ARTICLE CASE

Saving ʻŌhiʻa: A Case Study on the Influence of Human Behavior on Ecological Degradation Through an Examination of Rapid ʻŌhiʻa Death and Its Impacts on the Hawaiian Islands

DAYNA MARTINEZ[1], ELENA M. I. DURAN[1], AND NATALIE BAUER[1]

[1]Center for Conservation Medicine, Cummings School of Veterinary Medicine at Tufts University, Grafton, MA, USA
Email: nataliehbauer@gmail.com

ABSTRACT ʻŌhiʻa lehua is a species of tree endemic to the islands of Hawaiʻi. Its existence is vital to the survival of many pollinator insects and endangered bird species and to the integrity of multiple islands' watersheds. Rapid ʻŌhiʻa Death (ROD) is an emerging fungal disease that poses a significant health risk for these trees and is spread by human traffic, ambrosia beetles, and wind dispersal. Loss of ʻohiʻa forests will negatively affect Hawaiʻi's economy and ecology and will have detrimental impacts on Hawaiian culture, particularly because of the role of lehua flowers in hula. While transmission of ROD Death is not yet fully understood, human activity is currently considered the main proponent of its spread. Hawaiʻi's economy is largely built on the tourism industry; however, tourists are often unaware of the disease and the practices implemented to contain the current outbreak while visiting the Hawaiian Islands. ROD is a conservation issue that connects humans with the environment and must be addressed using a one-health perspective. This article aims to elucidate the anthropogenic factors contributing to the depletion of ʻohiʻa lehua through the spread of ROD and to propose prevention measures that can be adopted by citizens and visitors. At the end of this case study, readers will understand the cultural, ecological, and economic significance of ʻohiʻa lehua. Readers will also be able to identify important stakeholders and examine the complexity of behavior change in conservation issues. KEYWORDS hawaiʻi, disease, behavior change, biology, invasive species, endemic, anthropogenic impact, conservation, one health, ecology

INTRODUCTION

In 2010, massive die-offs of ʻōhiʻa forest were observed on the island of Hawaiʻi (Hauff et al., 2020; Mortenson et al., 2016). Although ʻōhiʻa in the Hawaiian Islands had experienced similar large-scale deaths in the 1950s due to ʻŌhiʻa Dieback, diagnostic testing revealed that the current mass mortality events were caused by an unknown pathogen (Barnes et al., 2018; Hodges et al., 1986). Three years later, the cause of the 2010 outbreak was identified as deriving from two different fungal pathogens of the same genus classification, *Ceratocystis huliʻōhiʻa* and *Ceratocystis lukuʻōhiʻa*. These two pathogens are collectively recognized as causing the disease Rapid ʻŌhiʻa Death (ROD; Barnes et al., 2018).

ROD is an emerging disease that is highly pathogenic toward ʻōhiʻa lehua, a tree species native to the Hawaiian Islands (figure 1). Because these trees function as keystone species, the high mortality rate from ROD could significantly threaten the state's forests. ʻŌhiʻa maintain natural ecosystems by providing food and shelter to many of the islands' birds and pollinator insects as well as establishing a secure root system for water filtration (Crews et al., 2000). The decline of these trees could contribute to biodiversity loss and possible flooding. However, the conservation issue extends beyond the environmental realm as ʻōhiʻa trees have considerable influence in Hawaiʻi's culture and economy.

As scientific advancements are made, it is evident that humans play a crucial role in contributing to the transmission of ROD. Although a cure for the disease is yet to be discovered, active management strategies allocate more time for researchers to combat the crisis. By raising

Case Studies in the Environment, 2020, pps. 1–13. electronic ISSN 2473-9510. DOI: https://doi.org/10.1525/cse.2020.1104118.

FIGURE 1. Image of ʻōhiʻa lehua in Hawaiʻi Volcanoes National Park. Adapted from *Flickr*, by Frank Hamm, May 3, 2010, https://www.flickr.com/photos/injelea/5540955466. Copyright 2020 by F. Hamm. Reprinted with permission.

FIGURE 2. A young ʻōhiʻa tree found on a hike in Kahuku. Adapted from *Hawai'i Volcanoes National Park Hikes & Events,* by Janice Wei, July 2, 2018, https://www.nps.gov/havo/learn/news/20180702_pr_events.htm. Copyright 2020 by NPS. Public domain.

awareness about the impacts of anthropogenic activities, conservation becomes a priority for effective policy.

CASE EXAMINATION

Part I—ʻŌhiʻa Lehua and One-Health

The moment we stepped out of the airport, we could hardly contain our excitement as we took in the breathtaking sights. Exotic flowers in bright oranges and reds complimented the warm tones of the setting sun (figure 2). In the distance beyond the town, we could see a dramatic landscape of jagged mountains in lush greens cutting into the horizon (figure 3). Elena,

FIGURE 3. An aerial image of Kauai Island. Adapted from *USGS Science for a Changing World,* n.d. https://www.usgs.gov/media/images/aerial-view-coastline-kauai-island. Copyright 2020 by USGS. Public domain.

Natalie, and I arrived here on the island of Kaua'i to assist in field research, but it hardly felt like we were here for work while the scenery looked like something from a postcard.

We boarded the shuttle bus, and suddenly the exhaustion from our long flight was replaced with enthusiasm. Excited to explore the island, we made plans to spend our weekend hiking Līhu'e-Kōloa Forest Reserve and even managed to book a helicopter tour. We would be exploring by land and air! The next morning near the trailhead entrance, I smelled the perfume of overgrown honeysuckle bushes before I saw them. As we continued our hike, I was amazed at the large patches of wild ginger growing and delighted by all of the different birds we were seeing. We stopped toward the top of the ridge, and that's when I noticed we were in a completely new forest. We became dwarfed by large ʻōhiʻa trees that had taken over the landscape. Their blooms resembled small fireworks, bursting in shades of bright red. I admired a young ʻōhiʻa tree closely; it's young leaves pale and soft to the touch were so different from the waxy, rich green adult leaves. A voice called out, "Be careful with your footing!" We turned around quickly. "There's a root in front of you. You can wound the tree by stepping on it." She continued, "Not that I think you'd hurt the tree on purpose, but we just want to keep it safe because the ʻōhiʻa are in our history and culture, and we consider them family." The stranger's name was Ardena, a native-born Hawaiian. She walked with us and shared the history of ʻōhiʻa.

