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The Challenge of Retarding Erosion of Island Biodiversity through Phytosanitary Measures: An Update on the Case of *Puccinia psidii* in Hawai'i¹

Lloyd L. Loope^{2,4} and Janice Y. Uchida³

Abstract: Most rust fungi are highly host specific, but *Puccinia psidii* has an extremely broad host range within Myrtaceae and gained notoriety with a host jump in its native Brazil from common guava (*Psidium guajava*) to commercial *Eucalyptus* plantations. When detected in Hawai'i in April 2005, the first invasion outside the neotropics/subtropics, there was immediate concern for 'ōhi'a (*Metrosideros polymorpha*). 'Ōhi'a composes 80% of native forest statewide, providing stable watersheds and habitat for most Hawaiian forest birds and plants. Within months, rust spores spread statewide on wind currents, but 'ōhi'a was found to be only a minor host, showing very light damage. The primary host was nonnative rose apple (*Syzygium jambos*), severely affected at a landscape scale, but the epiphytic subsided as rose apple was largely defoliated or killed within several years. The limited and stable host range in Hawai'i (versus elsewhere) led the local conservation community to explore possibilities for excluding new genetic strains of *P. psidii*. Although national/international phytosanitary standards require strong scientific justification for regulations involving an infraspecific taxonomic level, hopes were buoyed when genetic studies showed no apparent genetic variation/evolution in Hawai'i's rust strain. A sophisticated genetic study of *P. psidii* in its home range is near completion; genetic variation is substantial, and host species strongly influences rust population structure. To prevent introduction of new strains, the Hawai'i Department of Agriculture is moving ahead with establishing stringent measures that restrict entry of Myrtaceae into Hawai'i. Meanwhile, *P. psidii* poses a major threat to Myrtaceae biodiversity worldwide.

ACCELERATED MOVEMENT of plants and plant products between biogeographical zones by human activities has become rampant worldwide (Brasier 2008, Wingfield et al. 2011). Fungi and insects that may have little impact in the plant communities where they have coevolved often trigger dramatically

negative effects when transported to new regions of the world where the native plants have little resistance. Dominant tree species are declining in many areas of the world and the introduction of pests and pathogens to new environments is a major contributing factor, resulting in disruption of fundamental ecosystem processes and changes in environments on which a variety of other species depend (Ellison et al. 2005).

Remote island ecosystems in general and the Hawaiian Islands in particular have long been recognized as especially vulnerable to invasions (e.g., Loope and Mueller-Dombois 1989). The Hawaiian Islands are justifiably famous for their biological uniqueness but have lost roughly half of their original native-dominated habitat. Dry and mesic forests have been reduced most drastically. Hundreds of species have been lost to extinction, including at least 106 of 1,300 plant taxa, three-

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fourths of approximately 1,000 endemic snail species, and at least 83 of 115 endemic land bird species (references given on pages 765–768 in Loope [1998]). With only 0.4% of the land area of the United States, Hawai'i harbors over 25% of the country's federally listed endangered species. Although habitat destruction by humans has been a direct factor in Hawai'i's ecological losses in the past, human-facilitated biological invasions are currently the primary agents of continuing degradation.

Agriculture interests in Hawai'i have long recognized the need for rigorous quarantine effort at ports of entry. Efforts at biodiversity conservation, invigorated in the 1970s and 1980s, resulted in strong multiagency support in the 1990s for increasingly sophisticated invasive species prevention efforts, recognizing that island situations with limited ports of entry allow excellent prevention opportunities. Although barriers to achieving optimal implementation (especially inadequacy of funding/resources and ambiguity of responsibility) quickly became apparent (Holt 1996), promising progress has been made in some areas (Fox and Loope 2007, Loope and Kraus 2009).

Detection of a rust fungus, *Puccinia psidii* (Winter, 1884), new to Hawai'i, on young 'ōhi'a (*Metrosideros polymorpha*) plants in an O'ahu nursery in April 2005 (Killgore and Heu 2005, Uchida et al. 2006) led to a remarkable test of Hawai'i's political will, of the flexibility of the international system that guides pest prevention to allow Hawai'i to take action, and of the role of science in shedding light on such issues. This article aims to use this case as an example of how important biodiversity issues may be addressed through the existing phytosanitary system.

