RAPID ‘ŌHI‘A DEATH

STRATEGIC RESPONSE PLAN

2020-2024

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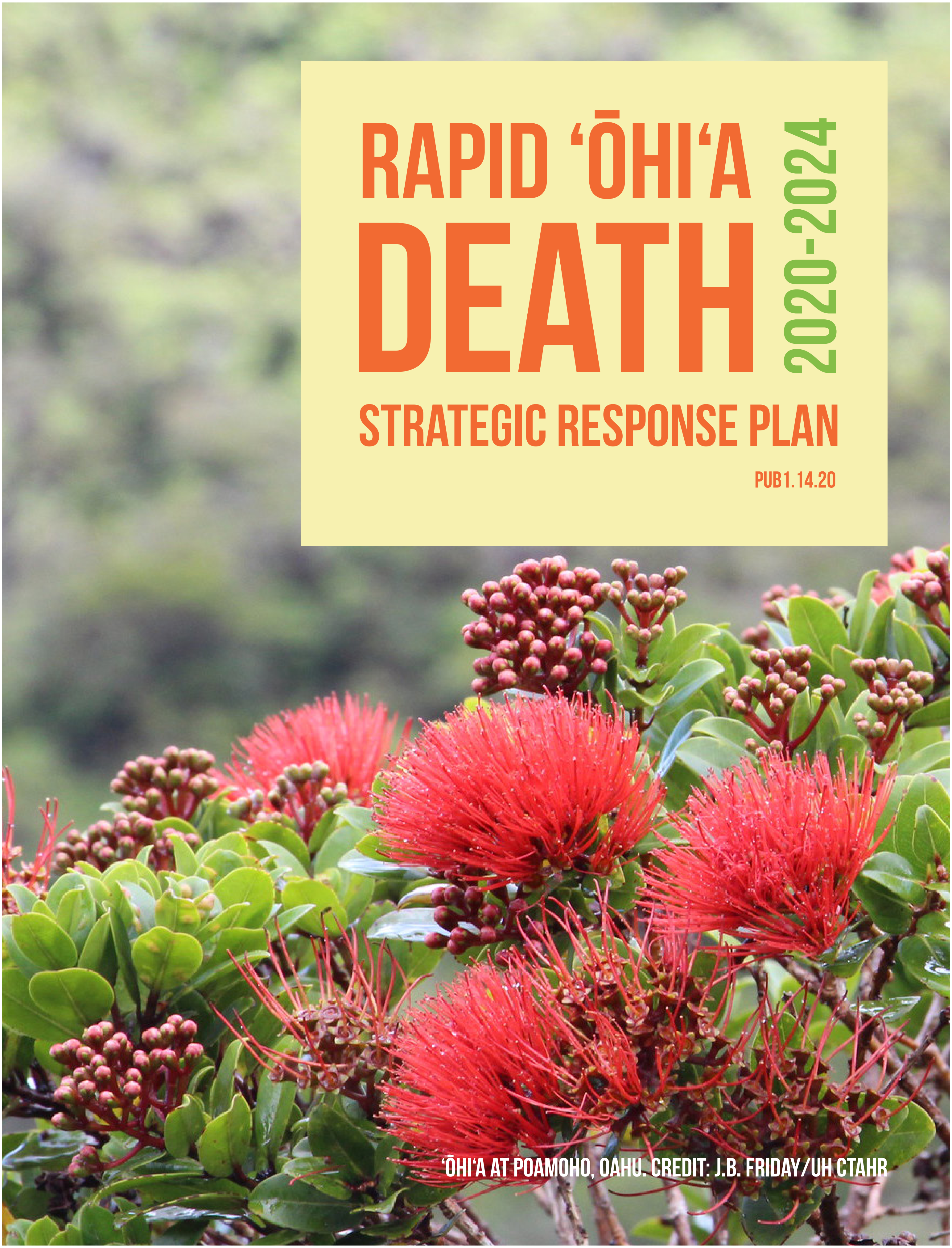

‘ŌHI‘A AT POAMOHO, OAHU. CREDIT: J.B. FRIDAY/UH CTAHR

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STRATEGIC RESPONSE PLAN TEAM

This plan was drafted by a core writing team with input from dozens of participants across the state and beyond. The leads for topics are as follows:

- Dr. Lisa Keith, USDA ARS PBARC: research on the pathogens, disease diagnostics, sample analysis, development of disease resistance
- Dr. Flint Hughes, USDA Forest Service IPIF: research on tools for improving forest management, forest monitoring and ecology projections
- Christian Giardina, USDA Forest Service IPIF: improving forest management, disease resistance, restoration, and plan coordination
- Dr. J.B. Friday, UH CTAHR-Cooperative Extension: public engagement and coordination of research
- Bob Peck, USGS PIERC (Hawaiʻi Cooperative Studies Unit): research on the ambrosia beetle, frass, and wind as vectors
- Bill Stormont, DLNR DOFAW: management actions
- Rob Hauff, DLNR DOFAW: plan coordination, budget, and lead editor
- Christy Martin, UH PCSU/Coordinating Group on Alien Pest Species: public engagement and plan coordination
- Dr. Jonathan Price, University of Hawaiʻi at Hilo: native ecosystem restoration

We greatly appreciate the following for review of the plan:

Dr. Josh Atwood (Hawaiʻi Invasive Species Council), David Benitez (Hawaiʻi Volcanoes National Park), Dr. Phil Cannon (USDA Forest Service), Dr. Sam Gon (The Nature Conservancy Hawaiʻi), Dr. Tom Harrington (Iowa State University), Dr. Jenny Juzwik (USDA Forest Service), Springer Kaye (Big Island Invasive Species Committee), Rachel Neville (Oʻahu Invasive Species Committee), Kim Rogers (Kauaʻi Invasive Species Committee), Sheri Smith (USDA Forest Service), Corie Yanger (UH College of Tropical Agriculture and Human Resources), and Emma Yuen (DLNR Division of Forestry and Wildlife)

