Biology of Hawaiian Streams and Estuaries. Edited by N.L. Evenhuis & J.M. Fitzsimons. *Bishop Museum Bulletin in Cultural and Environmental Studies* 3: 23–33 (2007).

The Hawaiian *Ahupuaʻa* Land Use System: Its Biological Resource Zones and the Challenge for Silvicultural Restoration

Dieter Mueller-Dombois
Department of Botany, University of Hawaiʻi at Mānoa, Honolulu, Hawaiʻi 96822, USA; email: amdhawaii@aol.com

Abstract

The land area of the major Hawaiian Islands was originally divided into districts called *moku*, and these were further subdivided into *ahupuaʻa*. The latter encompass landscape segments from the ocean to the mountain that served as the traditional human support systems. These life support systems were based on three to five biological resource zones. These were the upland/inland forest zone, or the *wao nahele*, the agricultural zone, or the *wao kanaka*, and the coastal zone, or the *kaha kai*. This latter zone included the strand area, fringing reefs, sea grass beds, lagoons, fish ponds, and estuaries, where present. Actually, estuaries, the *muliwai*, are mostly on the windward side of the islands and are part of a fourth biological resource zone, the *kaha wai* or freshwater ecosystems and streams. The ocean (*kai*), near the shore can be considered the fifth biological resource zone. Thus, the traditional land use was based on the vertical arrangement of a volcanic high island's natural ecosystems. This vertical arrangement allowed for maximizing the use of biodiversity over short distances and acknowledged the interactive influences of the biological resource and production zones. This interactive influence begins at the top, in the *wao nahele*. What happens there influences the three other production zones. Therefore, any *ahupuaʻa* restoration that aims at the reintroduction of adaptive and integrative management should start with silvicultural research at an operational scale. Silviculture is concerned with the care of forests. It is based on knowledge gained from research in forest ecology and should be a form of "low input management". With regard to the *ahupuaʻa* model, silviculture must focus on enhancing the natural processes associated with the function of the forested watershed and stream ecosystem. Silviculture should also aim at restoring a "Hawaiian sense of place" in those *ahupuaʻa* selected for stream restoration. This concept will be explained in some detail in this paper.

Introduction

The traditional land use in the Hawaiian Islands evolved from shifting cultivation into a stable form of agriculture around 1200 AD (Kirch, 2000). Stabilization required a new form of land use. This was the *ahupuaʻa* land use system, which consisted of vertical landscape segments from the mountains to the near-shore ocean environment, and into the ocean as deep as a person could stand in the water (Isabella Aiona Abbott, personal communication). The reason for converting from a shifting to a stabilized land use can be attributed to an increasing population pressure. Areas for cultivation are spatially more limited on islands as compared to continents. At the same time, also agricultural land use, to be stabilized in tropical environments, had to become more sophisticated than the traditional slash and burn practice of the initial colonizers, who are believed to have become settled in the windward valleys of Oʻahu around 300 AD (Kirch, 2000).

In the term *ahupuaʻa*, the words *ahu* (stone altar or stone mound) and *puaʻa* (pig), are combined. The *puaʻa* was a carved wooden image of a pig head. These stone altars served as border markers and deposition places for offerings to the agricultural god *Lono* and a high chief (*aliʻi nui*), who was the god's representative. Each *ahupuaʻa* in turn was ruled by a lower chief, or *aliʻi ʻai*. He in turn appointed a headman, or *konohiki*. The *konohiki* served as general manager responsible for the use of an *ahupuaʻa* as a resource system. He in turn was assisted by specialists, or *luna*. For example, the *luna wai* was responsible for the fresh water flow and irrigation system (Kamehameha Schools, 1994).

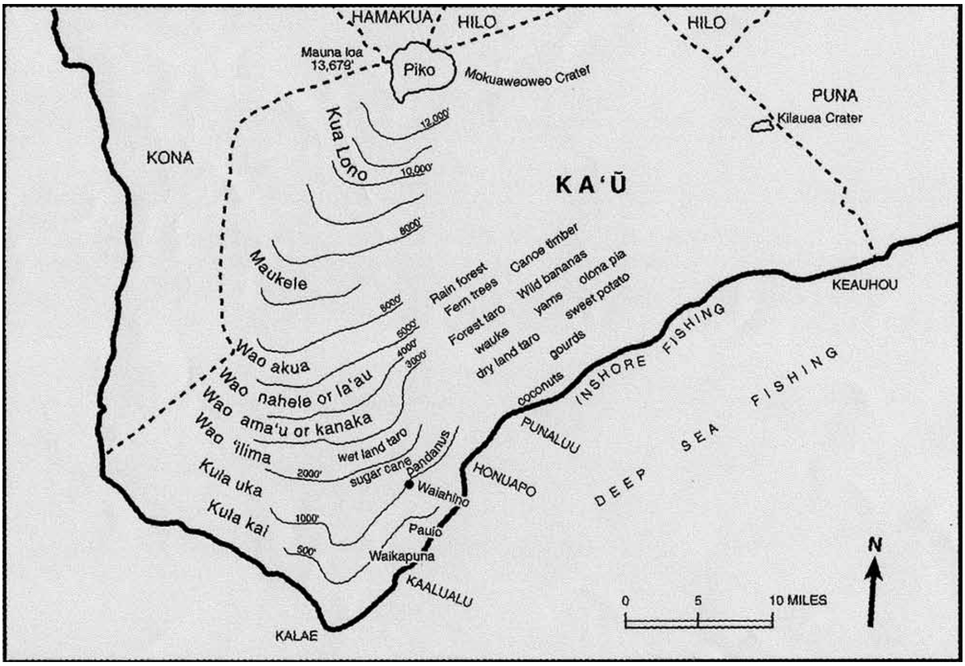

Figure 1. The vertical arrangement of Hawaiian ecological zones on the south slope of Mauna Loa, Hawai`i Island [after Handy & Handy (1972) with slight modifications].