INTERNATIONAL AND NATIONAL
PHYTOSANITARY REGULATION IN A
NUTSHELL

A recent book on this subject makes a succinct and effective case for the current phytosanitary system that has evolved over the past two decades (Heather and Hallman 2008, Chapter 1:1):

It is estimated that the loss caused by invasive species globally is about US\$1.4 × 10¹² or 5% of the world gross national product (Pimentel et al. 2007). Although tens of thousands of species have invaded other lands, millions have not. . . . Phytosanitation aims to keep that damage and number of new invasive species as low as possible through regulation of trade of items that could carry invasive species. But these requirements are a primary impediment to international trade, a key and growing component of most economies. . . . Mumford (2002) points out that domestic consumers pay for quarantine restrictions in higher prices for quarantined goods while domestic producers of those goods or, we might add, reasonable replacements for them, benefit.

In conformity with the World Trade Organization (WTO) Sanitary and Phytosanitary (SPS) Agreement (WTO 2007), categorized quarantine pests are restricted to those that are absent from the place which takes action to prohibit entry of the pest or its host if this could lead to entry and establishment, or to pests which are present but suppressed or contained.

Brasier (2008:795) provided a recent critique of the way the phytosanitary system is applied in the United Kingdom and elsewhere, particularly as it applies to plant pathogens:

The protocols principally involve the production of lists of named harmful organisms. These tend to concentrate on organisms likely to affect widely grown agricultural commodities and timber. The case for inclusion of each organism must be founded in 'sound science.' By definition, all 'unlisted' organisms remain unregulated. However, the lists principally comprise pathogens that have *already* escaped from their geographical centres of origin and started to cause overt disease in another part of the globe. Many of these 'newly escaped' organisms were previously unknown to science and were not therefore on any international list before they escaped. . . . Dutch elm disease, sudden oak death, phytophthora disease of alder, and box blight in the UK . . . are all examples of major disease episodes caused by previously unknown pathogens. . . . Based on these and similar examples, and on estimates that only 7–10% of all fungal species having so far been identified . . . some 90% of pathogens may be unknown to science.

Agriculture has a standard, usually viable option when quarantines for plant pathogens fail: development of resistant strains of the crop in question is generally the best management tool (Ploetz 2007). Selection of resistant clones of *Eucalyptus grandis* and other *Eucalyptus* spp. has been achieved by the forest industries in Brazil, and the genetic basis for that resistance is becoming increasingly understood (Junghans et al. 2003, Moon et al. 2007,

Mamani et al. 2010). Resistant cultivars of guava have also been effectively developed (Ribeiro and Pommer 2004). Unfortunately, the strategy of developing clones resistant to plant pathogens rarely provides a viable remedy for biodiversity conservation, especially in the case of an ecosystem dominant. *Metrosideros polymorpha* forest in Hawai'i provides a classic example of the contrast between the pathogen-prevention needs of biodiversity conservation and those of agriculture/forestry.

As the trade in plants and plant products has increased, the conundrum of what phytosanitary rules are allowable or not allowable in actual practice has presented formidable challenges to political entities that want to protect their natural heritage (Campbell 2001, Loope 2010) as well as to others that want export or import for economic reasons. Although there is a relatively effective suite of standard options in quarantine entomology for mitigating the risk of known pest introduction on commodities (e.g., Follett and Neven 2006), fewer opportunities exist for effective mitigation of the threat of introduction of plant pathogens (Rossman 2009). Hawai'i Department of Agriculture's Plant Quarantine Branch (HDOA) is Hawai'i's "first line of defense" in keeping pests out of the Islands to protect the state's people and environment, but such responsibility and authority is shared with two federal agencies (Loope and Kraus 2009, Loope 2010). HDOA has understandably been challenged by the dilemma they have faced for the past 5 yr over how to justify actions aimed at preventing potential arrival of a genetic strain of *Puccinia psidii* virulent for Hawai'i's dominant forest species 'ōhi'a given that the species *P. psidii* is already present.