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ACRONYMS

CTAHR: College of Tropical Agriculture and Human Resources

DLNR: Department of Land and Natural Resources

DOFAW: Division of Forestry & Wildlife

DOI: Department of the Interior

EDRR: Early detection/rapid response

HDOA: Hawaiʻi Department of Agriculture

PCSU: Pacific Cooperative Studies Unit

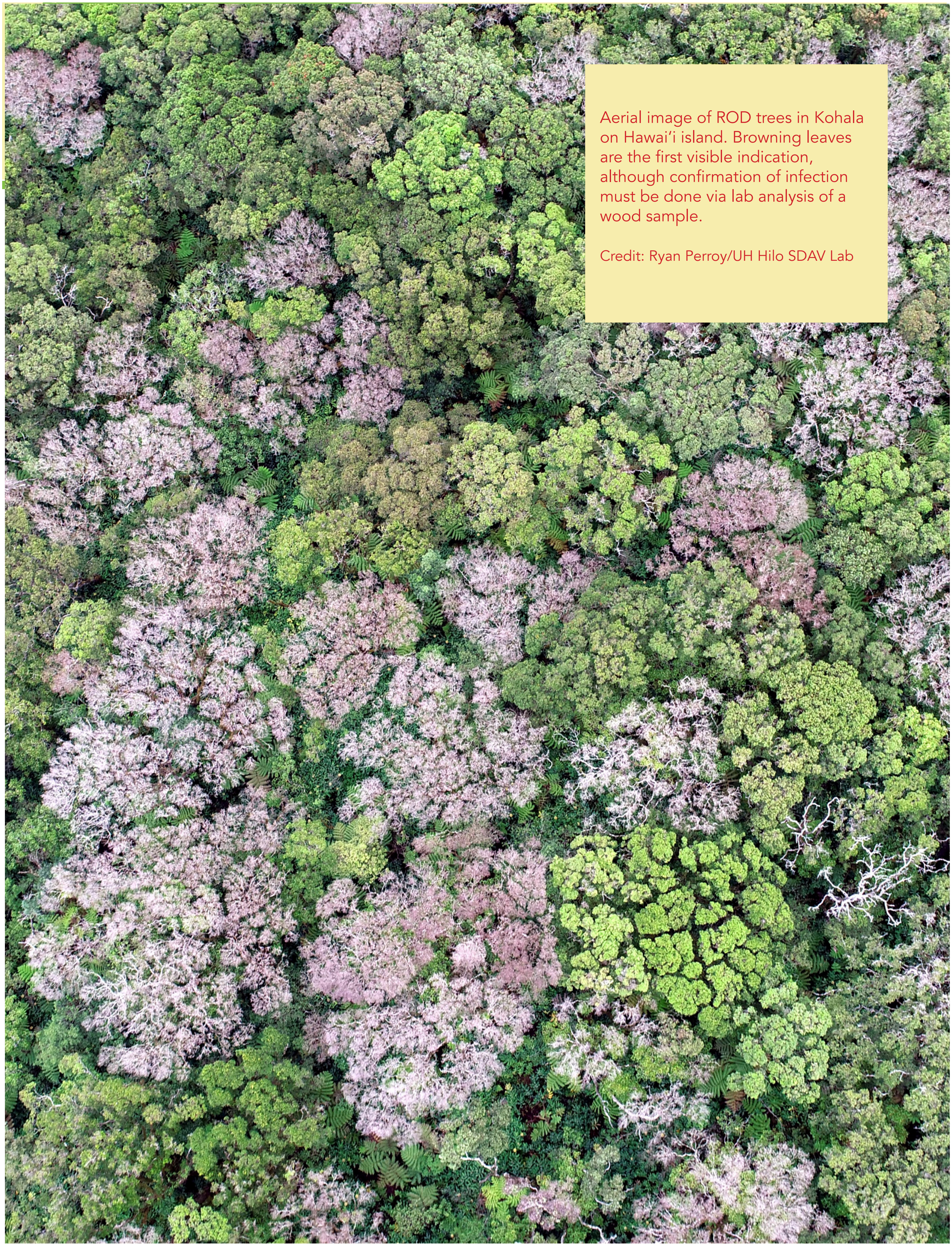
RCUH: Research Corporation of the University of Hawaiʻi.

ROD: Rapid ʻŌhiʻa Death

UH: University of Hawaiʻi

USGS: U.S. Geological Survey

USDA ARS: U.S. Department of Agriculture-Agricultural Research Service



Aerial image of ROD trees in Kohala on Hawai‘i island. Browning leaves are the first visible indication, although confirmation of infection must be done via lab analysis of a wood sample.

Credit: Ryan Perroy/UH Hilo SDAV Lab

INTRODUCTION

FOREWORD

In this 2020-2024 update to the 2017-2019 Rapid ʻŌhiʻa Death (ROD) Strategic Response Plan, we describe our significant progress in understanding and addressing ROD, and the important challenges that lie before us. As with the previous plan, we provide recommendations for priority actions accompanied with cost estimates. The components of this plan were developed in stages, starting with a progress review and discussion at the ROD Science Symposium in May 2019, followed by drafting by a small team of editors who work on the different elements of the ROD response. The draft plan was then sent to 20 reviewers, internal and external to the response. The resulting 2020-2024 ROD Strategic Response Plan describes the needs for this emergency response as well as for the long-term health of Hawaiʻi's forests.

Our understanding of the disease and the microscopic fungi that cause ROD – their biology, impact and movement in individual trees, and dispersal patterns and mechanisms has improved through significant investments in time, energy, and resources in research, prioritized in large part by the ROD Science Team. Our development and testing of science-driven management options continues to improve our approaches to controlling the disease and protecting ʻōhiʻa forests. In addition to the statewide ROD Working Group, each island has formed multi-agency working groups for information exchange, effective and efficient resource allocation, and swift response to new positive detections. Public engagement and outreach efforts through the ROD Outreach Team, using direct outreach, film, radio, print, and electronic media, have proven invaluable in developing broad public awareness of the disease, its impacts to our native forests and watersheds, and how to protect ʻōhiʻa.

Up until relatively recently, ROD occurred only on Hawaiʻi island, where it has become progressively widespread because of environmental factors. Unfortunately, ROD has now been found on other Hawaiian Islands as well; dozens of trees have been found on Kauaʻi, four infected trees have been detected on Oʻahu, and one tree has been detected on Maui. Each of these incipient outbreaks have elicited well organized, swift responses that apply containment and, in some cases, eradication tactics developed using the best available science.

The current status and distribution of the disease has also broadened our recognition that each island must have adequate capacity for actions across the detection and response spectrum, and that the needs for research, tools, and management also differ. These efforts can and must continue in order to protect, as best we can, our critically important ʻōhiʻa-dominated native Hawaiian forests.

Agencies continue to utilize permanent staff and in-kind support for Rapid ʻŌʻhia Death, but additional funding is needed to support much of the important work described in this plan. We estimate project needs to be approximately $4M/year over the next five years.

IMPORTANCE OF ʻŌHIʻA

With an estimated 350 million ʻōhiʻa lehua trees (*Metrosideros polymorpha*) growing across more than 800,000 acres statewide, the native Hawaiian forest is essentially and fundamentally an ʻōhiʻa forest. ʻŌhiʻa can be found in a wide variety of ecosystems, from sea-level lava field deserts to high-elevation bogs. Its forms can be equally diverse, with mature trees at a height of two feet or one hundred feet tall, and leaves that are fuzzy or glossy, thick or thin, depending on variety, species, and location. ʻŌhiʻa are perhaps best known by their flowers, which range in color from red to orange to bright yellow.

ʻŌhiʻa has long been recognized as an important component of watershed forests, with the rain and mist soaking into the mosses and other plants growing on ʻōhiʻa. Today, we understand that ʻōhiʻa forests are up to 50% more effective at capturing and holding that moisture, feeding streams, and recharging our aquifers than non-native strawberry guava forests. ʻŌhiʻa forests are the source of water for irrigation for local agriculture, habitat for native stream species, and fresh water for municipal use. Further, our ʻōhiʻa forests store more carbon than any other forest type in the state, nearly 40% of the total estimated aboveground forest carbon in Hawaiʻi.

ʻŌhiʻa is the keystone species of our forests, the single species upon which thousands of other native Hawaiian plants and animals depend on for survival. Nearly 500 species of arthropods have been collected from ʻōhiʻa canopies, all of them found only in Hawaiʻi. ʻŌhiʻa forests also provide critical habitat for 18 of the 19 threatened or endangered forest bird species including the scarlet ʻiʻiwi and ʻapapane, the woodpecker-like ʻakiapōlāʻau, the inquisitive ʻelepaio, and the newly reintroduced Hawaiian crow, ʻalalā.

When the Polynesians arrived in Hawaiʻi, the ʻōhiʻa forests were already firmly established. The relationship between the ancient Hawaiians and ʻōhiʻa lehua had multiple aspects, many of which continue in some form today. Hawaiians viewed plants and animals as direct kin, and themselves as their caretakers, and ʻōhiʻa lehua were particularly important and sacred. ʻŌhiʻa were considered manifestations of Kū, one of the four principal Hawaiian deities, although Laka, the goddess of hula, and Pele, the volcano goddess, could also manifest as ʻōhiʻa. As such, ʻōhiʻa wood was used for sacred or spiritual purposes, and the use of the flowers and other products carried significance and powerful intentions.

Besides softening the impact of rain drops and protecting soil from erosion, the ʻōhiʻa leaves and the mosses and ferns that grow on the bark of ʻōhiʻa also capture water from humidity and mist even when it isn't raining. ʻŌhiʻa lehua create the environmental conditions that support water recharge and the habitat necessary for thousands of native plants and animals. Credit: Nate Yuen

This reverence for, and relationship with the natural world is celebrated through hula, chant, and other cultural practices. Through these traditions, there is an enormous repository of ecological, hydrological, spiritual, and cultural information about ʻōhiʻa. Traditional Hawaiian perspectives embrace ʻōhiʻa as a revered kupuna or senior family member, and this high level of respect defines the relationship between ʻōhiʻa and the Hawaiian people to this day. In a very broad and all-encompassing way, the crucial role that ʻōhiʻa forests play in our daily lives and livelihoods was widely recognized in ancient times:

"Hahai no ka ua i ka ululaʻau" translated,
"The rain follows after the forest."

