Strategy to control the invasive alien tree *Miconia calvescens* in Pacific islands: eradication, containment or something else?

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Abstract: *Miconia calvescens* (Melastomataceae) is a notorious plant invader in the tropical islands of French Polynesia, Hawaii and New Caledonia. A small tree native to Central and South America, it was first introduced as an ornamental in private botanic gardens in Tahiti (1937), Honolulu (1961), and Nouméa (1970s) where it escaped, became naturalised, and formed dense monospecific stands. More than 80,000 ha are currently invaded in French Polynesia, 10,000 ha in the Hawaiian Islands and 140 ha in New Caledonia. Control programmes have been under way in the Hawaiian Islands (Oahu, Maui, Hawaii, Kauai) and French Polynesia (Raiatea, Tahaa, Nuku Hiva, Fatu Hiva) since the early 1990s, and in New Caledonia (Province Sud) since 2006. Despite more than 15 years of intensive control efforts and millions of plants destroyed, eradication has not been achieved in any of these islands, mainly because the species has multiple features that thwart its elimination (e.g., prolific seed production, active dispersal by alien and native frugivorous birds, large and persistent soil seed bank, shade-tolerance), combined with the difficulty of detecting and destroying plants on rough terrain and steep slopes, insufficient control frequency, and limited financial and human resources. Miconia's life cycle requires at least four years growth from seedling to fruiting. Consequently, prevention of fruit production may be an effective management strategy for small populations. This "juvenilization" process may allow the eradication of small populations when carefully conducted over a quarter century.

Keywords: management strategy, invasive plant, juvenilization, seed bank

INTRODUCTION

Pacific islands, along with most other islands worldwide, are vulnerable to the establishment and invasion of alien plant species. In some tropical oceanic islands, such as Hawaii and French Polynesia, the number of plant species that have established, formed sustainable populations and reproduce without human intervention (i.e. naturalised; see e.g., Richardson *et al.* 2000) approaches or exceeds the size of the native flora. Some naturalised species have become invasive and alter native ecosystems, cause severe economic losses, or are responsible for the two combined. Furthermore, the rate of species introductions is increasing, enhancing the risk of new invasions. Major cities, such as Honolulu in Hawaii, Papeete in French Polynesia and Nouméa in New Caledonia have international airports and harbours that act as "transport hubs" for people, goods, and plant and animal species, accidentally or intentionally introduced from Asia, Australia, and the Americas. The high human population density and *per capita* gross domestic product (GDP) of Hawaii, New Caledonia and French Polynesia (Denslow *et al.* 2009; Kueffer *et al.* 2010) may partially explain the high proportions of naturalised and invasive alien plants found in these islands. Moreover, these French and US territories support many public and private botanical gardens that were established in the last century to acclimatise "useful" plants from other tropical and temperate countries, including many forestry and ornamental species, some of which are now considered aggressive plant invaders. Management of current and potentially invasive alien plants has now become a priority for Pacific island countries (Sherley 2000; Meyer 2004).

The most cost-effective strategy for managing invasive species is preventing entry into a potential new range (e.g., Wittenberg and Cock 2001). Weed risk assessment, quarantine regulations, and other biosecurity and phytosanitary measures form a first barrier to plant invasion. When a species is already established and naturalised, three management strategies may be appropriate (Carter 2000; Grice 2009): 1) eradication for recently established species or species with a limited distribution; 2) containment for species which are beyond eradication (or where eradication has been rejected as a goal) but still in an early stage of invasion and expanding their range; and 3) control for large and extensive populations ("sustained control" *sensu* Parkes and Panetta 2009; or "maintenance control" *sensu* Hulme 2006) that may include biological control. An alternative option is to do nothing.

Eradication is the "removal of all individuals of a species from an area to which reintroduction will not occur" (Myers and Bazely 2003) or the "permanent removal of discrete populations" (Parkes and Panetta 2009). Eradication is a function of the area over which the weed is distributed and must be searched for repeatedly following control (gross infestation area), and constraints such as site accessibility, plant detectability, the species' characteristics, control efficacy, and funding support (Panetta and Timmins 2004; Parkes and Panetta 2009). Containment and control are sometimes combined because their common aim is reduction of the density of the target species or its rate of spread.

