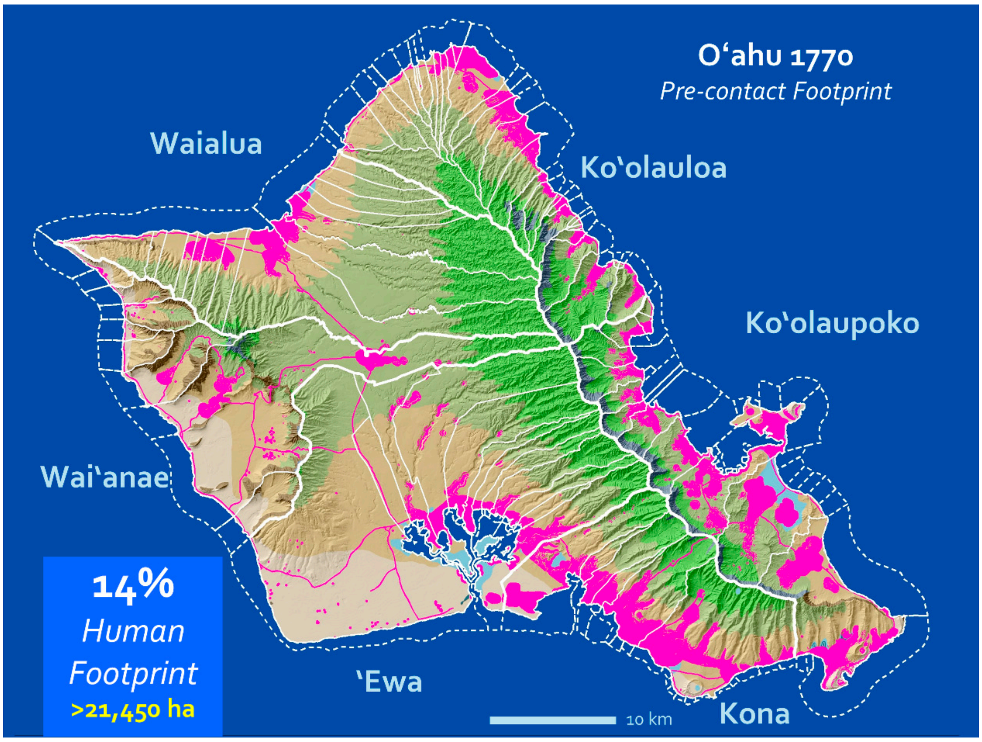
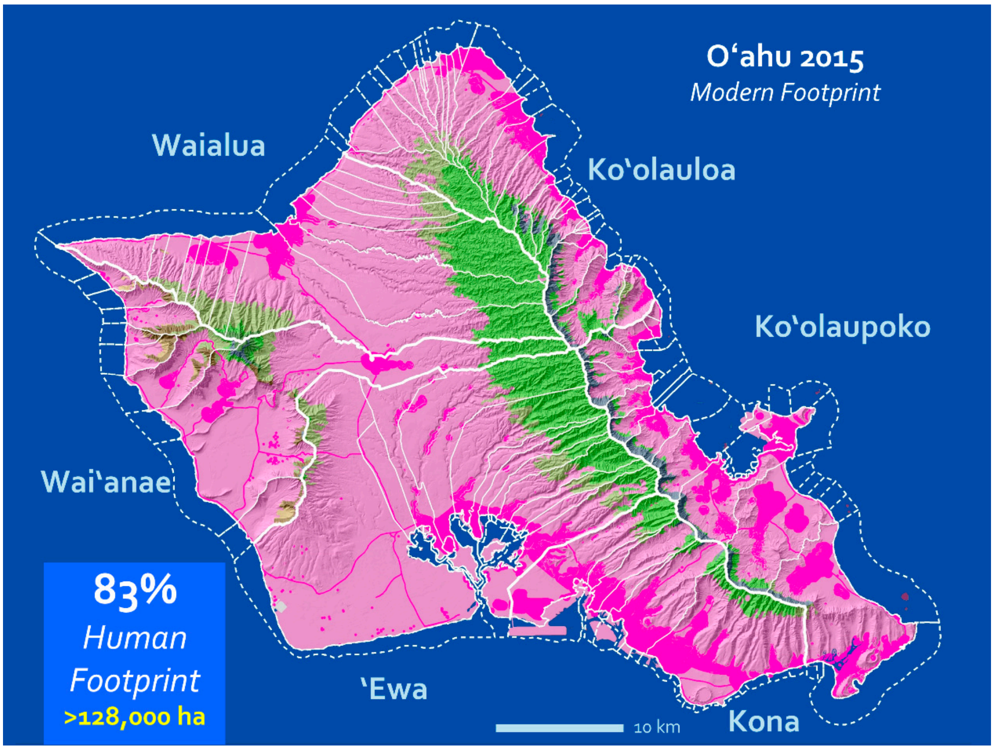


Figure 2. (**A**) Hawaiian footprint, prior to Western contact, resulted in <12% native habitat loss on the islands of Kauaʻi and Niʻihau. (**B**) Modern footprint resulted in 72% and 96% native habitat loss, respectively. Key: dark pink = pre-contact footprint; light pink (for comparison) = modern footprint; white line = *moku*, districts and *ahupuaʻa*; colored basemap = major native vegetation zones, after the Hawaiʻi Ecoregion Plan [36].