ʻŌlelo Noʻeau: Hawaiian Proverbs and Poetical Sayings, by Mary Kawena Pukui

SITUATION UPDATE

The following is an executive summary of the status of ROD on each island. To date, the ROD pathogens have not been detected on Lānaʻi and Molokaʻi.

Status of ROD

- Researchers established that two non-native, microscopic fungi new to science, *Ceratocystis lukuohia* and *C. huliohia*, are the cause of ROD.
- *C. lukuohia* a "wilt disease", quickly spreads throughout the trunks of trees, clogging the flow of water and causing the tree to die within months. In contrast, *C. huliohia* is characterized as a "canker disease", which affects trees more slowly and requires multiple infections to kill trees. There is some evidence that *C. huliohia* has been present in the islands longer that *C. lukuohia.*
- On Hawaiʻi Island, where these fungi were first detected five years ago, approximately 180,000 acres of ʻōhiʻa forest have some level of ROD, ranging from 95% mortality to less than 1%. ROD is now found in all districts of Hawaiʻi Island, and management has shifted to focus on reducing impacts to high-value forests.
- On Kauaʻi, ROD was initially detected in a few trees in 2018. Since then, additional surveys have confirmed approximately 100 ROD trees, some with *C. huliohia* and some with the more aggressive *C. lukuohia*, and crews are working to contain the disease. On Maui, one tree with *C. huliohia* was discovered via public report in 2019 and subsequently destroyed. On Oʻahu, four trees with *C. huliohia* were detected in 2019, triggering a rapid response that resulted in the felling and tarping of three trees to date.
- The multi-agency framework of active surveillance, sampling, management, research, and outreach is ongoing with existing staff from agencies and non-government organizations, supplemented by over 20 positions funded through grants to the ROD Strategic Response.

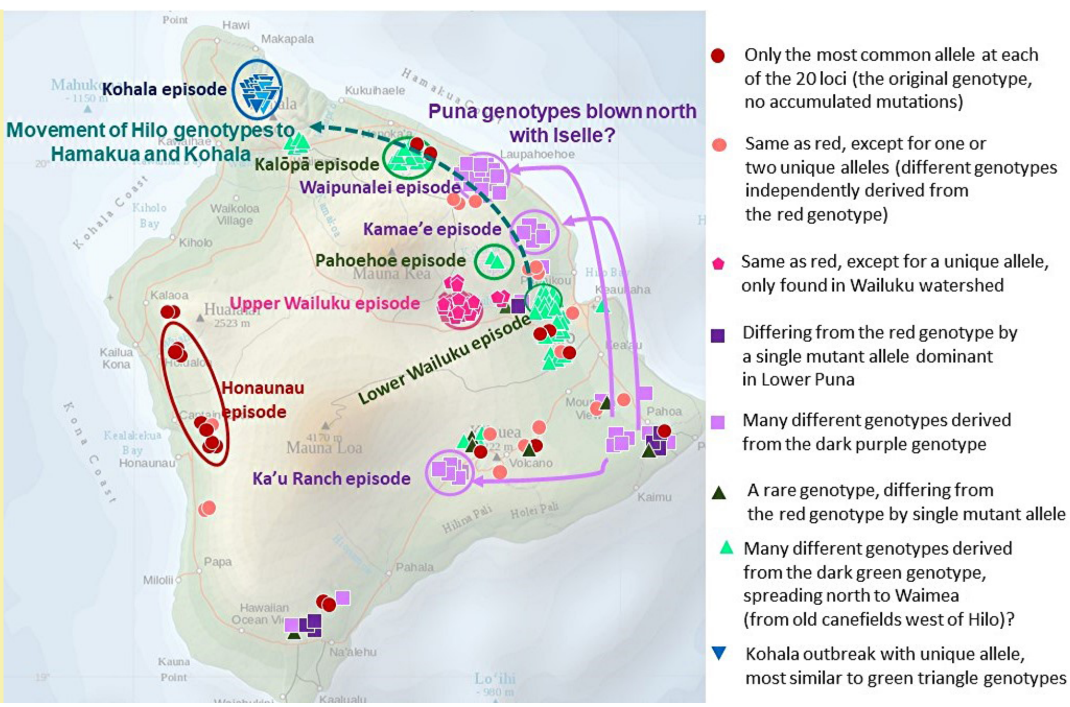
Crews felled and tarped an infected ʻōhiʻa in remote and steep terrain on Oʻahu. Credit: UH PCSU-Oʻahu Invasive Species Committee

ACCOMPLISHMENTS

The following is a summary of accomplishments illustrating important progress and providing context for the needs detailed later in the plan.

Accomplishments in research and management

- Researchers developed a rapid molecular-based diagnostic test to detect the presence of the *Ceratocystis* pathogens in samples and differentiate between the two species.
- Research results supported the HDOA quarantine rule passed in 2016 by testing ʻōhiʻa wood and soil pursuant to HDOA permit conditions. To date, 150 of 1500 proposed shipments of ʻōhiʻa or soil materials were found to be positive for *Ceratocystis* and denied shipment.
- Conducted host range testing on more than 20 forest and agricultural species and demonstrated that both *Ceratocystis* species can only infect ʻōhiʻa
- Developed genetic markers of *Ceratocystis* to track differences among outbreaks, showing patterns of disease movement across the landscape.
- Demonstrated that beetle-boring sawdust from infected trees contains living disease spores that enter the soil or become windborne, and that this dust can infect healthy trees.
- Determined that ambrosia beetles can act as disease vectors by transporting *Ceratocystis* spores on their bodies (5% of beetles were found to carry the living disease spores), although it is not yet clear whether beetles spread disease by attacking healthy trees.
- Developed effective sanitation treatments of ʻōhiʻa material and products, including heat and vacuum-steam processes for ʻōhiʻa logs, and tested fungicide drench treatments for infective sawdust and wood chips.



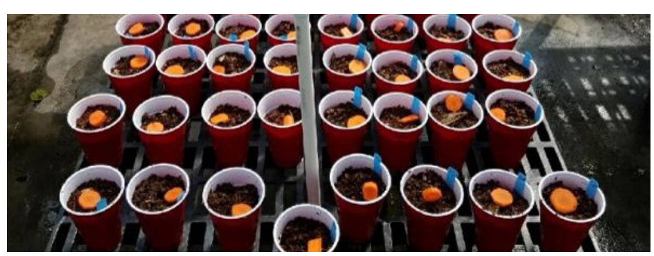
The minute changes in the genes of both types of *Ceratocystis* are being used to map how each disease may have spread over time. This map is for *C. lukuohia*, the more aggressive pathogen that causes ROD. Credit: Map created by Tom Harrington/ Iowa State University

- Tested the efficacy of a variety of fungicides to protect individual healthy ʻōhiʻa trees.
- Developed decontamination protocols for forest users and installed boot brush stations at trailheads across the state to reduce the spread via movement of soil on hiking boots.
- Conducted island-wide, high resolution airborne imaging of ʻōhiʻa forests to map the progression of mortality. Results revealed that fencing and ungulate exclusion are associated with lower levels of ROD mortality.
- Established an extensive network of 200+ forest inventory plots in areas where ROD is present to determine levels and patterns of ʻōhiʻa mortality under varying ecological conditions and management. Results indicate that ʻōhiʻa mortality is highly variable.
- Conducted regular helicopter surveys across the state's ʻōhiʻa forests to detect new disease outbreaks and map distribution.
- Field crews and partners followed up on aerial detections of suspect dead and dying trees, collecting thousands of samples to diagnose whether trees were infected with *Ceratocystis*.
- Developed and used a decision tree to guide whether or not to fell diseased trees, and felled thousands of trees to minimize disease spread where feasible and appropriate.

