Eradication programmes complicated by long-lived seed banks: lessons learnt from 15 years of miconia control on O'ahu Island, Hawai'i

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Abstract The invasive tree *Miconia calvescens* (Melastomataceae) is a priority for control on the Hawaiian Island of Oʿahu due to its potential to replace native ʿōhiʿa (*Metrosideros polymorpha*, Myrtaceae) forests and degrade watershed function if allowed to establish. The Oʿahu Invasive Species Committee (OISC) is attempting to eradicate this species from the island of Oʿahu. OISC uses a buffer strategy based on estimated seed dispersal distance to determine the area under surveillance. This strategy has worked well enough to suppress the number of trees reaching reproductive age. The number of mature trees removed annually is now less than the number initially removed when the programme started in 2001. In 2016, just 12 mature trees were removed from 54.71 km^2 surveyed compared to 2002, when 40 mature trees were removed from 8.26 km^2 surveyed, a 96% drop in mature trees per square kilometre surveyed. However, miconia has a long-lived seed bank and can germinate after 20 years of dormancy in the soil. Funding shortages and gaps in surveys due to refusal of private property owners to allow access have resulted in some long-range extensions. OISC's results suggest that seed bank longevity is an important factor when prioritising invasive species risk and that allocating more resources at the beginning of a programme to eradicate a species with long-lived seed banks may be a better strategy than starting small and expanding.

Keywords: invasive species, invasive plants, watershed, outreach, cloud water interception, *Miconia calvescens, Metrosideros polymorpha*

INTRODUCTION

The tree miconia (*Miconia calvescens* – Melastomataceae) has been recognised as a threat to forests on Pacific Islands where it has been introduced (Meyer, et al., 2011; Medeiros, et al., 1997). Native to tropical Central and South America, it is under control programmes in French Polynesia, New Caledonia and Hawaiʿi (Meyer, et al., 2011). In areas where miconia has invaded, it has formed monospecific stands, shading out all plant species beneath it (Meyer, 1996). A miconia-dominated forest would likely not perform watershed services as well as Hawaiʿi's multi-layered native forests. Runoff and water would likely increase and replenishment of the islands' freshwater aquifer through cloud water interception would likely decrease. (Nanko, et al., 2013; Takahashi, et al., 2011). Because of its potential to outcompete native forest flora and its potential deleterious effects on watershed function, miconia has been prioritised for eradication on the Hawaiian Island of Oʿahu. Miconia was introduced to Oʿahu at the Wahiawā botanical garden in 1961 (Medeiros, et al., 1997). It was not until the late 1990s that its invasive potential became known and efforts to control it began (Medeiros, et. al., 1997). Here we describe the results of the island-wide eradication programme for miconia implemented by the Oʿahu Invasive Species Committee (OISC) since 2002.

The Koʿolau Range forms the eastern spine of the island of Oʿahu and is the location of the island's primary aquifers supplying water to the urban centre of Honolulu (Board of Water Supply, 2016). Data from miconia's native and invaded ranges shows that this species occurs in tropical areas with more than 1,500 mm of rainfall (Libeau, et al., 2017). Oʿahu rainfall data indicates that most of the Koʿolau Range, including the areas encompassing the island's most important aquifers, could support miconia (Giambelluca, et al., 2013).

Miconia's potential to replace forest ecosystems with monospecific stands is evident from its invasion history in French Polynesia (Meyer, et al., 2011). There, dense stands occur over 80,000 ha from sea level to 1,400 m (Meyer, et al., 2011). To put those numbers in perspective, the forested area of the Koʿolau Mountains is approximately 40,469 ha and its highest peak is 960 m (Koʿolau Mountain Watershed Partnership, 2017). The rainfall and elevation of the Koʿolau Range are similar to those areas in Tahiti where miconia has formed monospecific stands and is therefore vulnerable to the transformative effects of a miconia invasion (Fig. 1).