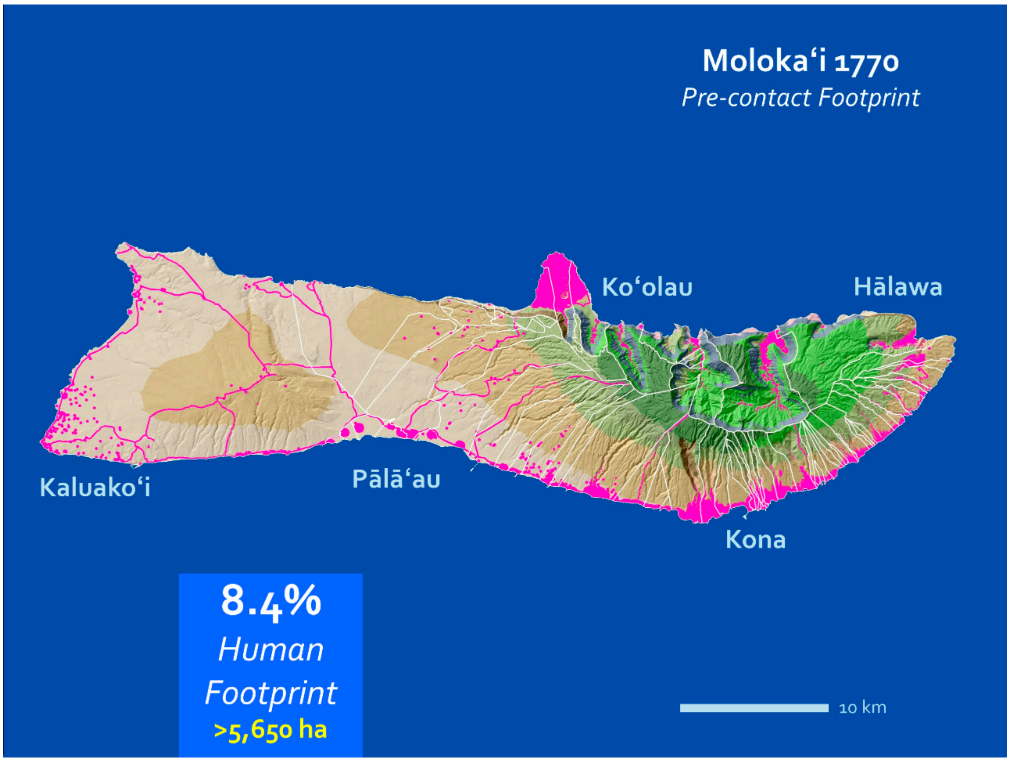


(**A**)



(**B**)

Figure 3. (**A**) Hawaiian footprint, prior to Western contact, resulted in 14% native habitat loss on the island of O'ahu. (**B**) Modern footprint resulted in 83% native habitat loss. Key: dark pink = pre-contact footprint; light pink (for comparison) = modern footprint; white line = *moku* (districts) and *ahupua'a*; dotted white line = historical nearshore fisheries, makai part of *ahupua'a*; colored basemap = major native vegetation zones, after the Hawai'i Ecoregion Plan [36].



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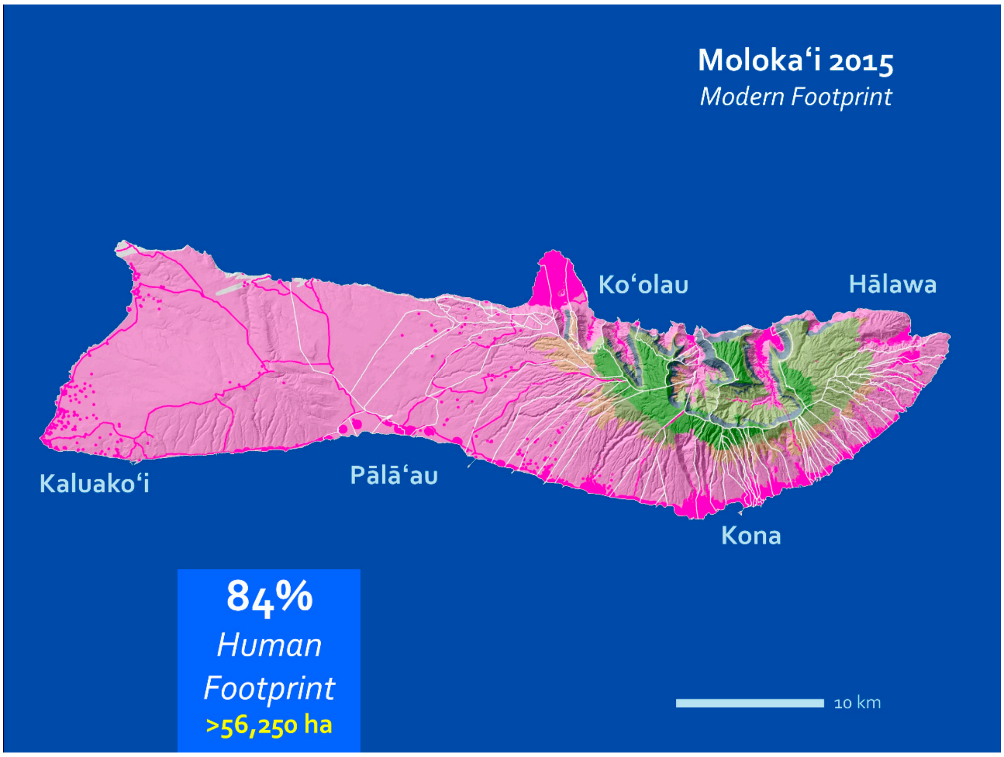


(**B**)

Figure 4. (**A**) Hawaiian footprint, prior to Western contact, resulted in <9% native habitat loss on the island of Moloka'i. (**B**) Modern footprint resulted in 84% native habitat loss. Key: dark pink = pre-contact footprint; light pink (for comparison) = modern footprint; white line = *ahupua'a*; colored basemap = major native vegetation zones, after the Hawai'i Ecoregion Plan [36].

