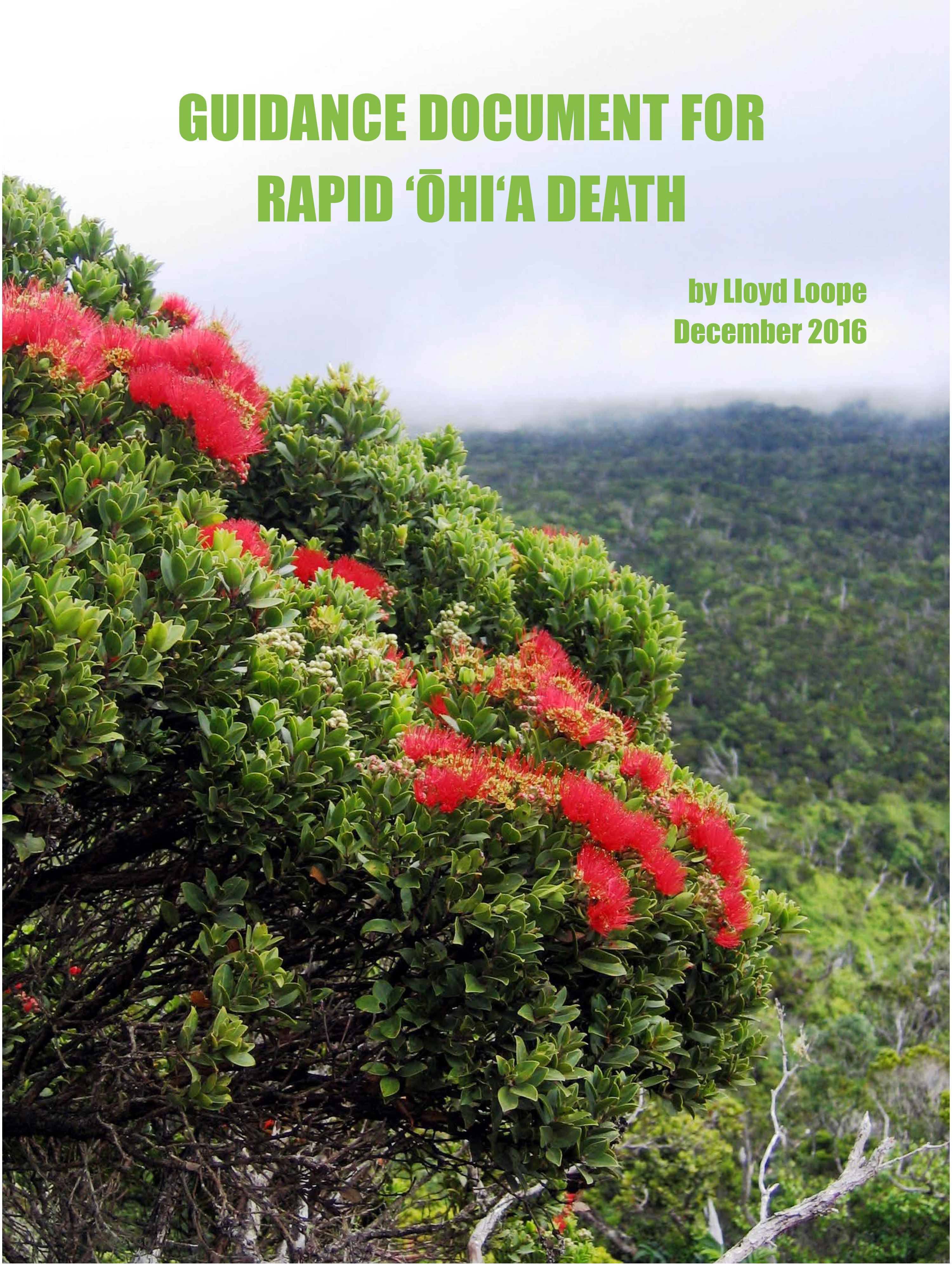
GUIDANCE DOCUMENT FOR RAPID ʻŌHIʻA DEATH

by Lloyd Loope

December 2016



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Background for the 2017—2019 ROD Strategic Response Plan

by

Lloyd Loope
December 2016

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Executive Summary

This document provides a summary of the current state of knowledge regarding *Ceratocystis*-induced Rapid ʻŌhiʻa Death and an initial presentation and analysis of the options to manage the disease. It also provides essential background information for use in development and refinement of a response plan.

ʻŌhiʻa lehua, *Metrosideros polymorpha,* is arguably one of the world's best examples of a "foundation species." It is a tree species essential for native forest ecosystem function and provides habitat to the rich endemic biodiversity of Hawaii's forests. Consequently, ʻōhiʻa has long held enormous cultural significance to native Hawaiians. The widespread dominance of ʻōhiʻa in Hawaiian forests has generated concern for over a century that if something were to drastically reduce the health and abundance of ʻōhiʻa forest stands, the result would be ecologically catastrophic. Concern over "ʻōhiʻa dieback" was first noted in the early 1900s and resurfaced in the 1970s. In contrast to Rapid ʻŌhiʻa Death, these episodes of dieback came to be recognized as a natural component of native forest succession in Hawaiʻi.

In 2009-2010, residents of the Puna district on Hawaiʻi Island began reporting abrupt mortality of ʻōhiʻa trees on their properties and adjacent forest stands. They described scenarios where on previously healthy-looking trees, all of the leaves of a major limb or the entire tree canopy would quickly turn yellow, then brown. Within a few weeks, the tree would appear dead. Spread of dying trees was at first slow, but accelerated over time. By 2012, 10% or more of ʻōhiʻa trees of all ages had died in a patchwork of ca. 1600 hectares (4000 acres) across the Puna district (Mortenson and others 2016). By 2014, the affected area had increased to ca. 6400 ha (16,000 acres), and the problem began receiving major attention and research. Initial sampling of roots of symptomatic trees revealed nothing unusual, but in 2014 UH-CTAHR isolated a fungus from wood samples of a symptomatic tree that was identified as belonging to the genus *Ceratocystis,* a genus that includes species that are pathogenic to a wide variety of tree species but had not previously been documented on ʻōhiʻa. By late-2014, pathogenicity tests conducted by Dr. Lisa Keith and colleagues (USDA-ARS, Pacific Basin Agricultural Research Center) had determined that an agent causing the disease is allied with the vascular wilt fungus *Ceratocystis fimbriata* (Keith and others 2015). Soon afterward, a second pathogen, also in the *Ceratocystis fimbriata* complex, was found

J.B Friday; The Nature Conservancy of Hawaiʻi

Reports by residents of previously healthy, mature ʻōhiʻa suddenly turning brown and dying within a few weeks led to the name Rapid ʻŌhiʻa Death.

by Keith and her colleagues to also be killing *Metrosideros.* Although several strains/genotypes of *C. fimbriata* have been present in Hawaiʻi for decades that affect sweet potato, taro, and *Syngonium* (a common ornamental plant in the same family as taro – Araceae), these newly identified pathogens appear to be either new strains or new species that cause the current dieback phenomenon that has been given the common name "Rapid ʻŌhiʻa Death," "ROD" for short. Symptoms of the disease ensue as the fungi invade and spread within the sapwood of affected ʻōhiʻa trees, essentially stopping the transport of water and sugars through their vascular systems.

It is not yet entirely clear how the ROD pathogens spread – particularly how they have spread so quickly. The current hypothesis being tested are that they are spread long distances by human activity (e.g., infected wood or other plant and soil matter, equipment, tools, and shoes) and by wind as spores embedded in tiny bits of insect frass -- the fine powdery refuse and excrement produced by wood-boring beetles and expunged from tunnels created within dead or dying trees infected by the fungi. However, it is likely that a confluence of factors may contribute to disease spread, and certain factors may play more important roles in some areas than in others. Prior research conducted elsewhere on closely related *Ceratocystis* species demonstrate that tree wounds are important and perhaps necessary for infection. Wounds provide entry of the pathogen into trees, and episodic strong windstorms may be important events that both move infective fungal spores embedded in frass/boring dust and create wounds in trees that allow ingress of spores inside trees. Beetles that bore into ʻōhiʻa wood may also carry durable spores either in their gut or on their exoskeleton that contribute to the infection of some trees. Again, transport of durable spores by humans on tools, vehicles, in firewood, etc. is a major concern (e.g., locally to Kona, Kohala, and Ka'ū, and potentially to other islands); much care is required to avoid this. Feral pigs and other ungulates are capable of moving the pathogen short to medium distances. They may be doing so, but no evidence is yet available to confirm this possibility.

Trees within a given stand in which the disease is present seem to die in a haphazard pattern; the disease does not radiate out uniformly from already infected or dead trees. Initial published data from ʻōhiʻa dominated forests where the disease occurs indicated that mortality was distributed across all size and age classes (i.e., small to large individuals) and that the average annual mortality rate of ʻōhiʻa individuals was about 25% (Mortenson and others 2016), a rate markedly higher than those documented for most other tree diseases elsewhere in the world. Follow-up work that includes data from Mortenson and others (2016) as well as additional forest monitoring plots across a broader array of ROD-infected forest stands now documents average ʻōhiʻa mortality rates averaging 12% (n = 52 plots; Flint Hughes, pers. comm.). In some wet lowland forests of the Puna district, up to 90+% of the ʻōhiʻa trees in a stand have succumbed to the disease within a span of just a few years. Invasive strawberry guava (*Psidium cattleianum*), *Melastoma* spp., and Koster's curse (*Clidemia hirta*) are in many cases poised to attain dominance following the demise of ʻōhiʻa stands in these areas.

As of February 2016 areas exhibiting ʻōhiʻa mortality believed attributable to ROD totaled ca. 15,000 ha (38,000 acres), across the Puna, Hilo, Kona, and Ka'ū districts, with the largest known infestations occurring in the Puna-Hilo-Volcano area. By September 2016 the total area of ʻōhiʻa mortality had increased to ca. 20,000 ha (50,000 acres). This increase was partly due to increased mortality and partly due to more total area having been surveyed in September 2016. It is now recognized that, in the absence of effective management approaches, the pathogen has the potential to eventually kill many if not most ‘ohi’a trees on Hawai‘i Island and threaten the persistence of ‘ōhi‘a forests statewide. Currently, however, 90% of ‘ōhi‘a forests on Hawai‘i Island remain healthy and are believed to be free of ROD, and ROD has not been found on any of the other Hawaiian Islands as determined by surveys and follow-up collections of wood samples from suspect trees on those as yet ROD-free islands. There is strong determination and growing capacity by organizations to restrict the further spread of ROD on Hawai‘i Island and to quickly detect ROD on other islands if and when it first arrives and to eradicate it. Experimentation and monitoring is underway on Hawai‘i Island to develop and refine methods relevant to those intentions and to eradicate new localized outbreaks of the disease before they become extensive infestations.

Hawai‘i Department of Agriculture (HDOA) has taken responsibility for enforcement to prevent transport of ROD to non-infested islands. The Hawai‘i Board of Agriculture (on August 25, 2015) passed an interim rule restricting movement of ‘ōhi‘a material and soil from Hawai‘i Island to any of the other Hawaiian Islands or beyond. The interim rule was finalized and made permanent in November 2016. Agencies and the public are asked to follow many precautions such as not moving ‘ōhi‘a wood, cleaning tools, pressure washing contaminated vehicles, cleaning clothing and boots, etc. (See www.rapidohiadeath.org for important details.)

Much of what we know about ROD involves “best guess” hypotheses – excellent but based on common sense observations and educated experience from elsewhere. These hypotheses need to be confirmed and refined or refuted and replaced through research. Meanwhile, there is consensus among managers and scientists that immediate experimental management actions are warranted, accompanied by research, with a promising opportunity to prevent the worst from happening with ROD.

Continued research is crucial and underway to: understand the etiology and epidemiology of the disease, develop more rapid and accurate means of detection in wood and soil (through DNA analysis), identify the primary vectors of spread, understand potential environmental constraints of the disease, monitor the distribution and impact of the disease from forest stand to landscape scales, and develop increasingly effective management and treatment approaches.

Natural host resistance or tolerance is also being tested. Prospects for developing resistance in ‘ōhi‘a will be pursued if necessary, with the aim to eventually restore pathogen-resistant ‘ōhi‘a forests to the extent feasible. Given that a full operational program for restoration of ‘ōhi‘a would take decades and may not succeed, it may be important to explore and test the feasibility and desirability of using carefully selected non-native tree species to compensate as much as possible for a disastrous loss of ‘ōhi‘a in order to maintain watershed functions and provide suitable habitat for endemic biota.

Although *Metrosideros polymorpha* is likely the only “foundation species” in the genus currently affected by ROD, 45+ species of *Metrosideros* occur outside Hawai‘i. Most occur in New Caledonia (21 spp.) and New Zealand (12 spp.), but species of the genus are found in many other Pacific Islands as well as in South Africa. Protection of these other *Metrosideros* species will depend on what scientists and managers learn about the disease, and how successfully we contain current ROD outbreaks in Hawai’i. Communication and collaboration with other countries about the threats posed to *Metrosideros* by ROD could help Hawai‘i develop and execute a more effective ROD control program for Hawai’i and other Pacific nations. Based on the current perceived threat of ROD, New Zealand has recently implemented a quarantine to prevent arrival of *C. fimbriata*, with particular attention to the importation of kiwi fruit (*Actinidia*, attacked by *C. fimbriata* in Brazil) and *Metrosideros*.

Preface

ʻŌhiʻa, *Metrosideros polymorpha* (Myrtaceae, myrtle family), is Hawaii's preeminent forest tree, both culturally and ecologically. Given the dominance of ʻōhiʻa in Hawaii's forests - ʻōhiʻa accounts for > 80% of the biomass of native forests across the Hawaiian Islands - concern has been raised for over a century that if something were to substantially reduce the abundance of ʻōhiʻa stands and individual trees, an ecological disaster would ensue. Fungal pathogens in the genus *Ceratocystis* (Microascales: Ceratocystidaceae) that are the etiological agents of the disease referred to as Rapid ʻŌhiʻa Death (ROD) in Hawaiʻi, may potentially be the cause of just such a long-feared catastrophe. In the absence of effective management approaches, it is possible that these pathogens may be on course to eventually kill most ʻōhiʻa trees on Hawaiʻi Island, and will threaten ʻōhiʻa forests statewide. Fortunately, ROD has not yet been detected anywhere on any of the other Hawaiian Islands, as determined by ongoing aerial surveys and testing of tissue samples for *Ceratocystis* presence or genetic screening from suspect trees on those ROD-free islands. Organizations on other islands are determined and are establishing capacity to quickly detect ROD if and when it first arrives and to eradicate it. There also appears to be much potential for limiting spread of ROD on Hawaiʻi Island. The success of management actions will likely depend on what we know and can learn about the disease as well as innovative and aggressive response through management using this knowledge. Because ROD is part of an unfortunate long-standing trend of the spread of similar foreign pathogens that affect important forest trees worldwide, we can draw on experience developed in combating such invasions elsewhere to inform our research and management priorities to address ROD in Hawaiʻi. We do this with the knowledge that there are likely unique elements of ROD for which experience from elsewhere may not be applicable or helpful.

Tom Harrington

Aerial view of ʻōhiʻa forest in East Hawaiʻi impacted by Rapid ʻŌhiʻa Death.

This document is intended to provide a concise but detailed summary of the current state of knowledge regarding Rapid ʻŌhiʻa Death, initial analysis of needed further research, and the options for management of the disease. It is intended to provide background information for the development and refinement of a response plan.

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What is ōhiʻa and why is it important?

Role of ōhiʻa as a foundation species in the Hawaiian ecosystem

ʻŌhiʻa (Myrtaceae: *Metrosideros polymorpha* Gaudich.) is the most abundant and widespread native tree in the Hawaiian Islands, occupying approximately 80% of all native forest statewide. Although Hawaiʻi has lost roughly half of its original native forest, about 350,000 hectares of ʻōhiʻa-dominated forest remains of which ca. 250,000 ha occurs on Hawaiʻi Island and 100,000 ha occurs on the other main Hawaiian islands (Jacobi and others In press).

ʻŌhiʻa is among the best existing examples of a “foundation species” (Ellison and others 2005). That is, it is essential to native forest ecosystem function and to the native biodiversity that Hawaii’s forests harbor.

Sam ʻOhu Gon

ʻŌhiʻa is a colonizing species on lava flows, and a domanant component of mature forests.

Analyses by Percy and others (2008) indicate that *Metrosideros* has been evolving in the Hawaiian Islands for nearly 4 million years and has become genetically adapted to diverse local environments. Derived by way of the Marquesas Islands from an ancestral species of *Metrosideros* that colonized new lava flows in New Zealand, ʻōhiʻa was apparently able to outcompete most other plant species in pre-contact Hawaiʻi and came to form the habitat matrix for evolution of a large fraction of Hawaii’s endemic flora and fauna. Although some other important plant groups underwent complex adaptive radiation, vigorous gene flow - ʻōhiʻa seeds are small, light, and easily transported great distances by wind - apparently kept Hawaii’s ʻōhiʻa from major radiation into multiple species.

> ʻŌhiʻa is a remarkable generalist, with the ability to dominate a broad range of sites in Hawaiʻi—from sea level to up to 2,500 m elevation, and from very wet (up to over 6,000 mm/yr) to dry (about 500 mm/yr) sites. It ranges from status as a colonizing species on Big Island lava flows to dominance on 4 million year old soils on Kauaʻi. It has been evolving in place for a long time and has adapted genetically to local environments, but specialization is limited by within-species gene flow (Vitousek 2004).

Nathan Yuen

Mature, yet minute ʻōhiʻa in the Alakaʻi Swamp, Kauaʻi.

Although multiple species and varieties have been delineated and named by various botanists, Percy and others (2008) concluded based on literature and analysis of chloroplast DNA that there is a single highly polymorphic species of *Metrosideros* in Hawaiʻi: *M. polymorpha*. However, after additional analysis the following year, almost the same group (Harbaugh and others 2009) suggested that, based on nuclear DNA microsatellite loci, there are possibly five species level genetic groups in the Hawaii *Metrosideros* complex:

M. polymorpha
M. dieteri & macrophylla
M. rugosa
M. tremuloides
M. macropus

The taxonomy of Hawaiian *Metrosideros* has not been completely resolved. Meanwhile, the tremendous variability in ʻōhiʻa has inspired others to recognize incipient ecological speciation on Hawaiʻi Island (Stacy and others 2014; Morrison and Stacy 2014).