Miconia leaves can reach up to one metre in length (Chimera, et al., 2000) (Fig. 2). These large leaves reduce light levels so dramatically that understorey and groundcover vegetation under a miconia canopy are severely reduced (Meyer 2004; Nanko, et al., 2013). Rainwater collects on the large leaves and funnels it to

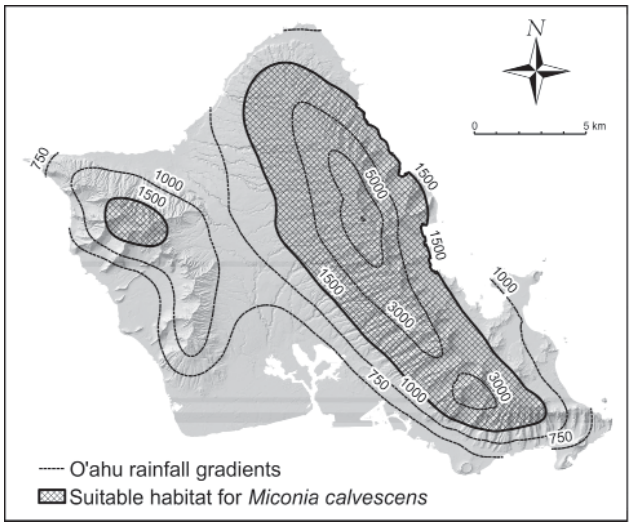

Fig. 1 *Miconia calvescens* occurs in areas with more than 1,500 mm rainfall annually. The area shown encompasses almost all of the Koʿolau mountain range on the eastern side of the island. (Rainfall data from Giambelluca, et al., 2011)

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the bare ground with a velocity high enough to accelerate erosion when hitting bare ground (Nanko, et al., 2013).

Water recharge of the island's aquifers may also be at risk. A study on Hawaiʻi Island found that native-dominated 'ōhi'a forest intercepted 454 mm more cloud water than strawberry guava (*Psidium cattleyanum* – Myrtaceae) dominated forests due to the differences in bark structure and tree shape (Takahashi, et al., 2011). Miconia has smooth bark similar to strawberry guava and would likely have similar rates of cloud water interception. This is important as cloud water interception may contribute up to 32% of total precipitation in Hawaiʻi's montane wet forests (Giambelluca, et al., 2011). Based on these studies, we surmise that a structurally complex, native forest is likely better at condensing fog and cloud drip and directing rain into the islands' aquifer than a forest dominated by monospecific stands of miconia.

CONTROL OF MICONIA ON OʻAHU

Control of miconia in the Hawaiian Islands began in 1991 after scientists and conservationists saw the damage it was causing in Tahiti (Medeiros, et al., 1997). On Oʻahu, miconia was planted at three botanical gardens, at two private residences and a commercially operated park (Medeiros, et al., 1997). All voluntarily destroyed their trees when requested by the state Departments of Agriculture (HDOA) and Land and Natural Resources (DLNR). Follow-up surveillance and control were conducted by volunteers and HDOA and DLNR employees until the Oʻahu Invasive Species Committee was formed as a project of the University of Hawaiʻi in 2001.

The miconia eradication project strategy is based on delimitation, defined as conducting enough surveillance to be sure that we know how far the invasion extends; containment, defined as containing the population by removing plants before they can mature; and extirpation, defined as removing immatures until the seed bank is exhausted (Panetta & Lawes, 2005; Panetta, 2007). In order to achieve the benchmarks of delimitation, containment and extirpation, OISC designates areas within a certain radius around reproductive trees for ground or helicopter surveys and conducts outreach to property owners and outdoor enthusiasts. The search area is currently at 91.39 km^2 and encompasses 4,000 different private property lots for which we must acquire permission to access in order to survey (Fig. 3).