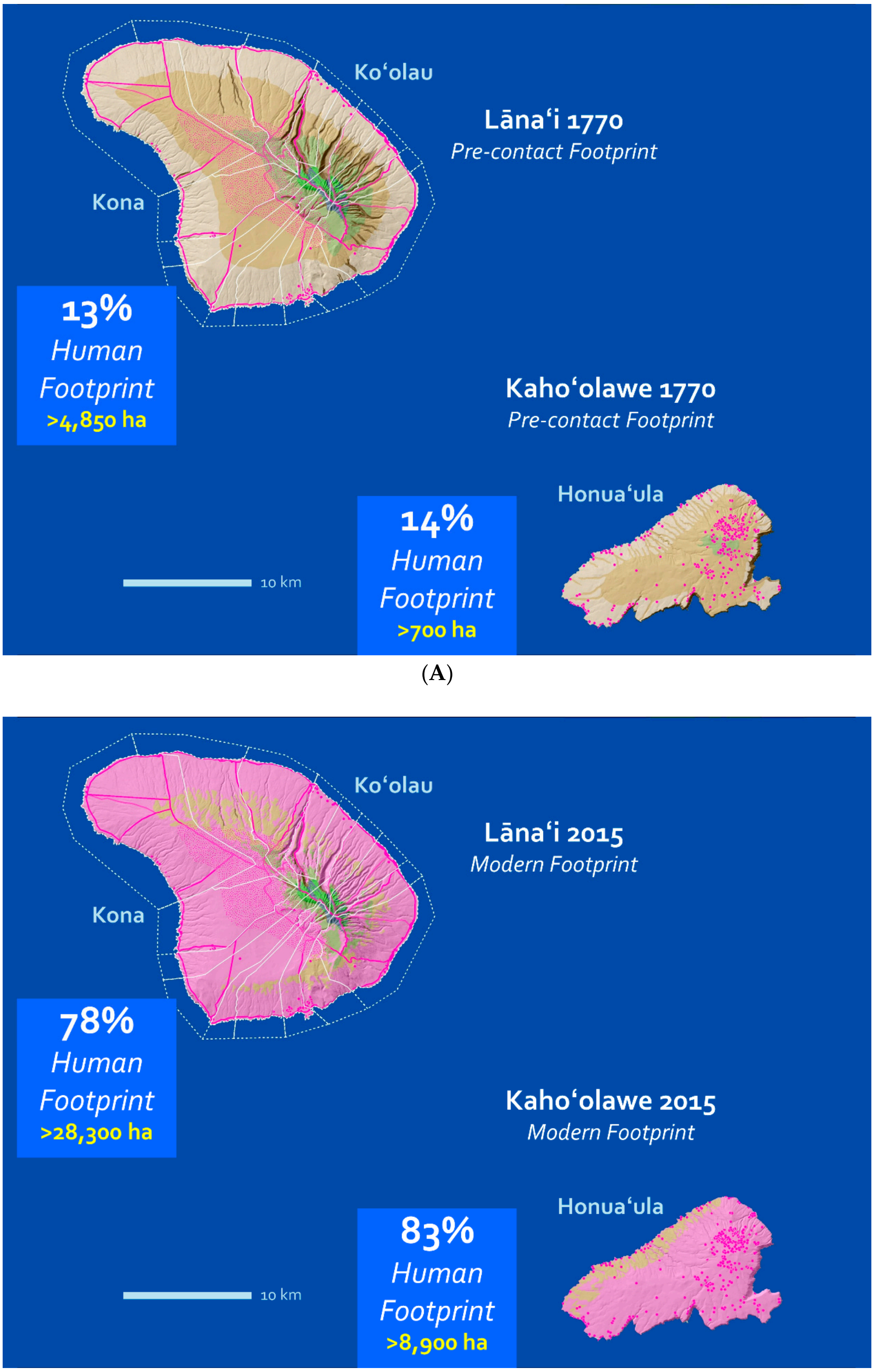
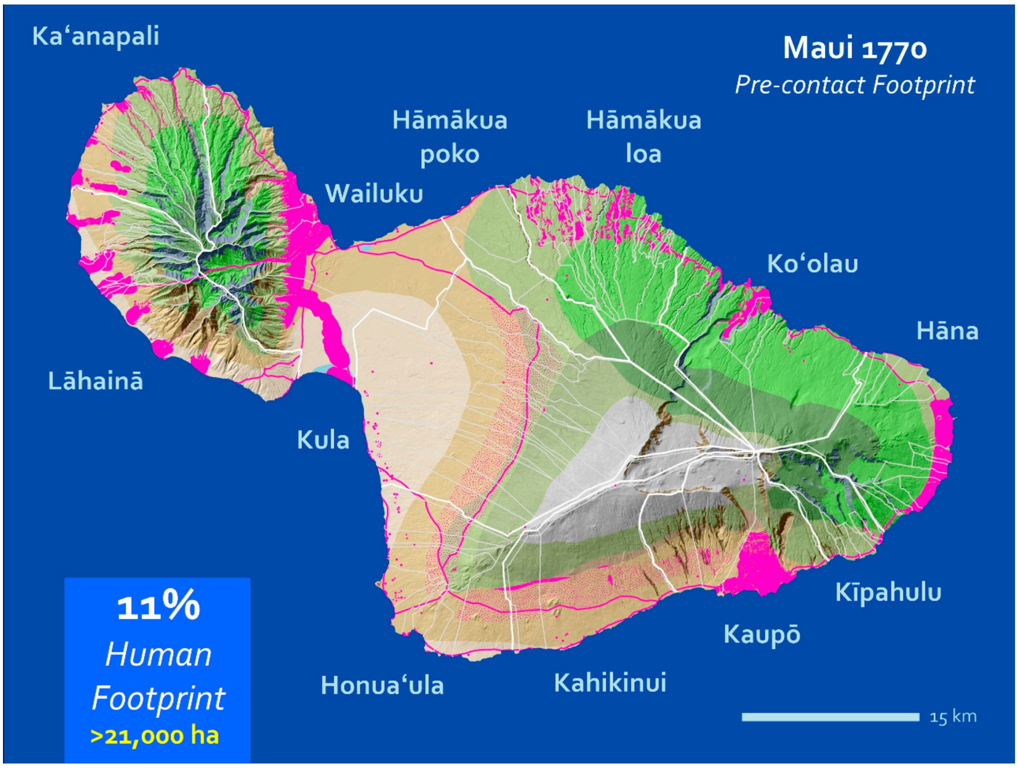


Figure 5. (**A**) Hawaiian footprint, prior to Western contact, resulted in <14% native habitat loss on the islands of Lāna'i and Kaho'olawe. (**B**) Modern footprint resulted in >78% native habitat loss. Key: dark pink = pre-contact footprint; light pink (for comparison) = modern footprint; white line = *ahupua'a*; dotted white line = historical nearshore fisheries, makai part of *ahupua'a*; colored basemap = major native vegetation zones, after the Hawai'i Ecoregion Plan [36].