Gruner (2004) recognized the preeminent ecological role of ʻōhiʻa, particularly regarding Hawaii's native fauna:

> It can be argued that *M. polymorpha* is the backbone of Hawaiian forests and one of the most important resources for the long-term stability of ecosystems and watersheds in the islands. *Metrosideros* is an important, year-round nectar resource for native bees, moths, thrips and other insects, and for native nectarivorous birds… Numerous insect species use ʻōhiʻa lehua as a resource for either food or habitat space, and it may have the largest fauna of any native plant…

Nearly 500 different endemic Hawaiian species of arthropods have been collected from ʻōhiʻa canopies (Gruner 2004), further demonstrating the rich biodiversity that ʻōhiʻa forest harbors. Furthermore, several of the largest endemic insect groups that associate with plants (e.g., leafhoppers, planthoppers, psyilds) contain species that rely exclusively on ʻōhiʻa and no other plant species (Zimmerman 1948).

Dan Clark

ʻIʻiwi on ʻōhiʻa.

Forests dominated by ʻōhiʻa are home to at least 22 extant species of forest birds, the Hawaiian hoary bat, and many of Hawaii's remaining native plants and invertebrates. Endemic Hawaiian honeycreepers, including eight that are federally listed endangered species, are dependent on these forests for essential habitat, as they have adapted to feed and nest in ʻōhiʻa trees (Pratt and others 2009). The widespread or total loss of ʻōhiʻa would spell disaster to forest birds, ensuring extinction of many species directly dependent on ʻōhiʻa, if not most species, given the foundational role that ʻōhiʻa plays in the forests these birds depend on. Three nectarivorous bird species (ʻapapane, ʻiʻiwi, and ʻākohekohe) heavily depend on ʻōhiʻa blossoms; even though they will visit flowers from other plant species, there is no substitute for the volume, geographic spread, and year-round source of nectar ʻōhiʻa provides (Dr. Eben Paxton, USGS, pers. comm.).

Non-nectarivorous bird species would also be impacted. Most species preferentially nest in ʻōhiʻa, even koa specialists such as the ʻakiapōlāʻau. Insectivore species like Hawaiʻi ʻākepa and ʻakekeʻe are specialists on ʻōhiʻa leaf and flower buds, and most insectivorous birds preferentially forage in ʻōhiʻa trees (vs *Acacia koa* trees). Even bird species that may not be entirely dependent on ʻōhiʻa for food resources (e.g., ʻelepaio and ʻōmaʻo) would likely be greatly affected by the substantial changes in native forest structure that would ensue with widespread ʻōhiʻa mortality. In short, the loss of ʻōhiʻa from native birds' forests would negatively impact them, with the amount of harm depending on the percent loss of ʻōhiʻa trees. The complete loss of ʻōhiʻa on all the main Hawaiian Islands would likely lead to the extinction of most of the 19 native Hawaiian bird species dependent on ʻōhiʻa dominated forests (E. Paxton, pers. comm.).

ʻŌhiʻa thus provides the foundational and functional framework for Hawaii's forested terrestrial ecosystems and the diversity of the native fauna and flora, roughly 90% of which is endemic, occurring nowhere else in the world. Although perhaps 10% of the plant species of the archipelago have been lost to extinction and 30% more are endangered, extensive and relatively intact tracts of native-dominated communities survive, mostly at higher elevations.

Not surprisingly for a single species with a very broad ecological distribution, ʻōhiʻa exhibits substantial genetic variability (Aradhya and others 1993; James and others 2004; Crawford and others 2008; Percy and others 2008, Harbaugh and others 2009, Izuno and others 2016), phenotypic plasticity (Cordell and others 1998; Cornwell and others 2007), and combinations of the two phenomena (Cordell and others 2000, 2001; Melcher and others 2000; Fisher and others 2007). Phenotypic plasticity refers to the important phenomenon involving single genotypes that can produce different phenotypes in different environments. ʻŌhiʻa is well adapted to the large climatic intra-annual variability, particularly with regard to rainfall that is so characteristic of Hawaiʻi (e.g., Lyons 1982; Loope and Giambelluca 1998). Scientists hope that the expressed and acknowledged genetic variation and phenotypic plasticity of ʻōhiʻa may provide for sufficient levels of resistance to ROD in certain ʻōhiʻa populations. Research is underway to discover whether or not such resistance is present, but this work would need to be much expanded to adequately address this possibility.

Cultural Importance of *Metrosideros* in Hawaiʻi

Gon (2012) wrote:

> As the dominant tree of the majority of forest communities in Hawaiʻi, it is no surprise that ʻōhiʻa lehua and other *Metrosideros* species bear great Hawaiian cultural significance. The tree itself is considered the kinolau (physical manifestation) of Kū, one of the four principal Hawaiian deities, though ʻōhiʻa may also serve as one of the kinolau of several other Hawaiian deities such as Laka (patron deity of hula) and Pele (goddess of volcanism). Its wood is incorporated into the two most sacred structures of the heiau (temples) of

Sam ʻOhu Gon

Red and yellow ʻōhiʻa blossoms and young leaves (liko) are used in lei.

> governance: the ki‘i akua (god figures) and the lele (offering platform). The flowers of ‘ōhi‘a, called lehua, are symbolic of the fires of Pele, the blood of warfare, and hard-won, long-trained expertise. The role that lehua blossoms play as the mainstay of Hawaiian honeycreepers and other nectarivorous birds was not ignored; the attraction of birds to lehua is used as a metaphor of courtship, popularity, and high regard. The bog form of lehua has a special name, lehuamakanoe, that denotes its mist-shrouded habitat and confers a sacredness afforded only to deities. Material and other cultural uses incorporate the wood of ‘ōhi‘a in houses, tools, weapons, religious structures, food preparation tools and containers, the foliage and flowers in lei, and the tender parts of flowers, foliage and roots in herbal medicine. As a prevalent and easily recognized presence in ecosystems from sea level to tree-line, numerous ‘ōlelo noeau (wise and poetical sayings) refer to ‘ōhi‘a as a positive symbol of strength, sanctity, and beauty. All of these primary cultural underpinnings should not be ignored when considering the value of ‘ōhi‘a as an element of essential biocultural conservation value.

In contrast to Western knowledge systems, which have developed understanding of the many bio-physical roles and ecosystem services of ‘ōhi‘a, native Hawaiian knowledge systems integrate understanding of ‘ōhi‘a’s many and complex social, psychological and spiritual linkages between person and species. A critical distinction between Western and native Hawaiian perspectives is that ‘ōhi‘a is embraced as a revered deity and respected family member, and this reverence and respect forms the bonds of a sacred relationship between ‘ōhi‘a and the Hawaiian people. Native Hawaiian organizations and institutions that serve native Hawaiians own, manage, or otherwise interact with a very large fraction of Hawaii’s native ōhi‘a forest. Approximately 17% of all land on Hawai‘i Island falls under the responsibility of native Hawaiian serving organizations, including Bishop Estate’s Kamehameha Schools, the Department of Hawaiian Homelands, and the Office of Hawaiian Affairs: 297,000 acres, 116,963 acres and 25,856 acres, respectively. These institutions are increasingly approaching management through the lens of sacred relationship to place. Consequently, native Hawaiians and especially practitioner communities are deeply concerned about ROD impacts on ‘ōhi‘a, the forests and biophysical linkages created by ‘ōhi‘a, and the sacred familial connections between people and ‘ōhi‘a.

Adapting traditional practices of forest gathering and ceremony to the presence and management of ROD will require ROD managers and researchers to work together with native Hawaiian communities to develop culturally appropriate strategies and approaches. Integrating traditional ways of knowing is important because the success and reach of ROD management activities is largely dependent on native Hawaiian and local community investment in and approval of ROD management prescriptions.

Worldwide occurrence and status of the genus *Metrosideros*

Globally, approximately 50 species of *Metrosideros* exist. The ancestral genus apparently occupied the ancient Gondwanan landmass that included present-day New Zealand and New Caledonia (and possibly South Africa). The New Caledonia and New Zealand ecoregions separated from Australia by continental drift ca. 85 million years ago. *Metrosideros* has very much more recently migrated, likely via wind dispersal of its small, lightweight seeds, to New Guinea, the Philippines, Polynesia, Vanuatu, and the Bonin Islands of Japan (Wright and others 2000, Wikipedia).

New Caledonia supports 21 species of *Metrosideros*, all of which are endemic to that archipelago: *M. brevistylis, M. cacuminum, M. cherneri, M. dolichandra, M. elegans, M. engleriana, M. humboldtiana, M. laurifolia, M. longipetiolata, M. microphylla, M. nitida, M. operculata, M. oreomyrtus, M. paniensis, M. patens, M. porphyres, M. punctate, M. rotundifolia, M. tardiflora, M. tetrasticha,* and *M. whitakeri* (Jaffré and others 2001, Dawson and others 2000, Wikipedia).

New Zealand supports 12 species: *M. albiflora, M. bartlettii*, *M. carminea* (Carmine rātā), *M. colensoi, M. diffusa, M. excelsa* (Pōhutukawa), M. fulgens (Scarlet rātā), *M. kermadecensis* (Kermadec pōhutukawa), M. *parkinsonia, M. perforata, M. robusta* (Northern rātā), and *M. umbellata* (Southern rātā).

Hawai'i is generally considered to support five species, all of which are endemic to the archipelago : *M. macropus, M. polymorpha, M. rugosa, M. tremuloides, and M. waialeale.*

New Guinea supports four species: *M. cordata, M. ramiflora, M. scandens,* and *M. whiteana.*

The remaining species are scattered across islands of the Pacific, with one extremely distant outlier endemic to South Africa.

Philippines: *M. halconensis*

Lord Howe Island: *M. nervulosa* (Mountain rose), *M. sclerocarpa*

Fiji: *M. ochrantha*

From Vanuatu in the southwest to French Polynesia in the east: *M. collina*

Samoa: *M. gregoryi*

Bonin Islands: *M. boninensis*

Solomon Islands: M. salomonensis

South Africa: *M. angustifolia*

Metrosideros does not occur in Australia, Indonesia (except for New Guinea), or Micronesia.

While other *Metrosideros* species may be infrequent to common components of forests elsewhere*, M. polymorpha* is probably the only "foundation species" in the genus. The extent and abundance of New Zealand's *M. excelsa* has been reduced by 90% (Bylsma and others 2014), and at least two species are on the verge of extinction: New Zealand's *M. bartlettii* (Drummond and others 2000) and *M. boninensis* of the Bonin Islands (Kaneko and others 2008).

'Ōhi'a: A century-long history of concern

Due to the overwhelming dominance of 'ōhi'a in Hawaii's forests, there has long been concern that if something were to drastically reduce its abundance, the result could be an ecological catastrophe. Early concern was raised by H.L. Lyon of the Hawaiian Sugar Planters' Association in response to the "Maui Forest Trouble" in the early 1900s. This phenomenon entailed death of 'ōhi'a on ca. 2000 ha at low elevations (i.e., < 915 m) between Kailua and Nahiku in the East

Maui watershed (Holt 1983, Hodges and others 1986). Up to 95% of the trees in the affected area suffered mortality, including associated subcanopy native tree species in addition to ‘ōhi‘a. The cause was believed to be toxic quantities of hydrogen sulfide and ferrous iron compounds produced in soil by bacterial fermentation under conditions of poor drainage. Lyon (1909) suggested that introduced tree species be planted that might be adapted to the wet sites – which happened later (mainly in the 1930s) on a large scale. Holt (1988) determined that in areas not replaced by non-native tree plantations across much of this historic dieback area, ‘ōhi‘a is still present but tall stands on low-gradient slopes have been replaced by low shrubs, matted ferns, and introduced grasses. Vigorous tall ‘ohi’a trees remain on better-drained side slopes in this region.

Concern over “‘ōhi‘a dieback” arose again in the 1970s when large sections of mature, even-aged ōhi‘a stands on the windward side of Hawai‘i Island experienced widespread canopy death. An assessment indicated that 50,000 ha of native ōhi‘a forest suffered extensive mortality (i.e., dieback) between 1954 and 1977 (Jacobi and others 1983). The cause of this phenomenon was not immediately apparent nor ever completely understood; leading hypotheses included impacts from introduced fungal pathogens, and a natural process linked to vegetation succession and substrate conditions. Major research efforts undertaken by University of Hawai‘i and U.S. Forest Service investigators concluded that ‘ōhi‘a dieback was a complex natural phenomenon involving cohort senescence and recovery of the forest (Mueller-Dombois 1985; Hodges and others 1986). However, findings indicated that extrinsic factors, particularly invasive plant species, may alter the outcome of natural succession following dieback. As of 2012, long-term plots, established in 1976, showed that many areas were recovering to a healthy canopy though plant invasions were indeed limiting natural recovery (Jacobi and others 2012; Boehmer and others 2013). Meanwhile, new dieback areas had developed, but were not considered cause for great concern. Throughout these intensive, multi-year research efforts *Ceratocystis* was never identified as a potential pathogen, nor was it encountered in any samples of soil, plant tissue, or associated biomass.

Forest and Kim Starr

The rust fungus* Puccinia psidii *on rose apple

Another potential threat to the health and persistence of ‘ōhi‘a forests statewide was realized by the discovery of the rust fungus *Puccinia psidii* on O’ahu in April 2005; within 6 months after its detection, this fungus had spread throughout the main Hawaiian Islands. The rust, originally associated with native guava in Brazil, was known to have a wide host range on members of the Myrtaceae family and known to have caused substantial damage to economically important non-native *Eucalyptus species* in Brazilian tree plantations. The main concern in Hawai‘i was the threat the fungus posed to ‘ōhi‘a, and the rust quickly acquired the local name “‘ōhi‘a rust.” In spite of concern, the damage to ‘ōhi‘a has been modest. In contrast, the non-native rose apple tree (*Syzygium jambos*, Myrtaceae) was nearly annihilated by *P. psidii*. However, the literature indicated that *P. psidii* exhibits many diverse strains, and concern remains that an additional virulent strain of this rust fungus could enter Hawai‘i and devastate ōhi‘a. Unfortunately, federal protection for Hawai‘i in this case was not forthcoming because *P. psidii* had been present in the U.S. (Florida) for several decades.

Hawaii’s Board of Agriculture unanimously approved an interim rule in August 2007 banning importation of plants in the myrtle family from “infested areas,” specified as South America, Florida, and California. The latter inclusion was based on knowledge that HDOA inspectors had repeatedly intercepted *P. psidii* on foliage of *Myrtus communis* from California. However, the interim rule was not made permanent by HDOA, and the department stated that given non-support from USDA APHIS PPQ it needed further information to formulate a long-term rule that would impose appropriate measures. Definitive further information was forthcoming from collaborative research between the USDA Forest Service and Viçosa University in Brazil which showed that several Brazilian strains of *P. psidii* aggressively attacked and damaged ‘ōhi‘a (Graça and others 2011; Costa da Silva and others 2014). No long-term rule has yet been established to keep out new strains of *P. psidii,* but federal/state rules are in the process of being finalized and are expected in 2017.

Ironically, several batches of seedlings of *Metrosideros* that were among the plants grown from families of seeds sent in 2008 from Hawai‘i to Viçosa University in Brazil for testing against multiple strains of *Puccinia psidii* became infested with the fungal genus *Calonectria* in 2010. As a result, *Calonectria metrosideri* was described (Alfenas and others 2013) as another fungal pathogen of ‘ōhi‘a. This pathogen is listed by Farr and Rossman (2016) and is an “actionable” species for USDA-APHIS.

What do we know about ROD, how does it spread, and what impacts has it/could it have?

Characteristics of *Ceratocystis,* its history in Hawai‘i, and the nature of its lethal interaction with ‘ōhi‘a

1. ‘Ōhi‘a newly under attack by a notorious pathogen

A pathogen allied with *Ceratocystis fimbriata* has already killed many hundreds of thousands of ‘ōhi‘a trees on Hawai‘i Island. Drastic mortality first appeared in 2009-2010 in residential areas and forests of the Puna district. Landowners observed previously healthy-looking ‘ōhi‘a trees exhibiting symptoms of disease (i.e., yellow and brown leaves) which led to mortality within days to weeks. By 2013, the spread of the disease began to accelerate. In 2014 significant mortality was present in patches across 2400 ha from Kalapana to beyond Hilo. The disease was detected in Kona and Ka‘ū by late-2015/early-2016. Pathogenicity tests conducted by the USDA Agricultural Research Service (ARS) in 2014-2015 determined that the agent causing the disease termed Rapid ‘Ōhi‘a Death (ROD) is allied with the vascular wilt fungus *Ceratocystis fimbriata* (Keith and others 2015). One strain of *C. fimbriata* has been present in Hawai‘i as a pathogen of sweet potato for many decades (Brown and Matsuura 1941). Additional distinct strains that affect *Syngonium* and taro have also been previously identified (Uchida and Aragaki 1979, Thorpe and others 2005).

The major pathogen aggressively attacking ‘ōhi‘a is now considered a completely new species of *Ceratocystis* and is in the process of being renamed and described (Lisa Keith, ARS, pers.

comm.); this is the first record of any *Ceratocystis* species affecting the genus *Metrosideros*. Remarkably, a second new *Ceratocystis* species, also currently considered "ROD", was in 2015 found to be killing *Metrosideros* on Hawai'i Island (Lisa Keith, ARS, pers. comm.). Perhaps less aggressive and as yet less well understood, it is currently referred to as "*Ceratocystis* sp. B"(see section IIC below). The more aggressive *Ceratocystis* ("sp. A") causing ROD manifests itself as dark, nearly black, staining in the sapwood along the outer margin of trunks of affected ʻōhiʻa trees. The stain is often radially distributed through the wood. When wood samples are incubated under moist conditions they produce characteristic fruiting bodies of *Ceratocystis* called ascomata (a.k.a. perithecia), and a fruity odor is often detected in infected wood (L. Keith, pers. comm.).