Sophistication in the traditional Hawaiian land use practices becomes evident already from the way island areas were divided vertically, often in units of watersheds, and horizontally, in zones of ecosystem significance. Furthermore, the functionality of the individual zones was well understood as to their bioenvironmental potential. Wherever possible, the zones were modified by enhancing their natural ecosystem services.

In this paper I will first focus on the Hawaiian understanding of ecological zones and their uses. These are closely similar to an ecosystem model interpreted and used by an ecologist. I will then focus on the current need for taking care of the inland and upland forest as the protective cover in Hawaii's watersheds. From a professional viewpoint such care-taking is known as silviculture. Silvicultural research and management is now in great demand for restoring a Hawaiian sense of place and for introducing an adaptive and integrative form of management in selected Hawaiian *ahupua'a*.

The Hawaiian Ecological Zones

It was of particular interest to me as an ecologist to learn that the early Hawaiians had not only a great number of plants and animals identified by names, often by binomials, but that they also recognized a number of vegetation units (i.e., different land forms and plant communities) and types of ecosystems. The native Hawaiian author, David Malo, who lived in the early part of the 19th century, provided a rich record of indigenous environmental and ecological terms with brief definitions. His writings were translated by Dr. Nathaniel Emerson in 1898 and first published in 1903. A second edition was published by the Bishop Museum in 1951 with a number of reprinted versions of this classic record; the latest was published as Malo (1997). Definitions of Hawaiian environmental and ecological terms are best clarified when shown on a map. Such effort appeared in the book by