Whether plant eradications are successful depends on the life history traits of the species, including growth rate, reproductive capacities, and dispersal abilities (distance and speed). A major obstacle for plant eradication is the existence of a soil seed bank, which can persist for several years or more.

To demonstrate the importance of plant life history characteristics to an eradication attempt, we report here on the history of miconia (*Miconia calvescens* DC.: Melastomataceae), which is one of the most damaging plant invaders in native forest of Pacific islands. Miconia is a small tree unlike the "agricultural weeds" such as grasses, herbs, vines, shrubs, and aquatic plants, which are targeted for eradication in California, USA (Rejmanek and Pitcairn 2000), Australia (Woldendorp and Bomford 2004; Parkes and Panetta 2009), or New Zealand (Harris and Timmins 2009). The species is capable of prolific reproduction, has a persistent seed bank (Fig. 1), and can invade species-rich, intact rainforest and cloud forests subsequently destroying native biodiversity. We review the current status and distribution of miconia, and compile the results of control efforts during the past decades in French Polynesia, Hawaii

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and New Caledonia. We discuss the accepted strategies for plant eradication, and propose an alternative strategy to more efficiently manage this species and its environmental threat to all Indo-Pacific tropical high volcanic islands.

CHARACTERISTICS AND INVASION HISTORY

Miconia grows to 4-12 m but may reach 16-18 m in its native range in tropical Central and South America. The species was introduced as a garden ornamental in several private and public botanic gardens worldwide because of its striking, large leaves with purple undersides. It was first introduced to Tahiti in 1937, to the Hawaiian Islands in the early 1960s and to Nouméa in the early 1970s. Historical evidence and molecular analysis (Le Roux *et al.* 2008) indicates that the first plants cultivated in Hawaii and New Caledonia were imported from Tahiti. In each of these island groups, where mean annual rainfall exceeds 2000 mm, miconia escaped from gardens and became naturalised in surrounding vegetation. The lag between introduction and clear signs of invasion in these three island groups has ranged from 20 to 30 years (Meyer 1998), a relatively long time span which may explain why control responses were often too late. The rainforests and cloud forests of all high volcanic islands of French Polynesia and Hawaii, which have relatively similar origins, ages, latitudes, climate, topography and biota, are likely to be under high risk of invasion by miconia. Although New Caledonia is a large continental island with a more subtropical climate and a large area covered by nutrient-poor ultramafic soils, a predictive model shows that miconia might invade up to 25% of Grande Terre rainforests (i.e. 4000 km^2) on sedimentary soils, mainly on the rainy east coast of Province Nord (Meyer *et al.* 2006).

Miconia is already considered to be the most disruptive invasive alien plant in French Polynesia and the Hawaiian Islands, and threatens native rainforests of New Caledonia, the Wet Tropics region of Queensland in Australia (Csurhes 2008), Sri Lanka (Meyer 1998) and some Caribbean islands (Meyer 2010). On Tahiti, Moorea, Raiatea (French Polynesia), Maui and Hawaii (Hawaiian islands) and in Province Sud of New Caledonia, miconia can form dense monospecific stands that suppress native vegetation. Because of its devastating impact on the endemic flora in Tahiti (Meyer and Florence 1996), miconia is viewed as one of the highest control priorities in Hawaii, New Caledonia, and Australia. Potential environmental impacts such as increased runoff and soil erosion, as well as reduced groundwater recharge (Kaiser 2006), make miconia a "transformer species" *sensu* Richardson *et al.* (2000). Miconia was legally declared a "noxious weed" in Hawaii in 1992; a "threat to the biodiversity" in French Polynesia in 1997; a "Class 1 weed", the highest priority category in Queensland, Australia, in 2002; and listed an "invasive exotic species" to be eradicated, by authority of the Code de l'Environnement of the Province Sud, New Caledonia, in 2009.