Crowns of affected ʻōhiʻa trees turn yellowish (chlorotic) and subsequently brown within days to weeks; dead leaves typically remain on branches for a relatively long period (i.e., weeks to months). On occasion, leaves of single branches or limbs of trees turn brown before the rest of the crown becomes brown. The pathogen may progress up and/or down the stem of the tree. It also may remain highly localized in a section of the trunks of individual trees. Trees within a given stand appear to die in a haphazard pattern in that the disease does not appear to radiate out from already infected or dead trees. In the locations most heavily impacted by the disease to date, nearly 100% of the ʻōhiʻa trees in a stand have succumbed to the disease within several years. Initial published data from ʻōhiʻa dominated forests where the disease was found present indicated that mortality was fairly evenly distributed across size classes (i.e., included small to large individuals), and that the average annual mortality rate of ʻōhiʻa individuals was about 25% (Mortenson and others 2016), a rate markedly higher than those documented for most other tree diseases elsewhere in the world. Follow-up work that includes data from Mortenson and others (2016) as well as additional forest monitoring plots across a broader array of ROD-infected forest stands now documents average ʻōhiʻa mortality rates averaging 12% (n = 52 plots). Preliminary

Box 1. -Genera documented as hosts of *Ceratocystis fimbrata* in Farr and Rossman Fungal Database as of May 11, 2016 http://nt.ars-grin.gov/fungaldatabases/

Anacardiaceae: *Mangifera, Pistacia*
Annonacae: *Annona*
Apiaceae: *Arracacea*
Araceae: *Alocasia*, *Colocasia, Syngonium*
Arecaceae: *Cocos*
Asteraceae: *Lactuca*
Betulaceae: *Betula*
Bignoniaceae: *Spathodea*
Cistaceae: *Cistus*
Convolvulaceae: *Ipomoea*
Euphorbiaceae: *Hevea, Ricinus*
Fabaceae: *Acacia, Cajanus, Cassia, Crotalaria, Dahlbergia*
Fagaceae: *Fagus, Quercus*
Lamiaceae: *Gmelina, Tectona*
Lauraceae: *Persea*
Lythraceae: *Punica*
Meliacae*: Carapa*
Moraceae: *Ficus*
Myrtaceae: *Eucalyptus, Metrosideros* (based on Keith and others 2015), *Pimenta*
Oleaceae: *Phillyrea*
Passifloraceae: *Passiflora*
Platanaceae: *Platanus* (accepted as *Ceratocystis platani* since 2005)
Proteaceae: *Protea*
Rosacae: *Eriobotrya, Kerria, Prunus*
Rubiaceae: *Cinchona, Coffea*
Rutaceae: *Citrus*
Salicaceae: *Populus*
Solanaceae: *Nicotiana*
Sterculiaceae: *Herrania, Theobroma* (species infecting these two genera accepted as *Ceratocystis cacaofunesta* since 2005)

analysis of this data also suggests that younger, small stature forests exhibit lower rates of mortality in presence of the disease than do older, taller forests. Reasons for these apparent mortality patterns are not currently known, but research is ongoing to determine salient factors (R.F. Hughes, pers. comm.). Other native forest trees such as kōpiko (*Psychotria* spp.) and ʻohe mauka (*Polyscias* spp.) are not affected by the disease. Invasive strawberry guava (*Psidium cattleianum*), *Melastoma* spp., and Koster's curse (*Clidemia hirta*) are in many cases poised to take over dominance when the ʻōhiʻa canopy dies, especially at lower elevations. In high-elevation, remote locations (where few non-native trees are established), decimated ʻōhiʻa is more likely to be replaced by other native tree species, but with resulting patchy, shorter, less structurally complex forest canopies.

2. *Ceratocystis fimbriata*

The genus *Ceratocystis* and the species *Ceratocystis fimbriata* Ellis and Halsted were first described from sweet potato (*Ipomoea batatas*) from the USA (New Jersey) in 1890. *C. fimbriata* has since been found infecting sweet potato in at least eight states of the USA and 14 countries in South America, North America, Africa, Asia, and the Pacific (Farr and Rossman 2016). It had reached Hawaiʻi on this host by 1941. Different genotypes of *C. fimbriata* had reached Hawaiʻi on *Syngonium podophyllum* (syngonium or arrowhead plant) and *Colocasia esculenta* (taro or kalo) by 1979 (Uchida and Aragaki 1979, Thorpe and others 2005). None of these previous genotypes are the fungi currently killing ʻōhiʻa. In the past 25 years, the genus *Ceratocystis* has emerged as one of the most important groups of plant, and especially tree, pathogens known worldwide (Roux and Wingfield 2009). The *C. fimbriata* complex has now replaced the rust *Puccinia psidii* as the greatest recognized plant pathogen threat to *Eucalyptus* (Myrtaceae) cultivation in Brazil (Harrington 2013). Nevertheless, the sudden appearance of strains/genotypes in the *C. fimbriata* compex in Hawaiʻi that threaten ʻōhiʻa was completely unexpected. The taxonomy of *C. fimbriata* is relatively complicated and not yet clearly resolved. Approximately 30 distinct species have been described within the *C. fimbriata* species complex (e.g., Mbenoun and others 2014, Fourie and others 2015), but opinion is divided as to whether or not these are true species (e.g., Harrington and others 2014, Oliveira and others 2015). Some researchers consider that most of the proposed species represent genotypes (or strains) that have been distributed around the world, mostly on plant propagative material, whereas other researchers consider that many such "strains" are distinct species based on molecular differences. We will elect to apply the name *C. fimbriata* to populations that are native to South and Central America and the Caribbean (Harrington and others 2011).

An analysis of data (Box 1) given by Farr and Rossman (2016) roughly indicates the remarkable diversity of hosts currently attributed to *C. fimbriata*, including 42 genera in 27 families. A newly recognized host not yet listed by them is *Actinidia deliciosa*, the kiwifruit, in the Actinidiaceae (Piveta and others 2016). The *C. fimbriata* complex represents a dramatic exception to the general rule for phytosanitary risk analysis that "pests are more likely to attack closely related plant species than species separated by greater evolutionary distance" (Gilbert and others 2012).

3. The Black Rot sweet potato disease in Hawaiʻi.

Ceratocystis fimbriata has been a serious pest of sweet potato (*Ipomoea batatas*, Convolvulaceae) in Hawaiʻi since before 1941. (It is also present in seven or more other U.S. states.) The fungus is spread by wind, water, soil, on harvesting baskets, on farm machinery, by some insects, by humans (clothing), and by contaminated tools. It survives in soil, in water, and on decaying organic matter such as sweet potato debris left in the field. It can survive for several years in the soil. Wounds on the sweet potato skin are important entry points for infection by the fungus; roots and stems are also susceptible to infection. Ascospores of sporulating *C. fimbriata* produce a fruity aroma; the aroma and the sticky spores are believed to be an adaptation for promoting fungal dispersal by insect vectors. Small, circular, slightly sunken, dark brown or grey spots on the sweet potato surface are among the early symptoms of disease, followed by large, circular, sunken, dark brown to black spots on the sweet potato surface. Brownish colored rot usually remains shallow, but can extend into the inner part of the potato, leading to rot by secondary organisms which can destroy the entire root. Crop rotation is an important practice for controlling black rot. Sweet potatoes should not be planted in the same field more than once every third or fourth year (Nelson n.d.). Molecular and cross-host pathogenicity tests conducted by USDA ARS PBARC have determined that *C. fimbriata* isolated from sweet potato in Hawai‘i is not the same genotype as either of the ‘ōhi‘a wilt pathogens and does not cause ROD.

4. *Ceratocystis fimbriata* on *Syngonium* and taro in Hawai‘i.

Tom Harrington

C. fimbriata *lesion on syngonium.*

In addition to causing black rot of sweet potato in Hawai‘i, *C. fimbriata* has been known since the 1970s to cause a serious black rot of corms of *Colocasia esculenta* (known as taro or kalo in Asia and the Pacific) as well as basal rot of the landscape plant *Syngonium podophyllum* (syngonium) (Uchida and Aragaki 1979, Thorpe and others 2005). These pathogens of Araceae are apparently two very distinct strains/ genotypes of *C. fimbriata*. The taro strain may have come from Asia/China, but may possibly have been introduced to Hawai‘i by the Polynesians. The syngonium strain, likely from the Caribbean, is also found in Florida and California (also Australia and Brazil). Importantly, molecular and cross-host pathogenicity tests conducted by Dr. Lisa Keith and colleagues at USDA ARS PBARC have determined that *C. fimbriata* strains isolated from syngonium and taro in Hawai‘i are not the same genotype as either of the ‘ōhi‘a wilt pathogens (sp. A or sp. B) and do not cause ROD.

5. Proof of pathogenicity and identity of the pathogen killing ‘ōhi‘a in Hawai‘i.

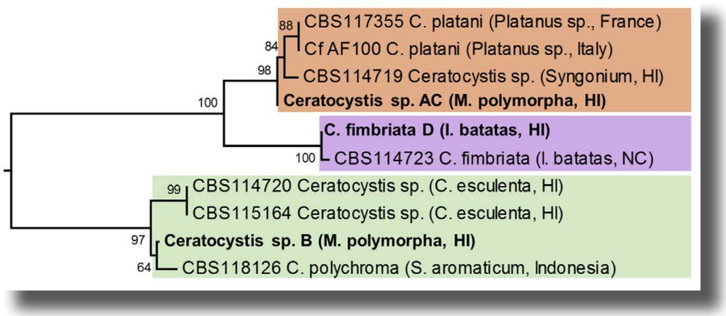
In 2014, Brian Bushe with the UH CTAHR Agricultural Diagnostic Service Center discovered the fungus *Ceratocystis* on an ‘ōhi‘a wood sample submitted by Drs. J.B. Friday and Flint Hughes on behalf of a private landowner residing in the Puna district of Hawai‘i Island. On Bushe's recommendation, Dr. Lisa Keith of the USDA ARS PBARC received the *Ceratocystis* isolate from ‘ōhi‘a and was recruited to help diagnose the disease. Keith, Friday, and Hughes, and interns re-visited several sites with mortality and trees were felled and cut up. The researchers found that cross-cut sections of most of the dead trees in this area showed dark, radial staining in the xylem (sapwood), while cross-cut sections from healthy trees in that same area showed no staining. The same fungus was consistently cultured from the stained parts of the wood at the PBARC lab and diagnosed as *Ceratocystis fimbriata* based on morphological and molecular characteristics. Dr. Keith successfully completed Koch's postulates. This process entailed isolating the fungus from infected (dying) ʻōhiʻa with typical ROD symptoms. Keith inoculated non-infected ʻōhiʻa seedlings with a pure culture of *Ceratocystis* (now known as species A); after about 8 weeks those seedlings showed the same external and internal symptoms as dying ʻōhiʻa trees. Keith then re-isolated the pathogen from the inoculated dying seedlings and showed it to be identical to the originally inoculated strain. The process was repeated numerous times, with controls. These experiments confirmed that this non-native fungus is pathogenic to ʻōhiʻa trees and responsible for *Ceratocystis* wilt, a.k.a. Rapid ʻŌhiʻa Death (ROD), across extensive areas of the native forest. To determine whether this *Ceratocystis* was the same genotype as pre-existing strains of *C. fimbriata* on various hosts found in Hawaiʻi, Keith's ARS-PBARC lab isolated and compared the DNA sequence of 7 genes of *Ceratocystis* from ʻōhiʻa, sweet potato, taro and syngonium. Results indicated that while there is genetic similarity, the pathogens attacking ʻōhiʻa are clearly different from the long-time resident strains of *C. fimbriata* in Hawaiʻi or those known elsewhere in the world (Keith and others 2015; Dr. T.C. Harrington, Iowa State University, pers. comm.). Microsatellite marker analysis (conducted by Dr. Irene Barnes, FABI, SA), mating studies (conducted by Dr. Tom Harrington, Iowa State), and cross-host inoculation studies conducted at the ARS-PBARC lab further support these findings.

6. Impact of *C. fimbriata* on trees elsewhere

Originally regarded as a pathogen of root crops and herbaceous plant species, a *C. fimbriata* strain genetically distinct from the pathogen attacking ʻōhiʻa in Hawaiʻi was first detected on dying non-native *Eucalyptus* (Myrtaceae, same family as *Metrosideros*) trees in a small part (Bahia) of Brazil in 1997 but spread widely (to six other Brazilian states) and caused increasing damage (Ferreira and others 2013). Different strains also cause cankers on rubber tree (*Hevea brasiliensis*) and manifest as lethal canker stain in gumhar (*Gmelina arborea*) plantations (Valdetaro and others 2015). A particular strain attacks *Carapa guianensis* (Meliaceae), a tree native to Brazil (Halfeld-Vieira and others 2012). Some strains that damage mango (*Mangifera indica*) in Brazil are closely related to those that attack *Eucalyptus* (Oliveira and others 2016). A Brazilian strain introduced to Pakistan damages mango and an important forest tree known as Indian rosewood (*Dalbergia sissoo*) (Pussio and others 2010). A severe *Ceratocystis* wilt disease in Indonesia attacks *Acacia mangium* (Tarigan and others 2011), with current mortality over roughly 1,000,000 ha (Dr. Philip Cannon, USDA FS, pers. comm.). Reported mortality of *Eucalyptus* in Uruguay, Congo, Uganda and South Africa is likely to have been caused by Brazilian strains of *C. fimbriata* (Harrington 2013). It must be said that the effects of *Ceratocystis* on *Metrosideros* appear to be more severe than the ones on most of the other tree genera (T.C. Harrington, pers. comm.). Harrington and Keith (pers. comm.) showed that the closest genetic match to *Ceratocystis* "sp. A" is *Ceratocystis platani*, which is currently having a devastating effect on native plane trees (*Platanus orientalis,* Platanaceae) in Greece.

7. Where did the pathogen likely come from and how did it get to Hawaiʻi?

The primary pathogen (*Ceratocystis* "sp. A") that causes ROD symptomatology is closely related to but distinct from the strain/genotype of *C. fimbriata* found by Dr. Janice Uchida on *Syngonium podophyllum* at a nursery in the Hilo area of Hawaiʻi Island in 1978 (Uchida and Aragaki 1979). The same genotype has also been documented in Florida, Brazil and Australia on *Syngonium*, and in Costa Rica on *Xanthosoma* and coffee. The same nurseries Uchida had visited and collected from in 1978 were revisited by Bushe, Keith and Harrington in 2016, and the same strain/genotype of Cer*atocystis* was found on *Syngonium.* One nursery has been



ARS-PBARC

Results of DNA sequencing indicate that the pathogens attacking ʻōhiʻa are clearly different from the long-time resident strains of* C. fimbriata *in Hawaiʻi or those known elsewhere in the world.

importing rooted cuttings from a nursery in Florida for several decades. A pure culture of the *Syngonium* strain was used in pathogenicity studies conducted at USDA ARS PBARC and did not cause ROD.

There may be other species of plants that are being imported into Hawaiʻi that can serve as hosts for *Ceratocystis*, such as *Xanthosoma* and other plants in the Araceae family, and *Ceratocystis* may be continuing to arrive on *Syngonium podophyllum*. A statewide survey of syngonium is being conducted (collaboration between Dr. Janice Uchida at UH CTAHR and Dr. L. Keith at USDA ARS PBARC) to determine whether and where other *Ceratocystis* strains exist on syngonium and if so how similar the populations are to the primary ROD pathogen (*Ceratocystis* sp. A). Import of *Eucalyptus* plant material may possibly be a conduit for movement of *C. fimbriata* into Hawaiʻi. This fungus is native to Brazil, and the disease has been present there on (non-native) eucalyptus since at least 1997. *Eucalyptus* material has been transported throughout the world, often via rooted cuttings. The arrival of *C. fimbriata* in China via imported *Eucalyptus* material and its subsequent infection of the fruit crop pomegranate is an example of the consequences (Li and others 2016). Other species in Hawaiʻi may be similarly vulnerable to the pathogens currently killing ʻōhiʻa individuals. It is possible that mutations or recombinations that lead to only one or a few base pair changes in DNA sequences may lead to drastic changes in pathogenicity or host specificity. Members of the *Ceratocystis fimbriata* complex sexually cross easily, facilitating the horizontal spread of pathogenicity factors between strains and species (T.C. Harrington, pers. comm.).

California may be another potential source of the ROD disease, just as it was for *Puccinia psidii*. The Farr and Rossman (2016) fungal database of USDA-ARS reports that *C. fimbriata* has been present in Florida on *S. podophyllum* at least since 1990 and in California on *Syngonium podophyllum* and *S. auritum* at least since 1989 (but recorded there on *S. auritum* by Davis 1953). *Syngonium auritum* is native to Puerto Rico and *S. podophyllum* was introduced there before 1982 (Liogier and Martorell 1999).

Most new pests arrive in Hawaiʻi either directly from the U.S. mainland, from foreign countries via the U.S. mainland, or directly from Southeast Asia (e.g., China, Thailand, Indonesia, etc.) (De Nitto and others 2015). Most pests travel on plant material (Liebhold and others 2012), but there are many alternate modes of ingress into Hawaiʻi. These include wood packing material (such as pallets and crates, Lovett and others 2016) and mud on the shoes of travelers (McNeill and others 2011). The presumed multiyear persistence of viable propagules (aleurioconidia) of *C. fimbriata* has increased the likelihood of accidental arrival and establishment of new genotypes in Hawaiʻi.

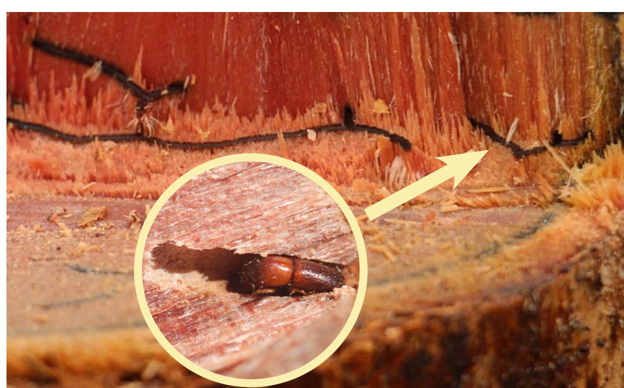
How is ROD moving and infecting new trees?

1. Spores and their transport to wounds

The pathogens on ʻōhiʻa in the *C. fimbriata* complex have spread quickly across some portions of Hawaiʻi Island, and it is not yet entirely clear how, although human transport is considered a very likely major pathway. There is educated speculation (T.C. Harrington, pers. comm.) that wind-blown *Ceratocystis* spores imbedded in frass, the fine powdery refuse and excrement produced by beetles boring in dead ʻōhiʻa trees, may provide an important pathway for disease spread. Previous studies elsewhere indicate that tree wounds are generally a prerequisite to allow for ingress of the pathogen (Harrington 2013). Short-lived conidia (asexual spores) and ascospores (sexual spores) are produced by *Ceratocystis*, as well as aleurioconidia (highly resilient asexual spores which survive well in soil, water, and wood). Aleurioconidia are dark, durable spores known to remain viable for two years or more in wood (Harrington 2013) and probably in soil as well. Ascospores, produced on fruiting bodies (ascomata), are hydrophobic and can adhere to the hydrophobic exoskeletons of beetles and may potentially be transported in this way (Harrington 2013). Ambrosia beetles, especially, are attracted to declining trees that are emitting various chemical odors; they penetrate the sapwood, excavate galleries and lay eggs; adults and larvae feed on ambrosia fungi. Aleurioconidia cannot likely adhere to insect exoskeletons but are expelled from the tree by the beetles from the galleries as boring dust/frass. The windblown or soil-borne frass and boring dust containing aleurioconidia can become inoculum for new infections. In collaboration with the U.S. Forest Service, Drs. Curtis Ewing and Gordon Bennett of the University of Hawaiʻi at Mānoa are modeling potential dispersal dynamics and range of frass and boring dust from different beetle species.