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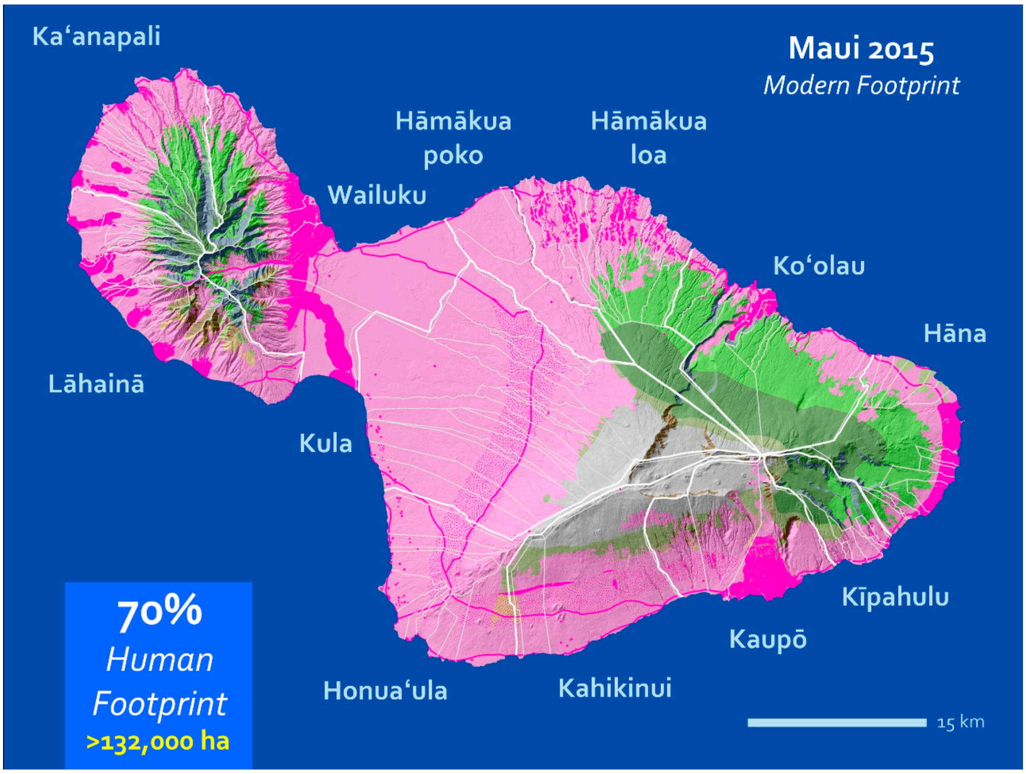
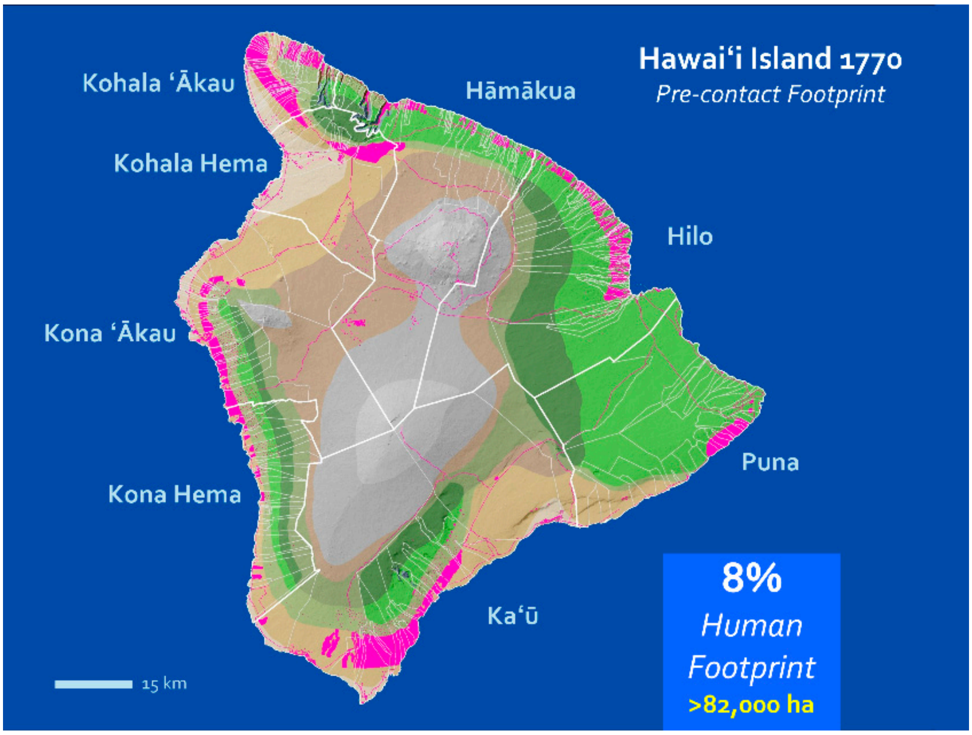


(**B**)

Figure 6. (**A**) Hawaiian footprint, prior to Western contact, resulted in 11% native habitat loss on the island of Maui. (**B**) Modern footprint resulted in 70% native habitat loss. Key: dark pink = pre-contact footprint; light pink (for comparison) = modern footprint; white line = *moku* (districts) and *ahupua'a*; colored basemap = major native vegetation zones, after the Hawai'i Ecoregion Plan [36].