Ground surveys are conducted for 800 m around every mature tree and 500 m around every immature tree every three years. The 500 m or 800 m radius around trees is called the ground buffer. An analysis of OISC's miconia field data shows that 99% of immature trees fall within 350 m of a mature tree (Fujkawa, pers. comm. 2017), confirming that the size of the search area is large enough.

Fig. 2 Typical leaf size for *Miconia calvescens*.

The frequency interval of every three years is necessary since miconia can mature in as little as four years (Meyer, 1996). Areas within this 800 m ground buffer that are too steep to survey by ground are surveyed by helicopter every two years.

Ground crews locate miconia visually during both ground and air surveys. In addition to their large size, miconia's leaves have vibrant purple undersides and this makes it fairly easy to detect on both types of surveys

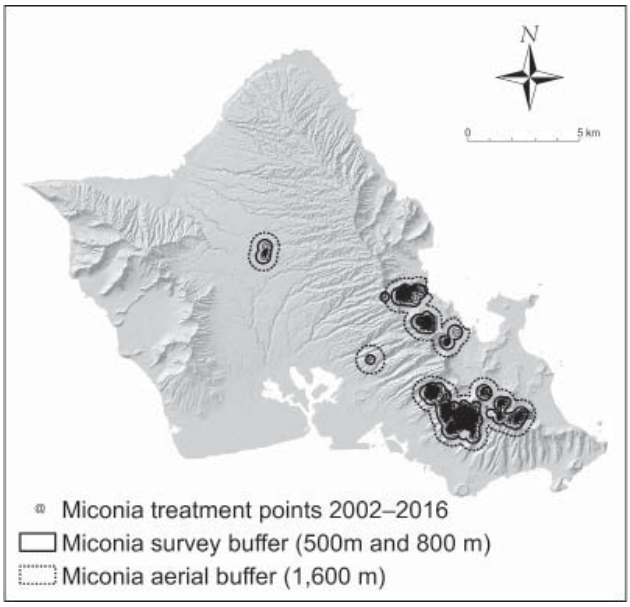

Fig. 3 The O'ahu Invasive Species Committee search area for *Miconia calvescens.*

Fig. 4 A sapling growing out of a patch of *Clidemia hirta* on O'ahu. The large leaves and striking purple undersides make miconia fairly detectable, although in heavy vegetation, trees can still be missed.

(Fig. 4). However, on ground surveys trees are sometimes missed due to dense vegetation that limits visibility. Steep terrain can also make trees difficult to detect as simply getting up a vertical slope safely may distract the surveyor from finding trees. Large trees that have already breached the canopy are also difficult to spot from the ground.

Surveyors can visually find miconia trees from a helicopter but the helicopter must fly very low and slow above the canopy. The large leaves are visible from the air and the rotor wash from the helicopter often blows the leaves around so the purple undersides are visible. Immature trees as tall as four metres have been spotted on helicopter surveys. One disadvantage of helicopter surveys is that in areas with a thick canopy, trees growing beneath may be missed. OISC's observations are that once a large tree has broken through the canopy it often matures very quickly, so areas designated as too steep for ground surveys within the ground buffer are flown every two years to compensate for the fact that trees will not be found until they are older.

Another 800 m from all mature trees is flown by helicopter to check for outliers. Despite the high cost of paying for helicopter time, the per-hectare cost is actually less than ground surveys because so much area can be covered quickly. Residential areas designated for helicopter surveys are done by ground or road in order not to disturb the residents. If a tree is found during an outlier survey, then an 800 m buffer is drawn around it and it becomes part of the area that is searched by ground.

Outreach to hikers, hunters and other outdoor recreationalists has been helpful in receiving reports of miconia. OISC engages organised groups of hikers and hunters through presentations, educational materials and social media with the aim of informing people how to identify and report miconia. We also present to schools and set up educational booths at community festivals in the areas where we are surveying. We believe that outreach also assists in gaining entry to private land. Our observation is that property owners who have heard about the invasive species problem before we call and ask their permission to survey, are more likely to let us on, although we have not specifically measured this.

