Impacts caused by *Hedychium gardnerianum* infestations

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Summary

Project and Client

- New Zealand's native forests are threatened by wild ginger (*Hedychium gardnerianum*), with an estimated 5,000 ha of infestation in the Northland region alone. Many regions in the northern North Island are now facing similar issues with increasing infestations of wild ginger. Better information about the harmful impacts of wild ginger is needed to help raise awareness about the importance of taking action against this weed and to secure funds to develop better control strategies, such as the use of natural enemies (biocontrol). Northland Regional Council therefore applied for an Envirolink grant for Landcare Research to compile information on what is already known about the detrimental impacts of wild ginger in New Zealand and overseas, and to identify knowledge gaps that will require future research.

Objectives

- To review the published literature as well as informal resources (e.g. web pages) to determine what is known about the impacts of *H. gardnerianum* in New Zealand and elsewhere in the world.
- To identify knowledge gaps that will require future research.

Methods

- A literature search was conducted using the WEB OF SCIENCE ™ website, specifying "All databases" and using the search terms "*Hedychium gardnerianum*" AND "Invasive".
- Similar searches were conducted using Google to identify potentially useful information not published in the scientific literature.

Results

Studies performed in New Zealand and elsewhere in the invasive range of *H. gardnerianum* have investigated the impacts of *H. gardnerianum* on factors such as soil microfauna and fungal communities; litter decomposition and nutrient cycling; effects on native plant establishment and on native food webs.

In New Zealand, *H. gardnerianum* is capable of growing at very low light intensities, in contrast to observations in the native range, where it is only found growing in sunny situations. The main impact of *H. gardnerianum* in invaded ecosystems is through inhibiting the regeneration of native plants: *H. gardnerianum* is reported to invade forest which has experienced no or little human disturbance in New Zealand, Hawai'i as well as on the Indian Ocean island of Reunion. Anecdotal information indicates that dense stands of *H. gardnerianum* are preventing regeneration of native plants in Reunion. Correlative and experimental studies have indicated that native seedling establishment regeneration is

substantially reduced by *H. gardnerianum* in both Hawai'i and New Zealand. The long-term prognosis for forest invaded by *H. gardnerianum* in these regions is not good: *H. gardnerianum* patches appear capable of persisting more or less indefinitely, so invaded forest will eventually become degraded as native plants senesce and die and are not replaced due to a lack of seedling regeneration.

H. gardnerianum is attacked by a limited number of herbivorous arthropods in New Zealand. Displacement of native plants that are host to a diverse indigenous arthropod community by *H. gardnerianum* is likely to result in broader ecosystem-level impacts by reducing the amount of arthropod biomass available for other trophic levels. Such impacts have been investigated in the Azores, where *H. gardnerianum* was estimated to decrease insect productivity by over 67% with consequences that will cascade through the food web to the community and ecosystem levels because of the loss of high-quality food sources for insectivores such as spiders, birds, mammals, and amphibians.

In New Zealand, *H. gardnerianum* occupies only a fraction of its potential range and, if unchecked is likely to become a much more widespread weed.

Conclusions

- *H. gardnerianum* is already having impacts on the regeneration of native flora in New Zealand forests. This is predicted to result in chronic degradation of the forest with broader impacts on native food webs, leading to detrimental ecosystem-level changes that could take decades or even centuries to become fully apparent.
- *H. gardnerianum* is too widespread to contemplate national eradication – indeed current control options are too costly for widespread suppression of *H. gardnerianum.* Relatively small, intensively managed areas could be kept free of *H. gardnerianum*, although this would be an ongoing commitment due to inevitable reinvasion from untreated areas.
- Biological control could potentially provide long-term suppression and restore ecosystem function to New Zealand forests invaded by *H. gardnerianum*. There are knowledge gaps regarding the ability of natural enemies to supress *H. gardnerianum* (in particular, whether the greater shade tolerance of *H. gardnerianum* in New Zealand is due to reduced herbivory/'enemy release' or a result of hybridisation with *H. coronarium*).