METROSIDEROS POLYMORPHA: AN
OVERVIEW OF ITS ROLE AND STATUS IN
HAWAII AND CONSEQUENCES OF ITS
POTENTIAL REDUCTION OR LOSS

'Ōhi'a (Myrtaceae: *Metrosideros polymorpha* Gaudichaud-Beaupré) is by far the most common and widespread native tree in the Hawaiian Islands. It occurs on all the main

islands and typically composes at least 80% of the trees in rain forests.

According to recent work by Percy et al. (2008), 'ōhi'a has been evolving in the Hawaiian Islands for nearly 4 million yr and has become genetically adapted to diverse local environments. Derived (by way of the Marquesas Islands) from an ancestral species of *Metrosideros* that colonizes new lava flows in New Zealand, 'ōhi'a was apparently able to out-compete most other plant species in precontact Hawai'i and came to form the habitat matrix for the evolution of a large fraction of Hawai'i's endemic flora and fauna. Although some other plant groups underwent complex adaptive radiation, vigorous gene flow apparently limited the diversification of 'ōhi'a (Vitousek 2004).

It can be argued that 'ōhi'a is the backbone of Hawaiian forests and one of the most important resources for the long-term stability of ecosystems and watersheds in the Islands (Gruner 2004). Forests dominated by 'ōhi'a are home to at least 22 extant species of forest birds, the Hawaiian hoary bat, and many of Hawai'i's remaining native plants and invertebrates. Endemic Hawaiian honeycreepers, including 16 on the endangered species list, are dependent on these forests for essential habitat, because they have adapted to feed and nest in 'ōhi'a trees (Buermeier et al. 2008). Gruner (2004) sampled arthropods in 11 *M. polymorpha* sites, nine on Hawai'i Island, and found 495 endemic species.

Not surprisingly for a single species with a very broad ecological distribution, 'ōhi'a has been shown to have substantial genetic variability (reviewed by Percy et al. 2008), as well as phenotypic plasticity (Cordell et al. 1998, Vitousek 2004, Cornwell et al. 2007). There are, of course, ecological limits to plant phenotypic plasticity (Valladares et al. 2007), and 'ōhi'a illustrates that fact well through its dieback during certain types of environmental stress (for example, Mueller-Dombois 1985, Hodges et al. 1986). Nevertheless, the phenotypic plasticity of 'ōhi'a could prove to be important for enabling a certain amount of ecosystem stability in the face of global climate change. The fate of this single dominant tree

species in relation to climate change is likely to be crucial for the survival of much associated biological diversity at high elevations in Hawai'i.

Though *P. psidii* was initially detected on 'ōhi'a and given the local name "'ōhi'a rust" (Killgore and Heu 2005), the damage to date for 'ōhi'a has been modest. In contrast, the invasive rose apple (*Syzygium jambos*) has suffered severe crown dieback at a landscape scale statewide, with death a common outcome (Plate I). Given the demonstrated destructive potential and because 'ōhi'a is the dominant tree in most forests in Hawai'i, there is a major potential threat of an outbreak of a highly virulent genetic strain on 'ōhi'a, similar to that observed on rose apple. Such an outbreak could result in drastic changes to the structure, composition, and the function of forests on a landscape level. Many (one-third to one-half) of Hawai'i's approximately 300 endangered plant species also depend on critical habitat in *Metrosideros polymorpha* forest. *Puccinia psidii* is most damaging to young, developing tissue. Although "evergreen," individual leaves of 'ōhi'a trees are retained for 1.5–2.5 yr (Cordell et al. 2001) and require continual replacement. Destruction of new 'ōhi'a growth would cause not only crown dieback but also likely result in low reproduction (few mature flower buds, reduced young fruit and seed formation). 'Ōhi'a seedlings would also be severely damaged, further reducing reproduction. (With the current *P. psidii* strain, high percentages of 'ōhi'a seedlings at some commercial nurseries have been infected, with 25% seedling mortality of highly susceptible 'ōhi'a genotypes not uncommon under conditions with substantial local inoculum [from rose apple] of urediniospores [C. Kadooka, University of Hawai'i, pers. comm.].) Eventually, repeated, severe crown dieback could result in the death of trees as nutritional reserves are exhausted and no new photosynthetic tissue is added. Increased light reaching the forest floor following canopy dieback would increase the likelihood of invasion by light-loving, fast-growing nonnative species, such as *Miconia calvescens*, *Psidium cattleianum*, and introduced

grasses. Watershed impacts are also possible with a rapid loss of overstory.

