Reforestation in the Hawaiian Islands

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Abstract

Although coconut-palm fringed beaches are the most common image of Hawai'i, the archipelago supports a wide range of forest types, from rainforests to open-canopied dry forests to alpine shrublands. Forest types are determined by elevation, aspect (with each island having a wet windward and dry leeward side), and substrate age. Only about one-third of Hawaii's original native ecosystems remain relatively intact, and many forests today consist of a mix of native and escaped agricultural, forestry, and ornamental trees. Polynesians arrived in Hawai'i sometime after 1,000 CE and cleared relatively small areas of land for agriculture and agroforestry. Westerners, led by Captain Cook, arrived in 1778 and made much more drastic changes to the landscape. Introduction of animals such as cattle, goats, and pigs in the late 18th century proved devastating to native forests that had evolved with no large herbivores. Tree planting to protect watersheds began as early as the 1880s during the days of the Hawaiian Kingdom. Much more widescale reforestation of lands denuded by overgrazing, fires, and unsustainable harvesting was undertaken from the 1920s through the 1960s, mainly to protect watersheds that provided a steady supply of irrigation for sugar plantations and urban areas. Most of these plantations were of nonnative tree species. Several large-scale commercial plantations, mainly of *Eucalyptus* spp., were established from the 1960s through the 1990s in hopes of developing a forest industry. Most forestry planting today is with native tree species to provide habitat for native bird and plant species. Commercial plantings with native species may be a way to provide ecosystem services such as wildlife habitat as well as economic value in the future. Local communities are increasingly becoming involved in reforestation and forest management.

Introduction

The volcanoes of the Hawaiian Islands emerged out of the sea over millions of years and developed into an archipelago of contrasts, from dry coasts to alpine deserts to rainforests. A few hundred species of plants colonized the isolated islands and evolved into hundreds of new species found nowhere else on earth. Beginning with the first Polynesian explorers, people transformed the landscape by clearing native vegetation for agriculture, ranching, and urbanization. Modern forestry arose in the 19th century out of a need to protect the watersheds rather than a desire to produce wood products.

Geography

The Hawaiian archipelago lies within the tropics, with the main islands lying between 18°54' and 22°15' north and running from 154°48' to 160°16' west. The main island chain stretches 390 mi (624 km) from the eastern tip of Hawai'i Island to the small island of Ni'ihau to the west. In terms of land area, Hawai'i is 6,423 mi^2 (16,638 km^2) or about 4,110,720 ac (1,663,550 ha), larger than the State of Connecticut but smaller than New Jersey. The islands were formed from volcanoes erupting from an undersea hot spot. As the Earth's crust has slipped, the hot spot has moved to the southeast, leaving Kaua'i, O'ahu, and Ni'ihau as the oldest of the main islands and Hawai'i Island as the youngest. Hawai'i Island is dominated by two large shield volcanoes, Mauna Kea and Mauna Loa, standing at 13,803 ft (4,207 m) and 13,679 ft (4,167 m) above sea level (figure 1). Maui is dominated by Haleakalā, at 10,023 ft (3,055 m) elevation. In addition to Kīlauea (the currently active volcano on Hawai'i Island), Mauna Loa, Hualālai on Hawai'i Island, and Haleakalā have all erupted in historical times. Lava erupting from the volcanoes has developed into landscapes of gradual

Figure 1. Mauna Kea is one of two large volcanoes on Hawai'i Island. In this photo, snow-capped Mauna Kea can be seen with native 'ōhi'a forest in the foreground, native māmane-naio forest upper left, and invasive gorse (*Ulex europaeus* L.) right middle distance. (Photo by J.B. Friday, 2020)

slopes, deeply dissected by streams where soils have developed. On the older islands, millennia of erosion and occasional catastrophic collapse of volcanic slopes have resulted in a topography of knife-edge ridges surrounding deep valleys (figure 2).

Precipitation is driven by the moist northeast trade winds hitting the mountain slopes of the islands. The wettest areas on the upper slopes of windward Maui and Kaua'i can receive over 400 in (10,000 mm) of rain annually (Giambelluca et al. 2013). Coastal lands in the rain shadow of Mauna Kea, on the other hand, typically receive less than 10 in (26 mm) of rain annually. Leeward Hawai'i Island receives afternoon rainfall during the summer months from offshore breezes, and all the islands may be hit by "Kona" storms coming from the west during the winter months. While not as seasonal as much of the tropics, Hawai'i typically receives more rainfall in the winter months. Studies indicate a general drying trend, with wet areas remaining constant but drier areas receiving less precipitation (Elison Timm 2015, Giambelluca et al. 2013). Near-constant trade winds keep temperatures mild near sea level, with average

Figure 2. Kalalau Valley on Kaua'i with high sea cliffs was created by millions of years of erosion. (Photo by J.B. Friday, 2015)

highs between 80 °F and 90 °F (27 °C and 32 °C) and average lows between 65 °F and 75 °F (18 °C and 24 °C). Temperatures decrease at higher elevations and frost damage is a limiting factor to planting trees above 6,600 ft (2,000 m) elevation (Scowcroft and Jeffrey 1999).

Soils on the younger islands are dominated by Histosols, derived from organic matter and lava rock, and Andisols, derived from volcanic ash (Deenik and McClellan 2007). On the wet windward sides of the older islands of O'ahu and Kaua'i, the ash soils gradually weather into acidic Ultisols and Oxisols. At lower elevations on the leeward sides of the islands, Mollisols predominate and, when irrigated, form very productive agricultural lands. Of the 12 USDA soil orders, 10 are present in Hawai'i.

Forest Types

The native flora of Hawai'i is unusual among tropical ecosystems in that there are relatively few species, but the majority of native plant species are endemic. Over millions of years, plant propagules colonized the Hawaiian archipelago through being carried by birds, floating on the water, or being blown in the wind from ancestral homelands in the Americas, Oceania, Australia, and Asia (Price and Wagner 2018). Fewer than 300 founder species have radiated into over 1,200 native species today, about 90 percent of which are endemic (Wagner et al. 1999). Approximately 300 of these species are trees (Little and Skolmen 1989). Hawai'i has no native conifers, figs (*Ficus* spp.), or mangroves, and only one native genus of palms (*Pritchardia*), but a large endemic diversity in the legume family (Fabaceae), coffee family (Rubiaceae), citrus family (Rutaceae), myrtle family (Myrtaceae), and hibiscus family (Malvaceae). Almost half (425 out of 940) of the plants species listed as threatened or endangered in the United States are endemic to Hawai'i. (https://ecos.fws.gov/ecp/).