Ground surveys and helicopter reconnaissance using GPS and GIS have been used to map miconia distribution. Control methods consist of manually uprooting seedlings and saplings, chemically treating the reproductive (or mature) trees on cut-stumps or bark, and carefully targeting spraying from helicopter (the latter only in Hawaii). Volunteers for short-term control operations or long-term funded teams, or both, have been involved and public awareness campaigns have been conducted in all island groups (Conant *et al.* 1997; Medeiros *et al.* 1997; Meyer and Malet 1997; Meyer 2010).

RESULTS

More than 80,000 ha of lowland rainforests and montane cloud forests are currently invaded in French Polynesia, ranging from near sea-level to 1400 m elevation; more than 10,000 ha are invaded in the Hawaiian Islands; and 140 ha in New Caledonia (Table 1). Management programmes detailed below were initiated in French Polynesia on the islands of Raiatea, Tahaa, Nuku Hiva, Fatu Hiva; the Hawaiian Islands on Hawaii, Maui, Oahu, and Kauai beginning in the early 1990s; and in New Caledonia (Province Sud) in 2006 (Table 2).

Raiatea (Society Is., French Polynesia)

Miconia was first introduced in the 1950s as a garden ornamental, then as a soil contaminant in the 1980s. About 250 ha were considered invaded in the early 1990s; infested sites ranged in elevation from sea-level up to 300 m elevation (Meyer and Malet 1997). An eradication attempt was started in 1992. Over 18 years, more than 470 ha has been surveyed (3% of the island surface) and 2.2 million plants have been manually removed, including more than 4500 reproductive trees. More than 3,500 people have been involved, including employees of the Departments of Forestry, Agriculture, Environment and Research, the

Table 1 Miconia invasion in the Pacific islands.
All data from the Hawaiian islands according to "Invasive Species Committees" (BIISC, KISC, MISC, OISC)

Island	Year of introduction	Number of invaded sites or valleys	Elevation range (m)	Invaded area (ha)
FRENCH POLYNESIA				
Tahiti	1937	> 100	10-1400	> 80,000
Moorea	1960s	> 20	10-1100	> 3500
Raiatea	1955	> 10	10-1000	> 470
Tahaa	1980s	1	20-200	< 10
Nuku Hiva	1990s	3	400-1100	< 5
Fatu Hiva	1990s	3	500-600	< 1
HAWAII				
Hawaii	early 1960s	> 100	10-820	> 10,000 (> 45,000*)
Maui	early 1970s	> 20	20-870	> 1000 (>15,000*)
Oahu	1961	> 6	10-500	> 700 (>12,000*)
Kauai	mid-1980s	> 2	40-310	> 220 (>1400*)
NEW CALEDONIA				
Province Sud	1970s	1	200-650	> 140

* surveyed areas including buffer zones of 1 km around all known occurrences, to allow for comprehensive surveillance ("gross infestation area" *sensu* Panetta and Timmins 2004).

Table 2 Results of miconia control efforts in Pacific islands.
Control methods: MC = Manual control; CM = Chemical control; BC = Biological control using the fungal pathogen *Colletotrichum gloeosporioides* f.sp. *miconiae*; (Year) = Year when control started.

Island	Degree of invasion	Control strategy	Control methods	Number of plants destroyed (reproductive trees)
FRENCH POLYNESIA				
Tahiti	High	Control in small areas of high ecological values	MC, CM + BC (2000)	Not evaluated
Moorea	High	Control in small areas of high ecological values	MC, CM + BC (2000)	Not evaluated
Raiatea	Medium	Eradication / Containment	MC, CM (1992) + BC (2004)	2,200,000 (> 4,540)
Tahaa	Low	Eradication	MC, CM (1995) + BC (2005)	10,000 (8)
Nuku Hiva	Low	Eradication	MC, CM (1997) + BC (2007)	8000 (14)
Fatu Hiva	Low	Eradication	MC, CM (1997) + BC (2007)	3000 (5)
HAWAII				
Hawaii	High	Containment	MC, CM + BC (1997)	Evaluation not available
Maui	Medium	Eradication / Containment	MC, CM + BC (1997)	Evaluation not available
Oahu	Low	Eradication	MC, CM (1993) + BC (1997)	16,000 (115)
Kauai	Low	Eradication	MC, CM (1993) + BC (1997)	8000 (23)
NEW CALEDONIA				
Province Sud	Low	Eradication	MC, CM (2006)	170,000 (> 180)