'Ōhi'a is also a species of major cultural significance to the Hawaiian people. Many native plants and animals that depend on 'ōhi'a forests have cultural significance, but 'ōhi'a stands out as having special symbolic and spiritual significance because of its connection to the deities Kū, Pele, and Laka. For example, as the native plant symbol of Laka, the deity of hula, 'ōhi'a is central to a large number of chants and dances, and its loss would affect the spiritual significance of hula and chant (Samuel Gon III, pers. comm., 2006).

Puccinia psidii: A RELATIVELY WELL-KNOWN AND NOTORIOUS PLANT PATHOGEN

A prescient paper by Walker (1983:103) on Pacific mycogeography cited references from the 1940s to 1960s documenting infection, often heavy, of Australian genera such as *Callistemon*, *Eucalyptus*, and *Melaleuca* in cultivation in South America by *Puccinia psidii*, most commonly found on the native *Psidium guajava* in a different subfamily of Myrtaceae. He further noted the urgent need for "a comprehensive taxonomic study" of what seemed to be a complex of 40 names of apparently similar rusts in the literature. "The susceptibility seen in several genera of Leptospermoideae, which have probably developed for a considerable time in the absence of rusts found in present-day Central and South America, is of considerable interest as well as having most important practical consequences for plant quarantine. The need for rigid exclusion of these rusts from the Australian region is obvious."

A paper by Coutinho et al. (1998) on eucalyptus rust brought *Puccinia psidii* to the broad attention of plant pathologists. The paper summarized a large body of literature from the 1980s that previously had been available only in Portuguese. *Puccinia psidii* was originally described from common guava (*Psidium guajava*) in Brazil in 1884 and had been observed on a *Eucalyptus* sp. in Brazil as early as 1912. The first "serious outbreak" in Brazil



PLATE 1. A stand of nonnative rose apple (*Syzygium jambos*) on a roadside in Ha'ikū, Maui, Hawai'i, completely killed by the rust *Puccinia psidii* over a period of about 5 yr, after repeated destruction of new growth resulted in exhaustion of carbohydrate reserves. (Photo by Forest and Kim Starr, March 2011, used by permission.)

was in 1973, with large-scale losses in nurseries and young plantations of *Eucalyptus grandis* in Espírito Santo province. The emphasis of the work in the 1980s in Brazil was upon addressing the threat of *P. psidii* to the country's extensive *Eucalyptus* plantations, especially through developing resistant strains of *Eucalyptus*. The work was largely successful toward that goal, and publishing effort in Brazil subsided in the 1990s. However, the recognition that the rust was an enormous threat to *Eucalyptus* plantations and native Myrtaceae worldwide brought much attention to *P. psidii* after the 1998 publication. Previously, the most attention the rust had received outside Brazil had been when it reached Jamaica in the 1930s (MacLachlan 1938) and Florida in the 1970s (Marlatt and Kimbrough 1979), decimating allspice (*Pimenta dioica*) in both locations until resistant allspice strains could be developed (e.g., Ploetz 2007). However, in the 1990s, the notoriety of the rust started to spread both for its threat to *Eucalyptus* plantations worldwide (e.g., Ciesla et al. 1996) and to native Myrtaceae outside the neotropics, especially in Australia (e.g., Booth et al. 2000).