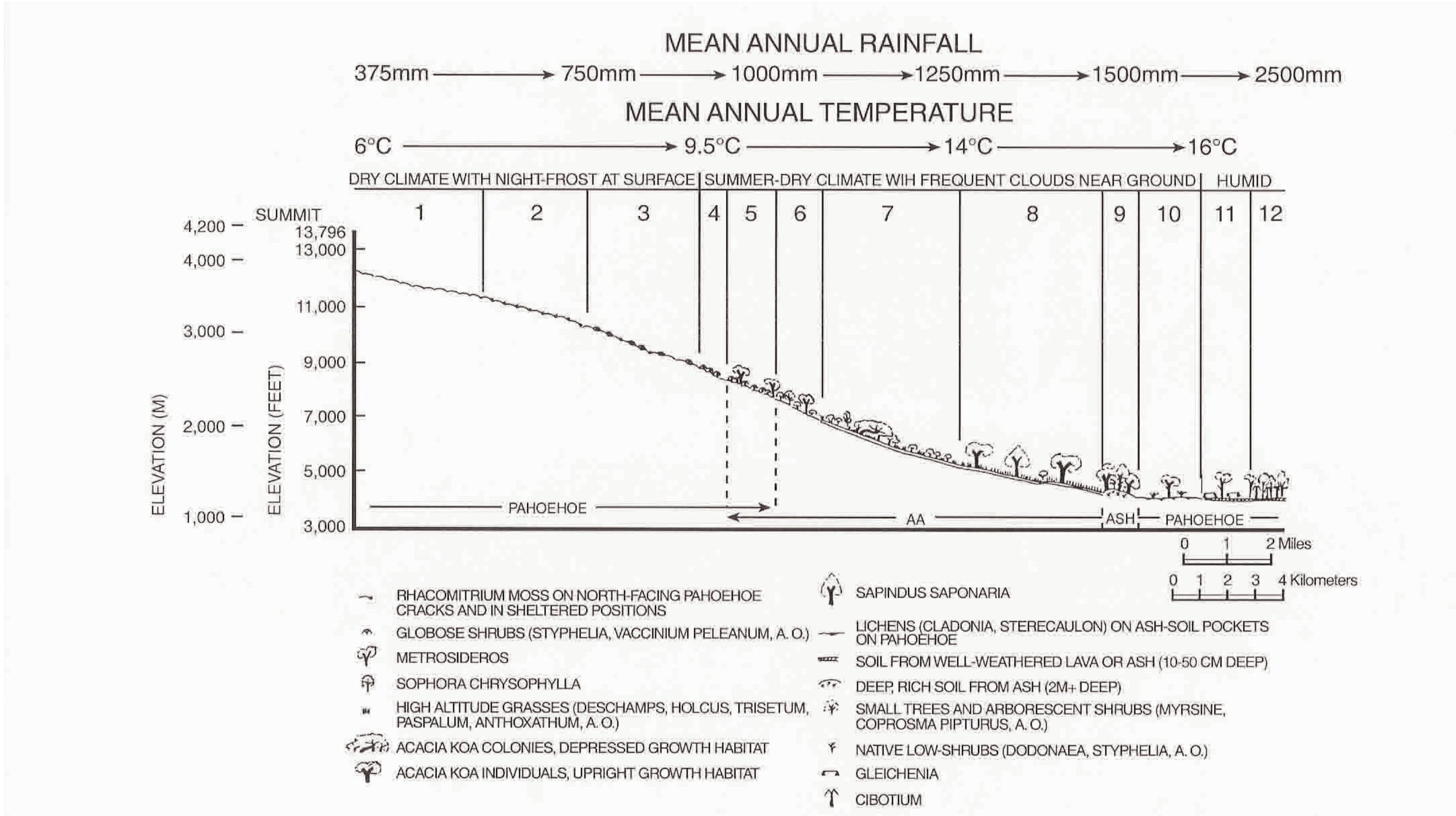

Figure 2. East-slope profile of ecological zones on Mauna Loa from 12,000 feet (3660 m) down to 4000 feet (1200 m) elevation near Kīlauea Caldera (after Mueller-Dombois et al. 1981). Profile segment 1 = Alpine stone desert, 2 = *Rhacomitrium* moss desert, 3 = Sparse alpine scrub, 4 = Alpine aggregate scrub, 5 = *Metrosideros* treeline ecosystem, 6 = Open subalpine *Metrosideros* scrub forest, 7 = Mountain parkland (formed by *Acacia koa* tree communities, *Styphelia* shrub communities, and grass communities), 8 = *Acacia koa-Sapindus* savanna, 9 = Closed kīpuka forest (segment 8 intergrades locally with segment 9), 10 = Open *Metrosideros* dryland forest (early successional stage), 11 = Open *Metrosideros* rainforest, 12 = Closed *Metrosideros* rainforest (near Thurston Lava Tube and Crater Rim Road).

Handy and Handy (1972), which is here reproduced with slight modifications as a map of the Ka'ū District on South Hawai'i (see Fig. 1).

Starting at the top of Mauna Loa, the crater is called *piko,* meaning navel and also naval string or umbilical cord (Pukui & Elbert, 1986). This Hawaiian term gives vivid reference to the crater's activity from which lava flows emerge and thereby create new land surfaces. The broad and barren summit area southward on the map diagram is called *kua lono,* which refers to a region near the mountain top (Pukui & Elbert, 1986). This area was classified as alpine stone desert and *Rhacomitrium* moss desert in Mueller-Dombois *et al.* (1981: 38 segments 1–2, Fig. 2).

The book of Malo (1997) gives additional *kua* zones. The word *kua* means "back", such as the back of a person. According to Malo, *kua-hiwi* refers to the backbone of the mountain implying spiny ridges, while *kua-lono* also refers to peaks or ridges and summits, but implies broader, plateau-like areas. *Kua-mauna* or simply *mauna* refers to the mountain side without any significant vegetation cover, perhaps including the sparse alpine scrub zone (segment 3 in Mueller-Dombois *et al.*, 1981: 38). Finally, the term *kua-hea* refers to the area below *kua-mauna,* where trees are stunted due to high altitude (Pukui & Elbert, 1986). This term refers to a zone of small trees, probably the open sub-alpine scrub forest (segment 6 in Mueller-Dombois *et al.*, 1981). It may also apply to the treeline ecosystem (segment 5), where forest gives way upslope to the alpine shrubland (segment 4). Alternatively, the term *kua-hea* may refer to the stunted trees on wind-swept ridges as found on the older, more dissected islands, which have similar stand structures. On the map diagram appears the term *maukele,* which simply means rainforest (*wao kele*, also spelled *ma'u kele* and *wao kele* in Pukui & Elbert, 1986). As rainforest, this area seems rather high in elevation on this map, shown here as from 6000 to 8000 feet (1830–2240 m). Malo points out that *wao-maukele* is also the area where "the monarchs of the forest grew". The monarchs were the tall (up to 30 m), endemic *Acacia koa* trees, which we know as having been assembled in mesic (less wet) higher elevation rainforests on Mauna Loa, Mauna Kea, and Haleakalā mountain.

The next four zones on Fig. 1 start with the term *wao,* which is a general term for inland region, usually forested (Pukui & Elbert, 1986). *Wao akua* literally means the wilderness of the gods and/or ghosts. In Malo's (1997) book, this zone is described as below *wao maukele,* which would fit the map diagram on Fig. 1. The *wao akua* is described as the zone in which smaller sized trees grew. The reduced tree size together with the distinction of this forest as being the realm of the gods (*akua*) and thus probably feared as a forest of ghosts, most likely points to *wao akua* implying what ecologists call "cloud forest". Next on the map is the *wao nahele* or *wao lā'au*, the general inland and upland forest region. This is followed down slope by the *wao 'ama'u* and *wao kanaka*. The latter refers to the zone where humans (the *kanaka*) work and cultivate the land. The former refers to the tall fern '*ama'u* (*Sadleria* spp.), which probably was a dominant plant in an open structured rainforest community, perhaps coexisting among cultivated, non-irrigated taro or *kalo* (*Colocasia esculenta*) and banana (*Musa* spp.) plantings interspersed with the endemic shrub *olonā* (*Touchardia latifolia*) used for cordage. Other cultivated plants were the Hawaiian introduced small tree *wauke* or paper mulberry (*Broussonetia papyrifera*) used for making *tapa* cloth, the sweet potato or *'uala* (*Ipomoea batatas*), and yams or *pi'a* (*Dioscorea pentaphylla*). These are vines with subterranean tubers, which were eaten by the Hawaiians cooked and when still warm (Neal, 1965). This species combination indicates that there was an agro-forest ecosystem present between 2000 and 4000 feet elevation (610–1220 m), which in the 20th Century was used for industrially grown sugar cane or *kō* (*Saccharum officinarum*). The fourth *wao* zone on the map diagram (Fig.1) is the *wao 'ilima*, so called because of the prevalence of the native shrub *Sida fallax*. That this shrub forms a zone below the *wao kanaka*, certainly indicates a reduction in mean annual rainfall below 3000 feet (915 m) on the *Ka'ū* map, which is definitely correct as shown in Mueller-Dombois *et al.* (1981: 30) on the climate diagram map of Hawai'i Island. Also wetland taro is indicated here, which in this drier zone can only refer to the cultivation of irrigated taro, since this is the same species as used for dryland taro cultivation in some rainforest environments such as the *wao ama'u* referred to above.