French Army, local volunteers, religious groups, employees of the island Counties, and schoolchildren (Meyer 2010). Campaigns against miconia were organised only once a year because of financial and logistic constraints. The discovery in 2002 and 2003 of isolated, but nonetheless dense miconia populations and reproductive trees at high elevation (up to 1000 m elevation) and in remote gulches and on inaccessible steep slopes, has subsequently shifted the goal to containment.

Tahaa (Society Is., French Polynesia)

A small miconia population was discovered in 1995 in the bottom of a wet valley between 20 and 200 m elevation, near an old track (Meyer and Malet 1997). Reproductive trees and thousands of seedlings have been removed. It is surprising that miconia has not been discovered elsewhere in Tahaa, including the nearby valleys, but detection in dense native *Hibiscus tiliaceus* lowland rainforest is particularly difficult.

Nuku Hiva (Marquesas Is., French Polynesia)

Miconia seedlings were discovered on Nuku Hiva in 1997 during a botanical expedition (Meyer 1998). Three small infestations, between 400 and 1,000 m elevation, have been detected; all originated from soil contamination during road construction. Two of the sites were on very steep slopes, enhancing the difficulty of detection and control. Ground-surveys and a helicopter fly-over were conducted in 2006 (J.-Y. Meyer and R. Taputuarai, unpub. data), but a few mature trees escaped detection in a nearby valley until 2008, after which thousands of seedlings were pulled out (F. Benne pers. comm.).

Fatu Hiva (Marquesas Is., French Polynesia)

Two small infestations of miconia were discovered in 1996 and 2002 by local pig hunters at between 500 and 600 m elevation (Meyer 1998). These populations have few reproductive trees but do contain thousands of seedlings in the understorey of dense native rainforest. Given the locations in the upper portion of a wet gulch, the risk is high that seeds may be washed down rivers. A new population was discovered in 2009 and some non-reproductive plants 4-6 m tall have recently been found at lower elevations (R. Taputuarai pers. comm.). The island's rugged topography makes plant detection and treatment particularly difficult.

Hawaii (Hawaiian Is.)

Miconia was introduced to Hawaii in the 1960s (Medeiros *et al.* 1997). Sustained control did not begin until 1995, due to the large size of the infestation. Comprehensive surveillance on Hawaii would currently need to cover > 45,000 ha (Table 1). Given limited resources, the current strategy involves preventing trees from fruiting along the upper-elevation margin of miconia distribution (J. Leialoha pers. comm. 2009).

Maui (Hawaiian Is.)

Control of miconia began in 1991 and was focused on major infestation sites by 1995. Comprehensive helicopter reconnaissance capable of detecting outlier trees was not initiated until about 2002. The current area surveyed for potential fruiting trees is 15,000 ha, allowing for a 1 km buffer zone around known miconia plants. Two "core" areas totalling about 1000 ha still have fruiting trees. The prognosis seems to be a *status quo* with a large but well-contained miconia population. Containment will require aerial and ground surveillance and control, costing about US$1 million per year, until effective biological control can be implemented.

Oahu (Hawaiian Is.)