Because the rust *P. psidii* had already become established in the 1970s in the United States in Florida (at latitude ca. 25–29° N), the federal Department of Agriculture has considered it a nonactionable, nonreportable pest nationally. Hawai'i and Florida are the only two U.S. states with native species in the myrtle family. It seems that no one in Hawai'i was aware of a threat from *P. psidii* until March 2005, when it was detected in an O'ahu nursery. This was the first time establishment of *P. psidii* had been documented outside the neotropics and subtropics. The 2005 outbreak in Hawai'i accelerated signs of concern in Australia, and three major publications on the rust appeared from there in 2006–2007 (Grgurinovic et al. 2006, Simpson et al. 2006, Glen et al. 2007). Simpson et al. (2006:549) reported: "Guava rust, *Puccinia psidii*, is now known to occur on species in both subfamilies of Myrtaceae, including one of two tribes of the subfamily Psiloxylloideae and seven of the 15 tribes of subfamily Myrtoideae, a total of 20 genera and 71 species. Susceptibility to

Puccinia psidii seems to be low among species of Myrtaceae from the Americas but more common among taxa from Asia, Australia and the Pacific."

PUCCINIA PSIDII IN HAWAI'I: THE FIRST 5+
YR—EFFECTS OF A SINGLE GENETIC STRAIN

Puccinia psidii has been found statewide (at latitude ca. 19–22° N) in Hawai'i attacking Myrtaceae from near sea level to 1,200–1,500 m elevation in areas with mean annual rainfall ranging from 750 to 5,000 mm (Robert Anderson, pers. comm.; J. B. Friday, pers. comm.). It is apparent that climatic conditions over much of Hawai'i at certain seasons (especially in winter months, December–March) are consistent with the requirements for *P. psidii* to thrive, with mild temperatures (ca. 15–23°C) and abundant wetness (based on diverse references cited by Glen et al. 2007). The introduced and invasive rose apple, *Syzygium jambos* (an Asian species), was severely affected at a landscape scale, with widespread crown dieback and many instances of complete tree death (Uchida and Loope 2009). *Syzygium jambos* was so severely affected that it became an abundant source of spores for essentially ubiquitous dispersal on wind currents, enabling rapid spread of the rust statewide and exposure of many additional Myrtaceae hosts (Uchida and Loope 2009). Nevertheless, in spite of billions of wind-dispersed rust spores produced from rose apple infestations following periods of moist weather conditions from 2006 to 2008, adjacent mature 'ōhi'a have been little affected to date by the rust strain in Hawai'i. Within the elevation range of the rust, *P. psidii* is generally found on less than 5% of the 'ōhi'a trees in the wild; on those 'ōhi'a trees on which the rust is found, it is usually found on less than 5% of the leaves (Robert Anderson, pers. comm.). Five of eight native Myrtaceae and at least 15 nonnative species have been observed as hosts of *P. psidii* in Hawai'i (Loope 2010). The federally endangered *Eugenia koolauensis* (nōioi) and the nonendangered indigenous species *Eugenia reinwardtiana* are severely damaged (J.Y.U., pers. obs.).

As events unfolded in Hawai'i after establishment of the rust, it came to be realized (through genetic sampling on multiple hosts based on microsatellite markers developed by Zhong et al. [2007]) that the rust population consisted of a single strain with no apparent genetic variation and lacking evidence of a sexual stage (Kadooka 2010; J.Y.U., pers. obs.). The strain in Hawai'i has not broadly infected many of the species known to be susceptible to damage by *P. psidii* elsewhere, including common guava, *Eucalyptus* spp., and allspice (with a few localized exceptions for the latter). The contrast in susceptible hosts of *P. psidii* with other areas is consistent with observations of apparent "race" or "biotype" differences elsewhere reported by Coutinho et al. (1998) and other sources summarized in Glen et al. (2007). There is also strong evidence that within host species there is variable susceptibility to individual variants of *P. psidii* (Rayamajhi et al. 2010, Zauza et al. 2010).

Loope (2010) concluded that, on the basis of the very substantial genetic diversity of the much-studied, crop-damaging species of the genus *Puccinia*, there is good reason to believe that numerous genotypes likely exist in the core range of *P. psidii* in Brazil with potential for dispersal by globalization. Nevertheless, such genotypes had not been studied and documented with respect to host species of *P. psidii*, though sophisticated genetic work has started in Brazil, focusing on genetic mechanisms of resistance of *Eucalyptus* to the rust (Junghans et al. 2003, Moon et al. 2007, Mamani et al. 2010).