Two more zones are indicated below the *wao 'ilima*, namely *kula uka* and *kula kai*. The term *kula* refers to open, mostly grassland vegetation, and *uka* to an inland/upland location and *kai* to a seaward or coastal location. These *kula* zones were most likely the result of periodic fires. Burning was promoted periodically for *pili* grass (*Heteropogon contortus*) production as this grass played an important role as house thatching material (Egler, 1947; Mueller-Dombois & Fosberg, 1998).

The *Ahupua'a* Model

Figure 3 shows an *ahupua'a* model as designed by Luciano Minerbi (1999), with minor modifications. It portrays a typical land division on the windward side of an older Hawaiian island. Not being as high in elevation as the Island of Hawai'i, generally only up to around 3000 feet (915 m), it begins on the mountain side (*mauka*) with the upland/inland forest zone, the *wao nahele*. Note that the *wao nahele* is including a *wao akua* (cloud forest zone) around its upper fringe towards the summit, the *kua-hivi*. Below the *wao nahele*, through a transition zone (an ecotone), follows the agricultural zone, the *wao kanaka*. Continuing towards the ocean (*makai*) through another ecotone, lies the coastal zone, the *kahakai*. Note that in the *wao nahele* appear some springs (*pūnāwai*) that feed into the stream ecosystem, the *kahawai*. Near the seaward end of the *kahawai*, where the ocean tide brings saltwater into a mixing zone with the stream's fresh water is the estuary, known to the Hawaiians as the *muliwai*.

Since the *ahupua'a* served as the complete life support system for Hawaiian family groups (the *'ohana*) prior to European contact in 1778, there are many other important features noted on the diagram (Fig. 3). Besides habitation sites in the *kahakai* and *wao kanaka*, there were also transitional habitation sites near and in the *wao nahele*. Both the *wao kanaka* and *kahakai* included temples (*heiau*) and burial places (*hē)* as well as irrigated terraces (*lo'i kalo*) for taro cultivation. The *lo'i* were fed with fresh water from the main stream through a system of artificial ditches called *'auwai*. Water in these ditches had to be flowing and cool enough to prevent rotting of taro tubers. The *lo'i* were an important agricultural engineering invention for intensified crop production. Dryland taro and a suite of other crop plants including fruit trees, such as the bread fruit, *'ulu* (*Artocarpus altilis*) and mountain apple, *'ōhi'a 'ai* (*Syzygium malaccense*) were cultivated in tree gardens. Another important engineering invention were the Hawaiian fishponds (*loko i'a*), located in the ocean often next to the estuaries. They were large (hectare-sized) stonewalled enclosures with a sluice gate (*mākāhā)* at the seaward end, which allowed small fish to enter, but prevented big fish to escape. A 90 minute video production by Nālani Minton with anthropologist Marion Kelly (1992), gives a vivid account on the *lo'i kalo* and *loko i'a*. Further detail is provided by Mitchell (1992) and in the popular *ahupua'a* textbook of Kamehameha Schools (1994).

A Silvicultural Approach to *Ahupua'a* Restoration

Since an *ahupua'a* is typically a watershed valley, silvicultural research and management, based on forest ecological knowledge, should be a top priority. As such it will have an important complementary task in those *ahupua'a* selected for stream restoration activity.

In Webster's dictionary, silviculture is defined as "A branch of forestry dealing with the development and care of forests." Silviculture can also be understood as the practical application of forest science or forest ecological knowledge. Silviculture always has an applied research component and may involve experiments at an operational scale. When not applied to commercial forestry, silviculture can be considered a branch of applied conservation biology. Silvicultural approaches must be based on simulating and enhancing natural processes. In terms of labor and materials, they should be considered "low input management". As such, silviculture can be contrasted to horticulture.

Horticulture, by definition, is garden culture, which requires "high input management". In Webster's dictionary, horticulture is defined as "The art and science of growing fruits, vegetables, or ornamental plants". When applied to conservation of plant species, horticulture can also be considered a branch of applied conservation biology. But for restructuring or restoring native rainforests, silvicultural rather than horticultural techniques should be developed. Such silvicultural techniques should be based on ecological research as done in the Hawaiian rainforests.