Accomplishments in public engagement

- Identified key messages to communicate, including the "Five Things" the public can do to help limit the spread of ROD.
- Engaged extension and outreach specialists from partner agencies, invasive species committees, and watershed partnerships from each island to extend our reach to communities statewide.
- Communicated with more than 20,000 people through classes, scientific meetings, community fairs and events, and more than 300 community meetings statewide.
- Held four science symposia for communities on Hawaiʻi Island, and one on Oʻahu that was live-streamed, and three family-oriented ʻōhiʻa festivals that engaged over 3,500 people.
- Produced an Emmy Award-winning documentary "Saving ʻŌhiʻa: Hawaiʻi's Sacred Tree", broadcast on television and shown at community events with an estimated reach of more than 750,000 viewers.
- Collaborated with Hawaiian Airlines to produce "ʻŌhiʻa – The Story of Hawaiʻi's Tree," viewed by tens of thousands of visitors and residents during Hawaiian Airlines flights.
- Established and maintained www.RapidʻŌhiʻaDeath.org, reaching 40,000 people; engaged thousands through Instagram and Facebook.

Liquid Drench Treatment	Product Category	ROD Survival (28 day post application)
Water only	*Control*	**100%**
RootShield Plus	*Biological fungicide*	**100%**
Trichoderma Ta04-22	*Biological fungicide*	**100%**
EM-1	*Beneficial microorganism*	**100%**
Oxidate 2.0	*Peroxide (oxidizer)*	**92%**
BanRot®	*Conventional fungicide*	**30%**



Developing and testing methods for killing the disease spores in ʻōhiʻa logs, wood chips, sawdust, and soil have been high priorities. This table shows the results of a variety of liquid drench treatments applied to sawdust and wood chips. Credit: Table and image by Marc Hughes/USDA ARS PBARC

- Cooperated with Island Invasive Species Committees and the Hawai‘i Ecotourism Association to conduct bio-sanitation workshops for eco-tour operators statewide, who in turn reached thousands of residents and visitors to our forests.
- Cooperated with the Hawai‘i Seed Bank Partnership to hold dozens of ROD Seed Banking Initiative workshops statewide and trained over 500 volunteers to safely collect ‘ōhi‘a seeds for conservation and research. Volunteers have added new collections of ‘ōhi‘a seed from hundreds of distinct locations across the state, and thousands of seeds have already been withdrawn for ROD resistance testing and restoration.
- Conducted surveys demonstrating wide-spread public awareness about ‘ōhi‘a and the threats posed by ROD to our ‘ōhi‘a forests.
- With the Department of the Interior and National Invasive Species Council Secretariat, held the "‘Ōhi‘a Challenge" contest with a DOI-sponsored $70,000 award to generate and identify novel technological solutions to address ROD, resulting in over 70 applications.

In 2017 there was one full-time outreach/extension staff that focused on ROD, and a handful of others that contributed time and efforts. Since then, the ROD Outreach Team focused on engaging potential outreach partners. To date, more than 60 outreach partners from across the state have participated in training workshops such as this field day in Hilo. Credit: Christy Martin/UH PCSU-CGAPS

SAMPLING AND ANALYSIS

Field staff on all islands spend considerable time and effort obtaining samples from sick ‘ōhi‘a trees reported by aerial surveys and the public. The only way to verify if a tree is infected with the fungus is to collect a small amount of wood from the tree and analyze it. Although the USGS "lab in a suitcase" is used in some instances for quick assessments, all samples are sent to the USDA ARS lab in Hilo for analysis.

Result	**Hawai‘i**	**Maui**	**Lāna‘i**	**Moloka‘i**	**O‘ahu**	**Kaua‘i**	**TOTAL**
C. lukuohia	1,378	0	0	0	0	47	1,425
C. huliohia	311	1	0	0	4	45	360
Both species	33	0	0	0	0	1	34
Negative	2,379	74	4	9	209	102	2,777
Pending	43	1	0	0	6	0	50
Total sampled	144	76	4	9	218	195	4,646

As of November 1, 2019, over 4,600 samples have been collected and analyzed.

Statewide coordination

- The ROD Working Group, 200+ people including government agency staff, private landowners, elected officials, and members of the public, met monthly to discuss research and management updates and needs on the ROD response. This strategic response has been recognized through local and national commendations.
- The ROD Outreach Team met monthly to coordinate outreach messages and events with communities throughout the state.
- The ROD Science Team met every other month to discuss recent findings, coordinate data gathering, and communicate recent findings to managers and the outreach team.
- Each island formed a ROD working group to address island specific needs and developed rapid response plans on islands where ROD is not well established.
- Statewide survey and monitoring data were collected in a standardized electronic format and hosted on a DLNR server where updated results can be accessed directly by project partners to guide management.

ROD researchers and response teams met in May 2019 to summarize and share the findings on ROD and discuss needs and next steps. Links to the presentations and other information can be found at www.RapidOhiaDeath.org. Credit: Christy Martin/CGAPS

The ROD Working Group won the 2019 Hawai'i Conservation Alliance award for Conservation Innovation for the scope, scale, and use of the partnership model in responding to ROD. Accepting on behalf of the ROD Working Group are (left-right) Dr. Flint Hughes, U.S. Forest Service-Institute of Pacific Island Forestry; Dr. Lisa Keith, USDA ARS PBARC; Rob Hauff, DLNR Division of Forestry & Wildlife; and Dr. J.B. Friday, UH CTAHR Cooperative Extension Service. Credit: Dan Dennison/DLNR

2020-2024 ROD STRATEGIC PLAN FRAMEWORK

Federal, state, county, and private funding and in-kind contributions of staff time and resources have supported a multi-faceted emergency response to ROD. This plan details the priorities for continuing the response, including management actions such as surveys, response, and control. The plan also includes the need to develop new tools to improve detection and advocates for the use of existing technologies to manage forests to reduce harm caused by ROD. Research is still needed to answer key questions involving the biology and source of the pathogens, how they spread, how much genetic resistance exists, and opportunities for forest restoration. As with the previous plan, this plan also prioritizes public engagement as an essential component.