Hawai'i has more than 35 percent forest cover, including both native and nonnative forests (Jacobi et al. 2017) (figure 3). The State of Hawai'i is the largest

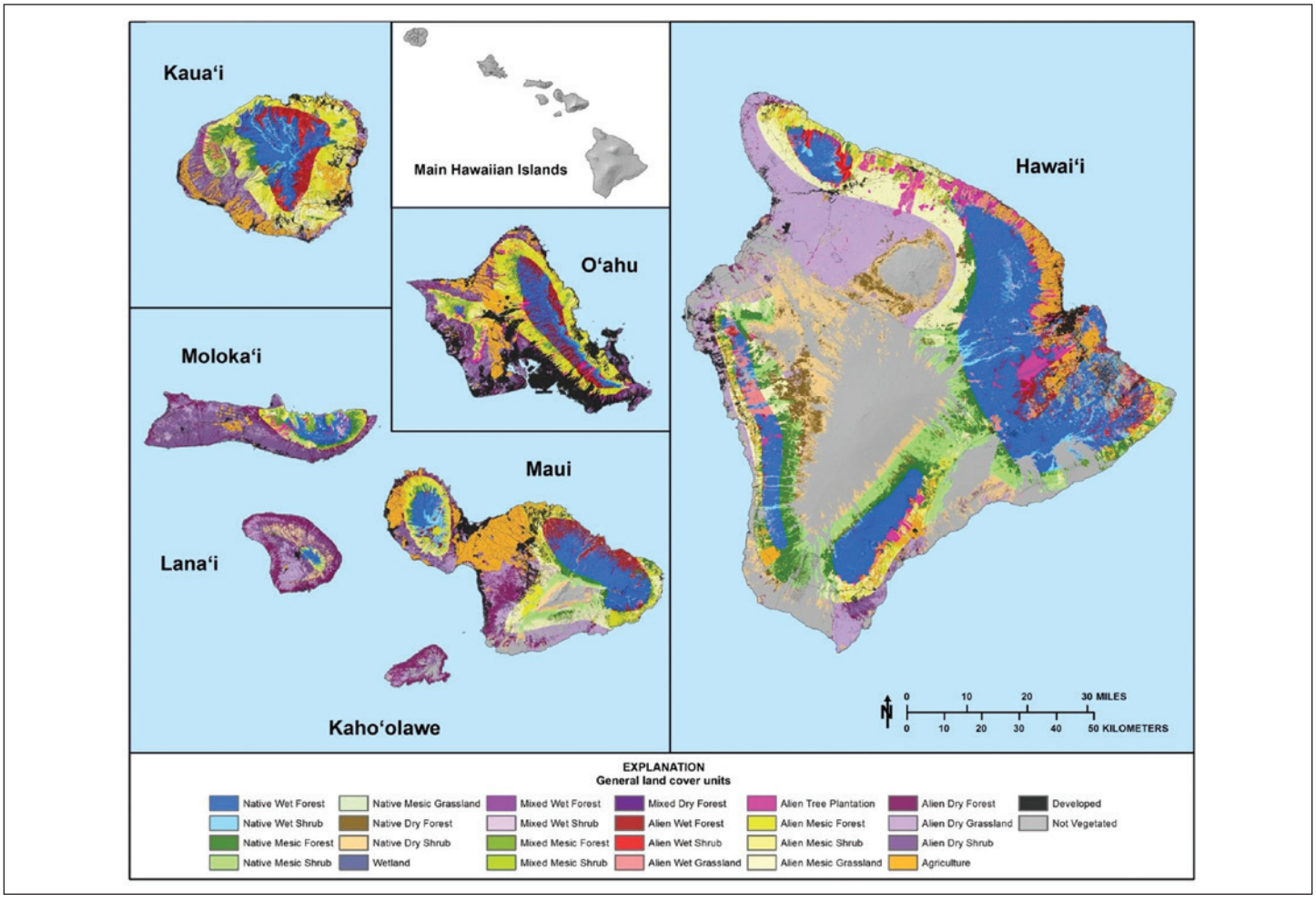

Figure 3. The land cover map of the Hawaiian Islands shows the diversity of ecological zones and the areas dominated by native and nonnative vegetation (Jacobi et al. 2017).

Figure 4. The montane wet forest of Kohala, Hawai'i Island, is dominated by 'ōhi 'a (*Metrosideros polymorpha*) with an understory of hāpu'u or tree ferns (*Cibotium* spp.). (Photo by J.B. Friday, 2009)

single forest landowner, followed by the Federal Government (mainly national parks, wildlife refuges, and military bases; there are no national forests in Hawai'i). About half of Hawaii's forests are privately owned (Zhang 2021). Land ownership is highly skewed: A few large estates and ranches own tens of thousands of acres, while there are thousands of private forest landowners on parcels of less than 10 ac (4 ha).

About 80 percent of native forests are dominated by 'ōhi'a (*Metrosideros polymorpha* Gaudich.) (Gon et al. 2006) (figure 4). 'Ōhi'a forests extend from the coastlines up to over 7,000 ft (2,100 m) elevation on the larger islands (Friday and Herbert 2006) and from young (150-year-old) lava flows on Hawai'i Island to the oldest weathered soils on Kaua'i. The tallest 'ōhi'a stands can reach 100 ft (30 m) in height on sites with deep soils and sufficient rainfall (figure 5), but trees are much smaller on young lava flows, on windswept ridges, or in bogs. In the wettest sites, which can receive over 200 in (5000 mm) of rainfall annually, 'ōhi'a can comprise almost 100 percent of the forest canopy, interspersed with the occasional loulu palm (*Pritchardia* spp. Seem. & H. A. Wendl.) or 'ohe mauka (*Polyscias* spp. J.R. Forst. & G. Forst.). If soils are poorly drained in these forests, bogs form which are dominated by the sprawling uluhe fern (*Dicranopteris linearis* Burm. f. Underw.) under an open canopy of 'ōhi'a. In montane wet to moderately dry forests, koa (*Acacia koa* A. Gray) is the other canopy dominant tree. At higher elevations (above 4,000 ft [1,200 m]) on Hawai'i Island and Maui, koa becomes the dominant overstory species.