FIGURE 4. A depiction of ʻŌhiʻa and Lehua—a legend which connects love and nature to describe the resilience of the tree and its cultural bond with the people of Hawaiʻi. Adapted from *Linda Rowell Stevens Art Gallery of Hawaiian Legends*, by Linda Stevens, n.d. https://www.lindarowellstevens.com/ohia-and-lehua. Copyright 2020 by L. Stevens. Reprinted with permission.

> *Hawaiian legend tells of a handsome warrior named ʻŌhiʻa. He had legs strong like tree trunks and a warm, gentle smile. He was in love with a maiden named Lehua. Her beauty was often compared to the moon and starlight. She had a kind heart and was loved by many in the village. Each night ʻŌhiʻa and Lehua would meet in the forest to see each other. One night, while ʻŌhiʻa was waiting for Lehua to arrive, a beautiful stranger approached him. He turned the woman away and told her that his heart belonged to someone else. The following night as ʻŌhiʻa met Lehua in the forest, the beautiful stranger approached him once more. Again, ʻŌhiʻa declined her advances. In a jealous rage, the stranger cracked the ground beneath the couple and lava started to surround them; for the stranger was Pele, the goddess of volcanoes and fire. In a frantic attempt to save the couple from Pele's wrath, spirits of the forest turned ʻŌhiʻa into a tree and turned Lehua into the tree's flowers. History says that if you take a flower from the ʻōhiʻa tree, it will begin to rain as the forest is saddened by the separation of the young couple in love (figure 4).*

With Ardena's history of ʻŌhiʻa and Lehua stuck in our minds, the three of us gained greater appreciation for the forest and looked forward to seeing the trees from the view of our helicopter tour. We flew above mountain ridges and deep valleys, and we were in awe by the cascading waterfalls that broke up the green vegetation. Suddenly, our hearts sank into despair. A patch of ʻōhiʻa trees were dead; their withered branches holding up crowns of brown leaves, devoid of any flowers or green color. In a defeated tone, the pilot said, "It's called Rapid ʻŌhiʻa Death. Apparently, it's a fungus that enters even the smallest wounds of ʻōhiʻa, and once it's infected, the tree dies within weeks." The pilot continued, "It's a shame. ʻŌhiʻa does so much for us and the island. I don't know what would happen if we lost all of the forests."

BACKGROUND. ʻŌhiʻa lehua is the most abundant native tree species in the Hawaiian archipelago (Loope, 2016). Its scientific name is *Metrosideros polymorpha*, and it can only be traced back to the Hawaiian Islands, making ʻōhiʻa lehua an endemic species. It can be found growing in different landscapes from lowlands to mountains and is usually the first plant to sprout from volcanic rock (Camp et al., 2019; Mueller-Dombois, 1992). ʻŌhiʻa plays a vital role in maintaining natural ecosystems by providing food and shelter to many of the islands' birds and pollinator insects (Crews et al., 2000). Some bird species, many of which are endemic or endangered, rely on these trees for survival. The ʻakikiki, a bird whose population is steadily declining in the wild, primarily nests and forages in mature ʻōhiʻa (Behnke et al., 2016). Habitat loss for these birds remains the biggest threat, and ROD only exacerbates the ʻakikiki's peril (figure 5).

ʻŌhiʻa is also important in healthy soil development, nitrogen fixation, and watershed management (Crews et al., 2000; Mortenson et al., 2016). As large numbers of

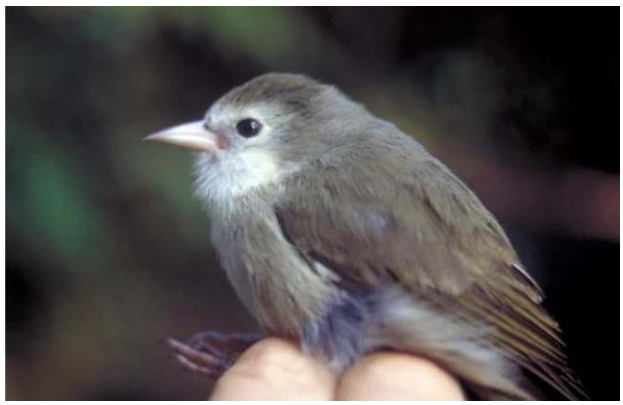

FIGURE 5. The ʻAkikiki, an endangered bird species found in Hawaiʻi, is dependent upon ʻōhiʻa lehua. Adapted from *USGS Science for a Changing World,* by Carter Atkinson, March 14, 2016, https://www.usgs.gov/media/images/endangered-honeycreeper-akikiki-kauai-creeper-hawaii-0. Copyright 2020 by USGS. Public domain.

ʻōhiʻa die, more subcanopy and floor vegetation take over. That vegetation outcompetes young ʻōhiʻa saplings for sunlight and nutrients. Much of Kauaʻi's flora in the lowlands, often in highly populated areas, are non-native and invasive species (Crews et al., 2000). Without canopy cover, there is more runoff and sediment, resulting in reduced water quality. This is especially important for people who live on young islands where the water-tables haven't been fully established and drilling for well water is unattainable (Crews et al., 2000). These trees are ecologically important to both wildlife and humans.

THE SPREAD OF ROD. Although both species of fungal pathogens are fatal to ʻōhiʻa lehua, there are differences in how each one affects the tree. *C. huliʻōhiʻa* infection may be more prolonged, causing death to the tree months to years after exposure (Barnes et al., 2018). Meanwhile *C. lukuʻōhiʻa* causes acute death, usually killing ʻōhiʻa within weeks from exposure. It is not known how these pathogens were introduced, but DNA analysis shows that the two fungal pathogens originated from different parts of the world. Studies have determined that *C. lukuʻōhiʻa* is most similar to a clade—a group of organisms from a common ancestor—of pathogens found in the eastern United States, while *C. huliʻōhiʻa* closely resembles a clade native to Asia. Despite the fact that ʻōhiʻa mortalities are generated by two different species, both pathogens are linked together as the causal agents of ROD (Barnes et al., 2018).