Up to the mid-1960s, rainforest research in Hawai'i had been very limited. The most significant ecological research was that of Harold H. Lyon and a few of his contemporaries, who spent a decade

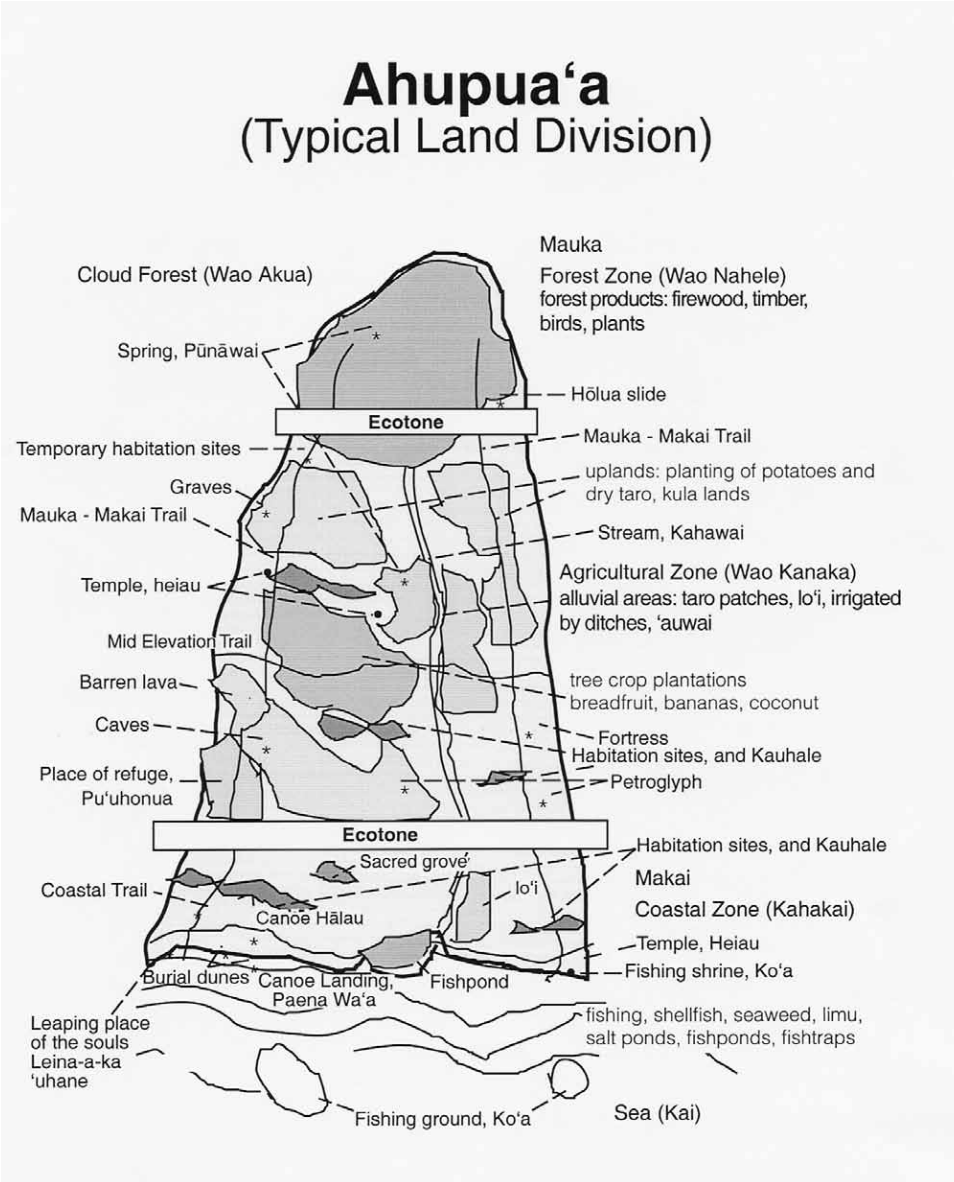

Figure 3. *Ahupua‘a* model after Luciano Minerbi 1999, slightly modified. Note the five biological resource and production zones from *mauka* to *makai*: *wao nahele*, *wao kanaka*, *kahakai*, *kai*, and the *kahawai* (stream ecosystem).

on researching the "Maui Forest Trouble" (Holt, 1983). This phase ended with Lyon's (1918) conclusion that (quote) "Our native forests are doomed".

Lyon's conclusion was based on his notion that the native *Metrosideros*-dominated rainforest was made up largely of pioneer species that could not adapt to aging soils. He thereafter postulated the idea that the missing climax species component has to be introduced from outside Hawai'i in order to save the Hawaiian watersheds. This was still the unwritten forest and watershed restoration policy in the state of Hawai‘i until about the mid-1970s.

Research under the Hawai‘i IBP (International Biological Program) during the 1970s focused on the biological organization of selected native Hawaiian communities (Mueller-Dombois *et al.*, 1981). Among these was an 80 ha study plot in the Kīlauea rainforest on the Big Island. Subsequent research on the canopy dieback syndrome in the Hawaiian rainforests extended this research across the islands of Hawai‘i, Maui, O‘ahu, and Kaua‘i and from there to the Pacific and Atlantic regions (Huettl & Mueller-Dombois, 1993).

For using a silvicultural approach to restoration, one needs to know first some of the keystone species that either stabilize or disrupt a specific rainforest community. Secondly, one needs to know something about their ecological properties and strategies. Such aspects will be discussed next. This will be followed by a set of silvicultural prescriptions for restoring Hawaiian rainforests.