Native subcanopy trees are much more diverse than canopy trees in the wet forests and include 'ōlapa (*Cheirodendron* spp. Nutt. ex Seem.), kōlea (*Myrsine* spp. L.), kōpiko (*Psychotria* spp. L.), and pilo (*Coprosma* spp. J.R. Forst. & G. Forst.). The understory is dominated by hāpu'u or tree ferns (*Cibotium* spp. Kaulf.). As forests become drier toward the leeward sides of the islands or at higher elevations on Hawai'i

Figure 5. Tall 'ōhi'a (*Metrosideros polymorpha*) trees, such as this one at the Hakalau Forest National Wildlife Refuge on Hawai'i Island, can reach 100 ft (30 m) in height. (Photo by J.B. Friday, 2013)

Figure 6. The typical dryland forest at Kaʻūpūlehu, Hawaiʻi Island, includes lama (*Diospyros sandwicensis*), left, and kauila (*Colubrina oppositifolia*), right. (Photo by J.B. Friday, 2008)

and Maui, both canopy and understory composition become more diverse. Canopy species can include kōlea, ʻiliahi or sandalwood (*Santalum* spp. L.), pāpala (*Pisonia* spp. L.), and mānele (Sapindus spp. L.). Understory species in the drier ʻōhiʻa forests include hōawa (*Pittosporum* spp. Banks ex Gaertn.), naio (*Myoporum sandwicense* A. Gray), and olupua (*Nestigis sandwicensis* [A. Gray] O. Deg., I. Deg. & L. Johnson).

Figure 7. The wili-wili (*Erythrina sandwicensis*), an endemic tree of the dryland forest, loses its leaves and flowers during dry seasons. (Photo by J.B. Friday, 2020)

Native dry forests are much less common than native wet forests, as most have been converted to ranches or destroyed by wildfires, but they are more diverse in tree species (figure 6). Lama (*Diospyros* spp. L.) is codominant with ʻōhiʻa on older substrates. Other tree species include māmane, naio, ʻiliahi, hōawa, wili-wili (*Erythrina sandwicensis* O. Deg.) (figure 7), and ʻohe makai (*Polyscias sandwicensis* [A. Gray] Lowry & G. M. Plunkett). A high-elevation dry forest that occurs at elevations over 6,000 ft (1,800 m) on Hawaiʻi Island is dominated by māmane and naio. A subalpine shrubland including ʻōhelo (*Vaccinium reticulatum* Sm.) and pūkiawe (*Leptecophylla tameiameiae* [Cham. & Schltdl.] C. M. Weiller) grows above the māmane-naio forest on Hawaiʻi Island and Maui.

In all but the most remote forests, native trees must compete with invasive woody species. In wet forests, the most common invader is strawberry guava (*Psidium cattleyanum* Sabine), which dominates the understory up to elevations of about 3,000 ft (910 m) (figure 8). The woody shrub Koster's curse (*Clidermia hirta* [L., D. Don]) and other shrubs and trees in the Melastomataceae family also compete with native plants for growing space. In dry forests, Christmasberry (*Schinus terebinthifolius* Raddi) is the most common invader. Escaped forest plantation trees such as silk oak (*Grevellia robusta* A. Cunn. ex R. Br.) also invade native, dryland forests.

Coastal forests usually comprise a mix of native and nonnative tree species (figure 9). The most common native species include hala (*Pandanus tectorius* Parkinson), milo (*Thespesia populnea* [L.] Sol. ex Corrêa), and kou (*Cordia subcordata* Lam.). These trees are usually found growing together with the Polynesian-introduced species coconut (*Cocos nucifera* L.), kamani (*Calophyllum inophyllum* L.), and noni (*Morinda citrifolia* L.), and modern introductions such as beach almond (*Terminalia catappa* L.). At low elevations on the dry, leeward sides of the islands a mixed nonnative forest comprised of koa haole (*Leucaena leucocephala* [Lam.] de Wit) and kiawe *(Prosopis pallida* (Humb. & Bonpl. ex Willd.) Kunth) predominates.

Figure 8. The invasive strawberry guava (*Psidium cattleyanum*) forms monospecific thickets in wet forests, as seen here on Moloka'i. (Photo by J.B. Friday, 2019)

Nonnative forests include both plantation forests and mixed forests comprised of vegetation that has regenerated after some change in land use, such as abandonment of agriculture, or disturbance such as fire. Mixed, nonnative forests dominate most islands' vegetation below about 2,000 ft (610 m) elevation and include escaped agricultural trees such as common guava (*Psidium guajava* L.), mango (*Mangifera indica* L.), and Java plum (*Syzygium cumini* [L.] Skeels); escaped forestry plantation trees such as albizia (*Falcataria moluccana* [Miq.] Barneby & J. W. Grimes) and Formosa koa (*Acacia confusa* Merr.); and escaped ornamental trees such as African tulip (*Spathodea campanulata* P. Beauv.). On the windward side of Hawai'i Island, a nonnative wet forest dominated by gunpowder tree (*Trema orientalis* [L.] Blume), bingabing (*Macaranga mappa* [L.] Müll. Arg.), trumpet tree (*Cercropia obtusifolia* Bertol.), and *Melocia umbellata* (Houtt.) Stapf has regenerated on abandoned agricultural lands (Little and Skolmen 1989). Extensive stands of kukui or candlenut (*Aleurites moluccanus* [L.] Willd.) in the backs of windward valleys are likely the remains of ancient Hawaiian agroforestry systems, where the trees were widely cultivated (Lincoln 2020) (figure 10).

Forestry plantations are dominated by eucalypt species (Nelson 1965). *Eucalyptus robusta* Sm. was the most commonly planted species in the 20th century, but plantations of *E. saligna* Sm., *E. camaldulensis* Dehnh., and *E. sideroxylon* A. Cunn. ex Woolls are also commonly encountered. *Eucalyptus grandis* W. Hill ex Maid. was planted on tens of thousands of acres of former sugar cane plantation lands in the late 1990s (figure 11). Other common plantation species include silk oak, paperbark (*Melaleuca quinquenervia* [Cav.] S. T. Blake), ironwoods (*Casuarina* spp. Adans), and tropical ash (*Fraxinus uhdei* [Wenz.] Lingelsh.). Planted conifers include pines (*Pinus* spp.), mainly

Figure 9. A typical Hawaiian coastal forest, as seen here at Pu'uhonua o Hōnaunau National Historical Park on Hawai'i Island, is comprised of native plants such as naupaka (*Scaevola taccada*), Polynesian introductions such as niu or coconut (*Cocos nucifera*), and modern introductions such as beach heliotrope (*Heliotropium arboretum*). (Photo by J.B. Friday, 2021)

Figure 10. A forest canopy of kukui (*Aleurites moluccanus*) and hala (*Pandanus tectorius*) has grown up in an abandoned agricultural site, Waimanu Valley, Hawai'i Island. (Photo by J.B. Friday, 2021)