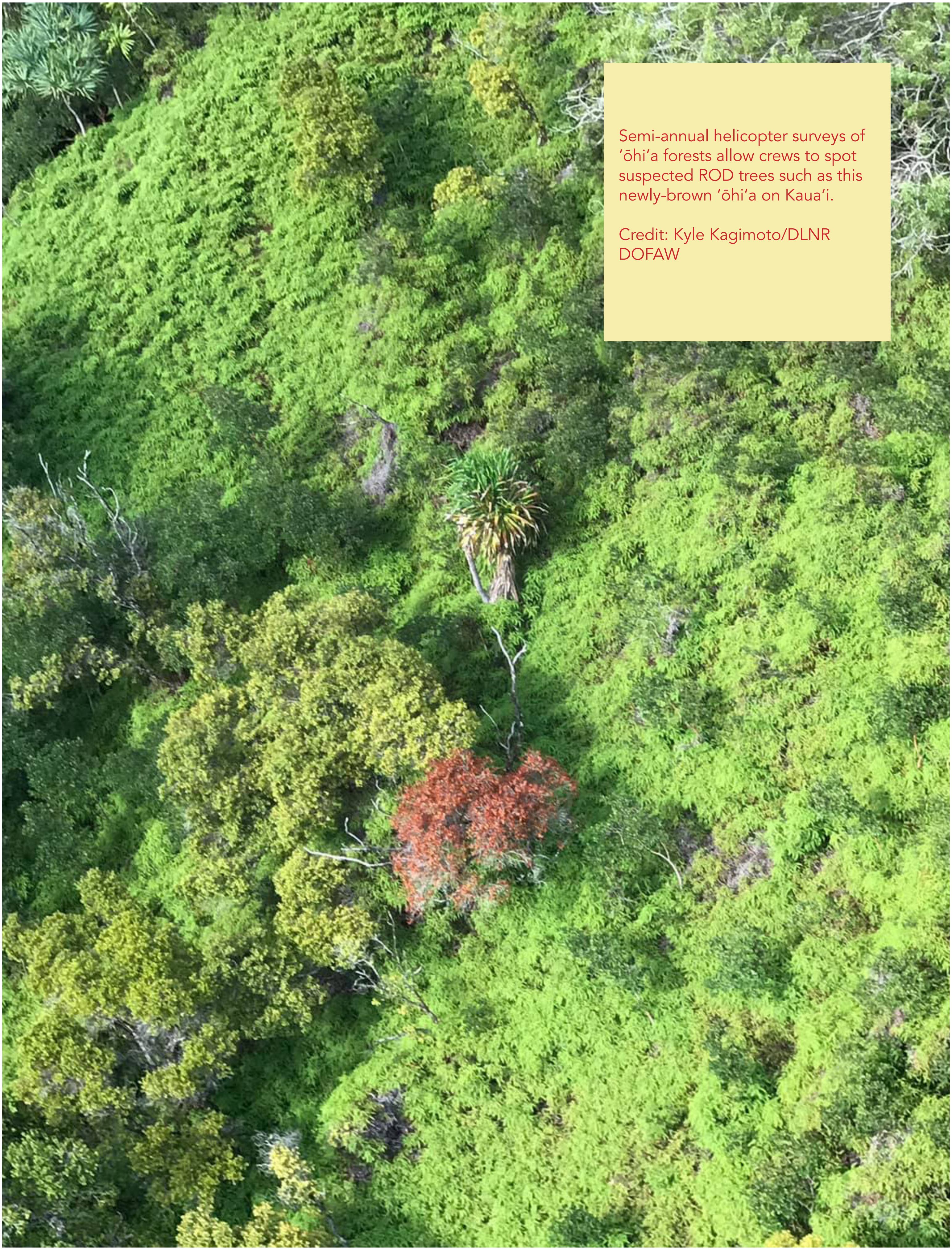
Management actions - survey, response, and control

Each island has established a multi-partner ROD Incident Command System framework for aerial surveys, followed by Early Detection and Rapid Response (EDRR) efforts. On islands where ROD is not yet well established, EDRR crews sample suspect ROD trees identified from aerial surveys or public reports.

As demonstrated most recently on Maui and O'ahu, the ROD Incident Command System was activated and crews quickly sampled suspect ROD trees; in each case trees found positive for *Ceratocystis* were promptly cut down and either destroyed or covered with tarps. On Kaua'i, where *C. huliohia* has been found in several areas, new detections of *C. lukuohia* have complicated the response. Limited resources have required prioritization of management actions to address ROD trees located in high quality native ecosystems or in high value watersheds. On Hawai'i Island, because both pathogens have impacted many 1000s of acres of native forest, EDRR crews are focusing on treating ROD trees located in high priority forest conservation areas; such areas include those of high ecological importance where disease occurrence is still limited, or areas of high aesthetic, cultural, or municipal importance.

Helicopter surveys of 'ōhi'a forest on each island are conducted twice a year with island-based DLNR DOFAW and partner personnel using tablets and the Digital Mobile Sketch Mapping app. These surveys allow rapid data collection and for spotting and mapping suspected ROD trees for follow-up sampling by ground crews.

GPS coordinates from helicopter surveys allow ground crews to follow up and take a wood sample. Even with GPS points on maps, it can take a significant amount of time to find the tree and take a sample. Credit: UH PCSU-Big Island Invasive Species Committee



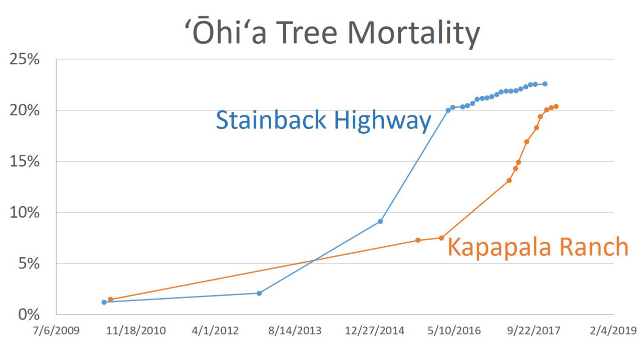
Semi-annual helicopter surveys of ʻōhiʻa forests allow crews to spot suspected ROD trees such as this newly-brown ʻōhiʻa on Kauaʻi.

Credit: Kyle Kagimoto/DLNR DOFAW

Helicopter-mounted video systems are being developed to provide low-elevation imagery over thousands of acres in a short period of time. Coupled with emerging computer-driven recognition technology, this will increase detection efficiency and have other potential benefits.

In addition, the use of drones has become an important tool for ground crews to get a bird's eye view of the surrounding forest. The team that sampled the first ROD trees on Kaua'i used a drone to see if there were any additional suspect trees nearby that they could not see from the ground. Drones are also an inexpensive method for collecting high-resolution images for detailed month-to-month disease progression data, both applications led by the Spatial Data Analysis and Visualization Lab at UH Hilo. A combined approach using all of these platforms permits island-wide coverage, while targeting certain areas for more detailed, frequent assessment.

Moving forward, we need continued support of surveillance efforts and EDRR crews on each island, enabling adequate detection, sampling and treatment of suspected ROD trees. This includes continued investments on Hawai'i Island to support surveillance and EDRR efforts in high priority forests. The surveillance costs including aerial surveys and ground sampling, as well as responding to prioritized outbreaks, amounts to approximately $1,440,000/year which goes toward helicopter contracts, RCUH staff salary (this effort requires more than can be fulfilled by agency staff alone), field supplies, and data management.



Data from series of drone images, combined with pre-ROD aerial photographs of the same locations are being used to monitor and assess disease progression in several sites. This graph shows the percent of dead 'ōhi'a over time at two sites. Credit: Ryan Perroy/UH Hilo SDAV Lab

A decision support flowchart guides the felling of confirmed ROD trees. Location of the infected tree, the release of spore-carrying sawdust from the chainsaw, safety, terrain, the possibility that the tree may hit and infect nearby 'ōhi'a, and the presence or absence of ambrosia beetles are all considered. Credit: J.B. Friday/UH CTAHR

Research on tools for improving detection and forest management

On Hawai'i island, repeat surveys using high resolution, spatially explicit, airborne-based, and island-wide data are used to map and assess ROD related mortality rates to understand the long-term implications of ROD for our 'ōhi'a forests. This data collection and analyses by the Arizona State University-Center for Global Discovery and Conservation Science are critical to developing management actions that reduce the impacts of ROD on our 'ōhi'a forests, our native biodiversity and our watersheds. Our understanding of the scale, patterns, distribution, and ecology of ROD is growing, and here we delineate landscape-scale priorities.