Keystone Species

Among plants, keystone species are usually the dominants or the more robust ones in the community. In particular they are those whose population dynamics have a strong effect on the other species in the community. In the mature Hawaiian rainforest such species are the *‘ōhi‘a lehua* tree (*Metrosideros polymorpha*) and the *hāpu‘u* tree ferns (*Cibotium* spp.). *‘Ōhi‘a lehua* dominates the canopy and the *hāpu‘u* typically the sub-canopy. In less wet rainforests, the *koa* tree (*Acacia koa*) often joins the upper canopy as a second keystone species. Depending on habitat factors and geographic location, *koa* may even become an emergent tree reaching above the general canopy. Locally, other native tree, shrub, and vine species can be added as playing key roles. Among trees they include in upper Manoa Valley for example *‘ahakea lau nui* (*Bobea elatior*), *hame* (*Antidesma platyphyllum*), *olomea* (*Perrotettia sandwicensis*), *lama* (*Diospyros* spp.), *kōpiko* (*Psychotria kaduana*), and *‘ōlapa* (*Cheirodendron* spp.), among shrubs they include *‘ohelo kau la‘au* (*Vaccinium calycinum*), *ha‘iwale* (*Cyrtandra* spp.), *ho‘awa* (*Pittosporum glabrum*), *naupaka kuahiwi* (*Scaevola gaudichaudiana*), and *māmaki* (*Pipturus albidus*), among vines *‘ie‘ie* (*Freycinetia arborea*) and *maile* (*Alyxia oliviformis*). Many other robust native rainforest plants are listed by Stone & Pratt (1994: 173)

A number of alien invasives have now assumed the role of keystone species. Foremost among them is the feral pig (*Sus scrofa*). Pigs tend to destabilize the Hawaiian rainforest, in particular, because they seek out the native tree ferns, the *hāpu‘u*, as a favored food item. They also promote locally the spread of strawberry guava (*Psidium cattleianum*), which is a key invasive tree in pig frequented sections of the Hawaiian rainforest. A shrub in this category is Koster’s curse (*Clidemia hirta*). Locally in watershed forests on O‘ahu, a particularly disturbing invasive keystone species is the often very tall (>30 m), canopy emergent albizia tree (*Falcataria moluccana*). Other recently spreading and penetrating trees are the introduced secondary and fast growing shoe button ardisia (*Ardisia elliptica*) and the octopus tree (*Schefflera actinophylla*). These secondary, fast growing trees form a new life-form group with several other alien species, which never really developed among the native species.

In the Hawaiian Islands, the primary rainforest has always renewed itself through the generational turnover of primary species without an intermediate successional phase that could be considered a “secondary forest”. As is well known, a secondary forest is a typical phase in disturbed continental tropical rainforests, in which recovery of primary forest is considered a very long-term process.

Ecological Plant Properties and Strategies

For the purpose of this paper, only a few characteristics will be emphasized, which can be used for a silvicultural approach to forest restoration. During the IBP and canopy dieback studies, we surveyed many rainforest plots and transects. We enumerated all woody species by cover, density, and size. We also studied their substrate and found that most of the native rainforest species became established on decaying wood in developed mature forests. This stands in contrast to rainforest development on lava flows, where an assortment of hardy native pioneer species establish themselves in rock fissures without or with only very little organic matter (Smathers & Mueller-Dombois, 1974, 2007).

In mature rainforests we noted only three species that started commonly on mineral soil. These were the *hāpu'u* tree ferns, the *koa*, and *naio* (*Myoporum sandwicense*) trees. Most others had a significant log establishment index, meaning they started as seedlings on logs above the mineral surface (Cooray, 1974; Santiago, 2000). That means that most Hawaiian plants have an epiphytic beginning.

Such observation can be made easily in mature native rainforests, if one knows where to look for native fern sporophytes and tree seedlings. The first place to look, are the tree fern trunks. They often are the most favorable seed beds for *'ōhi'a lehua* germinants and small seedlings. If left alone, eventually one of them may succeed in becoming a sapling and thereafter a mature tree by extending its roots into the mineral soil. A precondition for this to happen is a canopy opening (Burton & Mueller-Dombois, 1984). This may occur naturally by loss of a tree fern frond or the decline of the tree fern itself after canopy opening. Many times one can observe stilt rooted *'ōhi'a lehua* trees that had an epiphytic start, either on a tree fern trunk or on a moss-covered dead tree trunk. For *'ōlapa* this seems to be the only mode of its natural establishment.

Silvicultural Restoration Tasks

Delimbing

Cutting off the limbs or big branches of the taller alien trees would be a useful first step in silvicultural restoration. This applies in particular to the huge albizia trees, which break easily and are a hazard for humans during strong winds. Delimbing should not be a clear-cut logging operation, but rather a carefully selected cutting and branch removal of selected alien trees to achieve partial opening of the forest canopy. Their limbs should be left on the ground and allowed to decompose *in situ*. To accelerate the decomposition process, the limbs, or thick branches, and in some situations the trunks of selected trees, may be cut into meter sections and split open. In mature and senescing Hawaiian rainforests, decaying logs, particularly when moss-covered, were found to be the favored micro-habitats for native fern gametophytes and woody plant seedlings to become established.

Fencing

Any section of rainforest considered for restoration needs to be fenced against pigs. Depending on financial resources one can begin with fencing of small enclosures, such as 100 m^2 plots. Of course, anything larger would always be preferable. The purpose is to create safe islands in *kīpuka* fashion within the larger forest infested by alien neophytes.