Recommendations

- Biological control has potential to provide cost-effective control and a programme is underway funded by a consortium of New Zealand and Hawai'ian funding bodies. Additional funding for biocontrol could safeguard this programme, which is at risk due to the lack of promising agents for Hawai'i, and enable work to be expanded on other candidate agents for New Zealand.

1 Introduction

Wild ginger, *Hedychium gardnerianum* Sheppard ex Ker Gawl., is native to the Eastern Himalayan foothills (http://www.cabi.org/isc/datasheet/26679). A plant believed to be a hybrid of *H. gardnerianum* and *H. coronarium* (G. Houliston, Landcare Research, pers. comm.), hereafter referred to as *H. gardnerianum* has been grown in New Zealand since at least 1865 (Orchard 1973). It has been widely distributed through New Zealand by garden plantings and subsequent dumping of garden waste and was reported to be naturalised in the North Island by 1940 (Orchard 1973). Seeds are contained within orange fruits and are dispersed locally in New Zealand by birds such as native tui and introduced blackbirds, and patches can also expand by means of branching rhizomes (Byrne 1992). *H. gardnerianum* is now widely distributed in the North Island, especially Northland, Auckland, the Coromandel Peninsula, Bay of Plenty, Taranaki, and the Wellington region. It is also widespread on the west coast of the South Island and in parts of the Marlborough Sounds (http://www.nzpcn.org.nz/plant_distribution_results.aspx?Species_Name=Hedychium+gardnerianum).

It has been estimated that *H. gardnerianum* currently infests 5,000 ha of native forests in Northland alone. Many regions in the northern North Island are now facing similar issues. Increasing infestations of wild ginger are now so widespread that control using standard manual and chemical control is too costly in most situations. Both native forest ecosystems and commercial forestry operations are affected by this weed. Currently, *H. gardnerianum* is estimated to cost the Northland economy between $3 and $5 million annually. This figure was estimated by comparing land values of areas with the same land cover type that were either infested with *H. gardnerianum* or currently free of it (Ashlee Lawrence, Northland Regional Council, pers. comm.). More specific information on control costs and economic production losses are largely lacking although Summit Forest spent c. $20,000 in 2016, controlling ginger in three areas of Aupouri Forest, excluding aerial pre-plant applications (Murray Braithwaite, Summit Forest, pers. comm.).

Better information about the harmful impacts of *H. gardnerianum* is needed to help raise awareness about the importance of taking action against this weed and to secure funds to develop better control strategies, such as the use of natural enemies (biocontrol). Northland Regional Council therefore applied for an Envirolink grant for Landcare Research to collate information on the impacts of *H. gardnerianum* to enable stakeholders to make informed decisions regarding control priorities in New Zealand.

2 Objectives

- To review the published literature as well as informal resources (e.g. web pages) to determine what is known about the impacts of *H. gardnerianum* in New Zealand and elsewhere in the world.
- To identify knowledge gaps that require future research.

3 Methods

- A literature search was conducted using the WEB OF SCIENCE ™ website, specifying "All databases" and using the search terms "*Hedychium gardnerianum*" AND "Invasive".
- Similar searches were conducted using Google to identify potentially useful information not published in the scientific literature.

4 Results

The Web of Science search resulted in 28 hits covering studies conducted in New Zealand and a range of other countries in the invaded range of *H. gardnerianum*. Google searches found a number of useful resources, including the Global Invasive Species Compendium (http://www.cabi.org/isc/datasheet/26679); the Global Invasive Species Database (http://issg.org/database/species/ecology.asp?si=57&fr=1&sts=&lang=EN) and weedbusters (http://www.weedbusters.org.nz/weed-information/hedychium-gardnerianum/59/).

The main findings of these studies are discussed below and summarised in Table 1.