Several ambrosia beetle species are known to chew through wood and excrete woody frass that may also contain aleurioconidia (*Xyleborinus saxesenii* and native and non-native species of the genus *Xyleborus*). As insects disperse to find a natal tree, they initiate new gallery formation, which often breaches the xylem wood. During this process they may be able to transmit small volumes of inoculum directly to ʻōhiʻa. This hypothesis is currently being tested.

2. Key role of insects



Curtis Ewing

X. saxesenni *and boring tunnels in infected ʻōhiʻa wood.*

Several groups of beetles that bore directly into wood for larval and brood rearing have been found in wood of ʻōhiʻa infected with *Ceratocystis*. Many of these include non-native beetle species, but there is also a wide range of native beetles known to specifically associate with ʻōhiʻa (Samuelson 1981). A subset of species that dominantly attack ʻōhiʻa in *Ceratocystis* infected stands has been identified by C. Ewing; they include the global pest species *Xyleborinus saxesenii, Xyleborus ferrugineus*, and *Xyleborus affinis*. The one native ambrosia beetle species found so far is *Xyleborus simillimus*. Hawaiʻi is also at risk for more introductions of ambrosia beetles that could contribute to disease spread (see for example Cognato and Rubinoff 2008). Several native longhorn beetles (Cerambycidae: *Plagithmysines*) have also been identified from infected ōhiʻa by C. Ewing. The ecological activities of these beetles may play a direct role in transmission of ROD disease. Ambrosia beetles are now hypothesized to be most important with regard to frass production and ROD dispersal (C. Ewing and G. Bennett, pers. comm.).

Ambrosia beetles are in the weevil subfamilies Scolytinae and Platypodinae (Coleoptera, Curculionidae); Hawaii's are primarily in the Scolytinae. They are major decomposers, and live in nutritional symbiosis with fungi. Platypodinae are present in Hawai‘i but they are apparently not associated with ‘ōhi‘a trees on Hawai‘i Island. Ambrosia beetles excavate tunnels in dead and dying trees where they cultivate fungal gardens, a major source of nutrition. Ambrosia beetle species usually have a primary fungal symbiont, sometimes several, and in some cases a pathogen can become part of the mix. After landing on a suitable tree, an ambrosia beetle excavates a tunnel in which it inoculates galleries with spores of its fungal symbiont. The fungus penetrates the plant's xylem tissue, digests it, and concentrates the nutrients on and near the surface of the beetle gallery. Most ambrosia beetles colonize xylem (sapwood and/or heartwood) of dying or recently dead trees. The beetles and their larvae graze on mycelium exposed on the gallery walls and on clusters of the fungus' spores. Most ambrosia beetle species don't ingest the wood tissue; instead, the sawdust (frass or beetle boring dust) resulting from the excavation is pushed out of the gallery. Following the larval and pupal stage, some adult ambrosia beetles collect masses of fungal spores (the symbiont, or possibly the associated pathogen) into their mycangia (organs specifically for carrying spores of symbiotic fungi) or possibly in their guts, and leave the gallery to find their own tree (Raffa and others 2015).

A number of ambrosia beetles in the genus *Xyleborus*, including *Xyleborus ferrugineus*, are known to bore into healthy trees and transmit pathogens. These initial infestations do not result in the production of offspring but the subsequent development of disease symptoms result in large scale attack and brood production. Screening of ambrosia beetles for the presence of *Ceratocystis* DNA and viable inoculum is ongoing. Screening using qPCR has shown that approximately 10% of ambrosia beetles collected in infected stands are positive for the presence of *Ceratocystis sp.*A. Current investigations are focusing on determining whether these beetles are carrying viable inoculum. If viable inoculum is found associated with the beetles future research will investigate the presence and efficiency of direct transfer of the disease to healthy trees.

As adult ambrosia beetles tunnel into the sapwood of dead or dying ‘ōhi‘a trees, their bore holes can overlap streaks of discolored xylem that are rich in *Ceratocystis* spores (as revealed by chopping into the tree). The chewing and tunneling activities of some species can lead to the ingestions and expulsion of spores that may be vectored to healthy uninfected trees. These mechanisms are currently being investigated. Beetles push the frass outside the tree, and the fine powder accumulates in bark crevices or at the base of the tree, or is perhaps left as a mound covering the gallery entrance or a “toothpick” sticking out from the tree trunk. *Ceratocystis* can be isolated from the ambrosia beetle frass (Harrington 2013). Cultured frass samples from ‘ōhi‘a have been confirmed to contain viable *Ceratocystis* spores by the ARS-PBARC lab. Drs. Ewing and Bennett have further verified that frass expelled directly from galleries contains *Ceratocystis* genetic material, indicating viable inoculum. Through direct sampling procedures that pair emerging beetles with their frass, Drs. C. Ewing and M. Hughes of UH CTAHR are further testing for infectivity of both to distinguish frass from beetle vectoring capabilities. Wood-boring beetles are not only attracted to various volatiles, but typically emit pheromones that attract conspecific individuals; this can result in heavy infestations attacking a dead ‘ōhi‘a tree, which in turn, can produce immense amounts of fine, spore-infested frass

3. Wind-blown spores in fine bits of frass

Scientists speculate that, based on the apparently random/haphazard distribution of infected trees as high as 1700 m (5500 ft) elevation in the Wailuku River drainage and elsewhere, wafting on the wind of spores imbedded in fine bits of frass may be an important means by which *Ceratocystis* has spread on Hawai‘i Island (T.C. Harrington, pers. comm.). Ongoing monitoring of wind samples in the Kahuku Unit of Hawai‘i Volcanoes National Park has made repeated detections of particulate matter that test positive for *Ceratocystis*, but the infectivity of these particles to ‘ōhi‘a has not been established (C.T. Atkinson, USGS, pers. comm.). While current evidence supports the hypothesis that wind dispersal is important for movement of the fungus, continued studies that document relationships with wind speed and direction are needed. Scientists and managers are concerned that it may be possible for frass to be carried on trade winds to Kona or with vog or tropical storms to nearby Maui and eventually other islands.

4. Wounding and spore dispersal by episodic wind events, exacerbated by architecture of tall ‘ōhi‘a trees

A tentative hypothesis for explaining the dramatic vulnerability of ‘ōhi‘a to ROD suggests that ‘ōhi‘a could be becoming the victim of episodic wind events, that simultaneously produce fresh wounds while massively transporting fine bits of *Ceratocystis*-infected frass (T.C. Harrington, pers. comm.). Tall ‘ōhi‘a trees may be exceptionally vulnerable to wounding and infection for at least three reasons – 1) their upper parts protrude above the forest canopy and are therefore exposed to the full force of wind gusts; 2) upper branches tend to fork at acute (narrow) angles to the main trunk(s); and 3) they commonly have split (codominant) main trunks with “included bark” (Lonsdale 2000). High wind events could produce much whiplash agitation and wounding as well as transport of infected frass. Included bark in a main crotch between codominant stems of an ‘ōhi‘a tree could provide a major wound site for frass accumulation, especially when these codominant stems are being subjected to twisting and turning by strong winds.

5. *Movement in soil*

Ceratocystis has been found in soils under stands infected by ROD in Hawai‘i (with durable aleurioconidia expelled in insect frass), and contaminated soil may transmit the disease (L. Keith, pers. comm.). Once in the soil, the pathogen could possibly directly enter roots, and transmission could occur on the feet of humans, on vehicles, or by feral animals. This topic needs much more research.

ROD is likely present in compost as well. The county transfer station in Hilo is producing tons of compost that that may be infected with *Ceratocystis* (R.F. Hughes, pers. comm.). Testing is warranted.

6. Movement in water

Plane tree (sycamore) is a riparian species, and movement in water is considered a significant means of transmission for *C. platani*, notably along canals in France and natural watercourses in Greece (Harrington 2013).

Based on observational evidence, the ROD pathogen may have been transmitted along branches of the Wailuku River above Hilo, Hawai‘i, given infection of ‘ōhi‘a in the headwaters of the watershed and along the river and tributary streams below (R.F. Hughes, pers. comm.). With high rainfall on steep watershed slopes, overland flow through *Metrosideros* forests could possibly be a means of transmission. Efforts to detect *Ceratocystis* in stream samples are ongoing, but have not clearly established that this is a pathway for movement of the fungus (C.T. Atkinson, pers. comm.).

7. Ungulates (feral cattle and pigs)

There is observational evidence that feral cattle may contribute to local spread of the ROD pathogen at high elevations in the Wailuku River watershed. Cattle in this area are scarring ‘ōhi‘a trees, producing vulnerable wounds by chewing and rubbing (R.F. Hughes, pers. comm.). Cattle are widespread in island forests but may be producing wounds primarily in the upper Wailuku River drainage, an area where cattle are being removed. Over 400 individuals have been removed from this area since ‘ōhi‘a wounding was discovered (Steve Bergfeld, DOFAW, pers. comm.). Managers believe the upper Wailuku watershed cattle may have been chewing ‘ōhi‘a bark because of a nutritional deficiency; they largely stopped the scarring after salt blocks were provided.

Feral pigs are much more widespread than cattle in Hawaii’s forests. Feral pigs would appear to have the potential to be dispersal agents of *Ceratocystis*, given their characteristic rooting, wallowing, and rubbing habits, their tendency to range over moderately large areas, and their relative abundance in many ‘ōhi‘a forests of Hawai‘i.

Pig rooting involves digging, grubbing, or plowing at and below the soil surface, using their snouts and strong sense of smell to search for and use food resources within the nutrient-rich upper soil horizon. Pigs in Hawai‘i often dig for earthworms (Diong 1982a; Lincoln 2014), and in Texas they have been known to root to depths as much as one meter (Campbell and Long 2009).

Feral pig wallows, defined as depressions in mud that are often filled with water, are sites of rolling, rooting, and loafing. Pigs lack sweat glands and typically visit wallows twice a day or more in warm environments to aid in their thermoregulation (Campbell and Long 2009; Bracke 2011). “Rubs” are frequently found in association with wallows, and these enable removal of the wet or dry mud-coated surfaces. Rubbing functions to remove excess or dried mud, hair, and ectoparasites. Pigs use whatever is available -- trees, fallen logs, fence posts, or utility poles as substrates on which to rub (Campbell and Long 2009).

Pigs are locally abundant and range widely. Home ranges of feral pigs of ‘ōhi‘a-koa forests in Kipahulu Valley, Maui, were found to have lengths of about 2 km for males and 1 km for females (Diong 1982b). Pig densities in native forests are difficult to determine but have been estimated to occupy parts of Hawai‘i Volcanoes NP from $<1/km^2$ to $6/km^2$ (Anderson and Stone 2004) and from $<1/km^2$ to $15+/km^2$ (Scheffler and others 2012).

How might feral pigs distribute *Ceratocystis*? Spores (including resistant aleurioconidia) are expelled with frass to the forest floor from infected ‘ōhi‘a trees by boring beetles or by sawdust of trees cut down. Viable spores could be carried stuck to pigs’ legs and bodies, especially with wallowing, and transported considerable distances and transferred to the soil, from which the disease may enter the trees. In some cases pigs may transfer the disease directly to the trunks of trees by scarring them during rubbing. Spores could also be transferred to surface roots of healthy ʻōhiʻa trees scarred by pig rooting.

Transport of ROD by pigs is plausible, but evidence is minimal. The most credible report of pigs spreading a plant pathogen in Hawaiʻi is that of Kliejunas and Ko (1976): "Feral pigs were trapped in ʻōhiʻa forests in the Hilo watershed area. Soils adhering to their hoofs (15-20 gm/pig) were collected and baited separately. Three of four pigs tested carried soil particles containing *Phytophthora cinnamomi*", a well-known fungal pathogen of plants. A recent Ph.D. thesis from Southwestern Australia (Li 2012) delved into the topic further with ambiguous results and concluded that "further research is therefore required."

8. Transport by birds

The role that forest birds may play in transport of infective spores is still speculative. Transport may be possible if contact is made with sticky ascospores during foraging on exposed wounds with fungal ascomata (perithecia) or through ingestion of insect prey contaminated with resistant aleurioconidia. Many native and non-native forest birds forage for insect prey on the trunks of ʻōhiʻa, probing under bark or in at least one case (the endangered ʻakiapōlāʻau) actually excavating galleries like woodpeckers in search of beetle larvae. This method of spread is still unproven, but might contribute to the patchy patterns of new infections that have been observed (C.T. Atkinson, pers. comm.).

9. Transport by humans

Humans are responsible for international transport of *Ceratocystis* through trade and travel (potentially on many items but especially on plants, wood, and shoes).

Humans are believed to be major dispersers of *Ceratocystis* spores on Hawaiʻi Island and potentially to islands other than Hawaiʻi. Moving infected ʻōhiʻa wood (including firewood) is very high-risk. Tools -- saws, pruners, chippers, etc. -- that come into direct contact with infected ʻōhiʻa wood are also high risk. It has been suggested that pruning saws may have the greatest probability of being effective instruments of transmitting the ROD pathogen in a way that it can easily start a new infection; for instance, a landscaping company or a tree service that is not sterilizing its equipment between visits to different properties could very easily (and innocently) spread this disease extremely rapidly over the range of properties where they operate (P. Cannon, pers. comm.).

J.B. Friday

The pathogen (visible in these logs as dark staining of the heartwood) can remain alive in ʻōhiʻa wood for a year or more. Movement of contaminated wood for posts, firewood, or to greenwaste facilities are high risk activities for spreading the disease.

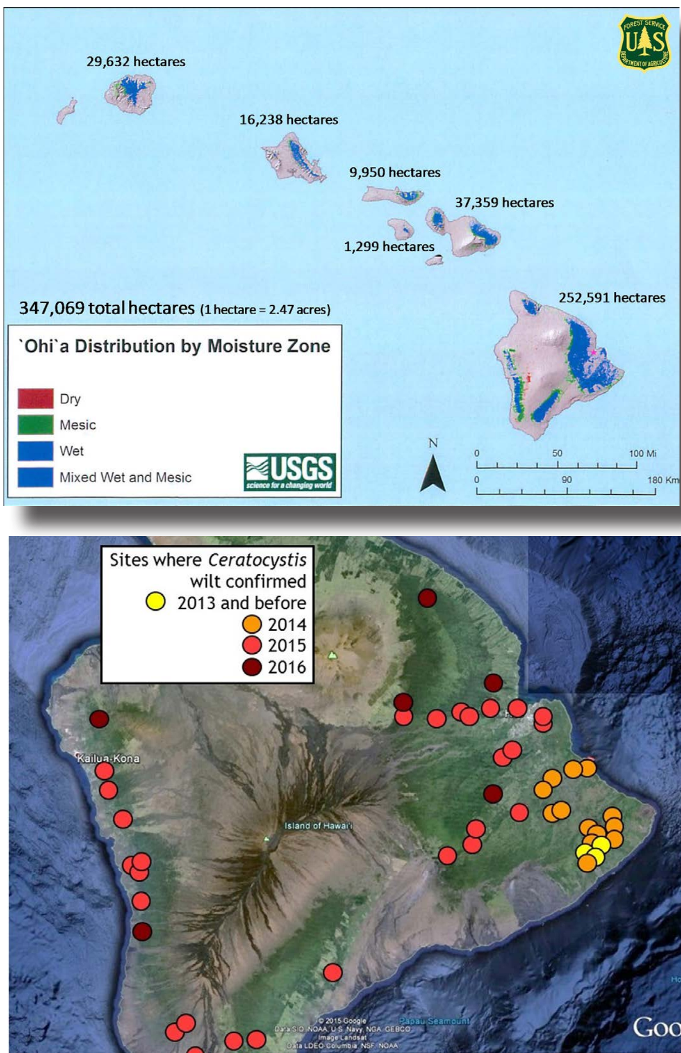
Frass expelled by insects boring into infected trees releases durable aleurioconidia to the air and to the soil. Vehicles used off-road in infected forest areas and heavy machinery (e.g., bulldozers) are especially dangerous for dispersing ROD without serious sanitation efforts.

Clothes and boots of anyone working on tree removal may also become infected.

10. Root grafting tree to tree

With some *Ceratocystis* diseases, movement through functional root grafts is potentially important for diseases affecting trees of sufficient age and size. This phenomenon is well known in Oak Wilt (*C. fagacearum*) and Canker Stain of Sycamore (*C. platani*), perhaps simply because the host trees normally have root grafting. Root grafting may be a possibility for *Metrosideros,* but the fact that the infection pattern is random or haphazard, not clearly spreading from a focus, suggests that this may not be a major vector for spread of ROD. More evidence is needed to discard this possibility.

Current distribution, rate of increase, and mortality based on information that we currently have in hand



USGS/USDA Forest Service; UH CTAHR

Top: Statewide ‘ōhi‘a distribution; Bottom: areas where dead ‘ōhi‘a have tested positive for ROD.

There are ca. 350,000 ha (865,000 acres) of ‘ōhi‘a-dominated forest statewide, with 250,000 ha (618,000 acres) on Hawai‘i Island (Jacobi and others In press). Based on available aerial imagery, substantial ‘ōhi‘a mortality in the vicinity of Leilani Estates in Lower Puna and a separate location just south of Hilo Airport appeared between 2007 and 2009 (T.C. Harrington, pers. comm.). In 2014, ROD was estimated to cover 2,400 ha (6,000 acres) in the Kalapana-Hilo area in stands locally showing greater than 50% mortality. A January-February 2016 aerial survey detected areas with at least 10% ‘ōhi‘a mortality, likely much if not most of it attributable to ROD, totaling ca. 15,000 ha (38,000 acres) across the Puna, Hilo, Kona, and Ka’ū districts, with the largest infestations in the Puna-Hilo-Volcano area. By September 2016 the total estimated area of ‘ōhi‘a mortality had increased to ca. 20,000 ha (50,000 acres), though that increase is regarded as partly due to more total area having been surveyed (Philipp LaHaela Walter, DOFAW, pers. comm.). It must be admitted, however, that a very small proportion of dead ‘ōhi‘a trees have actually been tested for *Ceratocystis* infection. A more systematic and comprehensive effort is needed for the mundane but important work of testing dead trees for ROD statewide.

There are still no known locations of ROD on other islands, in spite of surveys and falsely suspected (but tested) ʻōhiʻa trees there. But again, increased/additional effort at detection and testing of dead trees for *Ceratocystis* is needed.