Reintroduction

From field research observations, it appears most efficient to begin with reintroducing the appropriate Hawaiian tree ferns into the fenced enclosures. On O'ahu Island this would preferably be *Cibotium chamissoi*, formerly named *C. splendens* (Palmer, 2003). But *C. menziesii* may also be considered. A natural hybrid of these two species was recently discovered in the Ko'olau mountains and called *Cibotium ×heleniae*. Such tree ferns are easily transplanted at any stage of their life cycle and/or raised in nurseries. Mature tree ferns are preferred. The reasons for reintroducing tree ferns are several. They can be planted directly into the mineral soil as they do not require a raised organic seedbed as do most of the other Hawaiian woody plants with exception of *Acacia koa* and *Myoporum sandwicense*. Tree ferns have a high value as watershed protectors in that they slow down the impact of heavy showers by forming a second canopy under the tree layer. They disperse the water away from their trunks in contrast to, for example, albizia trees. Albizia trees act as funnels for rain water due to their generally upward angled branch system. Because of this, they have a high rate of stem run-off, which is further accelerated due to their smooth bark. They are thus ill adapted as watershed tree cover in wet forests, where excess water is a problem. In contrast, tree ferns are expected to increase the rate of water percolation into the soil rather than contributing to run-off and erosion as do the alien albizia trees. A third major advantage is that tree fern trunks serve as epiphytic seed beds for many native ferns and woody plants. As mentioned before, many *Metrosideros* trees and almost all *Cheirodendron* trees start as seedlings epiphytically on tree fern trunks.

Weed control

In some situations, weed control may be the prerequisite prior to the introduction of native tree ferns into the *kīpuka*-type enclosures. Certainly, weed control may be considered an ongoing task until the tree ferns themselves become excluders of weeds on account of having developed a closed subcanopy in the *kīpuka*-type enclosures.

Inoculation

Wherever native woody plants and ferns are too far removed from the *kīpuka*-type enclosures, it may become necessary to inoculate the tree fern trunks and decaying coarse woody log segments on the ground with seeds and spores of selected native plants.

Monitoring

Another silvicultural research task involves monitoring the tree fern trunks and inoculated decaying wood segments for native plant establishment, growth, and survival. Monitoring will also be necessary in the *kīpuka*-type enclosures to keep weeds under control and the fencing in repair.

Soil scarification

In some of O‘ahu's watershed forests, for example in the Kahana *ahupua‘a*, it has been found that soil scarification will encourage germination of *koa* seeds. An abundance of koa seedlings has been observed there by Wirawan (1978), after removal of the *hala* litter associated with scarification of the surface mineral soil. Currently, there are only a few old senescing *Acacia koa* trees left in the canopy otherwise dominated by native *hala* (*Pandanus tectorius*) trees. Soil scarification in forest gaps will increase the *koa* component in the inland forest (the *wao nahele*) of the Kahana *ahupua‘a*. It may also work in other *ahupua‘a* where *koa* is in decline.

Removal of woody debris from streams

Hawaiian streams are known to be highly dynamic (Fitzsimons *et al.*, 2005). Their distances from *mauka* to *makai* are typically short, a few kilometers only, and their initial descents from the *wao nahele* are typically steep. Thus they can swell up quickly during rain storms. Woody debris that accumulates in the streams can be a cause of unexpected stream diversions as was the case in the damaging October 2005 flood in Mānoa Valley. Similarly in Kahana Valley the uncontrolled advance and overgrowing of the *hau* tree (*Hibiscus tiliaceus*) becomes a serious impediment for the dynamics of the Kahana stream which can result in flood damage in its *wao kanaka* and *kahakai*. It also interferes with the amphidromous native freshwater fauna (Fitzsimons *et al.*, 2005). Prevention of accumulation of woody debris in Hawaii's streams is a task falling into the realm of both silviculture and stream management which are in need of integration.

Conclusions

There are five major biological resource zones in an *ahupua‘a*. These are the ***wao** nahele*, the *wao kanaka*, the *kahawai* the *kahakai*, and the near-shore *kai*, i.e., the ocean in front, including the coral reefs where present. Each of these five zones can be divided into subecosytems depending on their specific bioenvironmental settings. Since these ecosystems formed an integrated landscape unit that served as the life support system, they are of great cultural and ethno-ecological importance. They were managed cooperatively as integrated management units for several centuries prior to European contact. In any attempt towards their restoration, they should also be studied cooperatively by multidisciplinary teams, such as envisioned by the PABITRA (the Pacific-Asia Biodiversity Transect) Network. A manual of methods for such multidisciplinary island studies throughout the tropical Pacific was recently completed and put on the PABITRA web site (www.botany.hawaii.edu/pabitra/biodiversity). A recently published case study of the Kahana Valley *ahupua‘a*, on windward O‘ahu (Mueller-Dombois & Wirawan, 2005) provides further insights in form of a research synthesis of the valley's archeology, paleoecology, tenure-related management changes, contemporary botanical ecology, and the effects of past climate changes and human influences on the valley's geomorphology and vegetation. In the same issue of the journal *Pacific Science*, which deals with PABITRA methodology, is a biological assessment of Kahana Stream by Fitzsimons *et al.* (2005) as well as a paper on design considerations for island stream surveys by Parham (2005).

The eight silvicultural restoration tasks for Hawaiian rainforests discussed above may be considered a first set of prescriptions for adaptive management. It is suggested that these are applied in *kīpuka*-like fashion. This means that restoration should begin with fenced-in island-like nuclei of robust native plants. These comprise the ancient vegetation in usually a larger area of vegetation composed of neophytes. These native plant *kīpuka* may be small areas such as 10 by 10 m plots to begin with. They should be protected, monitored, and studied. Such native vegetation *kīpuka* will certainly provide a sense of Hawaiian place in our watershed forests. If they prove to have a reasonable survival value, they may eventually be expanded by silvicultural nurturing to become the vegetation matrix for reintroducing rare and endangered Hawaiian plants and animals. With further practical experiences gained from silvicultural experimentation at an operational scale, additional prescriptions will surely be developed.