RESULTS

OISC hired its first staff in November of 2001 and surveys started in 2002. The number of square kilometres surveyed per year has grown as more funding became available. Since 2002, OISC has been able to achieve a 96% reduction in mature plants from 4.8 mature trees per km^2 surveyed to 0.2 mature trees per km^2 surveyed (Table 1). There were 40 mature trees found and removed over 8.26 km^2 in 2002 and just 12 found and removed over 54.71 km^2 in 2016.

OISC also counts and takes GPS points for trees that are immature but over two metres tall. Trees over two metres that are missed will likely be mature the next time the field crew surveys. Therefore, the number of trees over two metres should also be at zero in order to achieve and ensure containment. OISC has achieved an 81% decrease in trees over two metres from 6.8 to 1.3 trees per km^2.

Three significant range extensions have recently occurred. As stated above, OISC's data shows that 99% of immature plants fall within 350 m of a mature plant. However, in 2015, one immature tree was found 6,900 m from the nearest mature tree. In 2016, another was found 1,600 m from the nearest mature tree. In 2017, a small patch of mature and immature plants was found 2,400 m from the nearest mature tree. The 6,900 m and 2,400 m extensions were found while the crew was surveying for other plant species.

DISCUSSION

Having the source trees removed from the botanical gardens and the few private properties, as well as detection of mature trees by agencies and volunteers before OISC was even formed in 2001, was a tremendous help to the eradication project. OISC was able to apply its strategy around the historical points and get a head start on delimitation. By 2010, the surveillance and delimitation phase of the project was complete. OISC did not have the resources to survey all suitable habitat, however, we took the steps described below to ensure that all known populations were mapped. We interviewed fellow natural resource agencies and hiker groups working in suitable habitats to ensure there was not a population in areas we did not have the time to look at. We conducted binocular surveys outside our survey areas in prime miconia habitat looking for large patches. We also calculated the distance of immature trees to the nearest mature tree in 2009. We found that 99% of trees fell within 400 m of a mature tree and maximum distance of an immature tree was just short of 1,600 m (Fujikawa, et al., 2009). This gave us confidence that by 2010, delimiting was complete.

After 2010, the project moved into the containment phase, but it has been difficult to achieve containment as defined by eliminating all mature plants. Although OISC has been able to achieve a significant decrease in the number of mature plants per square kilometre surveyed, we have not been able to completely suppress maturation.

Trees that are missed during one survey cycle are sometimes missed due to human error—thick vegetation and steep terrain are two factors that may decrease the efficacy of surveillance. Although our success rate with getting property owners to agree to let field crews survey their property is 95%, there are some property owners who have been reluctant to agree to surveys. In one case, it took

Table 1 Number of mature, >2m tall trees and km^2 surveyed 2002–2016.

Year	No. mature trees	No. trees >2m	Km^2 surveyed
2002	40	94	8.26
2003	4	21	9.37
2004	7	14	9.00
2005	9	54	21.00
2006	6	27	25.16
2007	6	25	29.37
2008	0	37	20.53
2009	4	89	14.07
2010	1	48	23.25
2011	3	27	27.00
2012	5	83	14.87
2013	2	94	22.20
2014	5	97	21.59
2015	12	123	39.44
2016	12	94	54.71

several years to acquire access from a property owner who owned an entire valley. By the time the crew was able to survey, trees had matured. Sometimes the 5% that say no or take a long time to say yes can be critical. In some years decreases in funding meant we did not have the resources to survey the area required by our strategy. The combination of funding fluctuations and time spent negotiating property access allowed some trees to mature. The presence of mature trees may have resulted in range extensions into new watersheds from long-distance dispersal events.

A review of the distances between immature and mature trees conducted in 2017 resulted in 99% of immature miconia falling within 350 m of a mature tree (Fujikawa pers. comm. 2017), which was similar to our 2009 results. However, the furthest immature miconia was now 6,900 m away from the nearest mature tree.