Miconia was introduced to the first of three botanical gardens on Oahu in 1961 (Medeiros *et al.* 1997). Two of these gardens (Wahiawa and Waimea) have marginal conditions for its growth with mean annual rainfall between 1500 and 1650 mm. Consequently, spread of miconia was limited, which led to the false belief that the species was innocuous. A single plant introduced to Lyon Arboretum, in Manoa Valley (annual rainfall > 3000 mm) in 1964 produced numerous seedlings that were noted and sporadically removed by staff from 1975. When control began in 1993, there were at least two naturalised populations (Medeiros *et al.* 1997). Fruiting trees on Oahu are currently removed upon detection; 115 have been removed since 1993, including four in 2009 (R. Neville and J. Fukishima, "Oahu Invasive Species Committee" (OISC) pers. comm.). Nearly 12,000 ha needs to be surveyed for miconia, but OISC lacks the resources to survey this entire area, which includes extremely steep topography and narrow valleys.

Kauai (Hawaiian Is.)

Miconia was found in forest on Kauai in 1995 (Medeiros *et al.* 1997), having been introduced in about 1985. An eradication/containment effort was initiated soon afterward. The current management goal is eradication, through detection and removal of potential fruiting trees through surveillance in nearly 1,400 ha, by foot or helicopter. The "Kauai Invasive Species Committee" (KISC) had not seen a fruiting tree from December 2004 to November 2009; however, several fruiting trees were detected and destroyed in late 2009 (K. Gunderson, KISC pers. comm.).

Province Sud (New Caledonia)

Miconia was first introduced from plantings in an 800 ha private botanical garden located above the main town of Nouméa during the 1970s (Meyer 1998). The invaded area is currently estimated to be 140 ha at between 200 and 650 m elevation, which consists of a single major infestation along with isolated trees in small gullies with steep slopes. From 2006 to 2009, 16 ha had been surveyed, and more than 165,000 plants destroyed, including at least six mature trees in 2009. A single isolated plant was discovered and destroyed in 2006 in a private garden at Yienghen 450 km north of Nouméa, but no other plants have been detected since.

DISCUSSION

Can miconia be eradicated?

Despite 4-17 years of intense management and the destruction of millions of plants, miconia has not been eradicated from any of the islands of French Polynesia, Hawaii and New Caledonia, even from small infested areas. We are left asking: why? Eradication success depends on: 1) the number and size of infestations, 2) the accessibility of infestations, 3) detectability of the species, 4) the biological characteristics of the species (or its invasiveness), and 5) effectiveness of the control (Panetta and Timmins 2004).

Furthermore, the most cost effective strategy against invasive plants is early intervention and eradication during a "lag phase" when populations remain small and localised (e.g., Hobbs and Humphries 1995; Loope and Stone 1996). Although news of the effects of miconia invasions on forests in Tahiti reached the Hawaiian islands in the late 1970s, responses to Hawaiian infestations were slow (Medeiros *et al.* 1997). In the Hawaiian islands, miconia had already been introduced to a botanical garden on Oahu and private lands on the island of Hawaii in about 1961. By 1980, miconia was obviously spreading near Hilo, Hawaii, but there was no action against these populations by state or federal agencies. Action began on Maui when miconia was discovered 8 km from Haleakala National Park in 1991, perhaps 20 years after it had been introduced. The concern raised on Maui spread to other islands and by 1995 control of miconia was underway on Maui, Oahu, Hawaii and Kauai.

In New Caledonia, miconia was known to be in a private botanical garden in the early 1990s but since the land owner claimed that the species was locally naturalised but not expanding, there was no control until 2006 when local authorities recognised the need for action. In contrast, there was an immediate response by managers when miconia was discovered in the late 1990s in the Marquesas (French Polynesia). Except in the latter example, early opportunities to eradicate the plant were not taken owing to a general lack of understanding of the threat.

In California, about one third of targeted "weed infestations" between 1 and 100 ha, and one quarter between 101 and 1,000 ha were successfully eradicated during 1972-2000 (Rejmánek and Pitcairn 2002), although biological and ecological attributes of the targeted species were not considered in this analysis. Our results in French Polynesia and Hawaii show that it is unlikely that miconia infestations larger than 500 ha ("net area" *sensu* Panetta and Timmins 2004) can be eradicated with current resources. Eradication may even be difficult with smaller infested areas (Table 3).