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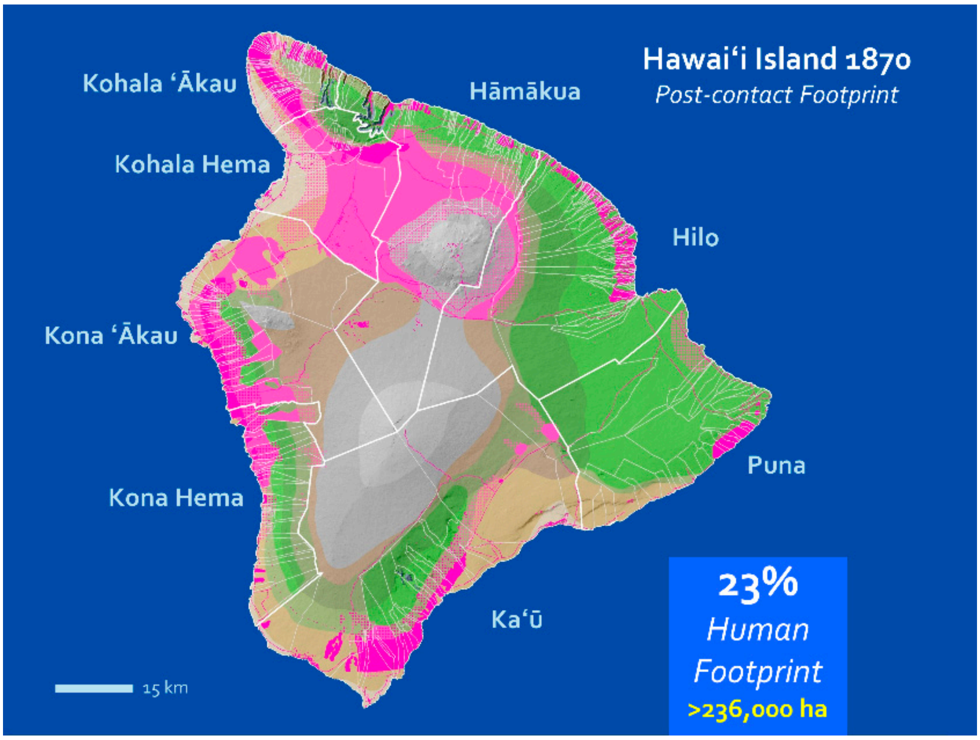
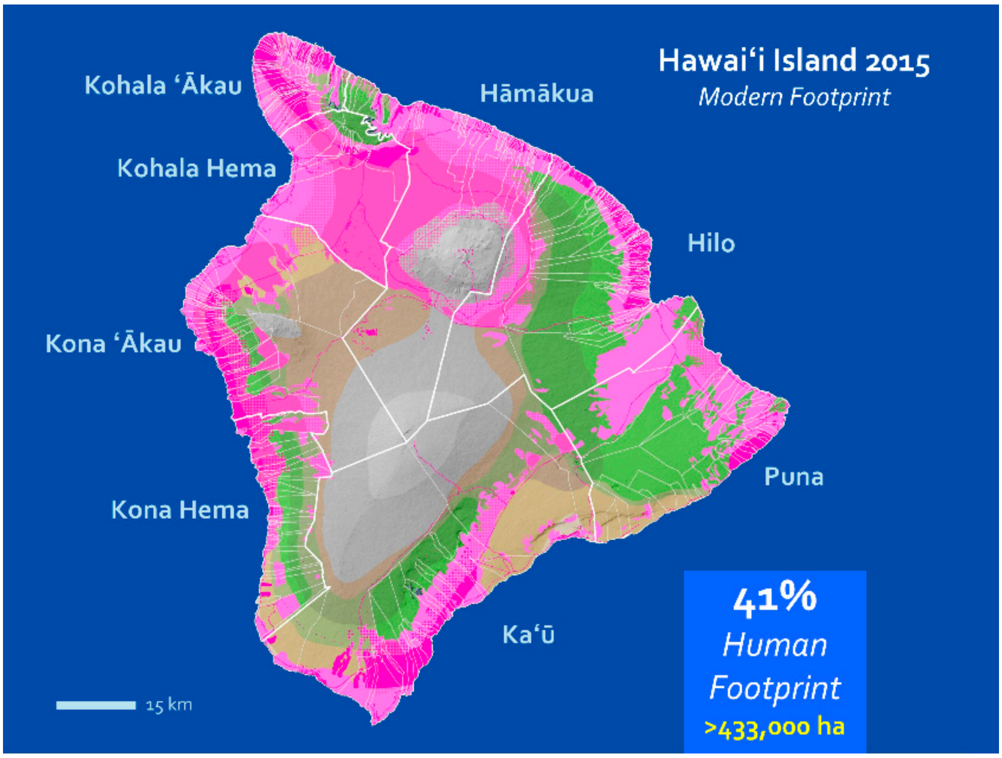


(**B**)

Figure 7. *Cont.*



(**C**)

Figure 7. (**A**) Hawaiian footprint, prior to Western contact, resulted in 8% native habitat loss on the island of Hawai'i. (**B**) The human footprint tripled 100 years after Western contact. (**C**) Modern footprint resulted in 41% native habitat loss. Social-ecological change over two centuries reflects the effects of commodification of land and resources, and loss of pre-contact biocultural relationships. Key: dark pink = pre-contact human footprint; medium pink (for comparison) = 1870 footprint, light pink (for comparison) = modern footprint; white line = *moku* (districts) and *ahupua'a*; colored basemap = major native vegetation zones, after the Hawai'i Ecoregional Plan [36].

The pattern of wet valley occupation and working of large seasonal fields applies across the archipelago. Using the population estimate methods described in Ladefoged et al. [27] and Kirch [29] which yielded population estimates of 400,000 to 800,000, we derived, using the pre-contact footprint for individual islands, population estimates for each of those islands. Table 3 depicts the distribution of the population among islands when using a total population of 500,000. As might be expected, the majority of the population was on the large Island of Hawai'i. It is remarkable to look on these results in terms of the human geography of ancient Hawai'i; when used as a backdrop for traditional stories and accounts, every prominent place name and every celebrated place was included, as shown in Appendix B.

Table 3. Pre-contact Hawaiian population estimates for the main Hawaiian Islands. A total population of 500,000 was selected for this table as it falls within the 400–800k range and simplifies presentation.

Island	Footprint (Ha)	%	Est. Population
Hawai'i	81,800	53.0	265,000
O'ahu	21,600	14.0	70,000
Maui	21,100	13.6	68,000
Kaua'i	16,000	10.3	51,500
Moloka'i	5600	3.7	18,500
Lāna'i	5200	3.4	17,000
Ni'ihau	2300	1.5	7500
Kaho'olawe	700	0.5	2500

4. Discussion

4.1. The Hawaiian Social-Ecological System As a Model of Sustainability and Self-Sufficiency

Based on the best available data at the time, the two major conclusions of the Hawaiian Footprint Project were that prior to Western contact in 1778, a substantial human population in the Hawaiian archipelago (estimated at 400,000–800,000 people) had affected less than 15% of the original area of native terrestrial ecosystems, and was necessarily 100% self-sufficient, that is, did not rely on any significant external inputs from the rest of global humanity. Thus pre-contact Hawaiʻi stands as a quintessential sustainability example of a large human population that practiced intensive agriculture, yet minimally displaced the native habitat that was the foundation of its vitality and development. This example of human sustainability in a finite (but extremely rich) high island setting was achieved because of a Hawaiian worldview that regarded nature as familial and ancestral, sacred and of immense value [17,18].

4.2. Using Pre-Contact Models of Sustainability in Transformed Landscapes

When the models for pre-contact agriculture were published and made publicly available [32], it generated many inquiries regarding the use of the mapped extent of pre-contact agriculture as guidance for revitalization of current biocultural restorations. To the extent that areas of pre-contact agriculture remain available for agricultural use in our times, it stands to reason that the model could indicate areas of greatest potential for successful social-ecological revitalization of Hawaiian traditional agriculture.