A remarkable complicating issue recently discovered and becoming increasingly apparent and troublesome is that there are two different *Ceratocystis* diseases that produce the outward symptoms of what is being called "Rapid ʻŌhiʻa Death" or ROD (Lisa Keith, pers. comm.). Both diseases are currently found only on ʻōhiʻa and only on Hawaiʻi Island and nowhere else in the world. These are:

> *Ceratocystis* sp. A, first documented by Keith and others (2015), recognized as the primary cause of the dramatic ongoing major epidemic killing ʻōhiʻa, a close relative of *C. fimbriata* and *C. platani*, and currently being described as a new species (L. Keith, pers. comm.). Species A has a definitive symptomatology (e.g, radial staining) in the sapwood of affected trees. Species A is usually the major agent recovered from trees in areas of widespread ʻōhiʻa mortality, and is likely the major fungal pathogen causing *Ceratocystis* wilt.
>
> *Ceratocystis* sp. B, first recognized by Lisa Keith in 2015 and also referred to as ROD, is much less well understood than sp. A. It is also being described as a new species (L. Keith, pers. comm.). Species B has been found in far fewer trees than sp. A, but still causes ʻōhiʻa death. It (sp. B) superficially causes symptoms similar to those of sp. A, but produces slightly different internal symptoms. It appears to kill trees more slowly than sp. A and more typically kills isolated trees. The scientific description of this disease is currently being addressed (L.Keith, pers. comm.). It is unclear where sp. B may have come from.

These two diseases are likely responsible for much of the death of ʻōhiʻa detected by the 2016 aerial surveys mentioned above. It has been assumed that *Ceratocystis* sp. A is overwhelmingly important, but we need to know and understand the status of the other *Ceratocystis* (sp. B) species killing ʻōhiʻa, as well as other causes of ʻōhiʻa mortality. For example, there are many dead ʻōhiʻa trees in the main Kilauea (Headquarters) unit of Hawaiʻi Volcanoes National Park, but none of them have yet been diagnosed as ROD in spite of substantial sampling efforts. Early detection of ROD (sp. A or sp. B) on other islands and in uninfected parts of Hawaiʻi Island is complicated by other causes of mortality with similar outward/visible symptoms, which may or may not involve other (as yet unknown) pathogens or may be entirely due to environmental causes such as drought.

What we are currently doing, given what we know

Sanitation, regulation to reduce chances of ROD spread, and fungicides

By 2016, ROD had spread widely on Hawaiʻi Island, but measures are being taken to prevent further spread. Efforts are currently being explored to determine whether ʻōhiʻa trees can be protected from becoming infected with *Ceratocystis* or to cure trees that exhibit symptoms of the disease.

> **Recommendations:** To reduce the spread of *Ceratocystis*, landowners are being asked not to transport untreated wood of infected ʻōhiʻa trees to other areas, since the pathogen may remain viable for two years or more in dead wood. Tools used for cutting

infected ʻōhiʻa trees should be cleaned with a 70% isopropyl (rubbing) alcohol solution. A freshly prepared 10% solution of chlorine bleach and water can be used as long as tools are oiled afterwards, as chlorine bleach will corrode metal tools. Chains should be removed from chain saws used to cut infected ʻōhiʻa and both the chain and the body of the saw brushed clean then sprayed thoroughly with cleaning solutions. After the saw is reassembled, it is recommended to run it briefly to re-lubricate the chain. Vehicles used off-road in infected forest areas should be thoroughly cleaned underneath with pressure washing so as not to carry contaminated soil to healthy forests. Shoes, tools, and clothing used in infected forests should also be cleaned, especially before being used in healthy forests.

Hawaiʻi Department of Agriculture's regulation of commodities moving between islands is crucial to prevent spread of ROD to non-infested islands. On August 25, 2015, the Hawaiʻi Board of Agriculture passed an interim rule that restricts movement of ʻōhiʻa from Hawaiʻi Island. The rule "imposes a quarantine on the intrastate movement of ʻōhiʻa plants and plant parts, including flowers, leaves, seeds, stems, twigs, cuttings, untreated wood, logs, mulch greenwaste and frass (sawdust from boring beetles) from the Island of Hawaiʻi. Transport of such items may be only conducted with a permit issued by the Hawaiʻi Department of Agriculture"; testing of wood and other items is being conducted by ARS for permitted interisland exports. The interim rule also restricts the movement of soil from Hawaiʻi Island. Interim rules are in force for only one year (until August 25, 2016 for the ROD rule) and needed to be made long-term. http://hdoa.hawaii.gov/blog/main/ohiaquarantine/ A long-term rule was pursued and finalized by HDOA in November 2016.

After passage of the rule (explained in the paragraph above), HDOA grants permits for ʻōhiʻa wood/logs for shipment from Hawaiʻi Island to other islands after testing by ARS-PBARC for ROD infection. Upon reflection, HDOA has expressed concern that very small samples are collected and tested. Thus confidence in the sampling is not strong – it can prove the presence of the pathogen but not the absence. Given that ʻōhiʻa wood is highly valuable and highly available due to the substantial mortality caused by ROD, diverse entities would very much like to have an available quarantine treatment. (Landowners are currently being encouraged to fell infected ʻōhiʻa trees to lessen transmission of ROD.) HDOA has suggested the desirability of a steam kiln or other heat or drying treatment as described in a recent review for the North American Plant Protection Organization (NAPPO 2014). Ideally, funding could be allocated by the State Legislature for HDOA to have a treatment facility built close to Kawaihae, the major port on the west side of Hawaiʻi Island. All loggers and shippers of ʻōhiʻa wood could use and pay for treatment of their shipments prior to shipping at the harbors. UH-CTAHR's forester J.B. Friday is currently working with national experts in the USDA Forest Service to determine the feasibility and cost of an effective heat/drying treatment.

Fungicides are being tested (L. Keith, pers. comm.) as a potential injection or soil drench for various potential uses. It is considered highly unlikely that a fungicide treatment could be successfully developed and applied effectively for ʻōhiʻa at a landscape scale. Fungistatics (chemicals that arrest, rather than prevent, fungal growth) are also being tested by Keith as a protectant/preventative, which could prolong the time for development of disease in ʻōhiʻa trees or nursery seedlings. There is possibility that an effective fungistatic could be applied to at least temporarily protect trees in new outbreaks of the disease -- particularly important for the other islands. In the cases of some other fungal diseases (i.e. Oak Wilt), a single application of a fungistatic can prevent the advancement of disease symptoms for one or two years, and then be reapplied effectively as a follow-up.

Monitoring of ROD spread and impact

1. Aerial survey efforts to date

Aerial survey efforts are potentially an important means of determining distribution and spread of trees that are symptomatic for ROD. Ideally, aerial survey can be used for detection of new outbreaks in uninfected areas, for locating possibly resistant individuals, and could be used to select ʻōhiʻa forest areas on Hawaiʻi Island for protection. In case of drought, they could be used to detect areas especially vulnerable to fire, with many standing dead or fallen ʻōhiʻa trees. Two excellent techniques have been used so far for ROD and others could potentially be used beneficially.

Greg Asner

DLNR DOFAW staff using Digital Mobile Sketch Mapping on a tablet to survey for, and record, sick and dead ʻōhiʻa on Hawaiʻi Island via helicopter.

Hawaiʻi Division of Forestry and Wildlife (DOFAW), in collaboration with the U.S. Forest Service (USFS), has made use of Digital Mobile Sketch Mapping (DMSM), a recently updated technique used nationally for recording forest insect and disease damage. Forest areas with mortality/damage are mapped manually on a tablet computer by an observer flying in an airplane or helicopter. Values are assigned to severity and type of damage. Data collected with the DMSM are synchronized via wireless connection to a USFS server in Ft. Collins, Colorado. This gives surveyors immediate access to newly collected forest health data and potentially provides field staff with an efficient method of giving aerial surveyors rapid and accurate feedback about what they are seeing on the ground. The ground-checking process in DMSM allows for edits or comments to be made to the data. This provides timely feedback and a new level of quality control for aerial survey data. (Michigan Department of Natural Resources 2016)

DOFAW first used DMSM for survey/mapping ROD on Hawaiʻi Island in January and February of 2016, reporting 15,000 ha (38,000 acres) of recent mortality. They also surveyed Maui, Oʻahu, and Kauaʻi in the spring of 2016. At least one site on Maui was identified as worth checking for ROD, but turned out to be negative for *Ceratocystis*. DMSM has many advantages – being relatively inexpensive, instantly available (with local capacity, though dependent on weather) and easily repeatable, but has the disadvantage of lower spatial accuracy (P.L. Walter, DOFAW, pers. comm.). Tentatively, DOFAW's plan is to conduct aerial detection surveys every 6 months.

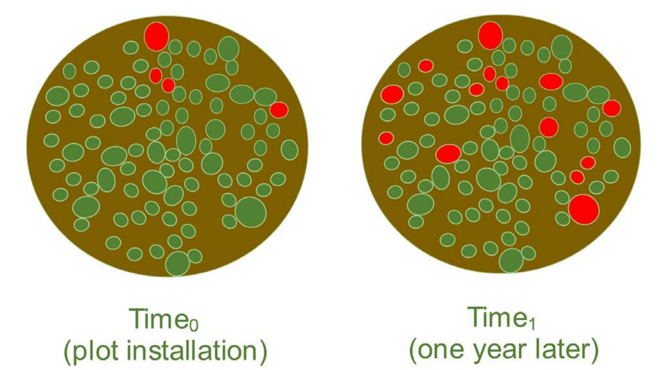
The Carnegie Airborne Observatory (CAO), developed by Dr. Greg Asner and used in California, Hawaiʻi, Central and South America, Africa, Australia and elsewhere, is a fixed-wing aircraft that utilizes laser-guided imaging spectroscopy (LGIS) to measure the 3D structure and chemical content of all canopy trees in a forest. The data can determine the location and height of each tree at a resolution of one meter. It can also delineate tree species and the condition of their foliage (e.g., live or dead, presence or color of leaves, level of water stress, etc.). This ability is well suited to positively identify dead, ROD- infected, and healthy ‘ōhi‘a with high-precision. It may be capable of yielding early detection of symptomatic ‘ōhi‘a via water content and nutrient status data. The platform is well-suited to providing an accurate baseline of information on Hawaii’s ROD infestation. The cost to remap Hawai‘i Island is approximately $0.50 per forested acre; however, mobilization costs from California to Hawai‘i require a minimum commitment of the fully forested portion of Hawai‘i Island, which is about 250,000 ha (618,000 acres).

The CAO obtained full coverage of Hawai‘i Island in January 2016. When analyzed (expected in January 2017), it can, among other uses, be used for comparison with DOFAW’s DMSM mapping in January-February 2016 to assess precision. The CAO coverage can identify the precise location of and canopy height of each ‘ōhi‘a tree.

A third potential source for ROD aerial survey solutions could be available locally from Resource Mapping Hawai‘i (RMH), based in Kea‘au, Hawai‘i Island. This company has worked with Hawaii’s conservation community for nearly a decade by developing and implementing techniques for detecting, mapping and monitoring invasive plant species over large landscapes (for example, detecting individuals of invasive Australian tree fern in Kauai’s forests to enable control). RMH could explore and implement technologies for more accurate (vs. DMSM) monitoring for presence of ROD in areas of special concern – most notably for early detection of ROD (individual trees) in locations where it has not yet been detected.

Unmanned aerial vehicles (UAVs or drones) can be used to monitor and photograph small areas (hundreds rather than thousands of acres) on a frequent basis at low expense. Dr. Ryan Perroy of the UH Hilo Spatial Data and Visualization Lab has flown many missions over selected areas, allowing scientists to gauge progress of the disease in selected forests. Because UAVs are locally available and the cost is low, they can be deployed quickly, within a day or two, to investigate a new outbreak.

2. Sampling of ROD occurrence and impact in long-term plots and correlation with environmental factors



Flint Hughts/USDA Forest Service

Graphic representation of annual monitoring plot data showing size and distribution of dead ‘ōhi‘a.

The USDA Forest Service has a program for Forest Inventory and Analysis (FIA) for long-term monitoring in collaboration with the states that has recently been brought to Hawai‘i. The core part of the national program (designed to potentially/eventually include all forested lands in the US, regardless of ownership) consists of one field sample site (0.1 ha) for every 6,000 acres. Field crews collect data on long-term plots on forest type, site attributes, tree species, tree size, and overall tree condition on accessible forest land (USDA Forest Service 2005).

On Hawai‘i Island, a network of ROD mortality monitoring plots (similar to but not FIA plots) have been established within ‘ōhi‘a forest, specifically for use in monitoring effects of ROD (R.F. Hughes, pers. comm.). As of June 2016, 52 plots (0.1 ha each) had been installed in areas with ROD, across gradients of forest stand age, lava flow age and type, elevation (temperature), and precipitation. Nine such plots (the first to be installed) were established in the Puna district in the winter of 2014 and resampled a year later. Results revealed average annual ‘ōhi‘a mortality rates of 24% and 28% based on basal area and stem density measures, respectively; annual mortality rates were as high as 47% in some field plots (Mortenson and others 2016).

The network of ROD plots will continue to be analyzed annually. This will help track disease progression within a given forest stand and will complement the landscape-scale data derived from remote sensing.

Efforts to date to detect new infestations

ROD is regarded as such a serious threat that there is much collaboration addressing detection of the disease. Aerial surveys may identify possibly infected sites on islands believed free of ROD. Agencies/landowners on Maui, Moloka‘i, Lana‘i, O’ahu and Kaua‘i who suspect *Ceratocystis* infection of ‘ōhi‘a trees should contact J.B. Friday, Flint Hughes, or Lisa Keith (addresses given at www.rapidohiadeath.org) with reports and precise locations of possibly infected areas. Digital photographs of crowns of infected trees and samples of wood showing the characteristic staining will help in assessing likelihood of an infection with Ceratocystis sp. A. Hawai‘i Department of Agriculture (HDOA) will convey the actual samples to Lisa Keith of ARS for testing. http://hdoa.hawaii.gov/blog/main/reportingohiawilt

Refinement is needed to provide rapid, accurate and reproducible methods to detect the ROD pathogen in all types of samples, including samples from trees, from wood and from soil. Drs. W. Heller and L. Keith at ARS have developed a qPCR (quantitative real-time Polymerase Chain Reaction for DNA analysis) method specifically for the two *Ceratocystis* species causing ROD, and it is currently used for HDOA and off-island samples (L. Keith, pers. comm.). Time to results has been reduced from 2 to 4 weeks to less than 24 hours. Dr. Carter Atkinson and colleagues at USGS have developed a portable method for rapid detection of ROD, i.e. “lab-in-a-suitcase” that does not require a dedicated laboratory and is adaptable to field use. The method is based on “isothermal” or constant temperature amplification of DNA, which can obtain accurate results within one hour. Ultimately, this technique could become routine for detecting ROD -- potentially allowing a determination using a “lateral flow test strip,” much like a home pregnancy test, or a portable field fluorometer, much like a qPCR assay. This method is currently undergoing field testing and refinement to determine sensitivity relative to the qPCR method developed by USDA. This rapid method could be particularly crucial for early detection of the pathogen on previously uninfected islands and also increase overall laboratory capacity for diagnosing the pathogen.

Dr. Dee Mills of Florida International University, attended the annual “Hawai‘i Ecosystems Meeting” in July 2016, and reported on her work with the laurel wilt pathogen (*Raffaelea lauricola*) currently threatening avocados in South Florida. Mills and her group at FIU have trained “detector dogs” to sniff out infected but pre-symptomatic avocado trees and then have applied a fungicide to the infected avocado trees to keep the disease from spreading. Dr. Kealoha Kinney of the Forest Service in Hilo recognized that this approach might be applicable to ROD. Kinney worked with Drs. Michelle Reynolds of USGS and Lisa Keith of PBARC to develop a proposal and initiate a collaborative project with the Florida group to determine the feasibility of this idea for ROD in Hawaiʻi. The project involves a protocol for capturing the scent of *Ceratocystis* from ʻōhiʻa and taking it to Florida to train Jack Russell dogs to bring to Hawaiʻi to test their reliability in detecting pre-symptomatic ROD. (The dogs would be small enough to backpack to remote sites.) The work will also test the fungicide Propiconazole for its effectiveness at protecting ʻōhiʻa pre-symptomatic for ROD, as well as evaluating non-target effects of Propiconazole. The project is already underway, and if all goes well, *Ceratocystis*-trained dogs and handlers will be flown from Florida to Hawaiʻi in early 2017 for three weeks of exploratory work. Conceivably, this work could prove highly useful for early detection and rapid response for ROD.

Experiment with containment of marginal infected stands and eradication of newly infected stands on Hawaiʻi Island

Harrington (2013) describes what limited recommendations exist in the literature for eradication of small populations of *Ceratocystis platani*, likely the closest analogue to ROD sp. A, in Europe:

> Complete eradication of an exotic *Ceratocystis* sp. from even a limited area is a difficult task, but local introductions may be eliminated if recognized quickly, and efforts using sanitation practices have proven effective in managing local epidemics.
>
> The prompt removal of diseased trees is recommended... In addition to the removal of symptomatic trees, at least one healthy plane tree should be removed on either side of the infected trees… Treatments with glyphosate or other herbicides are used to kill the root systems and prevent further spread via root graft transmission. When diseased trees are removed, a minimum of cutting is recommended, and all sawdust generated should be collected in tarps and properly disposed of… Traffic in the area should be minimized to prevent the wind movement of sawdust, and trees should not be sawn on a windy day. As much of the root system should be removed as possible, as well as removing the contaminated soil. The entire area should be treated with disinfectant or fungicide.
>
> …logs should be removed or otherwise disposed of before ambrosia beetles and other wood-boring insects enter and release contaminated frass.

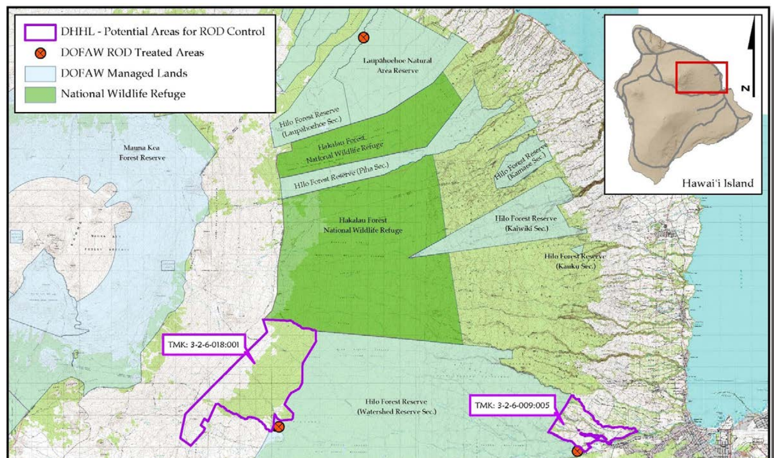
No eradications of ROD have been yet attempted but trials for localized ROD suppression/ containment have been initiated in two areas on Hawaiʻi Island, felling recently killed trees to reduce inoculum pressure and disease spread. In such efforts, a danger from felled but not destroyed infected trees is that resistant ROD pathogen spores can survive in dead sapwood and be dispersed with frass by boring of ambrosia beetles, into the nearby soil and potentially to wounds on nearby ʻōhiʻa trees. (However -- see below -- ROD-infected trees that have been cut down may possibly produce much less airborne frass than standing trees). It is obvious that human crews conducting this work must practice impeccable sanitation and do everything possible to reduce dispersal of sawdust. ROD-specific tools and gear are being used only in areas where ROD is known to be established.