Koa, *Acacia koa* A. Gray

Koa trees provide the timber Hawai'i is known for around the world. Koa wood is usually reddish but ranges from golden to dark brown in color and often has beautiful figure (Skolmen 1974) (figure 12). Today, the wood is used for high-end furniture, cabinetry, and musical instruments. Koa supplies have steadily decreased and wood prices have increased in the past 30 years. In ancient times, Hawaiians carved canoes from giant koa trees cut from upland forests (figure 13). Koa is endemic to Hawai'i and is in the legume family (Fabaceae). Koa and 'ōhi'a dominate the canopy of most upland wet and mesic forests in Hawai'i. Of the two species, koa grows much faster, often increasing 3 ft (1 m) in height annually during the early stages of growth. In mixed forests, koa, being shade intolerant, regenerates in gaps from a buried seed bank and is eventually replaced by 'ōhi'a (Baker et al. 2009). Mature trees on good sites commonly reach 80 ft (24 m) in height and 5 ft (1.5 m) in diameter (Friday 2010) (figure 14). In the 19th and 20th centuries, much of Hawaii's native koa forest was cleared for pastures. Because koa is a pioneer species on disturbed sites, it is by far the most commonly planted native tree in Hawai'i (figure 15). Wildlife plantings, mainly done on public lands, provide habitat for Hawaii's endangered forest birds such as the 'akiapōlā'au (*Hemignathus wilsoni* Rothschild). Private landowners, encouraged by increases in the value of koa timber, have begun reforesting hundreds of acres of koa annually for potential future commercial harvests.

cluster pine (*P. pinaster* Aiton), Monterey pine (*P. radiata* D. Don), and slash pine (*P. elliottii* Engelm.); cypress (*Cupresses* spp. L.); and Norfolk Island pine (*Araucaria heterophylla* [Salisb.] Franco) and Cook pine (*Araucaria columnaris* [G. Forst.] Hook.).

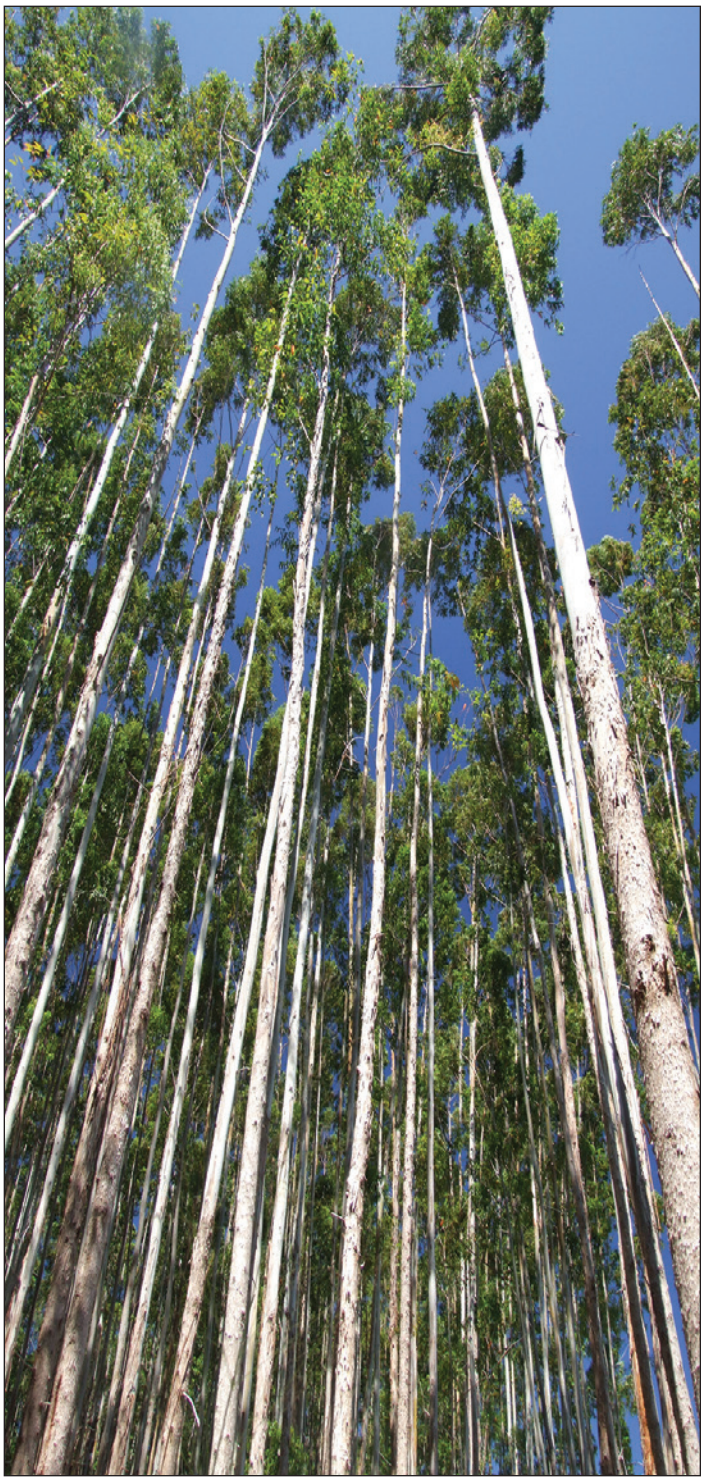

Figure 11. A 13-year-old industrial plantation of *Eucalyptus grandis*, Hawai'i Island, is slated to be harvested for bioenergy. (Photo by J.B. Friday, 2011)

Figure 12. Koa (*Acacia koa*) veneer is made into fine furniture such as this table. (Photo by J.B. Friday, 2015)

Figure 13. Hawaiians continue the ancient tradition of racing koa (*Acacia koa*) canoes in Hilo, Hawai'i. (Photo by J.B. Friday, 2016)

Figure 14. Tall forest koa (*Acacia koa*) trees are rare but can provide logs for carving racing canoes. (Photo by J.B. Friday, 2009)

Figure 15. Hundreds of acres of former pasture lands are being reforested with koa (*Acacia koa*) seedlings, Hawai'i Island. (Photo by J.B. Friday, 2017)

Forest History

Polynesian voyagers arrived in Hawai‘i between about 1,000 and 1,100 CE, sailing up from Tahiti or the Marquesas (Athens et al. 2014). Experienced colonizers, they carried with them the plants needed to support life and begin farming in their new home. For staple crops, they carried taro (*Colocasia esculenta* L. Schott), yams (*Dioscorea* spp. L.), breadfruit (*Artocarpus altilis* (Parkinson) Fosberg) (figure 16), coconuts, and bananas (*Musa* spp. L.). The tree species they brought included kukui, from which they obtained a useful oil from the nuts; noni, which still is used medicinally; hala, for the leaves to weave mats and sails for canoes; and kamani for its beautiful wood and nuts that yield a medicinal oil. Hawaiians initially settled in wet, windward valleys, where they cultivated irrigated taro, but over the centuries, populations expanded into the upland, where they cultivated sweet potatoes in open fields and breadfruit and yams in agroforestry systems (Kirch 2019). Captain Cook estimated the population in 1778 as being up to 400,000, but other estimates of population range up to double that number, not that much lower than the current population of 1.4 million (Stannard 1989).