The first clinical sign of ROD is the yellowing of leaves (Barnes et al., 2018; Hauff et al., 2020). Leaves eventually lose their color and turn brown but will stay attached to limbs and branches for quite some time (figure 6). Signs of ROD can be seen by aerial viewing since it is usual for the entire tree crown to lose its color (Hauff et al., 2020). The inhibition of water intake is the primary cause for these symptoms. The fungus affects the xylem and associated tissues, preventing proper water transport (Loope, 2016). Infected tissues become stained, creating a black ring located toward the outer part of the trunk. It is important to note that visual detection of dark wood staining is not a true diagnosis for ROD. Samples must be analyzed for lab confirmation before a diagnosis can be made (Barnes et al., 2018; Heller & Keith, 2018).

The fungal pathogens of *C. huliʻōhiʻa* and *C. lukuʻōhiʻa* primarily enter through tree wounds (Roy et al., 2019). Wood boring insects, such as ambrosia beetles, create wounds in the tree (figure 7). If that tree is infected or if the beetle has been feeding on an infected tree, the pathogen is excreted in its frass, which is blown by wind to other susceptible trees (Roy et al., 2019). It should be noted, however, that ROD is most commonly transmitted by human traffic (Loope, 2016). People such as tourists, hikers, loggers, and hunters often carry fungal spores on

FIGURE 6. Aerial image illustrating the first clinical sign of ROD. Adapted from *ScienceMag*, by Timo Sullivan, 2018, https://www.sciencemag.org/news/2018/08/fears-lessen-invasive-fungi-will-completely-wipe-out-hawaiis-iconic-native-tree. Copyright 2018 by T. Sullivan. Reprinted with permission.

FIGURE 7. This image of an ʻōhiʻa log displays tunnels dug by ambrosia beetles as well as the staining of wood that could be indicative of infected tissues. Adapted from *USGS Science for a Changing World,* by Carter Atkinson, December 15, 2017, https://www.usgs.gov/media/images/inside-ohia-log-tunnels-created-wood-boring-beetles. Copyright 2020 by USGS. Public domain.

their shoes and equipment. They can carry spores for longer distances than wind and insects, making humans the biggest threat of disease spread. Along with the human-associated spread of the infection, there are also less understood mechanisms of natural transmission that likely involve spreading the fungal disease via wind. Roots damaged by humans or machinery expose the tree to risk of infection by wind-blown spores, thereby combining human and natural transmission. Newly developed environmental sampling devices are being implemented to capture wind-blown spores to investigate the possible pathways of fungal movement (Atkinson et al., 2019). ROD has been detected throughout the island of Hawaiʻi, in the eastern and northern regions of Kaua'i beginning in 2018, and in 2019, a single affected tree was discovered and destroyed in Maui, as well as four affected trees in O'ahu (Hauff et al., 2020).

Part II—Hawaiian History, Spirituality, and ʻŌhiʻa Lehua

Dayna, Natalie, and I had been in Kaua'i for a few months now and were no longer naive to the risks ʻōhiʻa faces. Hoping to gain further understanding of the trees' cultural significance, we approached Kai, a practitioner of hula, and asked to discuss the importance of ʻōhiʻa lehua. "It's a vital piece of the ceremony," she began, "Not just for the adornments, but for the act of gathering itself. When we gather from the seashore or from the mountains or from the forest, we are not simply extracting supplies for our dance. We are going to our mother, exchanging our gifts in hula for the gift of the land, which is also the embodiment of a god. It is an exchange of mana, really."

Mana, she told us, is the spiritual natural force that flows from the gods and is found in humans and in the natural world. ʻŌhiʻa in particular is essential to hula, since it is the kino lau—physical manifestation—of major gods in the Hawaiian spirituality and is worn during the practice to evoke these gods. Wearing ʻōhiʻa is wearing a god in physical manifestation.

Kai went on, "ʻŌhiʻa is so much more than a headband or an anklet. That is why we decided not to gather ʻōhiʻa for hula while ROD persists—because we recognize how dire this situation truly is. But, its meaning to me and fellow hula dancers is also why we hope it can be stopped. Our tradition depends on it."

Referenced, adapted, and fictionalized from Miner, M. (2016) and Kamahele, M (2000).

BACKGROUND: HAWAIʻI'S ANCIENT HISTORY. Polynesian voyagers arrived at the Hawaiian archipelago around 500 AD. The reason for these explorations has never been clearly identified—maybe due to lack of resources, trade, or a general sense of adventure. As time passed, voyagers' culture and spirituality were molded to fit life on the Hawaiian Islands and a culture that was markedly Hawaiian emerged (Hukilau Network, 2020).

Early Hawaiian spirituality was founded on the concept of natural gods that existed as a part of the world rather than separate from it. The prevailing concept throughout the spirituality is that mana flows from the gods to the chiefs and to the people and also flows through all aspects of the living and nonliving earth (Williams, 1997). The four major male spirits are Kāne, Kū, Lono, and Kanaloa, while the major female spirits are Hina and Pele. These spirits are able to take earthly forms, which are called the kino lau, meaning "many bodies." While Kāne is called the leading spirit, Kū has the most elaborate heiau, or places of worship. At Kū's heiau, chiefs offered sacrifices to the spirits. Kū, the spirit of the works of men, has many kino lau—the breadfruit trees, the coconut, the hawk, and importantly, ʻōhiʻa (Williams, 1997). Pele, described earlier in the legend of ʻŌhiʻa and Lehua, is the goddess of volcanoes and fire and is said to be the creator of the Hawaiian archipelago. Pele's significance in relation to ʻōhiʻa is described not only in the story of the two lovers but also in that Pele is highly

important in the practice of hula. Pele's sister, Hi'iaka, the goddess of hula dancers, medicine, and sorcery, was the first to dance hula. Hi'iaka's sister is honored in many hula dances and chants (Fisher, 2018).