Results from ongoing aerial surveys have shown that fenced areas where ungulates have been removed are less vulnerable to ROD, and analyses of 'ōhi'a monitoring plot data show significantly lower mortality rates where there are low levels of pig activity compared to plots exhibiting high levels of pig activity. The most

Feral animals, either goats or cattle stripped the bark from a number of 'ōhi'a trees growing on lava substrate in Ka'u. *Ceratocystis lukuohia* can be seen growing on the open wood, and many of the injured trees in this area also tested positive. Credit: Emma Yuen, DLNR DOFAW

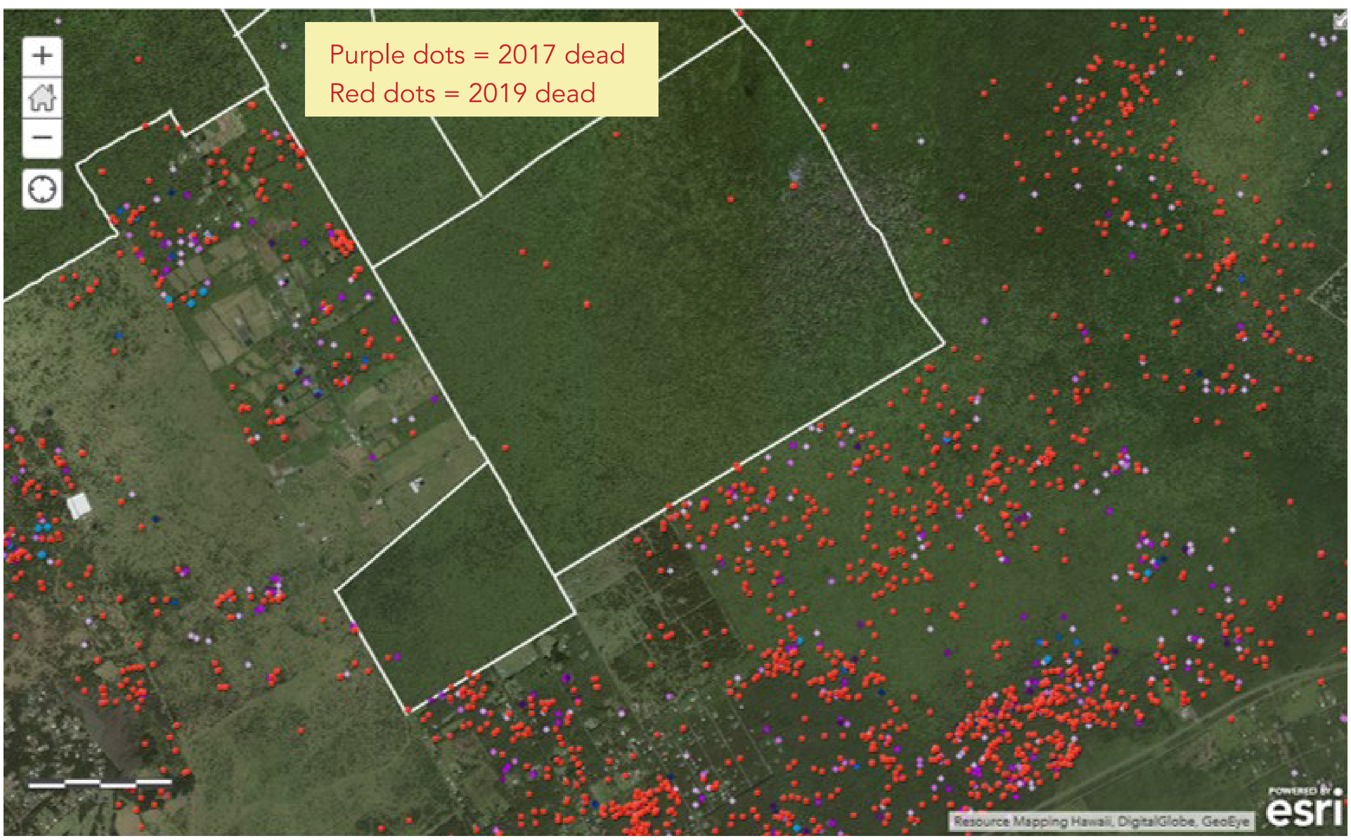
TOOLS NEEDED TO MANAGE ROD:

Managers are using the best current knowledge on ROD to protect our forests. Several tools have been identified by managers that would allow us to be more effective. These include:

- **Registered insecticides or other control methods for stopping beetles from burrowing into ROD-infected trees and releasing disease spores into the environment.**
- **Ways to quickly detect disease spores in the environment, including air, water, and soil using eDNA or other techniques, combined with a way to assess spore viability.**
- **Techniques for detecting ROD-infected trees before the symptoms become visible, including canine detectors, spectroscopy, or other means.**
- **A method for quickly screening 'ōhi'a trees for disease resistance.**
- **Fungicidal treatments to protect high value trees from infection, and an easy, inexpensive application method, as well as treatments for wounds to prevent infection of otherwise healthy 'ōhi'a.**
- **Improved tools for sanitation such as mobile units at baseyards for cleaning trucks and heavy equipment and more effective hiker boot brush stations with decontamination.**
- **Effective biological controls for priority invasive plants that prevent 'ōhi'a regeneration.**

logical explanation for these patterns is that reduced wounding of tree trunks and roots by feral animals results in lower stand level infection rates. This aligns with the fact that *C. lukuohia* and *C. huliohia* cannot enter and infect trees without a wound. Further research is needed into the role of feral ungulates in transporting and/or transmitting ROD. This plan advocates for resource managers to prioritize effective ungulate management (i.e., fencing and removal) for the most ecologically important forests to reduce unnecessary tree damage and enhance a given forests' ability to resist new infections.

The U.S. Forest Service-Institute of Pacific Islands Forestry conducts monitoring of hundreds of ʻōhiʻa forest plots located across a diversity of elevations, rainfall amounts, geological substrates and soil types has resulted in several key findings to inform management. First, ROD-induced mortality rates of ʻōhiʻa trees are highly variable from plot to plot – ranging from a low rate of no ʻōhiʻa trees dying from ROD in a given year to 45% of the ʻōhiʻa dying from ROD per year, with an average mortality rate for all plots of 10% per year. Second, monitoring data show that mortality rates for younger, smaller-statured



Repeated surveys and data analysis by the Arizona State University Airborne Observatory (formerly the Carnegie Airborne Observatory) showed the coincidence of ROD trees outside of some property lines. Further research and on-the-ground work with collaborators on several fenced and ungulate-free areas such as the Olaʻa fenced unit, clearly shows the greatly reduced incidence of ROD inside the fence. While not completely free of ROD infection inside the fence, this research points to one of the few possible forest protection options for Hawaiʻi island. Credit: Flint Hughes/U.S. Forest Service

ʻōhiʻa trees are much lower than for older, larger-statured ʻōhiʻa trees. Larger and older trees may be more easily infected by the pathogens (greater surface area and greater exposure to wounding from animals and storms; slower growth rates of older trees mean they are less able to defend against infection). Third, in lower elevation plots (< 3500 ft elevation), invasive plants such as strawberry guava are spreading, outcompeting and occupying more and more of former native forest areas, preventing natural regeneration of ʻōhiʻa. In lower elevation forests where ʻōhiʻa and invasive plants co-occur, there is almost a complete lack of ʻōhiʻa seedlings.

Both remote sensing data and field observations indicate that some ʻōhiʻa forests are less susceptible to ROD than others. Cooler and drier forests seem to have lower rates of infection than warmer or wetter forests. Research is needed to determine whether these patterns have an underlying environmental basis or whether forests that seem healthy today will be severely impacted by ROD in the future.

Knowledge of the susceptibility of ʻōhiʻa forests to ROD will help managers prioritize which forests to protect.

Research will continue to assess the effects of ʻōhiʻa mortality on other native species, the ecosystem, and water resources, as well as inform management strategies that could aid long term forest health.

While remote sensing scientists are working on techniques to detect infected trees before they show the characteristic wilting and browning of leaves, research conducted over the last two years showed that canines can reliably detect *C. lukuohia* and *C. huliohia* in trees that are not showing visible symptoms, in controlled settings and in the environment. A ROD detector dog program could support inspection of ʻōhiʻa logs and other items at ports and could aid in the Early Detection & Rapid Response framework. To operationalize the use of detector dogs would require handlers and trained canines, the infrastructure and funding to support canine

Tall ʻōhiʻa in a sea of strawberry guava. The understory of this Puna area forest is nearly 100% non-native strawberry guava. Although these remaining ʻōhiʻa flower and produce millions of wind-dispersed seeds, there is a virtual absence of ʻōhiʻa seedlings and young ʻōhiʻa. The advance of ROD underscores the need to keep invasive plants like strawberry guava from forever replacing native forests. Credit: J.B. Friday/UH CTAHR

An ambrosia beetle (*Xyleborus ferrugineus*) boring into ʻōhiʻa wood, and the sawdust, or frass that is pushed out of the tree by a single ambrosia beetle. The ROD pathogens create a fruity smell as it infects ʻōhiʻa, which attracts ambrosia beetles. The beetles bore into the wood and push out frass that carries the pathogen. Research has found that about 5% of ambrosia beetles carry and can spread the disease, but it isn't known whether or not healthy or stressed ʻōhiʻa are being attacked by these beetles, and the exact role of beetle frass in disease spread is also not clear. Credit: Kylle Roy/USGS

care, housing, and training, priorities which are also in the Hawaiʻi Interagency Biosecurity Plan.