CLARIFICATION OF THE GENETICS OF *Puccinia psidii* IN RELATION TO HOSTS

Research funded by the U.S. Forest Service and others is currently under way in Brazil to determine relationships between genetics and potential aggressiveness of *P. psidii* against 'ōhi'a (Cannon et al. 2009). An important portion of the genetic work has involved a Ph.D. dissertation by Rodrigo Graça, a student of Prof. Acelino Alfenas at the Federal University of Viçosa, Brazil, who has completed some of the laboratory work at Washington State University. Graça's dissertation

is currently being prepared for publication and has substantially expanded knowledge of genetic variation within *P. psidii*. Here are excerpts from a poster presentation (Graça et al. 2010: poster):

To determine population genetic structure of the pathogen in the putative center of origin, approximately 150 single-pustule isolates of *P. psidii* have been collected from diverse host species and locations in Brazil and scored for variation at 10 microsatellite loci. Additional isolates have been collected from Hawai'i, California, Paraguay, and Uruguay . . .

Preliminary results for Brazil indicate that 1) considerable genetic diversity is present; 2) species of hosts strongly influence population structure; and 3) distinct multilocus haplotypes are uniquely associated with specific hosts across diverse geographic locations. In contrast, all 49 rust isolates collected from five different hosts in Hawai'i (O'ahu, Maui, Kaua'i and Hawai'i—"Big Island") share a unique multilocus genotype, indicating a recent introduction of a single rust genotype. This information will help identify rust races that pose threats to global populations of Myrtaceae and help prevent their introduction into new regions. For example, none of the rust genotypes in Brazil are known to occur in Hawai'i. At present, it seems prudent to focus on avoiding the introduction of any novel genotypes to new regions with populations of known hosts. Furthermore, potential recombination of genotypes could generate new virulent races of the pathogen with unpredictable consequences. Population genetics and molecular characterization of *P. psidii* isolates collected from around the world will provide critical information on pathways of spread and assessment of future risk.

POTENTIAL FOR ADDITIONAL GENETIC STRAINS OF *Puccinia psidii* TO ARRIVE IN HAWAII

Much attention has been given to the likely source of the initial establishment of a strain of *P. psidii* in Hawai'i. The source is in fact uncertain but is likely to have been either imported nursery stock or decorative foliage of common myrtle (*Myrtus communis*) from the mainland United States (Loope and La Rosa 2008). Transmission of *P. psidii* on imported nursery stock is a plausible pathway, but no interceptions have been reported by HDOA. However, since 2006, HDOA inspectors have repeatedly intercepted *P. psidii* in infected shipments of incoming cut (decorative) myrtle foliage (Loope and La Rosa 2008, Loope 2010). An outbreak of *P. psidii* on cultivated myrtle in southern California in 2005 was re-

ported (Mellano 2006); most of Hawai'i's imported cut foliage and flowers are shipped from California. Another candidate vehicle for establishment of Hawai'i's initial rust strain is waxflower (*Chamelaucium uncinatum*), a species native to Western Australia and an important filler species in the international flower trade, first noted as a host of *P. psidii* in Hawai'i (Loope 2010).

Authorities in Hawai'i have assumed that just as the initial rust strain entered in 2005 or before without warning, new strains/genotypes of the rust could potentially enter Hawai'i on the same or other Myrtaceae species, perhaps most notably juvenile *Eucalyptus* leaves (*E. cinerea*, *E. pulverulenta*, and perhaps other species), highly important in the national/international foliage trade (Loope 2010).

Loope (2010) reviewed evidence that spores of *P. psidii* can potentially survive for 3 months, and the pathogen can be transported to Hawai'i on Myrtaceae from anywhere in the world through the United States mainland. Furthermore, there is much geographic reshuffling of flowers and foliage among the far-flung firms in the trade, especially for bouquet making. Because *P. psidii* is a nonactionable and nonreportable pest in the United States, foliage and flowers of the myrtle family can move freely into the country (usually but not necessarily always through the ports of Miami or Los Angeles) and from state to state.