HAWAIIAN CULTURE AND 'ŌHI'A LEHUA: THE CASE OF HULA. Hula is one aspect of Hawaiian history that has undergone many levels of transformation from ancient times to present yet still remains an undeniably significant part of culture in Hawai'i. In ancient Hawai'i, hula was used to preserve social hierarchy, with the dances telling stories of ancestry and accomplishments of important houses. Hula also was used to revere the gods, but this was a secondary purpose to that of preservation of the social system. Another dance, called haà, was used more in spiritual practice than hula (Chan, 2011).

The transformation of hula's identity began at the time of European contact with the Hawaiian Islands. Early European colonizers first described hula as childlike and then as overly sexualized. As early as the 1700s, the Hawaiian hula girl was sexualized by Europeans, and hula became synonymous with immorality, desire, and exotic allure. In the eyes of European colonizers, hula took on a religious identity and a sexual identity, which ultimately led to the inferiorization of Hawaiian spirituality (Chan, 2011).

In more recent history, hula has become the center of the Hawaiian tourism industry. The Hawaiian hula girl has long been the symbol of Hawai'i in tourism—a representation of the exotic allure of the islands (Chan, 2011). Those who practice hula traditionally, or in the modern sense of tradition, find hula in the tourism industry to be distorted—especially in tourism's image of the hula girl who does not truly represent those who were the native practitioners of the art (Kamahele, 2000). Presently, those who identify as Native Hawaiian continue to practice the traditional spirituality in which the relationship between the land and the people is characterized as both familial and reciprocal (Kamahele, 2000). Hula includes the practice of gathering earth materials for use in the dance. Gathering materials from the land involves the exchange of mana between the dancer and the land, in which the dancer will replace the mana of the earth materials with the mana of the dance (Kamahele, 2000). 'Ōhi'a plays a particularly important role in hula. Lei headbands, anklets, and bracelets are made from lehua blossoms, while dancing sticks and altars are made of 'ōhi'a branches. Lloyd Loope, author of the official Guidance Document for ROD, characterizes the relationship between Native Hawaiians and 'ōhi'a by saying, "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" (Loope, 2016).

In the 1980s and 1990s, hula underwent a major cultural revival as Native Hawaiians began to retake ownership of the practice rather than leave it to the distortion of the tourism industry. In February 1997, the state legislature attempted to pass Senate Bill 8, which would prohibit the collection of natural materials used in hula because gathering rituals interfered with land development (Kamahele, 2000). The bill created a rallying point for hula practitioners who came together and found that native gathering rights had a historical precedent of being protected, even under colonial law. After massive demonstrations and debates, the proposed bill was torn in front of the protestors. The killing of this bill did not end the struggle of protecting gathering rights but marked significant progress (Kamahele, 2000).

Regarding the gathering of materials for hula today, though, dancers are approaching the practice with a perspective that is in true accordance with the land ethic so integral to the spirituality. The Merrie Monarch festival is a hula competition that occurs once a year in Hawai'i. Dancers prepare for months, practicing, training, participating in rituals and spiritual cleansings, and gathering native plants. For some, participating in the festival is considered a true dream (Watson, 2013). Although 'ōhi'a is central to hula, it has had a noticeable absence in the festival in recent years, as participants have decided not to gather because of the risk of ROD (figure 8). In stark contrast to the bans of the past, this has been a cooperative effort between hula practitioners and scientists alike, with hula and spirituality at the center of each decision made (Ashe, 2017).

Part III—'Ōhi'a and the Economy

Jeff Feldman is a local business owner on Hawai'i Island. His furniture store uses reclaimed wood from fallen trees to transform the pieces into delicately crafted household items. In his warehouse, one can find multiple tree species, but there are no signs of 'ōhi'a lehua despite its availability. As of 2020, over 728 sq. km of 'ōhi'a forest on

FIGURE 8. A landscape view of an ʻōhiʻa lehua blossom looking down into the valley of Kaneohe. Adapted from *Flickr*, by Lincoln Ishii, March 11, 2008, https://www.flickr.com/photos/linkzi/2327768385/in/photolist. Copyright 2020 by L. Ishii. Reprinted with permission.

Hawaiʻi Island are impacted by varying levels of ROD (Hauff et al., 2020).

Since the 2015 quarantine of ʻōhiʻa products by the Hawaiʻi Department of Agriculture, Feldman has stopped importing ʻōhiʻa to his store. "Not only did I lose money from the portion of my inventory that was found to be contaminated, but I also lost valuable time sending wood samples and waiting for the lab results to earn a certificate of inspection for each shipment," explained Feldman with desperation in his voice. Even the furniture pieces that tested negative for *Ceratocystis* spp. were difficult to sell due to the lower demand since the discovery of the fungus, especially from neighboring islands that are trying to remain isolated from disease outbreak. Despite the devastating impacts on Feldman's business, he still strongly supports the trade restrictions to limit disease progression. He even posts signs to clarify why ʻōhiʻa products are not sold in the store to raise awareness about ROD for his customers.

ECONOMIC STAKEHOLDERS. There are numerous economic stakeholders associated with ʻōhiʻa lehua, whose livelihoods directly depend on the tree. Local businesses that sell products made from ʻōhiʻa wood have been greatly affected by ROD. Anyone wanting to ship wood, leaves, flowers, or seeds of ʻōhiʻa lehua must have their cargo inspected beforehand, which can be expensive and time consuming. Therefore, many companies have to deal with the financial burden of the quarantine, which is particularly affecting sawmill operations since cutting trees in this manner creates the potential for releasing the fungal pathogen into the environment. Mixed with beetle-boring frass from infected trees, the sawdust may contain *Ceratocystis* spp. and can travel miles by wind, rapidly spreading the disease to healthy trees (Schuler, 2016). ʻŌhiʻa timber and honey industries have also suffered from this ROD-induced market crisis (figure 9).

In comparison to a tree like koa, ʻōhiʻa lehua is only a small part of Hawaiʻi's forest industry, which is further minimized by industries such as tourism and agriculture (Schuler, 2016). Therefore, ʻōhiʻa's real economic value is as a keystone species of Hawaiʻi's forests. It is widely distributed across the state, covering nearly 4,000 sq. km, which accounts for a quarter of Hawaiʻi's total land mass (Schuler, 2016). The tree is capable of contributing to the overall health of ecosystems by improving air quality through carbon sequestration, recharging ground water, and providing a habitat for wildlife (figure 10). This is particularly influential for Hawaiʻi's evolutionary history, which is characterized by rare and threatened species found nowhere else on Earth (Schuler, 2016). Therefore, conservationists are invested as additional stakeholders to the ROD issue.