Support for these combined technical developments and management recommendations will cost $670,000 per year. In addition to activities and costs outlined in this plan, ungulate management through fencing and removal by DLNR and its partners under the Aloha + Challenge sustainability targets needs continued support to protect ʻōhiʻa forests from long-term impacts of ROD.

Research on the pathogens and how they spread

Based on research over the past three years, it is clear that the two ROD pathogens differ—the more aggressive *C. lukuohia* quickly spreads throughout the tree, clogging the flow of water and causing the tree to die within a few months. In contrast, *C. huliohia* clogs the flow of water and nutrients at the point of entry, forming a canker which results in the death of individual limbs before gradually spreading enough to kill the tree. This information is used to help guide whether or not to fell certain trees, and the best protocol for testing ʻōhiʻa logs for quarantine purposes. Additional basic research into these two new pathogens will continue to improve the strategic response in many areas.

Understanding how the pathogen spreads between trees is among the most important unanswered questions. We know that boring dust, or "frass" expelled by wood-boring ambrosia beetles attacking ROD-infected trees, is the most likely way by which the sticky spores of the pathogen enter the environment. Live disease spores within frass particles may fall onto soil, be picked up and carried by wind, or attach

Research on beetle activity in ʻōhiʻa logs and frass collection in wind monitoring stations are some of the ongoing studies by the U.S. Geological Survey. Credit: USGS Pacific Island Ecosystems Research Center

to beetles looking to attack another tree. These, or other, mechanisms may allow the pathogen to move from an infected tree to a healthy tree. Further research is needed to understand more fully the nature and importance of these mechanisms and vectors.

Live spores within the soil do not appear to infect undamaged roots of healthy ʻōhiʻa, but roots damaged by pigs and other animals, or machinery, exposes the tree to the risk of infection if disease spores are present (lab studies of infection through undamaged and damaged roots have also provided some support for this). The exact role and magnitude of the wind in spreading the disease is still being studied. The wind can carry beetle-boring frass with disease spores, and researchers have been able to detect the DNA of the pathogens in tiny wood particles captured in devices that sample wind-blown material. However, sampling to-date has not found infectious spores in wind-borne frass. Much more work is needed to assess whether and under what climatic conditions living pathogen spores can be transmitted via wind. Computer simulation models of airborne particle transport could help answer some of these questions. Preliminary research has also shown that ambrosia beetles are able to carry live spores on their body and may be able to transmit the disease if they attack healthy trees. While ambrosia beetles are not typically attracted to healthy trees, they might still play a role in direct disease transmission.

It is critical to determine how long spores of* C. lukuohia *and* C. huliohia *remain viable in different materials and under varying environmental conditions.

Because the amount of frass produced by beetles varies among species and with their abundance, it is important to determine how forest structure, climate zones, and geographic location influence ambrosia beetle communities. Knowledge of beetle communities and the environmental cues that beetles use to locate and bore into infected trees could prove important in managing beetle densities and the production of infected boring dust.

Funding for 2020-2024 is needed to support ongoing field research that will determine how beetle communities vary within and among islands and how their abundance influence the release of sawdust carrying the pathogen spores. The identification of chemical compounds released by trees infected with ROD will help identify scent cues that help beetles find the dying trees, which in turn can be used to develop lures to trap beetles, or to develop products that deter beetles from attacking trees.

One of the most important components of the ROD emergency response framework is the rapid and accurate screening of samples to diagnose the presence or absence of the ROD pathogens.

The ROD diagnostic laboratory also analyzes soil, frass, ambrosia beetles, shipments of ʻōhiʻa wood, and other items for the presence or absence of ROD. These functions are crucial to understanding and managing the disease, and support the strict quarantine and biosecurity measures set in place by HDOA. In-kind support of this diagnostic and research work is contributed by the USDA Agricultural Research Service- Daniel K. Inouye U.S. Pacific Basin Agricultural Research Center which provides lab space and equipment, and the time of the lead pathologist on ROD. Beetle and windborne frass studies led by the U.S. Geological Survey-Pacific Island Ecosystems Research Center are supported through state and federal funds. Additional funds from federal, state, and private grant sources support the state's only forest pathologist, several lab technicians, and other personnel amounting to $950,000. Continued funding will support lab and diagnostic capacity and additional molecular analysis by international experts in fungal pathogens.

Development of disease resistance and restoration techniques

Initial research on ROD disease resistance in all five ʻōhiʻa species and ten varieties in Hawaiʻi is underway. Previous work that found resistant genotypes exist in the wild, therefore, the goal is to determine how common they are, whether they exist among all varieties and species of ʻōhiʻa, the degree and durability of resistance to ROD, and whether resistance is passed on from mother tree to offspring – in other words, is resistance heritable? Especially important in this early phase work is refinement of a quick greenhouse assay to find genetically resistant parents. The use of such resistance screening assay has been key in many other resistance programs across the United States. Field trials can confirm the validity of greenhouse assays as well as the monitoring of the durability and

Research at USDA ARS has shown that there are resistant ʻōhiʻa varieties, and work is underway to answer remaining questions before a traditional breeding program can be successful in producing resistant ʻōhiʻa for outplanting. Credit: Lisa Keith/ USDA ARS stability of resistance. Initial screening today for resistant genotypes will provide plant material available for disease testing in about two years, but the screening of *Metrosideros* genotypes from across Hawaiʻi is an enormous task. We anticipate that across the coming five years, significant investment into staffing a fully dedicated screening resistance selection program is critical to: 1) identifying how much resistance occurs in the wild, 2) determining which genotypes harbor putative resistance to ROD, and 3) providing private land owners and large-scale restoration efforts with material needed for long-term success costing $150,000 per year.

Outreach events such as the ʻŌhiʻa Love Fest in Hilo help teach community members what they can do to help reduce the spread of ROD. This booth asked kids to "drive" toy cars through the mud, then use the spray bottle to wash their car. Credit: Christy Martin/UH PCSU CGAPS

There is a need for practical approaches to restore, or at least maintain ecosystem function for high-value ROD-impacted ʻōhiʻa forests. This plan identifies a critical need for developing and implementing additional invasive plant management tools, particularly biological control tools to reduce the seed production and rapid growth of some of Hawaiʻi's worst invasive plants. There is also need for practical approaches to restore ROD-impacted ʻōhiʻa forests including development of silvicultural guidelines for ʻōhiʻa and co-occurring native species. Because ʻōhiʻa seedlings, saplings, and even young trees appeared to be less susceptible to ROD infection, restoration with ʻōhiʻa may be feasible as a short-term (< 30 years) solution for enhancing ʻōhiʻa presence in ROD impacted forests. Experimental restoration trials would cost approximately $150,000.

Public engagement

People can unknowingly spread ROD short and long distances by moving contaminated materials, or put healthy ʻōhiʻa at risk of infection through damaging or cutting into ʻōhiʻa.

Community awareness, support, and behavior change is important for reducing the spread of the disease and protecting and enhancing the remaining healthy ʻōhiʻa forests. A survey conducted by Ward Research for the Coordinating Group on Alien Pest Species

The pathogens can be spread by moving untreated wood from ʻōhiʻa that were killed by ROD and by tracking soil containing living disease spores from infected areas into pristine forests. Injuring or cutting into a healthy ʻōhiʻa tree can open it up for infection, and when tools or machinery are used on an infected ʻōhiʻa, that tool can then spread the infection to healthy trees if not properly decontaminated.

found that by September, 2017, 92% of Hawaiʻi island residents and 43% of residents in Maui county, Kauaʻi, and Oʻahu had heard of Rapid ʻŌhiʻa Death. Through a combination of direct outreach, news media, print, radio and television and social media, the "5 Things" messages have been presented to a number of priority audiences and the public. However, there remains a lot to be done to reach additional audiences to affect behavior change, and to continue to reach existing audiences with emerging information.