4.3. Post-Contact Changes to the Social-Ecological Landscape of Hawaiʻi

In the 240 years that followed initial contact with the Western world, much has changed in both the social-ecological setting and the biocultural setting of Hawaiʻi. The acceleration of native ecosystem loss since Western contact has been dramatic with the smaller, drier islands such as Niʻihau losing essentially everything. Hawaiʻi Island, by virtue of relatively vast and remote interiors, too high and cold for cultivation, retains the highest percentage in modern times, the only island with less than a 50% footprint today. Several different reviews of these changes point to the imposition of Western worldviews that viewed land and natural resources as commodities to be exploited to feed capitalist economies, leading to practices such as large-scale ranching and mono-crop agriculture of sugarcane and pineapple that supplanted multi-crop and semi-wild systems of the pre-contact Polynesian social-ecological system and induced wholesale erasure of native biodiversity across hundreds of thousands of hectares. [37–39]. Our recent geospatially explicit review of land use changes on Hawaiʻi island between 1770 (pre-contact) and 1870 (one century after contact), demonstrated that the human footprint had more than tripled in size. These changes entirely transformed lowland social-ecological landscapes, and extended high into the montane zones on the highest islands of Maui and Hawaiʻi, displacing biocultural resources there and reducing inherent biocapacity. This is a trend that has continued into the 21st Century, resulting in the modern human footprint that is more than five times larger than the pre-contact Hawaiian Footprint on the Island of Hawaiʻi. Self-sufficiency, expressed as a lack of importation of goods, has plummeted from 100% in pre-contact times to 15% or less in the 21st century [40,41].

The same phenomenon noted when assessing the biocapacity of urban areas, such as large cities, can be applied to Hawaiʻi. Any given city's biocapacity is largely appropriated from areas outside of the city limits [21], and treats the metropolitan core as a social-ecological island that has low inherent biocapacity and extremely high population density, compensated for via importation of resources from other areas both within immediately adjacent regions and increasingly more broadly. In like manner, the economy of Hawaiʻi, currently driven by tourism, sees both an increased effective population size made up of a varying stream of transient visitors (1.4 million permanent residents, +7–10 million additional visitors per year in Hawaiʻi) whose demands far exceed local biocapacity, and has created a growing urbanization in many areas that were once prime agricultural lands, further limiting efforts to increase self-sufficiency and sustainability [40]. This is compensated for by a high importation rate, and contributes to our low self-sufficiency.

4.4. Non-Native Species

During the 1000 years of the pre-contact period, perhaps 50–60 species of plants had been introduced into the highly endemic Hawaiian Islands terrestrial flora, summarized in Appendix A [41]. The majority of these Polynesian introductions were agricultural crops, plants used in cordage and plaiting, other ethnobotanical species, and a handful of agricultural weeds inadvertently introduced. Nearly all of these were largely confined to agricultural settings, and did not naturalize readily into surrounding native vegetation. *Kukui* (*Aleurites moluccana*), and possibly *hau* (*Hibiscus tiliaceus*), are exceptions and have naturalized readily, frequently as canopy dominants in lowland riparian situations on all of the larger islands [37,42]. The otherwise non-invasive nature of the majority of the Polynesian plant introductions meant that even in areas completely converted to croplands, any fallow areas would have converted back into native successional communities. Even in those areas dominated by *kukui*, native subcanopy and groundcover diversity would have remained, and a mixed forest with strong native composition would still be present. The greater impact of Polynesian introduced animals, in particular *'iole*, the Polynesian rat (*Rattus exulans*), is undeniable see: [37,43,44], but the same patterns of native vegetation recovery and dominance in response to this disturbance would hold true.

Two-hundred and forty years of plant introductions without adequate biosecurity measures since Western contact have completely changed that picture and disrupted the process of vegetation succession in Hawai'i. Perhaps 15,000 or more taxa of vascular plants had been introduced to Hawai'i [45]. Among these are hundreds of habitat-modifying species that not only degrade native vegetation composition and structure, but can disrupt traditional agriculture and greatly increase the labor required to remove aggressive weeds and successfully grow desired crops. Introduced animals, including wetland invertebrates such as Apple snails (*Pomacea canaliculata*) and crayfish (*Procambarus clarkii*) damage both the plants and the traditional infrastructure of *lo'i kalo* (flooded field system), adding further impediments to biocultural restoration of traditional agriculture. Introduced bacterial and fungal diseases are another major challenge to *kalo* and other traditional crops [46]. The post-contact introduction and spread of non-native ungulates, such as cattle, goats, and sheep, and their wholesale denudation of the forested watershed on all islands created the watershed crisis of the turn of the 20th century [47].

It becomes more and more clear that inadequate biosecurity stands as one of the greatest current and future impediments to biocultural restoration and sustainability in Hawai'i [48]. Invasive non-native species have already caused significant harm to natural and cultural resources, economy, and way of life; for example, they affect critical native ecosystem services, such as long-term reliability of freshwater resources, as well as agricultural productivity, human health and community well-being. We must support, implement and augment efforts to establish stronger biosecurity in Hawai'i as the current context of highly appropriated biocapacity to support a tourism economy continues into the future. Moreover we must develop more effective tools for dealing with a long history of intentional and unintentional introductions of habitat modifying non-native species that greatly impair the potential for biocultural restoration.

4.5. Climate Change

In an era of increasing climate change affecting both marine and terrestrial systems, predicted effects on precipitation and temperature could affect the potential for biocultural restoration. The high islands of Hawai'i exhibit elevation zonation in both temperature and moisture, as seen in Figure 7, and it is anticipated that zones will shift in their placement, and that novel zones currently not present will come into being [49]. Because the models for both *kalo* and *'uala* are sensitive to precipitation (*'uala* particularly so), the archeology of sweet potato agriculture on Maui already demonstrates a mismatch: archeological complexes associated with seasonal *'uala* agriculture on the western slope of Haleakalā extend into areas with annual precipitation that is currently insufficient for the crop, as shown in Figure 8. It is a clear indication that over 240 years ago, slopes that are currently too hot and dry for growing sweet potatoes were seasonally worked for that crop. This means that in the decades to come, with warming and drying trends predicted for the lowlands of the Hawaiian Islands, the model generated for the pre-contact Hawaiian footprint will have to be adjusted in various ways to track the optimal rainfall conditions of the future.