4.1 Impacts in New Zealand

As is often the case for invasive environmental weeds, a relatively limited number of scientific studies have investigated the detrimental impacts of *H. gardnerianum* in New Zealand, which are discussed below:

Byrne (1992) investigated the impacts of *H. gardnerianum* in the Waitakere Ranges, where densities of *H. gardnerianum* stems were found to be as high as over 100 shoots per 3 x 3-m quadrat (i.e. at least 33 shoots per square metre). Byrne (1992) noted that some stands of *H. gardnerianum* growing in New Zealand were known to have been present for at least 70 years, indicating that untreated infestations are capable of persisting for long periods of time, if not indefinitely. She noted that *H. gardnerianum* was found growing at very low light intensities, in contrast to observations by Naik and Panigrahi (1961) who recorded that in the native range *H. gardnerianum* is only found growing in sunlight and never as an undergrowth plant. Nevertheless, the greatest densities of *H. gardnerianum* in the Waitakere Ranges were found along forest edges and clearings where light intensity was highest. Counts of seedling and sapling numbers indicated that native forest regeneration was strongly inhibited by the presence of *H. gardnerianum*, with native seedling numbers reduced by an average of *c.* 87% beneath the densest *H. gardnerianum* stands. A few native seedlings were found under *H. gardnerianum*, with nikau *Rhopalostylis sapida* being the most abundant. The number of native saplings was very low, compared with the number of seedlings, and followed the same pattern as seedling numbers (sapling numbers were almost 90% lower beneath dense *H. gardnerianum* stands than beneath sparse *H. gardnerianum* or areas where *H. gardnerianum* was absent). Byrne (1992) concluded that replacement of the understorey by *H. gardnerianum* would have "long-term effects on the successional processes of invaded forest communities, resulting in the formation of monotypic stands of ginger with the exclusion of all native plants in such areas." Byrne

(1992) also investigated the efficacy of various control options and concluded that eradication of *H. gardnerianum* from the Waitakere Ranges using conventional control techniques would not be possible and that a more practical objective of control would be to reduce ginger populations to a level where invaded native plants communities could perpetuate.

Yeates and Williams (2001) studied the impact of *H. gardnerianum* on soil microfauna but found no consistent impacts. For example, the number of nematode taxa detected was lower in areas infested by *H. gardnerianum* at Oponui, but higher at Rangitawa and Nelson.

Williams et al. (2003) investigated the impact of *H. gardnerianum* on forest processes by comparing native conifer-broadleaved forest patches with different densities of ginger at Opononi and Whangarei in Northland. They found that native seedling density and richness were lower in dense ginger stands, and that seedling composition was dominated by species with large (> 200 mg) seeds, i.e. *Corynocarpus laevigatus, Dysoxylum spectabile*, and *Rhopalostylis sapida*, that were presumably better able to cope with competition with *H. gardnerianum*, compared to small-seeded species. Williams et al. (2003) concluded that over time this selection for recruitment of native species that produce large seeds may produce a different forest canopy from that currently found in areas where ginger is sparse. Furthermore, these large-seeded species are dependent on kereru *Hemiphaga novaeseelandiae* for dispersal. The impacts of ginger could therefore be greater in areas where kereru are scarce and the forests lack the means to disperse the main plant species capable of regenerating through the invasive ginger, resulting in an "invasional meltdown" scenario (*sensu* Simberloff & Von Holle 1999).

Bassett (2014) investigated the impact of *H. gardnerianum* on invertebrate diversity and found that invertebrate numbers, but not diversity were influenced by the presence of *H. gardnerianum*. Ginger was associated with lower numbers of individuals per trap for Acari (mites), Amphipoda (amphipods), Araneae (spiders), Diptera (flies) and Hemiptera (bugs). By contrast, Isopoda (ispods) were more numerous in traps beneath ginger than uninvaded forest.