To calculate the economic value of a healthy ʻōhiʻa forest, there must be a clear understanding of the connection between Hawaiʻi's forests and water supply. According to Burnett, a research economist at the University of Hawaiʻi, "water has an economic value that we can measure and quantify and monetize more directly" (Schuler, 2016). ROD's disturbance toward the island's natural hydrology may be its greatest economic impact (Schuler,

FIGURE 9. Lehua honey, purchased in Maui, is one example of a product supported by thriving ʻōhiʻa lehua, by Elena Iacono, 2020. Copyright 2020 by Elena Iacono.

FIGURE 10. Many bird species rely on the ʻōhiʻa tree for habitat. Adapted from *Flickr*, by Dan Dzurisin, June 16, 2008, https://www.flickr.com/photos/ndomer73/2582866562/in/photolist-4WeSf7. Copyright 2020 by D. Dzurisin. Reprinted with permission.

FIGURE 11. People travel from around the world to visit the Hawaiʻi Volcanoes National Park and contribute to the leading industry of tourism. Adapted from *Tourism to Hawaiʻi Volcanoes NP creates $199,923,400 in Economic Benefits*, by Janice Wei, April 20, 2017, https://www.nps.gov/havo/learn/news/precon04202017.htm. Copyright 2020 by NPS. Public domain.

2016). The tree's branches support a system of lichens and mosses that serve as sponges to absorb raindrops. As the water filters through the ground, it recharges the aquifers. The deep roots prevent flooding and runoff (Solomon, 2016). Corie Yanger, an education and outreach specialist with University of Hawaiʻi's College of Tropical Agriculture and Human Resources, is primarily concerned about the irrigation water for agriculture, a multibillion-dollar industry (Schuler, 2016).

Tourism plays a significant role in Hawaiʻi's economy (figure 11). It is the single largest contributor to the state's gross domestic product, comprising roughly 21% of the entire economy (Wilson, 2013). The tourism industry not only provides service jobs for a large proportion of the islands' inhabitants, but people visit from all over the world to explore the enchanting wildlife found only in Hawaiʻi. Unfortunately, recent aerial surveys show signs of ROD already devastating trees in popular tourist destinations like Hawaiʻi Volcanoes National Parks (Solomon, 2016). This means less nectar available for the endangered bird species of Hawaiʻi like the ʻapapane and consequently less people participating in bird watching as a popular tourist activity. According to one study, more than 1.8 million people visited Hawaiʻi Volcanoes National Park in 2015 spending about $151 million on Hawaiʻi Island. If the park's ʻōhiʻa trees were depleted on the scale of Lower Puna, a region covering approximately 1,000 sq. km, and just 1% of those visitors chose to travel elsewhere, it would mean a drop of $1.5 million a year (Schuler, 2016).

A bill was enacted by the legislature of state in 2017 to appropriate money for research to combat ROD. The funding supports researchers from the U.S. Department of Agriculture, the University of Hawaiʻi, and the Division of Forestry. For example, the University of Hawaiʻi was awarded grants for a postdoctoral researcher to assist an interagency team of scientists in the Hilo area to examine the transmission pathways for invasion and possible reservoirs of the fungus (Hawaiʻi Invasive Species Council, 2018). Scientists rely on policy and government cooperation for effective management of ʻōhiʻa forests. Numerous state and federal agencies have partnered to develop and disseminate up-to-date information about ROD that will impede further spread and give researchers time to create treatment options (Hawaiʻi Invasive Species Council, 2018).

Through a campaign called "Save the ʻŌhiʻa Challenge," Conservation X Labs and the Interior's Office of Native Hawaiian Relations encouraged scientists around the globe to propose affordable identification methods for infected trees before they show symptoms of disease (Conservation X Labs, 2018). Their goal was to incentivize innovators with an outside perspective who may have previous experience involving similar situations. Tools for early detection, containment, and elimination of the pathogenic fungus, *Ceratocystis*, are required to preserve ʻōhiʻa forests. This competition was successful in attracting innovators from across the world to present

their unique ideas. The prize winner's team comes from the University of Hawai'i at Hilo. They plan to analyze a variety of large, complex spatial data sets using machine learning and also deploy drones to collect samples from suspect trees. The innovative combination of these technologies will increase the ability of officials to have a real-time, current perspective of where the infection is located and spreading (Blackmore, 2019).

Part IV—Behavior Changes and Solutions

Steve arrived on the Hawai'i Island yesterday and was already overwhelmed by the island's natural beauty. He put on his hiking boots and grabbed a hat before meeting the tour group in the lobby. The eager travelers gathered at the park trailhead as the guide explained how the forest is recovering from the recent eruption of the Kīlauea volcano in May 2018. Steve looked around throughout the hike spotting the damage and remains of ash. However, there was a slight glimmer of hope as a tree with fire-colored flowers pushed its way through the cracks of dry lava. Steve was amazed by this tree's resilience toward the inhospitable environment.

Later on the hike as they made their way deeper into the forest, the guide pointed out another 'ōhi'a lehua tree, but this one looked different. Its leaves were brown, and there was a faint fruity odor. As Steve peered closer into a splitting branch, he noticed dark stains on the sapwood. Just moments later, a bright yellow sign appeared that would answer all of his questions (figure 12). The National Park Service announced that ROD has been detected in this area. The sign briefly identified the source of disease as a fungus and then provided a list of recommendations for visitors traversing through the park. It suggested staying on established trails, cleaning shoes before and after entering the forests, and washing gear and clothing to prevent the spread of ROD. At the end, there was a message indicating how each individual can make a difference and contribute to the overall solution. After reading this, Steve felt accountable for his actions and wanted to take every measure possible to conserve this keystone species.