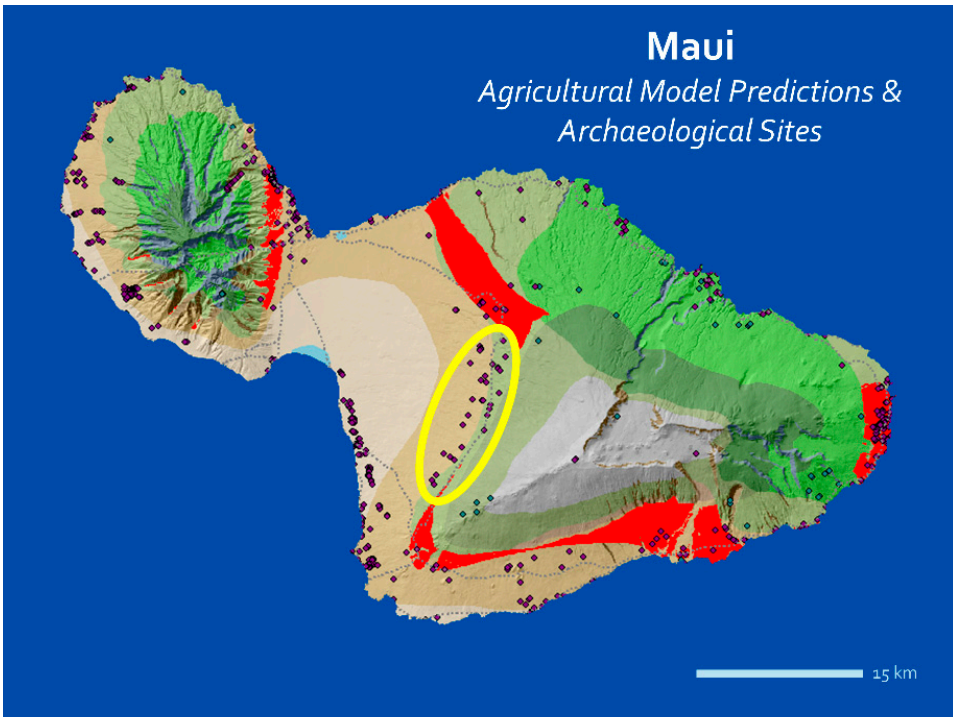


Figure 8. Map showing mismatch of *'uala* agricultural model prediction (red) with archeological complexes (dots) on the west flank of East Maui (yellow oval).

In a somewhat less direct manner, drying trends may convert streams that are currently continuous and perennial (and therefore suitable for *kalo*) into intermittent streams that may provide insufficient water for the crop. If the predicted trends are for warming and drying, this likely means an overall reduction in the potential area for wet *lo'i kalo* production.

In similar manner, each of the traditional crops of Hawai'i, and indeed all future potential crops, should be assessed for their optimal climate envelopes, and plans made to shift the areas designated for those crops according to shifting climate patterns in the decades to come. A similar analysis was already conducted for every native flowering plant in Hawai'i [50], and this tool is already being promulgated and applied in conservation efforts involving assisted migration of rare plants out of habitat that is becoming climatically suboptimal. This has broad relevance to biocultural restoration planning, adding another complex factor to consider in the geographic placement and selection of species involved, anticipating future optimal climate envelopes.

4.6. Diversification

One of the major advantages of the broad range of life zones in Hawai'i is the great potential for diversification of agriculture, enhancing biocapacity. While the models for the pre-contact footprint were based on the optimal range of the two major staple crops of those times, modern agriculture in Hawai'i has already seen an expansion to include a wide variety of agricultural products, including coffee, macadamia nuts, tropical fruit, ornamentals, and vegetable crops that were not available in pre-contact times. While we should likely never again consider a large-scale monoculture approach that was the signature of the sugarcane and pineapple eras of agriculture in Hawaiʻi, the future offers a broad range of possibilities. It may be feasible to develop agroforestry models such as those used traditionally and successfully in other island nations (e.g., Pohnpei) and gain both agricultural diversity as well as the benefits of ecosystem functions that derive from maintaining forest cover and diverse understory structure. These have the potential to minimize erosion and sedimentation of our streams and nearshore marine habitats, increasing both terrestrial and marine habitat viability and the potential for food production and biocultural restoration.

5. Conclusions

Reconstructions of pre-contact agricultural hotspots are instructive in demonstrating the potential for a closed island social-ecological system to sustainably support a large human population in an entirely self-sufficient manner while creating a relative small land-use footprint that allows for maintenance of strong native biological diversity and vital ecosystem processes and services. While it might be desirable to recapture that ancient situation, several factors have imposed themselves over the last 240 years of post-contact history and greatly complicate any simple schemes to restore that pre-contact state. One is the presence of thousands of non-native plants and animals that impose their own ecological influences that impede agricultural success via competition, predation, and pathologies that did not exist in pre-contact times. Another is the irreversible land developments that have displaced many areas of formerly rich agricultural production. A third is the effect of sheer numbers of people present in the islands, far exceeding the estimated 400,000–800,000 Hawaiians that comprised the archipelagic human population prior to contact. Finally, the anticipated changes in climate, including temperature and precipitation, will require adjustments of the models of optimal agricultural output, and may render some of the original areas unusable, while other areas may emerge as optimal in the future. Knowing these limitations is a vital step toward addressing and surmounting them. While we may not be able to turn the clock back, we are more able than ever to take intelligent action to frame our future.

More importantly however, is the lesson of the thousand years of pre-contact Hawaiian presence, and the social-ecological system that developed as a result of a worldview with a strong foundation of biocultural relationships. These regarded the natural world as family in a reciprocal and caring relationship wherein human health and welfare was viewed as one with the health and welfare of the surrounding living community. In such a context, humans stand not intrinsically apart from nature, and not solely as a threat to nature, but acknowledge that we are a force of nature with potential to damage or to repair. The consequences of shifting from this social-ecological system into one of land and resources as economic commodities has clearly resulted in a post-contact history of loss of native habitats, sustainability, and self-sufficiency. Recapturing and reestablishing those traditional island values in a modern context is a core underpinning in biocultural restoration.

In our analyses of pre-contact Hawaiʻi we see that it is possible to support a thriving human population, practice intensive sustainable agriculture, and establish a social-ecological system that maintained the native habitat that was the foundation of *ʻāina momona*. It becomes clear that a future shift that strives to recapture the best of the pre-contact social-ecological system is sorely needed in Hawaiʻi and by extension, Planet Earth. Achieving this biocultural restoration will take the best of indigenous values combined with the best of 21st Century knowledge to realize.