Female ambrosia beetles likely respond not only to chemical cues (e.g., fruity odor, pheromones) for attraction to infected ʻōhiʻa trees, but also likely respond simultaneously to visual cues, though such beetles have very poor eyesight; they are believed to be attracted to silhouettes of the boles of standing trees (P. Cannon, pers. comm.; Mayfield and Brownie 2013).

Consequently, ROD-infected trees that have been cut down may produce much less airborne frass (than standing trees), reducing the overall frass plume of ambrosia beetles tunneling into the sapwood of killed trees, thus reducing wafting of spores to infect newly wounded trees. [However, it is possible that cutting may also increase ʻōhiʻa volatiles that could draw in more insects to the damaged wood. It has been observed that beetles attack standing stumps of recently felled trees (C. Ewing and G. Bennett pers. comm.)]. This hypothesis is currently being tested.

Efforts began in March 2016 to test this ʻōhiʻa felling strategy in a relatively small, isolated high-elevation hotspot in the upper Wailuku River watershed at about 1600 m (5000-5500 ft) elevation. Later, testing began at low elevation (ca. 460m or 1500 ft) above Piʻihonua, just west of Hilo. [It may, however, be difficult to fully evaluate this possibly promising strategy. The challenge seems to be that of comparing frass production/wafting from downed trees vs. standing trees – not so easy but probably doable.]

If experience with felling trees to limit ROD spread turns out to be promising, there is current consensus that the best strategy is to focus on preventing movement of ROD north of a line running roughly from Hilo west to and through Waimea (including the Kohala Mountains). This is an area until recently believed to be completely free of ROD, and it contains high-quality ʻōhiʻa forests, including those of Hakalau Forest National Wildlife Refuge and Laupāhoehoe Natural Area Reserve. Detection of ROD in mid-November 2016 of a large ʻōhiʻa tree in the Hilo Forest Reserve west of Laupāhoehoe (http://www.hawaiitribune-herald.com/news/local-news/rapid-ohia-death-kills-Hāmākua-tree) suggests that this line may have already been breached, increasing the urgency to perfect management methods for containing spread of the disease. If the disease becomes established in Hāmākua, not only may high-quality Hāmākua ʻōhiʻa forest likely be devastated, but trade winds will likely push the inoculum further west. Spread of ROD to the northwest portion of Hawaiʻi Island would increase the likelihood that a tropical storm could carry airborne inoculum to Maui and perhaps even to islands beyond. Efforts were underway in mid-December to determine whether there are other infected trees in the Hāmākua forest and to attempt to eradicate/contain this new disease outbreak.



DLNR DOFAW

DLNR DOFAW and partner agencies conducted experimental felling of dead ʻōhiʻa combined with research on ambrosia beetle activity and frass production before, during and after felling.

Other land management needs

1. Access restrictions

Land managers may be called upon when needed to use proper judgment in restricting access to certain areas. An obvious need would be for an area where an extended eradication effort is in progress on an otherwise non-infected area. How to do this discretely (perhaps without calling attention to the specific area) and wisely remains to be determined. Part of Hawaiʻi Volcanoes NP in upper Kahuku was closed to the public when *Ceratocystis*-infected trees were found.

Installing signs alerting people not to remove vegetation or soil from infested areas might be used where access cannot be effectively controlled. Signs have been posted by the Hawaiʻi Department of Transportation along the Saddle Road realignment warning people not to collect ʻōhiʻa wood from downed trees in that area.

2. Ungulate control

Although there is as yet no solid proof that feral ungulates are significant dispersal agents of ROD, it is plausible that this may be the case. Many conservation areas on non-infected islands are already ungulate-free and should be kept that way. If a ROD infection is discovered on a previously non-infected island in a non-ungulate-free area, the infestation arguably needs to be fenced off ASAP – if possible concurrently with the start of the ROD eradication effort.

What do we additionally need to learn/know?

Much of what we think we know about ROD involves speculative hypotheses that are based on common sense observations, educated experience and evidence from elsewhere. These hypotheses need to be confirmed and refined or refuted and replaced through research.

Detection, spread, severity, and environmental limits of ROD

1. Determine and use optimal aerial imagery combined with ground truthing for detection of new foci of *Ceratocystis* sp. A or sp. B.

DOFAW's DMSM (Digital Mobile Sketch Mapping) imagery has many merits, especially that of being relatively inexpensive, but may lack the precision necessary for detection of new disease foci and individual declining trees. Because mapping trees with onset and fully developed ROD is central to tracking the pattern and spread rate of the fungus, there is a critically important need for testing a variety of airborne mapping and monitoring techniques. This may include simple photography (e.g., using drones) to high-tech 3-D spectral imaging (Carnegie Airborne Observatory). Working with Resource Mapping Hawaiʻi (located at Keaʻau, Hawaiʻi) could be considered to explore and implement technologies for more frequent and more accurate monitoring for presence of ROD in areas of special concern.

2. Increase monitoring efforts by adding additional long-term forest plots (circular, 18 m radius, 0.1 ha area) and gathering much more detailed information.

Bring the total number of annually monitored forest plots to a total of at least 100 plots that encompass the broadest range of physical (e.g., lava substrate and age, climate) and biological characteristics (e.g., forest size, age and composition) of forests where ROD is currently present. Collect additional data in each plot on ʻōhiʻa epidemiology. This would be done by determining the cause (i.e., sp. A, B, or something else) responsible for mortality of individual trees in or immediately adjacent to each established plot through time. Results would include temporal dynamics of the cumulative proportion of deceased trees for each of the identified diseases. This work will necessitate much more intensive tracking of mortality (e.g., tagging trees). (Previously, sampling for *Ceratocystis* in diseased trees in or adjacent to potential monitoring plots has been limited to an initial sampling of 1 or 2 ROD-killed trees in each plot.) This will help track disease progression on a much finer scale than the remote sensing projects and will serve to complement that data.

Drs. Lucas Fortini and James Jacobi of USGS will make use of the copious data (including cause of mortality) from the 100 ROD plots as well as the Carnegie Airborne images and other available data to characterize the physical and biological factors that correlate with the distribution and spread of ROD (*Ceratocystis* sp. A and sp. B) across the landscape and create spatial models to predict future spread.

More in-depth knowledge of *Ceratocystis* in Hawai‘i

1. Improve diagnoses for detecting *Ceratocystis* sp. A (and sp. B). Develop rapid, accurate and reproducible methods to detect C*eratocystis* in both pre-symptomatic (early infections) and symptomatic (late infections) trees and in environmental samples including ‘ōhi‘a wood, sawdust, water, soil and insect frass.

2. Further characterize pathogen genetics as it relates to host range, virulence, and host susceptibility/resistance to infection. Determine and publish appropriate Latin names for *Ceratocystis* sp. A and sp. B., determine genetic basis for virulence in Species A and B, the genetics of host resistance/susceptibility, the origins of the two pathogen species and their current host range on ornamental plants.

3. Develop a better understanding of the epidemiology of the disease. Obtain more knowledge of the nature of wounds involved in pathogen infection. For example, how much of a wound is necessary for infection, how long does a wound remain susceptible, how many infective propagules are necessary for infection of a wound, how long does it take after inoculation for symptoms to become apparent and does this vary with host genetics, host phenotypes and environmental factors such as temperature and elevation.

4. Survey nurseries throughout Hawai‘i for genotypes of *Ceratocystis* on *Syngonium* and on other potential hosts of *Ceratocystis* to determine how ROD likely arrived in Hawai‘i, how other damaging genotypes of *Ceratocystis* might arrive or already be arriving, and how to prevent that from happening.

5. Determine more precisely the longevity of *Ceratocystis* spores in dead trees, wood, soil, etc. and develop methods capable of making wood and soil safe for disposal, use, transport, etc.

More in-depth knowledge of the role of insects, feral ungulates, birds, and environmental factors in transmission of the pathogen

1. Continue to test hypotheses regarding the major role of ambrosia beetle frass in short and long-distance spread of ROD. Determine which beetle species attack dead and dying ‘ōhi‘a and produce frass, which beetle species increase in numbers in ROD-diseased stands, their key life history characteristics, and their role in directly transmitting ROD spores from one tree to another with fungal spores attached to the insect body surface, in specific organs (mycangia), or in the gut.

2. Investigate the effect of tree felling on beetle populations and frass dispersal and how this approach may slow spread of the infection. Determine how timing of beetle/frass buildup relates to the timing of tree infection, whether tree felling markedly decreases beetle populations, and how widely frass is dispersed during tree felling.

3. Develop a more refined understanding of how feral ungulates, birds and human activities contribute to spread of the pathogen.

4. Determine the association between episodic wind events, rainfall, and humidity on short and long-distance spread of ROD by wind and water borne inoculum (frass with embedded spores). Model short and long-term spread in relation to wind speed and direction, rainfall, humidity, and stream flows within infected watersheds to determine which environmental factors have the greatest impact on spread of infection.

What we most importantly need to do, both in terms of Hawaiʻi Island and the other islands

Although much of what we think we know about ROD involves “best guess” hypotheses that need to be confirmed and refined, or refuted and replaced through research, there is general agreement that experimental management actions are warranted now with the goal of protecting remaining healthy ʻōhiʻa forests from ROD. Large areas of ROD-free ʻōhiʻa forest still exist, both on Hawaiʻi Island and on other islands. The currently favored hypothesis for disease spread is that trees killed by ROD are attacked by ambrosia beetles which bore into the wood of trees, creating fine boring dust and excrement (frass) that includes viable pathogen spores. This fine material is transported by wind and serves as inoculum for spreading ROD in the environment. Reducing the amount of inoculum exposed to prevailing winds, soils, and streams could have a marked impact on reducing spread of the disease.

Methods need to be tested and refined to rapidly contain and eliminate outbreaks of ROD in the earliest stages of infestation in otherwise healthy ʻōhiʻa forests of Hawaiʻi Island and neighbor islands. This will require development of new methods for detecting asymptomatic early infections, and use of detector dogs might be a significant step forward in this area. Additionally, containment of localized outbreak infestations of ROD in peripheral areas could help reduce spread into nearby healthy ʻōhiʻa forests. Methods need to be evaluated to determine whether the approaches being used are effective at arresting the spread of ROD into a wider area and revised as new information becomes available.

We need to put in place a plan and the means to both accurately and frequently survey for ROD on all the islands and to respond to any detected isolated outbreaks of the disease. Optimal aerial imagery (see sections III.B.1. and IV.A.1.) is critical (and unfortunately is not yet worked out). It must be combined with ground truthing for early detection of new foci of *Ceratocystis* sp. A or sp. B. We are trying to come up with approaches to protect uninfected areas on Hawaiʻi Island and learn how to do that for the other islands in the process. We urgently need to come up with a more systematic way of sampling on the neighbor islands, aside from responding to occasional dead tree reports and aerial surveys. Use of environmental monitoring techniques to detect wind or water borne insect frass might be a cost effective way to do this in conjunction with aerial imagery, particularly in very remote or difficult to sample areas, but much more work is needed to determine whether this approach will work.

Currently, best management practices when isolated infected trees are detected recommend prompt felling of diseased trees. When possible, trees should be felled without scarring (wounding) adjacent uninfected trees. Sanitation protocols should be strictly followed, and tree felling should occur on days with calm, moist weather to minimize spread of infected frass/boring dust and sawdust. To minimize beetle infestation and movement of wind-borne frass, felled trees should be destroyed or covered in a manner appropriate to site conditions. Ideally, felled logs and all woody material would be cut up, carefully gathered, bagged or wrapped, and sent to an incinerator. Logs or other material left on site should be covered with clear plastic to aid in drying or with burlap or other permeable material to aid decomposition. Inoculation with a rot fungus may be considered to hasten decomposition. Sites should be fenced and kept ungulate-free to prevent pathogen movement by animals, and quarantined, if possible, to restrict access and reduce the risk of accidental spread by people. Follow-up monitoring will be conducted to determine whether intervention efforts are effective at eliminating ROD at the site. response crews will employ strict sanitation protocols. Equipment will be cleaned and disinfected before use in future operations. Sites will be monitored at monthly intervals to detect newly symptomatic ʻōhiʻa trees in the area; trees that are tested and confirmed positive for *Ceratocystis* should be felled and treated as described above.

Another urgently needed action is to provide an effective treatment to allow for permitted quarantine shipments of ʻōhiʻa logs and other ʻōhiʻa wood products from Hawaiʻi Island to other islands. ʻŌhiʻa posts are highly valuable, and logs from ROD-killed trees are currently abundant. HDOA and others have suggested the need for a steam kiln or other heat or drying treatment, ideally near Kawaihae, the major port on the west side of Hawaiʻi Island. All loggers and shippers of ʻōhiʻa wood could use and pay for treatment of their shipments prior to shipping at the harbor. The problem is need for funding from the Hawaiʻi Legislature or other source to build such a facility.

In case of the worst: Possibilities for restoring/replacing ʻōhiʻa

There is commitment in Hawaiʻi to doing what can be done to prevent the decimation of ʻōhiʻa given the presence of the destructive ROD pathogens. If these efforts fail, what are the options for mitigating the devastating loss? Both options described below would require substantial long-term commitment and expense.

Prospects for developing resistance in ʻōhiʻa

The potential loss of ʻōhiʻa as an overwhelmingly dominant species would be calamitous for Hawaiʻi. Native U.S. forests in general have suffered enormous losses from pathogens and insects introduced from other countries in the past 100+ years. Some important tree species have been essentially eliminated as integral components of the forest. The American chestnut was the earliest and is the most well-known, while many other species are currently suffering severe declines. The effect of invading species on forest ecosystems can be profound and extend beyond the host species -- to flora and fauna that depend upon host species for habitat and food. Such ecosystem impacts grow every year as more invasive pest species establish in the country (Campbell and Schlarbaum 2014; Lovett and others 2016). Although these pests are destined to be permanent fixtures in our forests, at least a low frequency of genetic resistance can be expected in even the tree species most severely affected (Sniezko 2006).

American chestnut (*Castanea dentata*) was the victim of chestnut blight (*Cryphonectria* *parasitica*), with 4 billion trees dying in the first half of the 20th century. It is a prime example of continuing attempts at development of pathogen resistance in and reintroduction of a tree species. *Castanea dentata* is an important model to inform reintroduction of forest species in general and foundation forest trees in particular (Jacobs and others 2013). However, the great progress to date with chestnut has taken place over a span of a half century as improved techniques have been developed. Other examples of promising programs that have been long underway include those for American elm (Dutch elm disease) and five-needle pines (white pine blister rust).

Resistance breeding of forest trees is now being undertaken increasingly and with some success (Sniezko 2006), although challenges exist, such as long tree generation times and the potential of the pathogen to evolve and escape resistance. Arguably, one of the most rapid and successful programs has been that for *Phytophthora lateralis*, a highly damaging pathogen causing root rot of Port-Orford cedar (POC, *Chamaecyparis lawsoniana*), primarily in Oregon, although it has taken roughly 25 years to reach fruition. The program started modestly with testing that exposed the pathogen to seedlings and rooted cuttings of four POC trees selected for phenotypic resistance (Hansen and others 1989). In 1997, the USDA Forest Service and USDI Bureau of Land Management began a large operational program to develop populations of POC with genetic resistance to *P. lateralis*. With essential ongoing forest pathology support from Oregon State University, this resistance program advanced rapidly. The program goal included developing orchards for production of resistant seed, while maintaining genetic variation and adaptability within the species. Using classical selection and testing techniques, over 12,600 initial field selections were made, resistance screening protocols refined, 13 breeding zones delineated, field trials established, eight seed orchards started, and resistant seed produced and being used for some breeding zones; at least two types of resistance became apparent (Hansen and others 2012; Sniezko and others 2012a,b). The POC program has much to emulate in working toward an operational program for developing resistance in ʻōhiʻa.

Other actively developing resistance programs include those for beech bark disease (Koch and others 2012), Butternut canker (Michler and others 2006, McKenna and others 2012), and red bay (Hughes and Smith 2014). The latter example may provide an excellent model for starting work on ʻōhiʻa resistance.

A potential model specific to the *C. fimbriata* complex involves the continual development of disease resistance (and other desirable traits) in *Eucalyptus* (Myrtaceae, same family as ʻōhiʻa) in Brazil (de Assis and others 2004, Zauza and others 2004, Zauza and others 2014). Another possibly useful model providing lessons is the pursuit of sustained resistance against *C. fimbriata* for mango (Araujo and others 2014, 2015, Oliveira and others 2016). Pilotti and others (2009, 2016) have been experimenting and are apparently slowly progressing in Italy to try to achieve broad-based resistance to *Ceratocystis platani* in European hybrid plane trees.

Early discussion toward developing resistance for ʻōhiʻa in Hawaiʻi has focused on identification of trees or small “islands of trees” with potential resistance, aided by aerial reconnaissance/imagery, within a matrix of dead ʻōhiʻa trees. Tentatively seeds could be taken from 40-50 “islands,” from as many as 200 mother trees, producing ca. 30 seedlings per mother tree. Propagated at a nursery on Hawaiʻi Island, at a predetermined size they would be exposed to the ROD pathogen. As the discussion progressed, it became clear that it would take several years to produce seedlings large enough for pathogenicity testing. Starting with vegetative cuttings from those potentially resistant mother trees would seem to be a much more practical solution. Besides Ramlal's (2014) work toward rooting of *Eucalyptus* microcuttings, techniques have been explored by Hughes and Smith (2014) for the ongoing development of resistance in red bay (*Persea borbonia*) in southeastern U.S.

UH-CTAHR plant pathologist Janice Uchida has pioneered and provided detailed methodology for propagation of ʻōhiʻa for pathogenicity testing using cuttings (Uchida and Kadooka 2013). The cut stem ends are dipped in indole-3-butyric acid; with specified care, cuttings are frequently rooted in 3-4 months. With proper care they grow quickly once well rooted. The Uchida method is very similar to that used in development for resistance in red bay (Hughes and Smith 2014); for mother trees of red bay, they used healthy, asymptomatic trees >7.5 cm dbh from each of six scattered sites where monitoring has been occurring and much mortality has occurred.