MOVING FORWARD. The ability to change one's behavior and the success of sustaining that behavior depend on variables that are intertwined in personal, cultural, economic, and political constructs. Conservation relies heavily on effective behavior change. Although studies have shown that providing information and education can influence people's attitudes, these alone do not adequately promote change in behavior (McKenzie-Mohr,

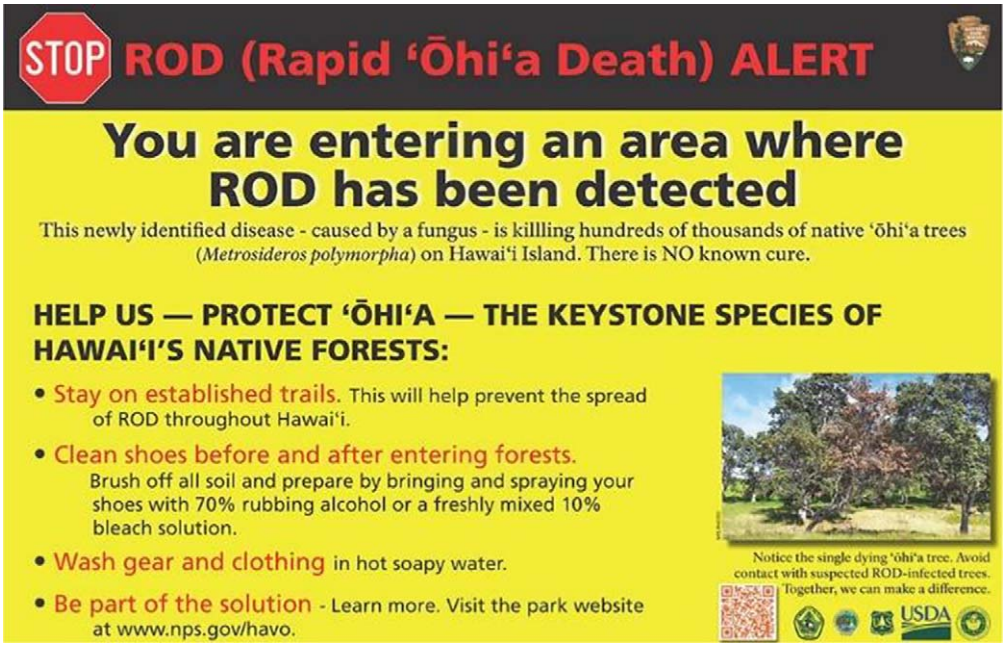

FIGURE 12. A sign that raises awareness towards the destructive force of Rapid 'Ōhi'a Death and how tourists can slow the spread. Adapted from *Rapid 'Ōhi'a Death: Help prevent the spread of this terrible disease,* by NPS photo, February 26, 2020, https://www.nps.gov/havo/learn/nature/rapid-ohia-death.htm. Copyright 2020 by NPS, Department of the Interior. Public domain.

2002). While behavior change processes can be implemented at different organizational levels, it is suggested that a community-based social marketing approach can be highly productive, especially in conservation-related efforts. The five steps in creating a successful community-based social marketing program are (McKenzie-Mohr, 2002):

1. Select a target behavior—Consider an audience to target in order to reach your goal and the action you desire to change.
2. Recognize the barriers and perceived benefits that are associated with the target behavior—Investigate what types of barriers are holding your audience back from achieving target behavior and focus on the most significant hurdles.

Types of barriers include the following:

Behavioral

- **Status quo:** preferring things to stay the same by doing nothing
- **Choice overload:** too many choices available becomes overwhelming
- **Lack of self-efficacy:** believing that one does not have the ability or capacity to accomplish the task
- **Hassle factors:** small inconveniences that prevent one from taking action or changing one's behavior (B. Tully, personal communication, March 2019)

Communication

- Information only; no suggestions to take action
- Vague direction or instruction
- Overwhelming sense of doom; feeling like nothing can be done to help (B. Tully, personal communication, March 2019)

3. Develop a strategy that reduces barriers and, at the same time, increases benefits of the target behavior—Consider a target behavior to encourage and a target behavior to deter while also addressing the benefits (e.g., encourage recycling and deter creating unnecessary trash waste for the benefit of decreasing our carbon footprint)
4. Pilot the created strategy—Be sure to plan a pilot based on the whole audience of the end strategy
5. Implement strategy on a broad scale after a successful pilot program and evaluate success on a routine basis

When executed correctly, social marketing strategies have a strong influence not only in changing people's attitudes but also in the ability to motivate change in actions toward a common goal. For example, many campaigns have been applied to motivate visitors to use simple bio-sanitation methods to prevent the spread of *Ceratocystis* spp. fungal spores. By spraying boots and hiking equipment with 70% isopropyl alcohol, and scrubbing dirt off with a brush after letting the alcohol soak for 15 s, the fungal spores die and are unable to spread infection of ROD (Loope, 2016). One way to truly support this behavior change would be to establish sanitation stations at the trailheads of state parks, with volunteers strategically placed to enforce and demonstrate the procedure. It will also be essential for tour guides to present on the issue before pursuing outdoor activities.

In the case of ʻōhiʻa lehua, behavior change can sometimes be linked to policy implementation. State policies are currently in place to prevent the movement of ʻōhiʻa wood products (Schuler, 2016). Also, to avoid the introduction of invasive species to the Hawaiian Islands, governmental agencies associated with the Department of Transportation are required to inspect any declared luggage that may contain agricultural items, while educational signage is posted throughout the airport encouraging visitors to be vigilant against the spread of non-native plants and animals (U.S. Department of Agriculture, 2020). Perhaps this signage could be applied to gift shops as well to elevate awareness among consumers. The government could also subsidize local businesses to encourage owners to transition away from ʻōhiʻa products.

CONCLUSION

Ultimately, ROD spread will only be halted if individuals take ownership of their actions that impact the environment. If tourists, hikers, hunters, birders, locals, or anyone who walks through these forests takes the necessary precautions, ROD spread can be mitigated. Behavior change, facilitated by policy change, may be the only way to limit the advancement of this disease, allowing scientists time to work on finding solutions beyond just limiting infection.

FIGURE 13. A close up of the ʻōhiʻa lehua blossom. Adapted from *Flickr*, by Forest and Kim Starr, February 22, 2015, https://www.flickr.com/photos/forest-and-kim/15998498344. Copyright 2020 by Starr. Reprinted with permission.