Site accessibility and plant detectability are key factors for the success of eradication. Miconia is conspicuous because of its large, bicoloured leaves, but the shaded understorey of dense native rain and cloud forests in French Polynesia, the Hawaiian Islands and New Caledonia limits easy detection of individual plants. The rough topography in these high volcanic islands adds further constraints to eradication.

Miconia life history characteristics and invasiveness

Whether seeds are transient or persistent is fundamental to successful invasive plant management. Eradications may fail for species with seeds that are long lived, buried, rapidly dispersed and spread by uncontrolled vectors such as birds and wind (Carter 2000).

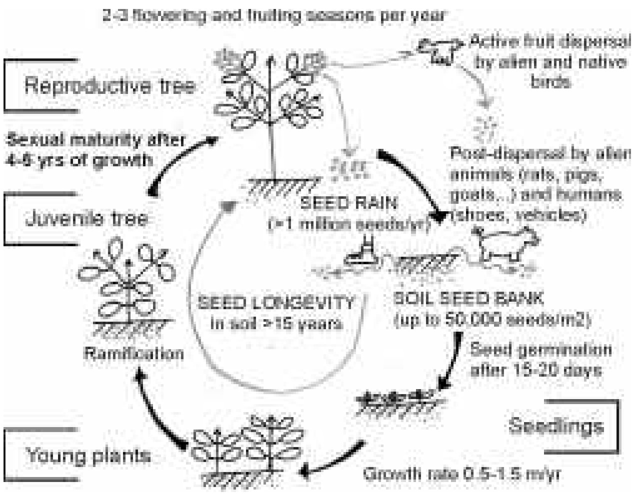

Fig. 1 Miconia life-cycle in Tahiti (*in* Meyer 2010).

Table 3 Proposed miconia control strategy according to the degree of invasion (total infested area and number of infestations).

Degree of invasion	Very localised (1-5 infestations)	Localised (5-50 infestations)	Widespread (> 50 infestations)
Area < 5 ha	Eradication	Eradication / containment?	Containment
Area >5-500 ha	Eradication / containment?	Containment	Containment
Area > 500 ha	Containment	Containment	No control/ biocontrol

Early enthusiasm for eradicating miconia in Hawaii underestimated the persistence its tiny seeds. In the Pacific, a single reproductive miconia produces millions of seeds each year, dispersal is by alien and native frugivorous birds, and a large and persistent soil seed bank is now known to last more than 15 years (Fig. 1). Miconia seeds are only C. 0.5 mm in diameter, so their long seed bank life may be a bit surprising (see Dalling and Brown 2009). The persistence of some invasive species as seeds appears related to the absence of fungal pathogens. For example, fungicide trials with seeds and seedlings of neotropical *Clidemia hirta* (Melastomataceae), which is highly invasive in Hawaii, indicate that fungal pathogens limit growth of *Clidemia hirta* in its native range but not in Hawaii (DeWalt *et al.* (2004). The seed bank longevity of miconia in the Pacific may also result in part from the plant's escape from its native range pathogens. Tropical forest plants, including species of Melastomataceae, are commonly classified into regeneration guilds or functional groups based on their light requirements for seed germination, seedling establishment or growth (Ellison *et al.* 1993). In its invaded range in the Pacific, miconia is a relatively shade-tolerant, late successional, long-lived pioneer, with a large and persistent seed-bank. Its regeneration strategy therefore differs from that of many other invasive trees such as the strawberry guava, *Psidium cattleianum* (Myrtaceae), seeds of which do not live beyond three months in the soil (Uowolo and Denslow 2008).

"Juvenilization", a strategy to control miconia

Control and removal of small populations within a limited area is more likely to be successful than removal over large areas. Moody and Mack (1988) suggest that containment programmes should give priority to small isolated populations ("nascent foci") rather than large infestations. In the case of miconia, small infestations are characterised by many seedlings and few reproductive trees, and large infestations by many reproductive trees and relatively few seedlings and saplings. Since seed production and dispersal rates are high, the management priority is to eliminate all mature trees in all major and minor foci (Fig. 2).