For ʻōhiʻa, many details will of course need to be worked out and funding sought and obtained. Cost will be critical for how ambitious the program can be. There is excellent expertise available to help develop the sophistication necessary to form an operational program for ʻōhiʻa resistance. Full exploration of the durability of resistance (degree of potential for evolution of the fungus, McDonald and Linde 2002) is essential.

Vertical resistance involves a genotype of a plant species exhibiting a high degree of resistance to a single race or strain of a pathogen. This ability is usually controlled by one or a few plant genes. Horizontal resistance, on the other hand, protects the plant against several strains of a pathogen, although even then protection may not be complete. It involves more resistance genes than the vertical resistance (Lozoya-Saldaña 2011).

It is possible that ʻōhiʻa will be found that exhibit natural vertical resistance to one or several strains of the ROD pathogen. Such germplasm would be helpful in a traditional breeding program for ROD resistance. However, this vertical resistance is not robust and may be defeated by natural mutation in the pathogen or the introduction and dissemination of additional pathogen strains. Genetic modification represents another source of resistance, and has been used to some success in other forest pathosystems. American chestnut trees expressing conventional transgenes (oxalate oxidase) and American elm trees expressing antimicrobial peptides have displayed resistance to chestnut blight and Dutch elm disease, respectively (Newhouse and others 2007, Newhouse and others 2014). Host induced gene silencing, a form of RNA interference, is a more recent and powerful resistance mechanism that is now being utilized in many agricultural crops for broad and durable resistance against pests and pathogens (see review by Koch and Kogel 2014). These modern breeding techniques could eventually be used as a last resort to engineer broad and durable resistance against ROD in ʻōhiʻa.

ARS PBARC

ARS PBARC researchers are testing different ʻōhiʻa varieties of for resistance to the ROD **pathogen.**

Experimentation with restoration of watersheds and habitat for native understory species in the face of loss of ʻōhiʻa

Two recent papers (Friday and others 2015, Ostertag and others 2015) are well worth consulting for ideas. These papers provide a useful foundation for starting to think about what tactics might be investigated before a program to develop ROD-resistant ʻōhiʻa is either well underway or reluctantly rejected as a possibility (e.g, because of lack of durability of resistance).

Friday and others (2015), evaluating "new directions for forest restoration in Hawaiʻi," address the primary current approach to restoration which emphasizes outplanting and intensive management of rare and endangered plants in relatively small fenced areas. While successful for stabilizing rare species populations, this approach largely neglects extensive degraded ecosystems dominated by invasive species. "Non-native plants might be appropriately used in restoration projects in Hawaiʻi and in other island ecosystems where they can function as nurse crops for threatened and endangered plant species, provide habitat for rare fauna, protect soil and water quality, or restore watershed function."

Ostertag and others (2015) advocate using "plant functional traits" for selection of non-native but non-invasive species in restoration of degraded, invaded Hawaiian lowland wet forests (where ʻōhiʻa had already been lost pre-ROD). The paper is mostly conceptual but it may provide the basis for work of practical value. They consider Polynesian introductions especially appropriate (as do Friday and others 2015) and specifically mention breadfruit (*Artocarpus utilis*) and coconut (*Cocos nucifera*) – neither is invasive in Hawaiʻi and both species have large leaves and seed (which helps make them more competitive), unlike most native plants

Research may be needed to explore and test the feasibility and desirability of using carefully selected non-native species to compensate as much as possible for the disastrous loss of ʻōhiʻa. A place to start might be the devastated low-elevation forests of Puna. On the other hand, there are some who believe that significant funding for large-scale restoration efforts is unlikely. Both scientists and stakeholders (including the Hawaiian community, of course) should be brought into discussions of this topic at a very early stage, before such research is initiated. Regardless, the current paramount priority for scientists and managers working to control the disease and its impacts on ʻōhiʻa forests is to reduce the further spread of the disease and to protect, in every manner feasible, the remaining large expanses of ʻōhiʻa forest.

Much of the ʻōhiʻa forest in Puna is owned by small, private landowners. Many of these might wish to restore and protect their forests from invasive species given devastating loss of ʻōhiʻa. Funds available through the state Forest Stewardship program and the USDA Natural Resources Conservation Service programs could assist these landowners in developing more resilient forest models.

Regulatory situation/Biosecurity

Federal and State agencies in Hawaiʻi involved in research, resource protection and biosecurity

1. **Federal jurisdiction (primary agencies):**

U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA APHIS PPQ) works in conjunction with the U.S. Department of

Homeland Security, Customs and Border Protection (DHS CBP), to safeguard agriculture and natural resources from the entrance, establishment and spread of plant pests in the U.S. They work closely with Hawaii's responsible state agency, HDOA, but are largely concerned with pests coming from international sources. They do not have jurisdiction over interisland movement of pests and would not be likely to provide funding to assist with addressing such problems. For example, USDA APHIS PPQ has been able to help Hawai'i to get Farm Bill funding to address coconut rhinoceros beetle (a species new to the U.S., that would threaten other parts of the U.S.), but not to address the Rapid ʻŌhiʻa Death pathogens as long as they are officially considered strains of Ceratocystis *fimbriata*, a species found widely in mainland U.S. Giving the *Ceratocystis* ROD pathogens new species names might possibly alleviate this problem.

U.S. Department of Agriculture (USDA), Forest Service in Hawai'i consists of the Institute of Pacific Islands Forestry (IPIF, an institute devoted to biodiversity and forestry research) and the Pacific Southwest Region's State and Private Forestry Program. IPIF is based at a facility in Hilo, Hawaiʻi. Although the Forest Service has no national forest land in Hawai'i, it conducts research on Pacific Island forest management and ecology, and provides funding, technical advice and training to Hawaiʻi and other island forestry programs through its State and Private Forestry Programs such as Forest Health Protection, Urban and Community Forestry, and Forest Stewardship and Legacy Programs. It also supports a major biological control effort for seriously invasive weeds in Hawai'i and assists state forestry programs involving plant pests and pest plants by providing forest health evaluations and funding in certain circumstances. The Forest Service is providing supplementary funding for work on ROD. IPIF's Forest Ecologist Dr. Flint Hughes has been central to the work on ROD.

U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), Daniel K. Inouye U.S. Pacific Basin Agricultural Research Center (PBARC) is based at a facility in Hilo, Hawaiʻi, adjacent to the USDA Forest Service. It develops basic and applied information to strengthen agriculture in Hawaiʻi and the Pacific Basin in an environmentally acceptable and sustainable manner, including demonstrating appropriate strategies for managing crop pests and providing economically viable technologies for controlling quarantine pests. PBARC entomologists and plant pathologists can assist in identification, detection and mitigation of invasive species. Their Plant Pathologist Dr. Lisa Keith has been central to the work on ROD.

U.S. Department of the Interior, Fish and Wildlife Service (FWS) is responsible for protecting federally Endangered Species and National Wildlife Refuges, which in Hawai'i are threatened primarily by biological invasions. FWS' Hakalau Forest National Wildlife Refuge was established in 1985 to protect and manage endangered Hawaiian forest birds and their ʻōhiʻa (and koa) rain forest habitat. Located on the windward (northeastern) slope of Mauna Kea, Island of Hawaiʻi, the relatively pristine 13,200 ha (32,733-acre) Hakalau Forest Unit supports a diversity of native birds and plants equaled by only one or two other areas in the State of Hawaiʻi. The Refuge also has a second unit (2,140 ha or 5,300 acres), south of Kailua-Kona, added in 1997. FWS is likely to devote very significant resources to protecting Hakalau Forest NWR from ROD, which is absent from the refuge's main unit as of late-2016.

U.S. Department of the Interior, National Park Service (NPS) manages seven parks in Hawai'i, with protection of biodiversity as a major goal. Hawai'i Volcanoes NP (130,700 ha or 323,000 acres) on Hawai'i island, Haleakalā NP on Maui, and Kalaupapa National Historical Park on Moloka'i have important high/middle-elevation ʻōhiʻa forest lands potentially vulnerable to invasion by ROD.

Hawaiʻi Volcanoes NP receives 1.5 million visitors per year. The Park has been actively working to monitor for ROD and to educate employees and visitors about ROD and sanitation measures (Ashe 2016). In 2016, 14 ROD infected ʻōhiʻa trees were found in the upper Kahuku section of the Park; the Park has felled the known infected trees, has temporarily closed the upper Kahuku area, and is working to keep ROD confined to the lower unit. As of late 2016, no ROD has been found in the heavily visited Kilauea section of the Park; recent death of ʻōhiʻa trees in that section is currently being investigated.

U.S. Department of the Interior, U.S. Geological Survey (USGS), Pacific Island Ecosystems Research Center (PIERC) provides scientific leadership in support of national, regional, and local needs to understand, conserve, and manage natural resources in Pacific island ecosystems. PIERC strives to help resource managers tackle current and emerging critical conservation issues. Several PIERC scientists are involved in important work with ROD.

2. **State jurisdiction (primary agencies):**

Hawaiʻi Department of Agriculture (HDOA) has about 240 employees, with the main goal of the agency being to work to support, enhance and promote Hawaii's agriculture and aquaculture industries. HDOA's Division of Plant Industry is the entity with far more responsibility than any other for protecting Hawaiʻi from invasive species. With about 95 employees, Plant Industry is comprised of three branches: Plant Quarantine (PQ), Plant Pest Control (PPC), and a Pesticides branch.

The HDOA Plant Quarantine Branch (PQ) regulates the importation (from U.S. domestic sources) and movement within the islands of all plants, nondomestic animals (including vertebrate and invertebrate), and microorganisms. Its primary goal is to prevent the introduction of harmful insects, plant diseases, illegal animals and other pests into Hawai'i, but it also has authority to address interisland and intraisland spread of pests. Its Inspectors all possess authority to access public and private property for pest control/eradication purposes. Plant Quarantine is also responsible for leadership through developing policy/rules for providing better protection for Hawaiʻi as new threats and improved understanding of threats unfold.

The HDOA Plant Pest Control Branch (PPC) has jurisdiction for containing, controlling or eradicating pest animals and plants which could cause significant economic damage to agriculture, the environment, and quality of life. This is achieved through statewide programs using chemical, mechanical, biological, and integrated control measures to eradicate or control non-native pests, including insects and mites, gastropods, weeds, and plant pathogens.

The HDOA Pesticides Branch regulates the distribution and use of pesticides to ensure safety and availability of important pesticides in Hawai'i.

Hawai'i Division of Forestry and Wildlife (DOFAW, part of Hawaii's Department of Land and Natural Resources-DLNR) is the managing agency for a large part of the State's natural and cultural resources through enforcement and permitting activities on Conservation District lands as well as on-the-ground management. DOFAW manages more than a million acres (>400,000 ha) of public land for watershed protection, forestry, wildlife conservation, public hunting and recreation. Natural Area Reserves are afforded special protection. The Division was formed more than a century ago to address the loss of forests to land uses, feral animals and their resultant impact on the state's water supply for agriculture and human consumption. DOFAW can be a strong partner in assisting with emergency responses to biological invasions. They are currently assisting in eradication efforts against coconut rhinoceros beetle on O'ahu. The agency helps to fund and manage grants for island-based Invasive Species Committees (ISCs) and landscape level Watershed Partnerships. The Chairperson of DLNR is Co-Chair (with the Chairperson of HDOA) of the Hawai'i Invasive Species Council (HISC), an important coordinating and funding body for efforts to combat invasive species in Hawai'i. Robert Hauff, DOFAW's State Protection Forester, is the primary liaison between federal and state agencies involved in work with ROD. Steve Bergfeld manages field operations on Hawaiʻi Island and is responsible for managing ROD on state forest reserves

The Department of Hawaiian Home Lands (DHHL) is the State agency currently administering the areas held in trust for Native Hawaiians by the state of Hawaiʻi under the U.S. Hawaiian Homes Commission Act of 1921. The department administers lands near Hilo on Hawaiʻi Island with ʻōhiʻa stands infected by ROD. These happen to be ideal locations for testing ROD containment strategies, and DHHL is supportive of this work.

The University of Hawaiʻi System has an enormous amount of specialized expertise in its campuses and departments potentially relevant to detection and emergency response to plant pathogens and other pests. For example, there are 55-65 faculty and staff in the UH College of Tropical Agriculture and Human Resources (CTAHR) who have one or more responsibilities for dealing with invasive pests. Extension Forester Dr. J.B. Friday of CTAHR was originally involved in assessing the ROD issue in 2010 when landowners in Puna were reporting rapid death of ʻōhiʻa; he continues to be a major player with ROD. Brian Bushe of CTAHR's Agricultural Diagnostic Service Center (ADSC) first recognized the fungus *Ceratocystis* in wood samples from a dead ʻōhiʻa tree. Entomologists on the UH-CTAHR staff (Drs. Gordon Bennett and Curtis Ewing) are involved in crucial work with beetles associated with ROD. Additional expertise exists in departments in the UH College of Arts and Sciences. The UH-Pacific Cooperative Studies Unit has assisted through hiring temporary research and monitoring teams.

3. Private and independent entities

The Nature Conservancy of Hawaiʻi, island based Invasive Species Committees, Watershed Partnerships and other entities are contributing to such important activities as outreach, detection, and feral ungulate and invasive plant control. Private entities, such as the Hauʻoli Mau Loa Foundation, the Gordon and Betty Moore Foundation, Marisla Foundation, the Koaniani Fund of the Hawai'i Community Foundation, Dorrance Family Foundation, and others have generously contributed financially, with the University of Hawai'i Foundation administering private foundation funds.

Biosecurity relevant to *Ceratocystis* and ROD

Palm and Rossman (2003), plant pathologists for USDA-APHIS, addressed "Invasion pathways of terrestrial plant-inhabiting fungi" for a book on "Invasive Species: Vectors and Management Strategies." They addressed the main problem succinctly: "Propagative plant material poses the greatest risk as a pathway for successfully introducing invasive fungi into a new environment. Such living plant material includes seeds, woody and herbaceous cuttings, bare-rooted plants such as nursery stock, and plants in growing media. These substrates are host to many fungi that may not be detectable by visual means."

Palm and Rossman (2003) went on to clearly state huge problems with assumptions of the international phytosanitary system as interpreted by USDA-APHIS:

> One assumption about invasion pathways of plant-inhabiting fungi is that no risk is posed by the repeated introduction of the same species once a fungus has been introduced. Numerous examples suggest that this is not true… It is important to understand that pathogenic strains can be morphologically indistinguishable from those already established in a country and therefore difficult to differentiate without the use of molecular techniques.
>
> A second assumption is that it is always possible to predict the risk of a fungus introduced to a new environment based on the biology, especially the pathogenicity, of that fungus on its native host in its native environment. …there are [well-documented] examples of fungi that had little effect on their native host but became serious pathogens when introduced to new areas. …when a fungus is introduced into a new habitat, particularly into a monoculture of susceptible plant hosts under conditions conducive to the disease, the disease can develop and spread rapidly. Further, when there is little host resistance to the pathogen or no natural antagonists or neither, the disease may be devastating.

Since the entity known as *Ceratocystis fimbriata* has been widespread in the USA (including Hawai‘i), it has not been considered “actionable” by USDA-APHIS for many years (Rossman and others 2006); i.e, APHIS would not have taken action to stop a known shipment containing what is regarded as *C. fimbriata* from other countries and generally has discouraged (but not prohibited) HDOA from prohibiting other states from exporting such “non-actionable” and “non-reportable” species to Hawai‘i. That situation is somewhat analogous to the situation since 2005 with *Puccinia psidii*, also already in the U.S. (Loope and Uchida 2012). As stated previously, it is hoped that in 2017, a joint federal/state rule protecting ‘ōhi‘a in Hawai‘i from new strains of *P. psidii* will finally be approved. Meanwhile, Hawai‘i has fortuitously been able to dodge the bullet of a potential new strain of *P. psidii* for a decade.

Realistically, there may have been little chance of preventing the devastating pathogen now killing ‘ōhi‘a from reaching Hawai‘i and spreading, given the long standing practice of allowing Hawai‘i nurseries to import propagative plant material (propagative cuttings, bulbs, tubers, etc.) from a relatively inexpensive source in Florida, California, or even a foreign country, then growing the imports to tree/shrub/mature size for sale. Another dangerous practice is chipping used pallets, as happens at the transfer station in Hilo. (Wood packaging material is a notorious source of pests, second only to live plants, Lovett and others 2016). Fungi are very unlikely to be detected on imports by quarantine inspectors since they are usually undetectable by visual means.

ROD caused by *Ceratocystis* has been present and undergoing rapid spread since before 2010 on Hawai‘i Island, but as of late 2016, there had been no detection of ROD on other Hawaiian islands. The two pathogens causing ROD are currently referred to as *Ceratocystis* species A and B. Plant pathologist Lisa Keith is in the process of describing both as new species, at which time it may become easier for other countries with *Metrosideros* to protect themselves from these dangerous pathogens.

As presented earlier, the Hawai‘i Board of Agriculture, in response to ROD, approved an interim quarantine rule in August 2015 and made it long-term in November 2016. The stringent quarantine is intended to prevent the intrastate movement of ʻōhiʻa plants and plant parts, including flowers, leaves, seeds, stems, twigs, cuttings, untreated wood, logs, mulch, greenwaste and frass to other islands from the Island of Hawaiʻi except when under permit. Hawaiʻi Department of Agriculture developed signage for airports and commercial locations warning travelers of the new ʻōhiʻa quarantine. Because some producers of ʻōhiʻa posts still wish to ship interisland, inspectors from the HDOA take samples from each post and submit them to the USDA ARS lab for testing for *Ceratocystis*. To date several batches of logs have been found to be contaminated with *Ceratocystis* and shipping permits were denied. *Ceratocystis* has also been found in soils under infected stands, leading to soil from Hawai'i Island also being under quarantine. One commercial fruit tree nursery on Hawaii Island has developed a compliance agreement with the HDOA in order to ship fruit tree seedlings grown in soil. After extensive testing of the soil in their containers and the soil pit on the Hāmākua coast where soil is sourced, it was concluded that shipping that particular soil poses a low risk of moving *Ceratocystis*. Regular testing of the soil in pots at the nursery and the soil source itself will ensure that the process remains safe.

HDOA

HDOA restricts the movement of Metrosideros (all species in genus) plants, plant parts, logs and soil from Hawaiʻi Island to other islands in the state, except by permit or under compliance agreement.