Although there are few native, edible fruits in Hawaiian forests, early Hawaiians were able to cut koa logs for huge, seagoing canoes, harvest ‘ōhi‘a for carving of everything from house posts to images of deities, and cut kou and milo to make fine carved food vessels. Other useful plants collected from the forest included olonā (*Touchardia latifolia* Gaudich.) for cordage, māmaki (*Pipturus albidus* [Hook. & Arn.] A. Gray) for medicinal tea, and maile vines (*Alyxia stellata* [J. R. Forst. & G. Forst.] Roem. & Schult.), and palapalai ferns (*Microlepia strigosa* [Thunb.] C. Presl) for lei. While the overall area of land cleared for agriculture was relatively small (Gon et al. 2018), the accidental introduction of the Polynesian rat had a significant impact on populations of some large-seeded species such as the endemic loulu palms, several of which are endangered today (Hodel 2012). Ancient Hawaiians described many ecological zones, but an overall understanding was that the lower elevation forests, along with agroforests and homesteads, were “wao kanaka” or the zone of people, whereas the upper elevation, pristine forests were “wao akua,” or the zone of the gods, to be entered only at need and with strict preparations.

Figure 16. Breadfruit or ‘ulu (*Artocarpus altilis*) was one of the traditional crops of ancient Hawai‘i and is regaining popularity today. (Photo by J.B. Friday, 2021)

Western contact in 1778 changed Hawaiian society drastically. Initially, sailors saw the islands as a convenient place to acquire fresh provisions. Captain Cook introduced goats to Hawai‘i, and Captain Vancouver introduced cattle and sheep in 1793. These animals were released into the forests, where, in addition to damaging the crops of local people, they began decimating the native forest vegetation. The whaling industry, which was the dominant industry in Hawai‘i in the mid-1800s, needed supplies of firewood to process the whale oil, and the slopes above the harbor towns of Honolulu and Lahaina on Maui were soon denuded by woodcutters. In the late 1700s, a sailor discovered that some of the firewood on board was actually sandalwood, which could be sold at a high price in China. The subsequent trade was a boom for merchants but a tragedy for the common people, who were forced to journey into the uplands to cut trees for the chiefs to sell to foreign traders.

Cattle ranching in Hawai‘i began expanding by the 1850s and resulted in increased forest loss. Increased flooding in urban areas and decreased stream and spring flow triggered calls for protection of remaining forests to protect water sources (Cox 1992). In 1856, William Hillebrand, a German-born botanist, blamed forest destruction mainly on cattle rather than lumbering, as local wood supplies were mostly imported from the continental United States. Hillebrand and others advocated for fencing, protection from cattle and other feral animals, and establishment of plantations. Hillebrand also imported many tree species to reforest the denuded

Figure 17. Haleakalā sandalwood (*Santalum haleakalae*) is endemic to the island of Maui. (Photo by J.B. Friday, 2018)

Sandalwood in Hawai‘i

Hawai‘i is home to 6 endemic species of ‘iliahi or sandalwood (*Santalum* spp.) out of about 25 species worldwide (Harbaugh et al. 2010) (figure 17). The discovery that this precious wood grew in quantity in Hawaiian forests set off the first big boom and bust in the modern Hawaiian economy (Merlin and VanRavenswaay 1989). Hawaiian chiefs, eager for cash to purchase Western merchandise, forced commoners up into the forests to cut wood to pay a newly imposed sandalwood tax. Western merchants then sold the wood to China for carving, cabinet making, and for its fragrant, essential oils. Ditches the dimensions of a ship's hull were dug into the ground and were to be filled with sandalwood logs before the ship's return; one of these ditches can still be seen on the island of Moloka‘i. At the peak of the trade, Hawai‘i exported over 1,000 tons (907 metric tons) per year of sandalwood. American gunboats arrived in Honolulu to enforce collection of debts, to be paid in sandalwood, from chiefs who had borrowed to purchase luxury goods. Farmers were forced to neglect their crops to complete this back-breaking labor. Stories are told of Hawaiians who would pull out any sandalwood seedling they saw, lest the trade continue and their children also be forced to cut sandalwood. By 1839, the Kingdom of Hawai‘i passed a law restricting sandalwood cutting, ostensibly to ensure sustainable harvests, but it was too late. Stocks had collapsed and trade moved on to other Pacific Islands to repeat the same cycle. While most of the dry forests that harbor sandalwood have been converted to ranches, some species, particularly *S. paniculatum* Hook. & Arn. on Hawai‘i Island, have remained relatively common, especially in parks and protected areas, although large trees are rare. In 2010, the first of several landowners in Kona on Hawai‘i Island began replanting sandalwood forests for future harvests. Although details of silviculture and rotations ages are unknown, hundreds of acres of dryland forests of sandalwood and its associated species are currently being planted.

slopes above Honolulu. In 1876, the legislature of the Kingdom of Hawai‘i passed an act to protect watersheds and create the first forest reserves. The growth of the sugar industry in the late 1800s increased local demand for firewood, exacerbating forest loss. The first Government tree nursery was established in 1882 to provide seedlings for reforestation of the slopes above Honolulu. Reforestation projects also began on Maui, Kaua‘i, and Hawai‘i Island. By 1887, over 200,000 trees had been planted to protect the watersheds above Honolulu (Walker 1887).

In 1893, the independent Kingdom of Hawai‘i was overthrown, and 5 years later, Hawai‘i was annexed by the United States. Government and Crown lands of the kingdom were transferred to the U.S. Federal Government and most were later transferred to the Territory and later the State of Hawai‘i. The new Territorial Government applied to Washington for assistance, and Ralph Hosmer, a protégé of Gifford Pinchot (first chief of the USDA Forest Service), took office as the first Territorial forester in 1904 (Cox 1992). The Territorial Forest Reserve system was established in 1906 and encompassed both public and private lands. The Forestry Division began fencing remaining forest areas; removing feral livestock, such as cattle, goats, sheep, and pigs; and planting trees. Nurseries were established on each island, not just to supply seedlings for public lands but also for distribution to private landowners. Harold Lyon, who was employed by the sugar industry, became of the strongest advocates for reforestation to ensure a steady supply of water for the plantations. Lyon, however, a plant pathologist by training, was convinced that the native forest trees were inevitably declining and could not withstand the new invasive plant species and feral animals that roamed the uplands. Lyon and botanist Joseph Rock imported trees from all over the world, which became the main species used in reforestation.