Eucalyptus forestry also provides dangerous pathways for movement of *P. psidii* (e.g., Ciesla et al. 1996). Wingfield et al. (2011:94) expressed concern very specifically about a standard practice of "international forestry and fruit tree growing companies . . . with holdings in many different countries" to move high-performance stock to other areas of the world where the companies also operate. "One might thus predict that diseases such as *Eucalyptus* rust that occur in plantations of forestry companies in South America will emerge in Asia where the same companies own land." Wingfield et al. (2011) also observed that once a pest or pathogen becomes established in a new area, subsequent introductions into other geographic areas appear

to occur increasingly rapidly. It is foreseeable that pathways/sources for new strains of *P. psidii* will proliferate in coming decades.

Hawai'i's Board of Agriculture unanimously approved a 12-month interim rule in August 2007 banning importation of plants in the myrtle family from "infested areas," specified as South America, Florida, and California. However, the interim rule has not been made permanent by HDOA; the department stated in 2008 that it needed further information to formulate a long-term rule that imposes appropriate measures. Since the interim rule expired in August 2008, HDOA has regulated incoming plant material in the family Myrtaceae by visual inspection. Inspection capacity and latent (asymptomatic) infections limit the ability to detect the rust. Loope (2010) summarized available information to date on *P. psidii* to assist in evaluating regulatory options. HDOA decided to await definitive results from the ongoing genetic study of *P. psidii* previewed by Cannon et al. (2009); now, having seen the findings of Graça et al. (2011) as well as other related publications in the works, HDOA is working toward effective regulation, expected to be in place by the end of 2012 at the latest (Okada et al. 2011; C. Okada, HDOA, pers. comm., November 2011).

REGULATION OF MYRTACEAE PATHWAYS TO
PREVENT NEW GENETIC STRAINS OF
Puccinia psidii: THE POTENTIAL
MECHANISM TO PROTECT HAWAII'S
METROSIDEROS FORESTS

Hawai'i Department of Agriculture's Plant Quarantine Branch (HDOA) has a clear mandate to protect Hawai'i's natural environment, forestry, and cultivated Myrtaceae (Loope and La Rosa 2008, Loope 2010), though the U.S. Department of Agriculture, Animal and Plant Health Inspection Service (USDA) has authority to harmonize state and federal laws and to regulate shipments coming from foreign countries. Principles of the World Trade Organization's Treaty on Sanitary and Phytosanitary Measures and the International Plant Protection Convention are consistent with the right of Hawai'i to take action

(Hedley [2004] and other references cited in Loope [2010]). Hawai'i has the right to regulate for exclusion of *P. psidii* to prevent entry of strains below the species level, pending appropriately rigorous scientific justification.

[I]n the absence of detailed scientific evidence, the 'precautionary principle', which supports taking protective action (e.g., banning particular imports or establishing new quarantine procedures) before there is complete scientific proof of a risk, exists as a fail-safe mechanism. In effect, action should not be delayed simply because full scientific information is lacking. The provisional measure must take into consideration available pertinent information. However, under the SPS Agreement any state adopting precautionary measures must seek to obtain the additional information necessary for a more objective assessment of risk, and must review measures within a reasonable period (Hulme 2011:309).

Work under way by Graça and colleagues (Cannon et al. 2009, Graça et al. 2011) provides synergy with other genetic work demonstrating that genetics can matter profoundly for the ability of this rust to infect various hosts. Furthermore, there seems to be no practical means to distinguish among incoming strains.

The current threat of *P. psidii* to Hawai'i is primarily posed by the importation of infected plants (cut flowers and foliage, as well as nursery stock) from the continental United States; however, that may change in the future. When Hawai'i takes a stand (through State regulation) to protect its native and introduced Myrtaceae, there is a strong likelihood that USDA would implement federal regulation of Myrtaceae from foreign countries.