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Appendix A

Known and Potential Polynesian Introductions of Plant Species to the Hawaiian Archipelago [42] including well-known species of Polynesian biocultural significance as well as others potentially introduced (questionably indigenous or early post-contact introductions). Status and scientific names as listed in Wagner et al.

Hawaiian Name	Biocultural Relationship	Status	Scientific Name
kou	wood, *lei*	Polynesian introduction	*Cordia subcordata*
kamani	*lei*, wood	Polynesian introduction	*Calophyllum inophyllum*
ʻuala	staple crop	Polynesian introduction	*Ipomoea batatas*
ipu	containers, music	Polynesian introduction	*Lagenaria siceraria*
kukui	oil, medicinal, wood, *lei*, relish, dye	Polynesian introduction	*Aleurites moluccana*
ʻauhuhu	fish poison	Polynesian introduction	*Tephrosia purpurea*
ʻulu	staple food crop, medicinal, sap, wood	Polynesian introduction	*Artocarpus altilis*
wauke	fiber, clothing	Polynesian introduction	*Broussonetia papyrifera*
ʻōhiʻa ʻai	fruit	Polynesian introduction	*Syzygium malaccense*
ʻawa	ritual drink, medicinal	Polynesian introduction	*Piper methysticum*
noni	medicinal, dye	Polynesian introduction	*Morinda citrifolia*
kī	food, medicinal, ritual	Polynesian introduction	*Cordyline fruticosa*
ʻape	famine food	Polynesian introduction	*Alocasia macrorrhiza*
kalo	mainstay food crop	Polynesian introduction	*Colocasia esculenta*
niu	food, wood, fiber	Polynesian introduction	*Cocos nucifera*
uhi	secondary crop, not naturalized	Polynesian introduction	*Dioscorea alata*
hoi	famine food, naturalized	Polynesian introduction	*Dioscorea bulbifera*
piʻa	famine food, naturalized	Polynesian introduction	*Dioscorea pentaphylla*
maiʻa hēʻī	wild food source	Polynesian introduction	*Musa troglodytarum*
maiʻa (varieties)	staple crop	Polynesian introduction	*Musa x paradisiaca*
kō	food	Polynesian introduction	*Saccharum officinarum*
pia	food	Polynesian introduction	*Tacca leontopetaloides*
ʻōlena	dye, medicinal, ritual	Polynesian introduction	*Curcuma longa*
ʻawapuhi	medicinal	Polynesian introduction	*Zingiber zerumbet*
pāʻihiʻihi	uncommon medicinal, accidental?	Polynesian introduction?	*Rorippa sarmentosa*
kāmole	wetland, accidental w/*kalo*?	Polynesian introduction?	*Ludwigia octovalvis*
ʻihi	medicinal; indig? seeds in pre-contact sites	Polynesian introduction?	*Oxalis corniculata*
—	cultiv. central Pac, 3 records from HI	Polynesian introduction?	*Solanum viride*
ʻohe Kahiki	tools, wood, music, container; indig?	Polynesian introduction?	*Schizostachyum glaucifolium*
—	seeds in pre-contact sites; indig NA, SA	naturalized?	*Daucus pusillus*
pohe	indig NA; pre 1871 HI records	naturalized?	*Hydrocotyle verticillata*
koali ʻai	famine food, poss indig?	naturalized?	*Ipomoea cairica*
koali kuahulu	pantropical, indig?	naturalized?	*Merremia aegyptia*
kākalaioa	indig/early intro; also *hihikolo*	naturalized?	*Caesalpinia major*
maunaloa	indig Honduras; 1st record HI 1825	naturalized?	*Dioclea wilsonii*
pāpapa	native to tropical Asia? edible	naturalized?	*Lablab purpureus*
—	pantropical weed	naturalized?	*Sida rhombifolia*
kāmole	accidental w/*kalo*?	naturalized?	*Polygonum glabrum*
pōniu	also *haleakaiʻa*; medicinal	naturalized?	*Cardiospermum halicacabum*
ʻakaʻakai	also *kaluhā*, indigenous to NA & SA	naturalized?	*Schoenoplectus californicus*
—	cosmop., accidental on *kalo*?	naturalized?	*Lemna aequinoctialis*
—	cosmop., accidental on *kalo*?	naturalized?	*Spirodela polyrrhiza*
—	indig Asia, Malesia; 1st HI coll pre 1871	naturalized?	*Garnotia acutigluma*
ʻiliʻohu	once noted near *kalo* fields; extinct?	indigenous?	*Cleome spinosa*
—	widespread in the S. Pacific	indigenous?	*Ipomoea littoralis*
kākalaioa	indig/early intro; *lei*, medicinal	indigenous?	*Caesalpinea bonduc*
—	widesp trop Indo-Pac, but 1st HI rec 1920	indigenous?	*Entada phaseoloides*
pakaha	indig NA, pretty flowers, no descr uses	indigenous?	*Lepechinia hastata*
pūkāmole	1st HI record 1794; medicinal	indigenous?	*Lythrum maritimum*
maʻo	indigenous NA	indigenous?	*Abutilon incanum*
hau	wood, fiber, medicinal	indigenous?	*Hibiscus tiliaceus*
milo	wood	indigenous?	*Thespesia populnea*
pōpolo	medicinal, dye, food	indigenous?	*Solanum americanum*
uhaloa	medicinal	indigenous?	*Waltheria indica*
ʻahuʻawa	fiber, plaiting	indigenous?	*Cyperus javanicus*
—	prob indigenous	indigenous?	*Carex thunbergii*
kohekohe	low elev marshes	indigenous?	*Eleocharis calva*
hala	brought, but also indig; plaiting, food	indigenous?	*Pandanus tectorius*

Hawaiian Name	Biocultural Relationship	Status	Scientific Name
mānienie ʻula	1st HI record 1819, widespread	indigenous?	*Chrysopogon aciculatus*
pili	thatch	indigenous?	*Heteropogon contortus*
mauʻu laiki	no rec uses; post-contact Hawn name	indigenous?	*Paspalum scrobiculatum*
—	accidental w/*kalo*? leafy pondweed	indigenous?	*Potamogeton foliosus*
—	accidental w/*kalo*? long-leaved pondweed	indigenous?	*Potamogeton nodosus*

Key: **Hawaiian name** (— = no known Hawaiian name); **Biocultural relationship** (Hawaiian uses, other salient info); **Status** (indigenous? = possibly indigenous; naturalized? = possibly early naturalized post-contact introduction).

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