From 1910 to 1960, over 12 million trees, including 800 different species, were planted on the Forest Reserves (Nelson 1965). Tree species native to Australia topped the list, with over 2 million *Eucalyptus robusta* planted (figure 18), followed by silk oak, paperbark, and ironwoods. The foresters of that era did not totally neglect the native trees, however, and over 1 million koa were planted. Sadly, none of the koa plantations of that era seem to have survived to the present, probably destroyed by feral ungulates, competition from weeds,

Figure 18. *Eucalyptus robusta* was the most widely planted tree in the first half of the 20th century in Hawai'i. These trees were planted in the 1930s at Kalopā on Hawai'i Island. (Photo by J.B. Friday, 2017)

and wildfires. In the dry coastal lowlands, foresters established plantings of kiawe, a mesquite relative, and koa haole to provide forage for livestock. Seedlings were not only planted on forest reserves but distributed to private farmers and ranchers. By the 1950s, foresters began planting more potential timber trees in hopes of developing a lumber industry. Several species of true pines were planted in the uplands, and on Hawai'i Island 12,000 ac (4,900 ha) of native forest were cleared to plant eucalyptus, Australian red cedar (*Toona ciliata* M. Roem., a mahogany relative), Queensland maple (*Flindersia brayleyana* F. Muell.), and tropical ash. With the final collapse of the sugar industry on Hawai'i Island in the 1990s, over 20,000 ac (8,100 ha) of former sugar cane lands and marginal pastures were planted with *Eucalyptus grandis* for short-rotation biomass crops. An additional 1,500 ac (600 ha) of a mixture of *Eucalyptus deglupta* Blume and the nitrogen-fixing legume *Falcataria moluccana* were also planted on former cane lands on Kaua'i. Markets for these trees have been difficult to find, however. About 2,000 ac (800 ha) of the Hawai'i Island eucalyptus plantations were harvested for peeler logs that were exported to China. The plantation managers are now planning to harvest the rest for biomass energy, and the Kaua'i plantations are also being harvested for biomass energy.

In the 1970s and 1980s, the emphasis of forestry programs moved to protecting and restoring native ecosystems. The Hakalau Forest National Wildlife Refuge was established in 1985 to protect habitat for endangered forest birds and has become the largest native forest restoration project in the State. The refuge's strategy has been to extend native forest up slope into degraded ranchlands by planting koa, which grows quickly and can overtop the introduced pasture grasses and escape frost damage during its first winter (Scowcroft and Jeffrey 1999). Once the koa has established a canopy, a suite of native understory plants is established, including fruiting species for frugivorous birds (figure 19). More recently, the refuge has obtained funding to increase populations of endangered native plants on the refuge. In the past 35 years, the refuge has planted over 600,000 native plants, mostly koa, and reforested over 4,000 ac (1,600 ha).

In addition to the Hakalau Refuge, many other native reforestation efforts have been driven by funding to provide habitat for endangered species. The Mauna Kea Restoration Project is replanting 1,000s of acres of māmane-naio forest on Mauna Kea to create additional habitat for the endangered palila bird (*Loxioides bailleui* Oustalet) (figure 20), which feeds on the māmane seeds (figure 21). In contrast, the Auwahi forest on Maui, the Ka'ūpūlehu forest on Hawai'i Island, and other dryland forest projects are re-establishing diverse native plant communities, including a mix of common and rare species, with intensive management on tens rather than thousands of acres.

In the last 10 years, increasing prices for koa lumber and the possibility of sustainable harvests of sandalwood have led to increased planting of these native trees. Private landowners on both Hawai'i Island and Maui are now reforesting hundreds of acres per year with these species, and some are planting other forest trees with the goal of creating a more natural forest. Sandalwood species, in particular, require a host plant

Figure19. Students and other volunteers have planted tens of thousands of native understory plants under previously established koa (*Acacia koa*) overstory at the Hakalau Forest National Wildlife Refuge on Hawai'i Island. (Photo by J.B. Friday, 2014)

for good growth (Speetjens 2021), and current sandalwood plantings employ a mix of host trees (figure 22).

Nurseries and Seedling Production

Seedlings for reforestation in Hawai'i are grown by a mix of both public and private nurseries, and some public agencies contract private nurseries to grow seedlings for them. The main State tree nursery is located in the town of Waimea on Hawai'i Island (https://dlnr.hawaii.gov/forestry/info/nurseries/), but the State forestry offices on Kaua'i, O'ahu, Maui, and Hawai'i Island also have their own nurseries to produce seedlings for local projects and for sale to

Figure 20. The palila (*Loxioides balleui*), an endangered Hawaiian forest bird, is dependent on decreasing populations of the māmane tree (*Sophora chrysophylla*) for both food and shelter. (Photo by Bret Nainoa Mossman, 2021)

Figure 21. The māmane (*Sophora chrysophylla*), is an endemic tree of high-elevation forests. The seed pods comprise the main diet of the endangered palila bird. (Photo by J.B. Friday, 2018)

Figure 22. Sandalwood or ʻiliahi (*Santalum paniculatum*) is hemi-parasitic and is usually planted under a host tree, in this case koa. (Photo by J.B. Friday, 2021)

the public during Arbor Day events (figure 23). In addition, each of the four main islands also has a rare plant nursery devoted to growing the species of greatest conservation needs (http://www.pepphi.org/). These nurseries are located at higher elevations, as most of the protected habitat for these rare plants is in upland areas. More than 90 percent of the trees produced by the State tree nurseries are native species, but they also produce some nonnative species such as conifers and eucalypts for ranch windbreaks and noninvasive ornamentals for landscape use. About one-quarter of the seedlings produced by the State tree nurseries are sold to the private sector, while the rest are planted on the State forest reserves.

In 2021, the public and private forestry and conservation nurseries in Hawaiʻi produced over 470,000 tree and shrub seedlings. The State tree nurseries produced about 76,000 seedlings, other public agency nurseries (such as those at the National Parks and Wildlife Refuges) produced about 25,000, and private nurseries produced the rest (figure 24). Almost all stock is grown in dibble tubes (e.g., Ray Leach Cone-tainer™ or Deepot™; Stuewe and Sons, Inc., Tangent, OR), with the most popular size being 10 in^3 (164 cm^3), although tubes up to 40 in^3 (655 cm^3) are commonly used. The larger contain-

Figure 23. The State tree nursery in Waimea, Hawaiʻi Island, grows seedlings such as these 6-month-old ʻōhiʻa (*Metrosideros polymorpha*) for reforestation projects on State lands and for sale to the public. (Photo by J.B. Friday, 2017)

Figure 24. Kōlea (*Myrsine lessertiana*) seedlings are produced for reforestation projects using a subirrigation system at Maui Native Nursery (https://www.mauinativenursery.com/). (Photo by J.B. Friday, 2014)

ers tend to be used for rare plants or dryland species. Seedlings for urban forestry are more commonly grown in 1 gal (3.8 L) pots. Over half of the tree seedlings produced in Hawai‘i are koa, followed by māmane, ‘a’ali’i (*Dodonaea viscosa* Jacq., an indigenous shrub or small tree), ‘iliahi, and ‘ōhi‘a. Most tree species can be grown in 3 to 12 months, but a few, for example ‘ōhi‘a, may take up to 2 years in the nursery. Over 900 ac (360 ha) were reforested with native species in 2021. In addition, many nursery-grown seedlings were used for understory plantings to enrich degraded forests. Nurseries reported growing 80 native species of trees and shrubs and 35 nonnative tree species in 2021, along with many other species of native forbs and grasses.