Overall, our native forests have been in decline due to a number of invasive species, such as strawberry guava, mosquito-borne diseases that kill native birds, and feral animals. The presence of ROD compounds these problems and speeds the decline of whole forests at a rate and magnitude that is difficult to comprehend and convey. Tools and methods for addressing invasive species (such as strategic fencing, the use of biological control where appropriate, and the implementation of the Hawaiʻi Interagency Biosecurity Plan) will continue to be integrated into the ROD public engagement strategy. This plan also recognizes that resource management agencies do not have the capacity to maintain native ecosystems across the vast amounts of forests under their jurisdictions, even without ROD. Privately held lands also represent additional opportunities for managing forests for the future. There is a need to engage and enable communities in more than the five actions to reduce the spread of ROD; we need to identify ways and empower community-based forest management.

Finally, it's important to continue to work with existing and new priority audiences on specific messages. This includes a wide variety of people on each island such as the local wood and nursery industries to implement wood and soil treatments to facilitate compliance with HDOA's quarantine rules, businesses that use earth-moving equipment, and even off-road enthusiasts that may enter ROD-impacted forests.

There continues to be strong community support for ʻōhiʻa, and many people want to know what more they can do. Fostering the love of ʻōhiʻa and providing opportunities and assistance in planting ʻōhiʻa can help engage individuals and communities in forest stewardship. Credit: Christy Martin/UH PCSU CGAPS

As prioritized in the 2017-2019 plan, investments were made in hiring dedicated outreach and extension staff through UH College of Tropical Agriculture and Human Resources, Pacific Cooperative Studies Unit, and the Research Corporation of the University of Hawaiʻi, with outreach efforts conducted by a much larger community of staff from agencies, non-governmental organizations, and businesses on each island. The staff and dozens of partners contributed their time and help, and we will continue to work with partners to extend our reach.

To accomplish the outreach goals in this plan, annual funding is needed for six full time outreach & extension positions: four existing positions and two additional staff to support capacity needs on O'ahu and in Maui County, and for operational funds including printing updated brochures, student booklets, airing radio spots, and producing short videos to be shared on social media. Funding would also provide partial support for the statewide Hawai'i Seed Bank Partnership staff, materials, and supplies to continue the 'ōhi'a seed banking efforts on each island. Support would also enable planning and support for community-based 'ōhi'a planting, and community-based restoration projects using 'ōhi'a and the suite of appropriate native plants. Funding is also needed to conduct ongoing assessments to determine the effectiveness of outreach approaches and improve programs.

Although not necessarily outreach, an assessment of the socioeconomic value of 'ōhi'a and the impacts of ROD, and possibly assessing the value of restoration may be worth investigating. A robust economic assessment could be conducted for $150,000, and the cost for public engagement priorities is $715,000 per year.

'Ō'hia seed collection and seed banking workshops have been in demand across the state. The Hawai'i Seed Bank Partnership is also starting to meet schools and community requests for help with locally-sourced 'ōhi'a seeds and planting. Credit: Hawai'i Seed Bank Partnership

Funding and community support will be needed to plant ROD-resistant 'ōhi'a such as this likely resistant 'ōhi'a in Puna. Credit: Lisa Keith/USDA ARS

RAPID ʻŌHIʻA DEATH STRATEGIC RESPONSE PLAN BUDGET 2020—2024

ANNUAL RESOURCE NEEDS

Management Actions - Survey, Response, and Control

Program Area	Personnel/item	Lead Agency	Annual
Hawaii Island	Big Island Invasive Species Committee	UH	$360,000
	Helicopter	DOFAW	$40,000
	Supplies, Equip., Contracts	DOFAW	$10,000
	HAVO	NPS	$140,000
Kauai	Kaua'i Invasive Species Committee	UH	$100,000
	Helicopter	DOFAW	$84,000
	Supplies, Equip., Contracts	DOFAW	$180,000
Oahu	O'ahu Invasive Species Committee	UH	$120,000
	Helicopter	DOFAW	$25,000
	Supplies, Equip., Contracts	DOFAW	$15,000
Maui Nui	Maui Invasive Species Committee (1 FTE)	UH	$85,000
	Helicopter	DOFAW	$65,000
	Response Planner	Maui County	$40,000
	Supplies, Equip., Contracts	DOFAW	$80,000
Statewide	Data Management	UH	$100,000
			$1,444,000

Research on Tools for Improving Detection and Forest Management

Program Area	Personnel/item	Lead Agency	Annual
Ecological Monitoring	Forestry Technicians (2.0)	US Forest Service	$150,000
	Ungulate Research Technician (1 FTE)	US Forest Service	$75,000
Remote Sensing	SDAV Lab (UH Hilo)	UH	$120,000
	ASU Global Airborne Observatory	ASU	$250,000
Other	Canine Detectors	USFS	$75,000
			$670,000

Research on the Pathogens and How They Spread

Program Area	Personnel/item	Lead Agency	Annual
Pathology/Entomology	Forest Pathologist (1.0 FTE)	USDA Forest Service	$100,000
	IPIF Pathology Lab (supplies, analyses)	USDA Forest Service	$60,000
	Pathologist Post-doc (1 FTE)	USDA ARS	$100,000
	Laboratory Technicians (2.0 FTEs)	USDA ARS	$160,000
	Pathology Lab (supplies, contracts for analysis, travel)	USDA ARS	$120,000
	USGS Lab (supplies, travel)	USGS	$60,000
	Disease Ecologist (1.0 FTE)	USGS	$110,000
	Entomologist (0.5 FTE)	USGS	$90,000
	Entomology Technician (1.0 FTE)	USGS	$80,000
	Intern (1.0 FTE)	USGS	$20,000
	Wind Dispersal Studies	TBD	$50,000
			$950,000

Development of Disease Resistance and Restoration Techniques

Program Area	Personnel/item	Lead Agency	Annual
Resistance	UH CTAHR, Forest Service, USDA ARS	USFS/UH	$150,000
Restoration	ʻŌʻhia Forest Restoration Pilot Project	DLNR (RFP)	$150,000
			$300,000

Public Engagement

Program Area	Personnel/item	Lead Agency	Annual
	Statewide Outreach Coordinator (RCUH)	UH CTAHR	$80,000
	Hawaii Island Outreach (CTAHR)	UH CTAHR	$80,000
	Kauai Outreach (RCUH)	KISC	$80,000
	Oahu Outreach (RCUH)	OISC	$80,000
	Maui Outreach (RCUH)	DOFAW	$80,000
	Intern (Kupu)	DOFAW	$25,000
	Media (radio, tv, internet)	DOFAW	$80,000
	Operations (Travel, supplies, contracts, etc.)	UH/DOFAW	$45,000
	Design and Printing Services	DOFAW	$35,000
	Public Awareness Survey	UH	$5,000
	Seed Banking Partnership (Lyon Arboretum)	UH	$125,000
			$715,000

Annual Total	**$4,079,000**

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"ʻAʻohe hana nui ke alu ʻia" translated, **"No task is too big when done together by all"**

ʻŌlelo Noʻeau: Hawaiian Proverbs and Poetical Sayings, by Mary Kawena Pukui

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Avatar Alliance Foundation
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Gordon and Betty Moore Foundation
Hauʻoli Mau Loa Foundation
Hawaiʻi Community Foundation
Hawaiʻi Conservation Alliance
Hawaiʻi Department of Agriculture
Hawaiʻi Forest Industry Association
Hawaiʻi Invasive Species Council
Hawaiʻi Seed Banking Partnership
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USDA Animal and Plant Health Inspection Service