According to Weedbusters, dense *H. gardnerianum* rhizomes replace all other species, and are shallow rooted, so when they become heavy with rain they can slip on steep sites and streambanks causing erosion, and it is also noted that *H. gardnerianum* is succeeded only by weedy vines (http://www.weedbusters.org.nz/weed-information/hedychium-gardnerianum/59/).

4.2 Impacts in other invaded countries

H. gardnerianum is reported to threaten a number of subtropical forest regions of the world, including the Indian Ocean islands of Mauritius (Florens 2003) and Reunion (Figier & Souleres 1991; Macdonald et al. 1991; Tassin & Riviere 1999); Brazil (Macedo 1997); Hawai'i (Thomas et al. 1998; Anderson & Gardner 1999; Carroll 2003; Allison & Vitousek 2004; Loope et al. 2004; Asner & Vitousek 2005; Kao-Kniffin & Balser 2008; Paret et al. 2008; Minden et al. 2010b); the Azores (Heleno et al. 2009; Penacho et al. 2009); and South Africa (Adam et al. 2016), as well as Australia, Madeira, and the Canary Islands (Djeddour & Shaw

2013). It is also reportedly widespread in Ecuador and in the early stages of invasion in Queensland, Australia (http://www.cabi.org/isc/datasheet/26679).

The impacts of *H. gardnerianum* have been studied in a number of these countries:

In Reunion, *H. gardnerianum* invades relatively intact primary forest remnants that have experienced no or little human disturbance, and where dense stands of weeds including *H. gardnerianum* appeared to be preventing regeneration of native plants such that "the future of the forest is precarious" (Macdonald et al. 1991). Macdonald et al. (1991) ranked *H. gardnerianum* as the fifth most important weed species for management, out of 33 alien plant taxa invading primary habitats in Reunion.

In Hawai'i, *H. gardnerianum* is a prominent understorey shrub in montane forests with its cover approaching 100% in some areas on the islands of Kauai and Hawai'i (Allison & Vitousek 2004). *H. gardnerianum* was found to produce litter that decomposes faster than many dominant native species. Moreover, fertilization with nitrogen (N) and phosphorous (P) accelerated the decomposition of *H. gardnerianum*, and Allison and Vitousek (2004) predicted that fertile sites may become even more so following invasion by this species, threatening ecosystem function, with slowly decomposing native ferns such as the endangered *Athyrium haleakalae* (Wood & Wagner 2017), being displaced by invasive angiosperms causing ecosystem-scale changes.

A study that used airborne imaging spectroscopy and photon transport modelling indicated *H. gardnerianum* reduced nitrogen concentrations in the forest overstory and substantially increased above-ground water content (Asner & Vitousek 2005). This finding on N does not necessarily contradict the previous findings of Allison and Vitousek (2004) regarding nutrient cycling because airborne imaging spectroscopy is sensitive to foliar N only in the upper canopy, and so the high N content of understory *H. gardnerianum* is undetectable. Using ground-based sampling, Asner and Vitousek (2005) confirmed that *Metrosideros polymorpha* stands that have been invaded by *H. gardnerianum* do have lower foliar N than uninvaded stands and they hypothesised that this is due to N uptake by nutrient-demanding *H. gardnerianum*. They also noted that, in addition to its biogeochemical effects, the dense shade and network of tubers and roots that *H. gardnerianum* forms in invaded sites serves as an effective barrier to the establishment of native plant species.

Kao-Kniffin and Balser (2008) found that the invasion of *H. gardnerianum* into Hawai'ian forests appears to have limited impact on soil microbial community structure, although there was a large impact on the abundance of saprotrophic fungi, which increased under *H. gardnerianum*. This finding was consistent with Allison and Vitousek's (2004) study, which showed that decomposition rates of *H. gardnerianum* litter were faster when compared with the litter of several native species. Kao-Kniffin and Balser (2008) suggested several possible reasons why *H. gardnerianum* invasion did not lead to large subsequent changes in the composition of the soil microbial community: for example, nutrients released from *H. gardnerianum* litter may be rapidly acquired by the plant, making the nutrients unavailable to soil microorganisms. This would explain Asner and Vitousek's (2005) finding that *H. gardnerianum* reduces overstorey foliar N concentrations in *M. polymorpha* forests, which indicates that the invasive plant is more effective in acquiring available soil N.