State Forestry Programs

Forest Stewardship

The State Forest Stewardship program was established in 1991 and is funded by both the State of Hawai‘i and the U.S. Department of Agriculture (USDA), Forest Service. The program provides technical and financial assistance on a cost-share basis to private landowners to promote stewardship, enhancement, conservation, and restoration of Hawaii’s forests (https://dlnr.hawaii.gov/forestry/lap/fsp/). Participants can receive support for management planning, timber or agroforestry production, native forest conservation and restoration, fire presuppression, watershed protection, and recreation and wildlife habitat enhancement.

Urban and Community Forestry

Hawaii’s Urban and Community forestry program began in 1991 and is funded by both the State of Hawai‘i and the USDA Forest Service. The program is called Kaulunani, which can be translated as “beautiful growth” but also refers to the connections between healthy communities and the urban forest. The purpose of the program is to strengthen the capacity of communities to plan for, establish, manage and protect trees, forests, and green spaces across Hawai‘i (figure 25). The program seeks to improve the understanding of the benefits of trees in urban areas and communities, increase tree canopy cover, reduce carbon emissions, conserve energy, improve air quality and increase other environmental benefits, support community tree planting and tree demonstration projects, support Arbor Day activities, enhance the technical skills and knowledge of the urban forest industry, and expand research and educational efforts (https://dlnr.hawaii.gov/forestry/lap/kaulunani/). In 2021, the program funded the planting of 5,000 trees in urban or residential areas.

Figure 25. ʻUlu lāʻau, Waimea Nature Park (Hawaiʻi Island), is a community park funded by the Hawaiʻi Urban and Community Forestry Program, Kaulunani. The park showcases many native trees including both red- and yellow-flowered varieties of ʻōhiʻa lehua (*Metrosideros polymorpha*). (Photo by J.B. Friday, 2013)

Other Agency Programs

In addition to State-funded programs, forest landowners in Hawaiʻi have been able to use other assistance programs including the USDA Natural Resources Conservation Service's Environmental Quality Incentives Program (EQIP) and the U.S. Fish and Wildlife Service Partners programs to implement forest management activities that protect soil and water resources, control invasive species, and create habitat for endangered plants and animals. In addition, Hawaiʻi County, the local government on Hawaiʻi Island, offers lowered property taxes on land dedicated to native forest restoration.

Challenges to Successful Reforestation

Invasive plants are probably the worst threat to native wet forests. When trees are killed by pests or diseases, they are most often replaced by weedy plant species. Most wet forests below about 3,000 ft (900 m) elevation are invaded by the understory tree strawberry guava, the shrub Koster's curse, the herbaceous kahili ginger (*Hedychium gardnerianum* Sheppard ex Ker Gawl.), or other nonnative weeds. While these forests may have a native overstory, they lack any native regeneration because the understory is completely occupied by weeds. Mechanical or herbicidal control is only cost-effective in limited areas. Effective biocontrol agents seem to be the only practical way to save these forests. Biocontrol efforts have had some success, for example in controlling the banana poka (*Passiflora tarminiana* Coppens & Barney) (Trujillo et al. 1994). Recent importation and release of a new insect biocontrol that attacks strawberry guava gives some hope that the weed's advance into native forests can be stopped (USDA Forest Service, no date).

Feral ungulates, primarily pigs in wet forests; goats and sheep in dry forests; introduced deer on Maui,

Figure 26. Feral bulls cause damage to forest plantations such as this sugi pine (*Cryptomeria japonica*) grove on Hawai‘i Island. (Photo by J.B. Friday, 2017)

Moloka‘i, Lana‘i, and Kaua‘i; and cattle in some areas; continue to destroy native species and spread nonnative plants in areas where they are not excluded (figure 26). Because these animals, except for cattle, are also game species, they are not excluded from most State-managed public forests. Nonnative pests and pathogens continue to arrive in Hawai‘i, often on imported plants. The disease Rapid ‘Ōhi‘a Death was first described in 2014 (Keith et al. 2014) and has since spread over Hawai‘i Island and killed over one million ‘ōhi‘a trees (figure 27). The disease is caused by two newly described species of the fungus *Ceratocystis* (Barnes et al. 2018). Because *Ceratocystis* is a wound pathogen, wounding by feral ungulates seems to be a contributing factor in the disease's spread (Perroy et al. 2021), and fenced and protected forest areas with low feral ungulate populations have low levels of disease. Another new pathogen of concern is *Austropuccinia psidii* Beenken, a rust fungus attacking many species of trees in the myrtle family (Myrtaceae) (Uchida et al. 2006). When it was first detected, the disease mainly attacked nonnative trees such as rose apple (*Syzygium jambos* [L.] Alston), but in 2016 and 2017, it caused widespread defoliation of ‘ōhi‘a trees on O‘ahu and Moloka‘i. Populations of the endangered nioi (*Eugenia koolauensis* O. Deg.) have also been drastically reduced by the fungus. A *Fusarium* wilt of koa (*Fusarium oxysporum* f. sp. koae) (Gardner 1980)

Figure 27. Rapid ‘Ōhi‘a Death is a newly discovered fungal disease that can cause almost complete mortality of a stand of ‘ōhi‘a (*Metrosideros polymorpha*). (Photo by J.B. Friday, 2016)

causes high levels of mortality to planted koa stands at lower elevations (below about 2,500 ft [760 m]). A program to select for disease tolerance (Dudley et al. 2015) has developed lines of koa that show high tolerance of the disease and good survival even at lower elevation, warmer sites.

Hawaii's forests have long suffered from nonnative insect pests. A moth, the kou leaf roller (*Ethmia nigroapicella* Saalmueller), defoliated and killed the native kou tree across the islands after its introduction in the 1890s (Swezey 1943) (figure 28). While kou was a principal shade tree in Honolulu in the 1800s, it was largely replaced in urban forestry settings by nonnative species after the moth was introduced. A gall wasp, *Quadrastichus erythrinae* Kim, was discovered in Hawai'i in 2005 and rapidly killed almost all coral trees (*Erythrina variegata* L.) across the State (Heu et al. 2008). While *E. variegata* is not native to Hawai'i, the trees were widely planted as an urban shade species and a vertical cultivar was planted as windbreaks for agricultural fields. The native congener wili-wili (*E. sandwicensis*) is slightly more tolerant of the wasp and has likely been saved by introduction of a biocontrol agent (Kaufman et al. 2020). A thrips species (*Klambothrips myopori* Mound and Morris), which was first detected in 2009, has caused up to 80 percent mortality on naio, one of the two native trees that dominated the rare māmane-naio forest type on Mauna Kea (Conant et al. 2009).