At the request of Hawaii's Division of Forestry and Wildlife, the U.S. Forest Service very recently completed (after four years in the making) a rigorous risk and pathway assessment for pests that could degrade Hawaii's dominant trees and shrubs, including ʻōhiʻa (DeNitto and others 2015). This was a demanding task but an excellent analysis; it identified 83 potential pest threats to *Metrosideros* (55 pathogens, 28 insects) not yet in Hawaiʻi. However, it understandably failed to identify any *Ceratocystis* species as a potential threat to ʻōhiʻa. It did identify *Ceratocystis albifundus* as a potential threat to *Acacia koa* and *Ceratocystis moniliformis* as a possible threat to *Erythrina sandwicensis.*

Ironically, an earlier USDA Forest Service risk assessment for importing *Eucalyptus* logs from Brazil by Kliejunas and others (2001) stated presciently that although damage by *Ceratocystis fimbriata* in the U.S. was so far modest:

> …..because the strains in South America may be different in pathogenicity than those in the United States, there is a potential for increased economic damage. This potential is increased because of the potential of other hosts that are not currently known or recognized, including herbaceous and woody species… The fungus has not been found there [Hawaiʻi] on woody plants… The introduction of new strains to Hawaiʻi could expose a wide range of woody plants to infection… Research into the differences in the strains and their hosts must be completed before firm conclusions regarding the actual impact can be stated. Until that is done, a high [risk] rating appears appropriate.

In practice, the above assessment was moot since *Ceratocystis fimbriata* was already present in the U.S. and thus not considered actionable by USDA-APHIS. Neither HDOA nor anyone else in Hawai‘i was aware of the threat, which anyway would likely have been considered "speculative."

There are 45+ species of *Metrosideros* outside Hawai‘i – primarily in New Caledonia (21 spp.) and New Zealand (12 spp.) – but also in many Pacific Islands and South Africa. Arguably, Hawai‘i has a responsibility to help protect those *Metrosideros* species. The protection of these other *Metrosideros* species may depend on what we learn and how successfully the ROD outbreak in Hawai'i is contained. Because of the nature of international phytosanitary regulations, these other countries could be helped by naming the ROD pathogens as new species, rather than simply treating them as genotypes of *Ceratocystis fimbriata*. (This is in fact being done, though not for that reason.) Partnering with other countries with *Metrosideros* could help Hawai‘i mount a more effective ROD control program for the benefit of Hawai'i and other Pacific nations. New Zealand has recently put a quarantine in place to prevent arrival of *C. fimbriata*, with particular concerns for kiwi fruit (*Actinidia deliciosa*, Piveta and others 2016) and *Metrosideros*.

During 2016, HDOA has contracted for what is intended to be a comprehensive "Interagency Biosecurity Plan" for Hawai‘i. There has repeatedly been excellent work done over the past quarter century evaluating what is needed and possible, beginning with a TNCH/NRDC (1992) document "The Alien Pest Species Invasion in Hawai‘i: Background Study and Recommendations for Interagency Planning." The new Biosecurity Plan has attempted to bring together these efforts, with extensive agency and public review.

Outreach & Engagement

ROD has appropriately elicited a collaborative interagency response both in science and outreach. The outreach effort has been exceptionally diverse and seemingly effective to date.

Monthly 90-minute "ROD Working Group" meetings have been held since August 2015 at the USDA Forest Service office in Hilo, facilitated by Dr. Ric Lopez, Director of the USFS Institute of Pacific Islands Forestry. Meetings are typically attended by 15-20 individuals in person and 25-30 on the telephone. As of November 2016 more than 200 individuals who have requested to be on the Working Group receive periodic updates via e-mail, including private citizens, managers, scientists, policy professionals, and communication specialists. Notes are taken for informational purposes and disseminated among all on the e-mail list, along with any updates, information, documents of the group, including several with expertise and interest from outside the State of Hawai‘i. Nearly any group/organization that has an interest in the topic of ROD participates monthly, through the interactions of the Working Group. The stated purpose of the meeting is to, "facilitate inclusive ongoing discussions/communication of all issues related to ROD, and share knowledge on a regular basis among group members, their organizations, and the people of Hawai‘i."

To assist the researchers and the ROD resonse, a ROD Outreach Working group was formed. Coordination of outreach work is conducted via ad hoc meetings and a monthly working group call one week following the monthly ROD Working Group call.

As seen throughout this document, the multi-agency nature of the response allowed partners to use their resources to fill gaps. One example for outreach was the early engagement of UH CTAHR's Extension Forester, who created a website focused on the disease in May 2015, (originally called www.ohiawilt.org but soon changed to www.rapidohiadeath.org - both URLs for the same website are still functioning). The site hosts highly informative videos, FAQs, maps, summaries and links to research publications and was redesigned using new software in September 2016. UH CTAHR also supported the hiring of a new assistant Extension Education Specialist in Hilo to focus on ROD outreach.

The ROD researchers have given multiple presentations, including at the August 2015 Hawai‘i Conservation Conference and at Hawai‘i Volcanoes National Park in September 2015, with frequent updates since then. The scientists have given talks to various groups, assuring that most conservation managers and scientists in Hawai‘i know the basic information about ROD, and are able to assist informally in outreach. Over 90 presentations on ROD and ‘ōhi‘a have also been given by the network of outreach specialists that are contributing time and effort in an ad hoc outreach working group, which began working together in August 2015.

The outreach working group recommended branding the disease as Rapid ‘Ōhi‘a Death to generate a sense of urgency and clarity, instead of the more scientifically accurate description of the disease as a "wilt." The outreach group identified a rough outline of actions and needs including a list of target audiences, key messages, presentations and outreach events, both on Hawai‘i Island and around the state. The five key messages letting the public know what they can do are:

1. Don't move ‘ōhi‘a wood or ‘ōhi‘a parts. If you don't know where the ‘ōhi‘a material is from, don't move it.

2. Don't transport ‘ōhi‘a inter-island. Follow the Hawaii State Department of Agriculture quarantine rule and help to keep ROD from reaching the other islands.

3. Clean tools used for cutting ‘ōhi‘a (especially infected ones) with 70% rubbing alcohol, a proven cleaning measure.

4. Clean gear, including shoes and clothes, before and after entering forests. Brush all soil off of shoes then spray with 70% rubbing alcohol. Wash clothes with hot water and soap.

5. Wash your vehicle with soap if you've been off-roading or have picked up mud from driving. Use a pressure washer with soap to clean all soil off of the tires and vehicle undercarriage.

The group developed, printed, and disseminated brochures and other print and online outreach materials, including an ROD Facebook page launched in October 2015, which is managed by members of the outreach group with consultation from the science team (www.facebook.com/rapidohiadeath). Outreach content was designed to simply communicate the latest science, the quarantine, a sense of urgency and a sense of empowerment and hope, focusing on actions people could take to slow or stop the spread of the disease.

In addition to reaching forest users, the conservation community, and other audiences such as inter-island travelers with these messages, the outreach working group recognized both the potential to communicate to a larger audience about ROD as well as the potential threat of accidentally spreading the disease throughout the state through the Merrie Monarch Festival, which draws thousands of visitors to and from Hawai‘i Island from both inside and outside the state.

While recognizing ‘ōhi‘a’s cultural importance and the unique opportunity for outreach and engagement presented by the Festival, the outreach team advised against telling cultural leaders what they should or shouldn’t do regarding ROD. Instead, the team focused on working with community and cultural leaders associated with the Festival to share information about the disease in order to enable practitioners to make their own decisions about actions they could take to reduce the risk of accidental spread. For example, Hawaiian community leader Kekuhi Keali‘ikanaka‘oleohaililani’s letter to the hula community (http://www2.ctahr.hawaii.edu/forestry/downloads/A_Letter_to_the_Hula_Community.pdf) showed her aloha and concern for ‘ōhi‘a as well as suggesting ways for the hula community to be actively involved in preventing the spread of ROD. Her letter was well received and largely heeded by Merrie Monarch participants and the larger community.

ROD Outreach Team

Outreach booth at the 2016 Merrie Monarch Festival.

The outreach group worked together with Kekuhi to create a positive cultural message: KŪ! KA ‘ŌHI‘A LAKA, which draws upon the image of the Hawaiian forest deity, Kūka‘ōhi‘alaka, who is associated with the multiple life cycles of the ‘ōhi‘a tree, and mature, healthy ‘ōhi‘a forests. This message aims to empower people to help in the recovery of ‘ōhi‘a by promoting the idea that thinking thoughts and saying words of health and wellbeing can be very powerful, in addition to being aware of the challenges ‘ōhi‘a is facing and being mindful of sterilization protocols for keeping things clean when going in and coming out of ‘ōhi‘a forests.

The Merrie Monarch 2016 competition organizers and judges understood the urgency ROD represents, and they allowed late substitutions in proposed lei materials for dancers, which has never been permitted before. Competitors were able to replace ‘ōhi‘a flowers and liko (new ‘ōhi‘a leaves) with other plants. The near complete absence of the iconic ‘ōhi‘a lehua from the annual craft fair, the royal parade, and each night of the competition was unprecedented. They also allowed the outreach group to set up an outreach and collection booth outside of the stadium each night of the competition to collect lei and plant material and share information about ROD and Kūka‘ōhi‘alaka.

To prevent ‘ōhi‘a products from being transported off Hawaii Island, the outreach group collaborated with the Hawai‘i Department of Agriculture on signage, inspector presence, and culturally appropriate ways to collect lei and plant material that had the potential of carrying the fungus to neighbor islands at both Hilo and Kona airports.

The group also worked with Kekuhi to create a community event and a new ceremony to celebrated our relationship with ‘ōhi‘a, and provide a way for the hula community to ho‘iho‘i (return) their lei to the environment without fear of spreading ROD. The sunrise Pua‘ena‘ena Ceremony took place at the County Ho‘olulu Complex adjacent to the stadium the morning after the competition. It was created based on the tradition of making offerings of lei at Halemaʻumaʻu Crater on Kīlauea Volcano, and incorporated fire and a ceremonial burning of the lei material that was collected throughout the week (a practice that is not typically part of the hula world). The ashes of the lei, along with the energy, sweat, and hard work of all the dancers and ceremony participants that went into everything during the festival, were then returned to the forest by outreach group participants.

The University of Hawai'i produced a series of three videos on ROD, featuring UH faculty Dr. Sheila Conant describing the value of ʻōhiʻa forests for habitat for native birds, Dr. Kalena Silva of UH Hilo describing the cultural value of ʻōhiʻa for Hawaiians, and Dr. J.B. Friday describing the threat posed by ROD. The Nature Conservancy of Hawaiʻi produced a 30-second PSA narrated by respected Hawaiian studies scholar Puakea Nogelmeier. It was posted online and aired on KFVE during the broadcast of the Festival. Through DOFAW's partnership with New West Broadcasting Corps, which operates 5 Hawaiʻi Island radio stations , the outreach team wrote and recorded a 1-minute Big Island Minute radio PSA about preventing the spread of ROD and a 30 second spot which aired a total of 179 times from 2/17-2/29. John Replogle of TNC and Kaila Olson of DOFAW also wrote and recorded a 30-second PSA in pidgin, which were played on Pacific Media Group's 8 Hawaiʻi Island stations. The PSAs aired a total of 408 times from 2/29-4/02. In addition, DJs announced variations of the script on the following stations: KAPA, KHLO, KKBG, KPVS - Hilo and Kona.

The University of Hawaiʻi Lyon Arboretum developed an informative video in conjunction with a crowdsourcing campaign (www.gofundme.com/ohialove, now at University of Hawaiʻi Foundation) for a project to collect and store ʻōhiʻa seeds to protect genetic diversity during the ROD crisis. Lyon Arboretum staff worked with the ROD researchers and outreach group to ensure consistent and appropriate messaging. The campaign reached their target funding goal in less than a month.

ROD Outreach

Multiple agencies and groups have assisted with ROD outreach, extending the audience reach.

A partial listing of agencies/groups doing ROD outreach includes UH Cooperative Extension (CTAHR), USDA Agricultural Research Service, USDA Forest Service, The Nature Conservancy, HDOA, DOFAW, Invasive Species Committees, CGAPS, and Watershed Partnerships. Groups/communities being targeted by outreach include (with coordination by CTAHR, DOFAW and TNC): wood industry, nursery industry, builders who use ʻōhiʻa poles, hunters, hikers, eco-tour operators, hula/cultural practitioners, hale builders, arborists and tree services, firewood cutters, HELCO, HDOT, county public works, major landowners (e.g. Kamehameha Schools), small landowners, politicians/decision makers, and the public at large.

The outreach team has worked with local, state, national, and international journalists to produce over 80 articles and videos that tell the story of 'ōhi'a and the threat of ROD to the world. Representative examples of press coverage include:

Outside Online magazine featured an article about ROD: “What’s killing Hawaii’s trees?” by David Ferry, March 10, 2016:

http://www.outsideonline.com/2060691/whats-killing-hawaiis-trees

“Scientists think insect is likely spreading ohia fungus”, Hawaii Tribune Herald March 23, 2016: http://www.hawaiitribune-herald.com/news/local-news/scientists-think-insect-likely-spreading-ohia-fungus

KITV March 23 http://www.kitv.com/story/31553119/scientists-testing-beetle-as-possible-culprit-spreading-deadly-fungus

Scenes of devastation: Chasing Hawaii’s deadly ohia fungus. Molly Solomon, Hawaii Public Radio, March 25, 2016 http://hawaiipublicradio.org/post/scenes-devastation-chasing-hawaiis-deadly-ohia-fungus This story was also featured on National Public Radio.

Legislators target Rapid Ohia Death. Colin Stewart. Hawaii Tribune Herald January 24, 2016. http://hawaiitribune-herald.com/news/local-news/legislators-target-rapid-ohia-death

Kumu call for kapu on ohia harvest. Brett Yeager. Hawaii Tribune Herald February 15, 2016 http://hawaiitribune-herald.com/news/local-news/kumu-call-kapu-ohia-harvest

The cultural significance of ohia lehua. Meghan Miner. Hawaii Magazine, April 11, 2016. http://www.hawaiimagazine.com/content/cultural-hawaiian-significance-ohia-lehua

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An American tragedy: Why are millions of trees dying across the country? Oliver Milman and Alan Yuhas. The Guardian. Monday Sept. 19 2016 https://www.theguardian.com/environment/2016/sep/19/tree-death-california-hawaii-sudden-oak

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Strategic Plan for Outreach and Engagement

It is now clear that the science and management tools in existence today cannot achieve the eradication of ROD from Hawai‘i. Further, early projections of the potential loss of ‘ōhi‘a from infection and mortality rates in monitoring plots are sobering. Therefore, the outreach working group worked together to craft this strategic plan for the next few years, along with a budget for achieving widespread awareness, support, and participation in reducing the chances of the public spreading the pathogen, and improving the resiliency of native forest habitat and function.

One of the main organizational goals is to transition the ad hoc outreach working group to a more formalized structure with several full-time staff to aid in messaging and engagement on each island. Some outreach capacity does exist, but these personnel must continue to provide outreach for their own organizations about a variety of environmental issues, such as other invasive species, and therefore can only assist part time on ROD outreach in their communities.

The second goal is to activate and empower people. While the situation is serious, public outreach and engagement must focus its messages on what can and should be done to help our forests. Similar campaigns have shown that the best way we can engage the necessary level of awareness and participation statewide, and move the public from emergency compliance to internalizing awareness and behavior change is to engage a wide variety of community leaders in each county to help amplify the messages and diversify the message delivery mechanisms. People must take the issue to heart, become personally invested, and we must involve more leaders in the work of protecting and perpetuating healthy and resilient ʻōhiʻa forests.

The third goal is to ensure outreach co-evolves with science. Our knowledge of this newly-identified pathogen, and the devastating effects on our keystone native tree is increasing every week. However, there are still many questions and different avenues of research that must be pursued in the coming years. Outreach should increase the percentage of the public who understand ROD and are aware of the current actions and avenues of research. Outreach must also be clear about the evolving nature of scientific research, provide timely updates to keep the public informed and communicate when new evidence requires a change in prevention methods.

The objectives are as follows:

- **Expand capacity through creating and supporting new ROD outreach positions statewide.** Create and support 6 new FTE: 1 FTE to coordinate statewide outreach and engagement on ROD, and 5 FTE to work on ROD outreach and community engagement for their islands (one each for West Hawaiʻi, Maui, Oahu, Kauaʻi, Molokaʻi/Lānaʻi).

- **Support to conduct public awareness assessments and surveys.** To better understand baseline awareness, support/opposition, and messaging support by the general public statewide, focus groups should be conducted as a first priority. Professionally-conducted focus group work will help refine messages and actions for years to come. Assessment of awareness and progress in coming years should be conducted via occasional benchmark surveys for quantitative measures, and engagement may be used for qualitative measures.

- **Support for outreach collateral and media.** To date, the production of outreach materials and media has been contributed in-kind, and have not been sufficient. Further, new staff will need operational funding and support for production and delivery of outreach materials via radio, television, print, and other means. Purchasing of expensive TV broadcast time is included in this need. Raising awareness about ʻōhiʻa is a core need, as many residents statewide are not aware of the value of ʻōhiʻa. Other items include statewide production and availability of decontamination kits for the public, trail signage, and other products that have been piloted on Hawaiʻi Island to great success.

- **Support for partnerships and community engagement of different groups**. Support for staff and materials will enable engagement of more potential partners. There are many cultural leaders, educators, community leaders, and others that could play a role in expanding outreach and engagement, yet it takes time and effort for staff to work with each group to build trust and ensure that ROD information and messages are understood and agreed upon.

- **Support for curricula development.** One key avenue for reaching the public is via schools. There are several examples of existing curricula aimed at K-6th grade levels that help students understand the value of ʻōhiʻa. These curricula can be updated, expanded to all grade levels including junior college, and modified to incorporate ROD information and helpful actions, and then aligned to the new standards on science and social science. Much of the existing curricula is not yet available on-line, so this and additional materials that should be developed will need to be made accessible to educators via the web. Appropriate curricula for intermediate and high school should also be developed, aligned, and made available. Curriculum development and alignment with the newly produced educational standards are a specialized skill-set, thus this would be done via contract to a specialist. The outreach network and staff will work with school administrators and teachers to conduct teacher training and help them incorporate the curricula into their existing lesson plans and goals for student assessments.

- **Support for Organizing or Participating in Educational Events.** Educational and cultural events help engage communities and provide a venue for increasing or perpetuating values. Each island has its own regular community and cultural events that can be used to share ʻōhiʻa messaging, and thus far we are limited by staff time and ready-to-use outreach displays and materials. Engaging the public in celebrating ʻōhiʻa is being pilot tested on Hawaiʻi island where awareness of ʻōhiʻa appears to be high. However, based on initial results of public surveys at Oahu and Maui hiking trails, resident awareness of ʻōhiʻa and ROD is much lower on these islands. Awareness of ʻōhiʻa is key to engaging the public in behaviors to protect ʻōhiʻa.

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