Minden et al. (2010ab) investigated the impact of *H. gardnerianum* on native plants by comparing infested plots, with uninvaded plots, and plots from which *H. gardnerianum* had been removed. Variation in the density of native seedlings and saplings indicated that *H. gardnerianum* prevented native regeneration and that removal of *H. gardnerianum* could restore ecosystem function. By contrast, invasive strawberry guava *Psidium cattleianum* was the only species other than *H. gardnerianum* that regenerated in *H. gardnerianum* plots, indicating a potential 'invasional meltdown' scenario.

Carroll (2003) investigated the impact of *H. gardnerianum* removal on three bird species on the island of Hawai'i and found that invasive Japanese white-eye birds were more common in two *H. gardnerianum*-dominated plots, compared with two plots where *H. gardnerianum* had been removed. Insectivorous native and largely canopy-feeding Apapane birds were unaffected by *H. gardnerianum* removal, while frugivorous Omao bird density was significantly lower in one area invaded by *H. gardnerianum*, but similar in the remaining plots. By contrast, the abundance of two endangered native birds, the Akikiki (*Oreomystis bairdi*) and the Akekee (*Loxops caeruleirostris*) in Kauai were lowest in areas of forest dominated by invasive plants such as *H. gardnerianum*, associated with a corresponding decline in native vegetation cover (Behnke et al. 2016).

Heleno et al. (2009) investigated the impact of *H. gardnerianum* on insect seed and fruit-feeding food webs in the Azores. They found that insect biomass was significantly reduced due to the replacement of large insects (e.g. Lepidoptera) which fed on native plants, by small insects feeding on *H. gardnerianum* (which was attacked by the larvae of a small cecidomyid fly). Furthermore, the impact of alien plants was sufficiently severe to invert the otherwise expected pattern of species-richness decline with increased elevation. Heleno et al. (2009) predicted a decrease in insect productivity by over 67% if conservation efforts fail to halt the invasion of alien plants in the Azores. They concluded that depletion of insect biomass in invaded areas is likely to have consequences that will cascade through the food web to the community, and ecosystem levels because of the loss of high-quality food sources for insectivores such as spiders, birds, mammals, and amphibians. Birds and probably the endemic bat (*Nyctalus azoreum*) were considered especially vulnerable, given that insect biomass is crucial to them at least during the breeding season. Other studies in the Azores have linked a range on invasive weeds, including *H. gardnerianum*, with declining habitat quality for the endangered Azores bullfinch (Ceia et al. 2011)

Table 1. Summary of impacts on invasive *Hedychium gardnerianum* on invaded ecosystems (see text for further details)