Wildfires are an increasing threat to Hawaii's dryland forests (figure 29). While small in total acreage relative to fires on the U.S. mainland, wildfires in Hawai'i affect as large a percentage of the State as they do in the fire-prone Western States (Trauernicht et al. 2015). Almost all fires are anthropogenic, but the increase is caused by the invasion of nonnative grasslands into native dryland forests, which are not fire-adapted (D'Antonio and Vitousek 1992), and growth of grasses and other flammable vegetation on abandoned agricultural lands (Pacific Fire Exchange 2021). Climate changes predicted for Hawai'i include increased precipitation in wet areas and reduced perception in dry areas, which will increase fire risk near high-value, high-altitude forests (Elison Timm 2015, Trauernicht 2018). Effects of wildfire are multiplied by the problems of increased invasive species and climate change. To improve

Figure 28. Kou (*Cordia subcordata*) is regularly defoliated by the kou leaf roller (*Ethmia nigroapicella*). These trees have been able to recover after each defoliation. (Photo by J.B. Friday, 2017)

communication among fire scientists, land managers, and fire responders, the Pacific Fire Exchange (PFX) (http://www.PacificFireExchange), 1 of 15 Fire Science Exchanges nationally, was formed in 2011 under the Joint Fire Science Program (https://www.firescience.gov), funded by the U.S. Department of the Interior and the Forest Service. The PFX has increased understanding of wildfire problems among local communities and political decision makers. Efforts have included promoting fuels management, practices such as fuel breaks around developed areas, and use of livestock to reduce fuel loads (Pacific Fire Exchange 2016). Increasing wildfires have led to increased demand for seedlings to restore burned areas. Because these demands are unpredictable, nurseries have recently begun banking large quantities of seed of common native tree and shrub species so they can quickly ramp up seedling production following a fire (Chau et al. 2019). Each State nursery and some other agency nurseries such as the one at Hawai'i Volcanoes National Park has a seed bank.

While Hawai'i has no forest protection act, many forests are legally protected by both State and county level zoning laws. Almost all lands which are not zoned conservation have already been developed on

Kaua‘i, O‘ahu, and Maui, but large areas of native forest are zoned agriculture on Hawai‘i Island. Conversion of forests for agriculture or residential areas is an ongoing problem on Hawai‘i Island. Landowners are free to clear these forests and develop them for agriculture, ranching, or housing. Ongoing suburban development in these areas leads to forest fragmentation and ingress of invasive species.

The decline of both planation agriculture and ranching in Hawai‘i since the 1980s has created the opportunity for landscape-scale reforestation of former agriculture or crop lands. To date, most native reforestation efforts have focused on creating habitat for endangered forest birds or rare plants. In the past few years, however, private landowners have begun reforesting with koa and, in some cases, sandalwood in an effort to create a sustainable forest industry based on these species. While there have been many recent harvests of nonnative plantation trees in Hawai‘i, there have been very few of plantation koa and none of planted sandalwood. The silviculture of each species is still being developed (Baker et al. 2009, Speetjens et al. 2021). Nevertheless, investments by private landowners could increase the area planted annually with native trees from hundreds to thousands of acres.

Figure 29. Koa (*Acacia koa*) seedlings can regenerate from the buried seed bank after a wildfire kills the overstory trees as seen here in Hawai‘i Volcanoes National Park. (Photo by J.B. Friday, 2018)

Future Directions

The most pristine native forests in Hawai‘i, both public and private, will benefit from increased protection in the future. As in the past, this protection will be based on their importance for watershed protection (Department of Land and Natural Resources 2011). Priority forest areas will be fenced and have feral ungulates and weeds removed, and buffers will be replanted with native species. Hawai‘i is committed to protecting 30 percent of high-priority forests protecting the islands’ watersheds by 2030 (Department of Land and Natural Resources 2017). Marginal and degraded forests, however, will likely continue to suffer loss of native species because of invasive plants, damage from feral ungulates, pests and diseases, wildfires, and conversion to agriculture or other nonforest uses.

Native reforestation projects, often with trees planted by community volunteers, create opportunities for people to reconnect with the forest. Native Hawaiians, in particular, are leading efforts to restore forests not just with valuable or rare plants but also with those of cultural significance. Cultural values are being combined with biodiversity and economic values to create biocultural approaches to forest management (Gon et al. 2018, Kamelamela et al. 2022, Kealiikanakaolehaililani et al. 2018). For example, there was an old tradition from the dry uplands of the Kona side of Hawai‘i Island of giving visitors lei made from flowers of the halapepe (*Dracena konaensis* [H. St. John] Jankaliski) (figure 30). In past decades, the tree has become endangered because of destruction by cattle, wildfires, and attack by new insect pests, and the tradition has died out. Local people, led by native Hawaiians, are now restoring those forests, and they have a vision that the halapepe might once again become so abundant that the tradition of using the flowers for lei can be revived. A related development is a new interest

Figure 30. Flowers of the halapepe (*Dracena konaensis*) were once used for lei by Hawaiians, but today the tree is endangered. (Photo by J.B. Friday, 2013)

in reviving traditional agroforestry systems based on breadfruit and other traditional crops for local food production (figure 31). Community groups are working to restore both social and ecological landscape functions by using a historical ecology approach, drawing on community and traditional Hawaiian knowledge as well as ecological information (Kurashima et al. 2017). This approach helps to create a working landscape with native plants and food crops that will support local communities as well as restore native flora. One of the oldest examples is the Hoʻoulu ʻĀina project in the forested valley above Kalihi, one of the most densely populated neighborhoods in Honolulu (www.hoouluaina.com). Here, urban community members, in particular native Hawaiian and other Pacific Islanders, have access to land for gardening traditional crops and participate in restoring the native forests of the valley. Whereas public and private forest lands have been centrally managed for the past century, these and other examples of community-based forest management are now being implemented. Public concern about the well-being of Hawaii's forests and involvement with forest restoration has never been higher in modern times than it is today.

Figure 31. A traditional agroforesty system at the Amy B. H. Greenwell Ethnobotanical Garden in Kona, Hawaiʻi Island includes taro (*Colocasia esculenta*, foreground), ʻawa (*Piper methystiucm*, understory), and breadfruit or ʻulu (Artocarpus altilis) trees. The garden is managed with constant help from community volunteers. (Photo by J.B. Friday, 2020)

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