Miconia's long-lived seed bank is a complicating factor in achieving containment. Research by Meyer (2010) has estimated the seed bank at 16 years in French Polynesia, but observations on Oʻahu suggest it may be as long as 20 years. The Wahiawā botanical garden where miconia was originally introduced has found seedlings and reported them to OISC as late as 2016. They removed their mature tree in 1996 (Medeiros, et. al., 1997) and OISC has surveyed the entire area at least three times without finding any miconia whatsoever, so the likelihood that the seedlings are from the 1996 mature tree is very high.

Lessons learnt

The long-term work done on miconia in French Polynesia is key to OISC's success in preventing a full-scale miconia invasion on Oʻahu. The research was critical to raising the alarm about the species and mobilising control efforts early. Miconia is one of the few species that OISC has taken on where the seed-bank longevity is known thanks to the long-term studies done by Jean-Yves Meyer (Meyer, et al., 2011). Research from Tahiti also formed the basis of the outreach narrative. For example, one of the key talking points for outreach was the enormous area of forest that had been turned into monotypic stands of miconia and a photograph of a landslide in Tahiti was a mainstay of state-wide outreach to explain the potential erosion effects. Both Tahiti and Oʻahu offer lessons to islands where miconia might be dispersed in the future.

If possible, having adequate funds at the beginning of an eradication project to complete delimiting as soon as possible may shorten the containment phase. It took OISC eight years to be sure where the miconia population was. Private property was a complicating factor. A small percentage of larger landowners would not let the field crew survey in a timely manner and trees were allowed to mature while we negotiated access. Delimiting and containing a species before it spreads to additional private property owners will be immensely helpful in achieving eradication as quickly as possible. Taking on additional species can also be helpful in detecting long-distance dispersal events. OISC volunteered to do aerial surveys for a forest pathogen because it would require us to fly over all habitat suitable for miconia. The small patch of mature and immature trees 2,600 m away from the nearest known mature tree was discovered during this survey.

Outreach has also been helpful for the survey effort and programme managers should consider dedicating funds and employees for outreach from the beginning of the programme. OISC did not have a full-time outreach specialist until four years after the programme started. OISC has had trees reported to us but more importantly, we believe outreach has helped OISC get access to survey on private land. People seem more willing to grant access if they have heard of the invasive species problem and miconia before they receive the call asking for permission to survey.

OISC's outreach is a combination of talking directly to community groups, hiking and hunting groups and schools through presentations, participating at events and social media. We have not had the ability to scientifically test the outreach and see which methods or messages work best. Anecdotally, we believe that explaining the larger ecosystem effects and the possible effects on the island's water supply will persuade a wider group of people than those who might be motivated by preserving the native flora of Hawaiʻi. Research about which messages would be received best would be welcomed.

Although completely suppressing maturation of miconia has proved difficult due to the long-lived seed bank, OISC has been able to achieve a 96% reduction in mature trees per square kilometre since the programme began in 2002. In 2016, only 12 mature trees were found across 54.71 km^2. OISC has been able to keep the density of mature trees very low, but the long-lived seed bank means that a missed tree due to human error, an area that the field crew cannot survey due to lack of funding or the inability to get access to private property will likely result in a mature tree once the crew has access to the area. Containment for species with long-lived seed banks will be long-term projects.

For this reason, when evaluating feasibility, prioritising species for control and planning eradications, seed bank longevity should always be taken into account (Panetta and Timmins 2004). Policymakers deciding which species should be restricted for import should also consider seed bank longevity as a critical factor. While a long-lived seed bank is certainly not the only factor that makes a species invasive, if a species with a long-lived seedbank starts to become a problem, eradication will be a long-term and expensive project. Seed-bank longevity is not known for many species, and conducting longevity studies to answer that question for species under management would be very helpful to plan eradication efforts.

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