Drastic restriction by HDOA, for more than a century, on entry of coffee plants has effectively kept coffee rust (*Hemileia vastatrix*) out of Hawai'i. This approach offers the strongest protection for Hawai'i's native forest ecosystems. Prohibition of Myrtaceae provides a means of keeping out *P. psidii* as well as other important pests of native and nonnative Myrtaceae (see Loope 2010 and Loope and La Rosa 2010). There would be a need to mitigate complete prohibition, through providing a means for bringing germplasm of certain Myrtaceae into Hawai'i by permit. This

could apply to *Eucalyptus* spp. for forestry (see Wingfield et al. [2011] for discussion of the risk), as well as to new Myrtaceae for Hawai'i's horticulture industry. Use of a molecular diagnostic test for assessing seeds could potentially be warranted and practical in such instances; such a test has been developed for use in Australia (Langrell et al. 2008). Postentry quarantine under permit could be explored as a potential tool by HDOA; Hawai'i has decades of operational experience with such quarantines.

IMPLICATIONS FOR OTHER ISLANDS AND COUNTRIES WITH MYRTACEAE

Myrtaceae is a large family with ca. 5,500 species (Biffin et al. 2010), with about one-fourth of the species in the neotropics and more than one-third in Australia. The other 2,000+ species are found mostly across southern Asia, central and southern Africa, and various islands, from Madagascar to the Pacific. Australia has acted on its extreme concern to try to put measures into place to protect its Myrtaceae (e.g., Booth et al. 2000, Grgurinovic et al. 2006, Langrell et al. 2008, Carnegie and Cooper 2011). Only about 4% of Australian Myrtaceae has been tested, but most were shown to be potential hosts of *P. psidii* (Zauza et al. 2010).

Five years after *P. psidii* was detected in Hawai'i, in April 2010, a taxon of rust in the *P. psidii* complex (*Uredo rangelii*, described by Simpson et al. (2006) but according to some authorities questionably distinct from *P. psidii*) was detected on several genera of native Myrtaceae at a cut-flower nursery in New South Wales, Australia, at about 33° S (Carnegie et al. 2010). Australia already had a contingency response plan in place, and an attempt was made to achieve containment and eradication. Nevertheless, in December 2010, "myrtle rust" (so named because *Myrtus communis* had been the host of the type specimen of *U. rangelii*) was detected at a small number of nurseries in Brisbane (27.5° S), Queensland (Invasive Species Council 2011), shortly before a period of extremely wet weather in that area in January 2011, with extensive and se-

vere floods. With the warm, moist conditions, the rust had spread as far north as Cairns (17° S) by February 2011. Much of Australia may turn out to be too dry or too cold for the rust to thrive, but tropical wet Queensland (12–28° S), with hundreds of species of Myrtaceae, likely has the highest vulnerability.

Australia will predictably act within its interpretation of international phytosanitary rules to keep out additional strains within “the *P. psidii* complex” (Carnegie et al. 2010, Carnegie and Cooper 2011), though the different binomial, *Uredo rangelii*, may simplify the phytosanitary issue. Information sharing with Australia may affect Hawai‘i’s success in enacting and sustaining effective regulations against new strains of *P. psidii*.

If *U. rangelii* were to become widespread in eastern Australia, it could pose an immediate potential threat to New Zealand North Island’s *Metrosideros* forests, because rusts are known to blow on the wind across the Tasman Sea from Australia to New Zealand (Viljanen-Rollinson and Cromy 2002). New Zealand, south from about 34° S, with six genera of Myrtaceae, may or may not prove mostly resistant to the rust because of cool temperatures. The ability of *P. psidii* s.l. to thrive at latitudes south or north of about 30° latitude will be tested in locations such as New Zealand, Australia, and California. The complexity of interactions between temperature and moisture conditions seems to make confident prediction particularly difficult.

The only other recent record of *P. psidii* establishment outside the neotropics and subtropics is that by Kawanishi et al. (2009) for Japan (Tateyama, Chiba, at 35° N).

Genetic strains of the *Puccinia psidii* complex are likely to spread to other areas with native and introduced Myrtaceae. Some Pacific islands are notably rich in Myrtaceae and thus have much to lose. Just for example, New Caledonia’s diverse flora has 21 genera (six endemic) and 234 endemic species of Myrtaceae (Jaffré et al. 2001). Many islands and countries are going to be challenged to protect their Myrtaceae from *P. psidii*. Perhaps a concerted international effort could make a substantial difference.

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