In our rapidly changing world, we are likely to face similar scenarios across the globe. As humans encroach further into areas previously untouched, and as global travel increases, the chance of spreading pathogens or encountering entirely novel pathogens will increase as well. There will be vital lessons learned from ROD, which will be applicable in future environmental crises. Therefore, it becomes increasingly important to find a solution—not only to mitigate the current crisis but to be able to apply this strategy to arising environmental disasters that are inevitable in the not very distant future (figure 13).

CASE STUDY QUESTIONS

1. Identify the stakeholders in the case study and the impacts they face from ROD.
2. Create a hypothesis for how ROD was introduced to the Hawaiian Islands.
3. Why is it important to understand history and culture in this context?
4. How is ʻōhiʻa represented in Hawaiian spirituality?
    a. Can you identify a piece of your own history or culture that may have a strong ecological tie?
5. How can governmental policies work to relieve the economic strain of ROD?
6. What limitations currently exist for developing a feasible ROD remedy?
7. What are some examples of environmentally or conservation-based behaviors?
8. Working in groups, develop a community-based campaign and create an effective marketing strategy (billboard, social media post, workshop, etc.) targeting a behavior of your choice in relation to ROD. Disseminate your work to the class and discuss.

AUTHOR CONTRIBUTIONS

DM: conceptualization and visualization. EI: critical analysis and application. NB: project administration and correspondence. All authors contributed equally to background research and writing—original draft, review, and editing.

ACKNOWLEDGMENTS

We wish to acknowledge the professors and guest educators within Tufts Conservation Medicine graduate program, whose knowledge and mentorship were responsible for broadening our perspectives surrounding the one-health paradigm. This case study was inspired by Dayna's externship in Kaua'i, and we would like to thank all the ecologists, researchers, and field staff there who have shed light on the topic of Rapid ʻŌhiʻa Death. We would also like to acknowledge the photographers and artists who granted their permission for use of their work in our case

study. Their beautiful photos and paintings greatly enhanced our ability to story-tell throughout this article.

COMPETING INTERESTS

The authors have declared that no competing interests exist.

FUNDING

No funding was received for this case study.

SUPPLEMENTAL MATERIAL

The supplemental files for this article can befound as follows: Teaching Notes. Docx.

REFERENCES

Ashe, I. (2017). Cultural cause: Hula community, science connect to protect cherished ʻōhiʻa. *Hawaii Tribune Herald*. https://www.westhawaiitoday.com/2017/04/10/hawaii-news/cultural-cause-hula-community-science-connect-to-protect-cherished-ʼōhiʻa/

Atkinson, C. (2016). An endangered honeycreeper, the ʻAkikiki (Kaua'i Creeper), in Hawai'i [Photograph] https://www.usgs.gov/media/images/endangered-honeycreeper-akikiki-kauai-creeper-hawaii-0

Atkinson, C. (2017). Inside of an ohia log with tunnels created by wood boring beetles [Photograph]. https://www.usgs.gov/media/images/inside-ohia-log-tunnels-created-wood-boring-beetles

Atkinson, C. T., Roy, K., & Granthon, C. (2019). *Economical environmental sampler designs for detecting airborne spread of fungi responsible for rapid ʻŌhiʻ Death* [Other Report, HCSU-TR087]. University of Hawaii at Hilo. http://pubs.er.usgs.gov/publication/70202226

Barnes, I., Fourie, A., Wingfield, M. J., Harrington, T. C., McNew, D. L., Sugiyama, L. S., Luiz, B. C., Heller, W. P., & Keith, L. M. (2018). New *Ceratocystis* species associated with rapid death of *Metrosideros polymorpha* in Hawai'i. *Persoonia*, *40*, 154–181. https://doi.org/10.3767/persoonia.2018.40.07

Behnke, L. A. H., Pejchar, L., & Crampton, L. H. (2016). Occupancy and habitat use of the endangered Akikiki and Akekee on Kauai Island, Hawaii. *The Condor: Ornithological Applications*, *118*, 148–158. https://doi.org/10.1650/CONDOR-15-80.1

Blackmore, W. (2019). *The global fight to save Hawai'i's forests*. https://www.savetheohia.org/

Camp, R. J., LaPointe, D. A., Hart, P. J., Sedgwick, D. E., & Canale, L. K. (2019). Large-scale tree mortality from Rapid Ohia Death negatively influences avifauna in lower Puna, Hawaii Island, USA. *The Condor: Ornithological Applications*, *121*(2), https://doi.org/10.1093/condor/duz007

Chan, C. E. (2011). *Beyond colonization, commodification, and reclamation: Recognizing and retheorizing the role of religion in Hula* [Pomona Senior Theses. Paper 3.] http://scholarship.claremont.edu/pomona_theses/3

Conservation X Labs. (2018). *Saving the ʻŌhiʻa- Hawai'i's sacred tree*. https://conservationx.com/challenge/invasives/ohia

Crews, T., Farrington, H., & Vitousek, P. (2000). Changes in asymbiotic, heterotrophic nitrogen fixation on leaf litter of *Metrosideros polymorpha* with long-term ecosystem development in Hawaii. *Ecosystems*, *3*, 386. https://doi.org/10.1007/s100210000034

Dzurisin, D. (2008). A male saffron finch, common along the Kona Coast of the Big Island, poses near a lehua blossom of an ohia tree at the Hawaiian Volcano Observatory, Kilauea Volcano, Hawaii [Photograph]. https://www.flickr.com/photos/ndomer73/2582866562/in/photolist-4WeSf7

Fisher, M. (2018). Passions of Pele: The Hawaiian goddess of fire. *Ancient Origins*. https://www.ancient-origins.net/history/passions-pele-hawaiian-goddess-0010415

Hamm, F. (2010). Lehua Blüte vom Ohia Tree—Hawai'i Volcanoes National Park, Jagger Museum, Kilauea Crater [Photograph]. https://www.flickr.com/photos/injelea/5540955466

Hauff, R., Keith, L., Hughs, F., Giardina, C., Friday, J. B., Peck, B., Stormont, B., Martin, C., & Price, J. (2020). *Rapid ʻŌhiʻa Death strategic response plan 2020–2024*. ROD Working Group. https://gms.ctahr.hawaii.edu/gs/handler/getmedia.ashx?moid=66598&dt=3&g=12

Hawaii Invasive Species Council. (2018). *Rapid ʻŌhiʻa Death, ROD Ceratocystis lukuohia (Wilt Disease), Ceratocystis huliohia (Canker Disease)*. hawaii.gov. https://dlnr.hawaii.gov/hisc/info/species/rapid-ohia-death/

Heller, W., & Keith, L. (2018). Real-time PCR assays to detect and distinguish the rapid ʻŌhiʻa Death pathogens *Ceratocystis lukuohia and C. huliohia*. *Phytopathology*, *108*(12), 1395–1401.