Acknowledgments

This paper was inspired by my involvement in the Lyon Arboretum crisis of Fall 2004 and the search for a new vision of its place in the Hawaiian culture. I thank my wife, Annette Mueller-Dombois, for computer processing and editorial help and Professor Isabella Aiona Abott for reviewing the manuscript and offering appropriate suggestions.

Literature Cited

Burton, P.J. & D. Mueller-Dombois. 1984. Response of *Metrosideros polymorpha* seedlings to experimental canopy opening. *Ecology* **65**: 779–791.

Cooray, R.G. 1974. Stand structure of a montane rain forest on Mauna Loa. *Hawaii International Biological Program Technical Report* **44**, 98 p.

Egler, F.E. 1947. Arid southeast Oahu vegetation, Hawaii. *Ecological Monographs* **17**: 383–435.

Fitzsimons, J.M., J.E. Parham, L.K. Benson, M.G. McRae & R. T. Nishimoto. 2005. Biological assessments of Kahana Stream, Island of Oʻahu, Hawaiʻi, with the use of procedures from the PABITRA Manual for Interactive Ecology and Management. *Pacific Science* **59**: 273–281.

Handy, E.S.C. & E.G. Handy. 1972. *Native planters in Old Hawaii: Their life, lore, and environment.* Bishop Museum Press, Honolulu. 233 p.

Holt, A.R. 1983. The Maui Forest Trouble: A literature review and proposal for research. *University of Hawaii Botanical Science Paper* **42**: 1–67. [http://www.botany.hawaii.edu/pabitra] (under Current and Planned Projects).

Huettl, F.R. & D. Mueller-Dombois, eds. 1993. *Forest decline in the Atlantic and Pacific regions.* Springer-Verlag. Berlin, London, New York. 366 p.

Kamehameha Schools. 1994. *The Ahupuaʻa Life in Early Hawaiʻi.* Third ed. Kamehameha Schools Press. Honolulu 59 p. plus colored poster.

Kelly, M. 1992. *Ahupuaʻa Fishponds and Loʻi: A film for our time*. Produced as VHS video by Nālani Minton and directed by Nā Maka o ka ʻĀīna. [http://www.film-hawaii.com/NaMaka].

Kirch, P.V. 2000. *On the roads of the winds: An archeological history of the Pacific islands before European contact.* University of California Press. 424 p.

Lyon, H.L. 1918. The forests of Hawaii. *Hawaii Planter's Record* **20**: 276–279.

Malo, D. 1997. *Hawaiian antiquities, Moʻolelo Hawaiʻi.* Translated from the Hawaiian by Dr. Nathaniel B. Emerson 1898. Second ed. 1951. 7th reprint 1997. Bishop Museum Press. Honolulu. 278 p.

Minerbi, L. 1999. Indigenous management models and protection of the ahupuaʻa. *Social Process in Hawaiʻi* **39**: 208–225.

Mitchell, D.K. 1992. *Resource units in Hawaiian culture.* Fourth ed. Kamehameha Schools. Honolulu. 102 p.

Mueller-Dombois. **D**., **K**.**W**. **Bridges & H**.**L**. **Carson**, eds. 1981. *Island ecosystems: biological organization in selected Hawaiian communities.* United States/International Biological Program Synthesis Series 15. Hutchinson Ross Publishing Co., Stroudsburg & Woods Hole. 583 p.

———. **& F**.**R**. **Fosberg**. 1998. *Vegetation of the tropical Pacific islands*. Springer-Verlag, New York. 733 p.

———. **& N**. **Wirawan**. 2005. The Kahana Valley ahupua‘a, a PABITRA study site on O‘ahu, Hawaiian Islands. *Pacific Science* **59**: 293–314.

Neal, **M**.**C**. 1965. In gardens of Hawaii. *Bishop Museum Special Publication* **50**, 924 p.

Palmer, **D**.**D**. 2003. *Hawaii's ferns and fern allies.* University of Hawai‘i Press, Honolulu. 324 p.

Parham, **J**.**E**. 2005. Aquatic survey techniques on oceanic islands: important design considerations. *Pacific Science* **59**: 283–291.

Pukui, **M**.**K**. **& S**.**H**. **Elbert**. 1986. *Hawaiian dictionary.* University of Hawai‘i Press, Honolulu. 572 p.

Santiago, **L**.**S**. 2000. Use of coarse woody debris by the plant community of a Hawaiian montane cloud forest. *Biotropica* **32**(4a): 633–641.

Smathers, **G**.**A**. **& D**. **Mueller-Dombois**. 1974. *Invasion and recovery of vegetation after a volcanic eruption in Hawaii*. National Park Service Science Monograph Series **5**, 129 p.

———. **& D**. **Mueller-Dombois**. 2007. *Hawai‘i, the fires of life.* Mutual Publishing, honolulu. 141 p.

Stone, **C**.**P**. **& L**.**W**. **Pratt**. 1994. *Hawai‘i's plants and animals*. Illustrations by J.M. Yoshioka. University of Hawai‘i Press, Honolulu. 399 p.

Wirawan, **N**. 1978. Vegetation and soil-water relations in a tropical rain forest valley on Oahu, Hawaiian Islands. Unpublished Ph.D. Dissertation, Botany Department, University of Hawai‘i, Honolulu. 420 p.