Miconia's "Achilles heel" lies in the four or more years required for growth from seedling to fruiting (Fig. 1). Prevention of the spread of fruit may therefore be an effective strategy for populations small enough to be managed over a long-term with limited resources. This "juvenilization" process is an essential step towards eradication of small populations if maintained for long enough, i.e. beyond the >15 year soil seed bank persistence. This may still seem a long period, but compared with pest animals, the eradication of weeds with long-lived seed populations will often require longer periods of funding and institutional support (Panetta and Lawes 2005). One of the most consistent contributors to success has been gaining widespread, sustained public acceptance of the need for the eradication (Mack and Foster 2009).

CONCLUSIONS

An integrated management strategy incorporating biological control may be the only achievable/sustainable option when miconia populations become so large that eradication is no longer possible; but again, long-term and adequate funding, political will, and institutional commitment are required. Fortunately, effective public awareness campaigns and reinforced biosecurity have prevented the spread of miconia to the other islands with suitable habitat including two high Hawaiian islands (Molokai and Lanai), other Society Islands (Bora Bora, Huahine), Marquesas Islands (Hiva Oa, Tahuata, Ua Huka, Ua Pou), and the southern Austral islands.

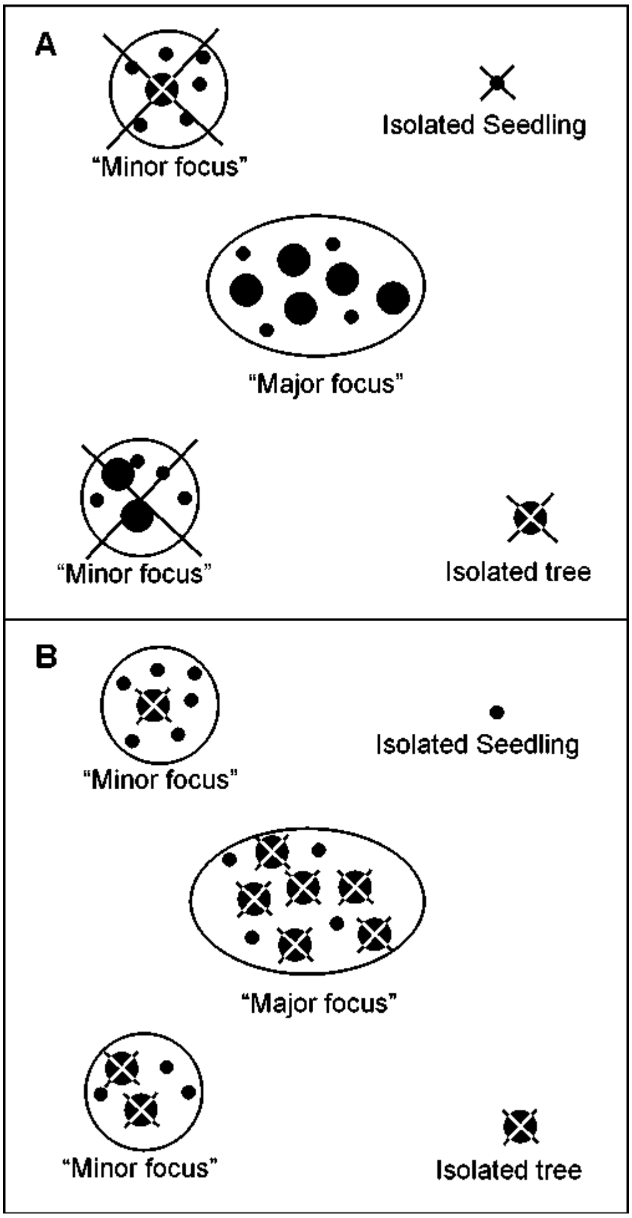

Fig. 2 Common invasive plant strategy following the "Moody & Mack model" (A); 'Juvenilization" miconia control strategy (B).

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