Hodges, C. S., Adee, K. T., Stein, J. D., Wood, H. B., & Doty, R. D. (1986). *Decline of Ohia (Metrosideros polymorpha) Hawaii: A review* [Gen. Tech. Rep. PSW-86]. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture.

Hukilau Network. (2020). *Ancient Hawai'i: Polyneisan migrations*. Info Grafik. http://www.hawaiihistory.org/index.cfm?fuseaction=ig.page&CategoryID=311

Iacono, E. (2020). Personal photo of lehua honey purchased in Maui [Photograph].

Ishii, L. (2008). Lehua blossom: taken at Wiliwili Trail, Kaneohe in the background [Photograph]. https://www.flickr.com/photos/linkzi/2327768385/in/photolist.

Kamahele, M. (2000). ʻlio'ulaokalani: Defending Native Hawaiian Culture. *Amerasia Journal*, *26*(2), 38–65.

Loope, L. (2016). *Guidance document for Rapid ʻŌr Ra Death*. U.S. Forest Service. https://www.fs.fed.us/psw/publications/hughes/psw_2016_hughes006_loope.pdf

McKenzie-Mohr, D. (2002). New way to promote proenvironmental behavior: Promoting sustainable behavior: An

introduction to community-based social marketing. *Journal of Social Issues*, *56*(3), 543–554. https://doi.org/10.1111/0022-4537.00183

Miner, M. (2016). The cultural significance of ʻōhiʻa lehua. *Hawaii Magazine*. https://www.hawaiimagazine.com/content/cultural-hawaiian-significance-'ōhi'a-lehua

Mortenson, L. A., Flint Hughes, R., Friday, J. B., Keith, L. K., Barbosa, J. M., Friday, N. J., Liu, Z., & Sowards, T. G. (2016). Assessing spatial distribution, stand impacts and rate of *Ceratocystis fimbriata* induced ohia (*Metrosideros polymorpha*) mortality in a tropical wet forest, Hawaii Island, USA. *Forest Ecology and Management*, *377*, 83–92. https://doi.org/10.1016/j.foreco.2016.06.026.

Mueller-Dombois, D. (1992). Distributional dynamics in the Hawaiian vegetation. *Pacific Science*, *46*, 221–231.

NPS. (2020). ROD Alert! sign [Photograph]. https://www.nps.gov/havo/learn/nature/rapid-ohia-death.htm.

Roy, K., Ewing, C. P., Hughes, M. A., Keith, L., & Bennett, G. M. (2019). Presence and viability of *Ceratocystis lukuohia* in ambrosia beetle frass from Rapid ʻŌhiʻa Death-affected *Metrosideros polymorpha* trees on Hawaiʻi Island. *Forest Pathology*, *49*, e12476. https://doi.org/10.1111/efp.12476

Schuler, T. A. (2016). Rapid ʻŌhiʻa Death—Threat to Hawaii's Water. *Hawaii Business Magazine*. www.hawaiibusiness.com/rapid-'ōhi'a-death-threat-to-hawaiis-water/

Solomon, M. (2016). *Rapid ʻŌhiʻa Death: The disease that's killing native Hawaiian trees*. National Public Radio. www.npr.org/2016/04/07/473384008/rapid-hia-death-the-disease-thats-killing-native-hawaiian-trees

Starr, F., & Starr, K. (2015). Ohia lehua blossoms are bursting forth right now. This is one of the first blooms on one of the many ohia trees we have planted at our place in Olinda [Photograph]. https://www.flickr.com/photos/forest-and-kim/15998498344

Stevens, L. n.d. ʻŌhiʻa & Lehua [Painting]. https://www.lindarowellstevens.com/ohia-and-lehua

Sullivan, T. 2018. Drone images reveal ʻōhi'a trees sickened by invasive fungi (red) or already killed (gray) [Photograph]. https://www.sciencemag.org/news/2018/08/fears-lessen-invasive-fungi-will-completely-wipe-out-hawaiis-iconic-native-tree

U.S. Department of Agriculture. (2020). *Agriculture inspection*. Lihue Airport. Retrieved March 3, 2020, from Hawaii.gov

USGS. n.d. Aerial view of the coastline of Kauai Island [Photograph]. https://www.usgs.gov/media/images/aerial-view-coastline-kauai-island

Watson, T. (2013). *Merrie Monarch festival celebrates 50 years*. U.S. Army. https://www.army.mil/article/99901/merrie_monarch_festival_celebrates_50_years

Wei, J. (2017). Visitors observe Kīlauea summit lava lake last month from the Jaggar Museum observation deck, open 24 hours a day in Hawaiʻi Volcanoes National Park [Photograph]. https://www.nps.gov/havo/learn/news/precon04202017.htm

Wei, J. (2018). The ʻōhi'a lehua tree is featured during a guided hike in Kahuku on Saturday [Photograph]. https://www.nps.gov/havo/learn/news/20180702_pr_events.htm

Williams, J. (1997). Spirits of nature. In *From the mountains to the sea: Early Hawaiian life* (Eds.), Kamehameha Schools. http://www.ulukau.org/elib/cgi-bin/library?e=d-0english-000Sec—11en-50-20-frameset-book—1-010escapewin&p=frameset&toc=0&d=D0.6

Wilson, R. (2013). Hawaii's $14 billion tourism industry back to pre-recession levels. *Washington Post*. https://www.washingtonpost.com/blogs/govbeat/wp/2013/09/27/hawaiis-14-billion-tourism-industry-back-to-pre-recession-levels/?noredirect=on&utm_term=.577cdbbb659f