Ecosystem function studied	Location(s) studied	Impact
Impact on soil microfauna communities	Hawai'i; NZ	No consistent impacts on diversity; some differences in abundance of soil invertebrates.
Impact on soil microbial communities	Hawai'i	Limited impact on community structure but substantially higher abundance of saprophytic fungi beneath *H. gardnerianum*.
Impact on litter decomposition/nutrient cycling	Hawai'i	*H. gardnerianum* was found to produce litter that decomposes faster than many dominant native species. Increased N recycling benefited only *H. gardnerianum* as N levels in a dominant canopy tree *Metrosideros polymorpha* were lower in presence of *H. gardnerianum*, indicating that *H. gardnerianum* is better at rapidly assimilating free N from the soil.
Impact on water	Hawai'i	*H. gardnerianum* substantially increased above-ground water content.
Impacts on native plants	Hawai'i; NZ; Reunion	*H. gardnerianum* is invading forest remnants which have experienced no or little human disturbance in all regions. Dense stands were considered to be preventing regeneration of native plants in Reunion and quantitative data indicate that native seedling regeneration is severely inhibited in NZ, with only a few large-seeded plant species capable of regenerating through *H. gardnerianum*. Experiments in Hawai'i also demonstrated *H. gardnerianum* substantially reduced native plant establishment, but did not prevent invasive *Psidium cattleianum* establishment, causing 'invasional meltdown'.
Effects on above-ground fauna	Hawai'i/Kauai, Azores	Increased abundance of exotic Japanese white-eye birds, but effects on native birds inconsistent in Hawai'i. The abundance of two endangered native birds in Kauai was lowest in areas of forest where dominating invasive plants, such as *H. gardnerianum,* have caused a reduction in native vegetation cover. Associated with a significant depletion of insect biomass in invaded areas in the Azores, which is likely to have consequences that will cascade through the food web to the community and ecosystem levels because of the loss of high-quality food sources for insectivores

4.3 Control options

Total eradication of widespread weeds is virtually impossible (Rejmánek & Pitcairn 2002) and Anderson and Gardner (1999) noted that where *H. gardnerianum* is widespread, chemical control is only affordable and environmentally safe in relatively small, intensively managed areas. Moreover, infestations in such areas will likely need to be regularly treated in perpetuity due to reinvasion from seed sources beyond the treated area.

Digging out plants is difficult and not always effective because plants can regrow from deep-rooted rhizome fragments (Harris et al. 1996). Chemical control using Escort (metsulfuron-methyl) can be effective, either by spraying plants using a knapsack sprayer or a hand gun, or by applying the herbicide to the cut shoots and rhizomes after cutting off the foliage (Byrne 1992; Harris et al. 1996). However, there are environmental concerns regarding the use of Escort including soil leaching capacity, potential ground water contamination and lethal effects on non-target species (Anderson & Gardner 1999). The use of Escort is not recommended along waterways and drainage courses (Harris et al. 1996).

There is a dearth of information on the current cost of controlling *H. gardnerianum* using these techniques New Zealand (or elsewhere). Assuming a cost of $2000–5000/ha, which is the cost of treating another environmental weed Japanese honeysuckle *Lonicera japonica* (Thunb.) in New Zealand (Paynter et al. 2017), it would cost NZ$10–25 million to treat all 5,000 ha currently infested by *H. gardnerianum* in Northland with a single application of Escort. A number of follow up applications would be required, as seeds survive for 2–4 years (http://www.weedbusters.org.nz/weed-information/hedychium-gardnerianum/59/). A widespread reduction of *H. gardnerianum* to low levels throughout Northland would likely cost tens of millions of dollars. Scaling this up to nationwide control would likely cost in excess of NZ$100 million. To put this in perspective, Howell (2008) listed 328 environmental weed species in New Zealand and a database of agricultural and horticultural weeds in New Zealand (http://www.massey.ac.nz/massey/learning/colleges/college-of-sciences/clinics-and-services/weeds-database/weeds-database_home.cfm) includes a further 47 species that were not listed as environmental weeds by Howell. The total expenditure by New Zealand defending its borders against new weeds and managing or controlling those ~375 species that are already present was reported to be $276 Million (Williams & Timmins 2011).

Under such circumstances biological control using host-specific natural enemies, which can result in permanent weed suppression, could be a highly cost-effective control option although there is no guarantee of success (see section 4.2.2).

A biological control programme (supported by the New Zealand National Biocontrol Collective, The Nature Conservancy of Hawai'I, and the Hawai'i Department of Land and Natural Resources and managed by CABI) has already commenced and identified a number of potentially damaging candidate biocontrol agents. To date the programme has had limited funding and progress has been hampered by bureaucratic delays obtaining export permits from India and because the agents are difficult to rear in captivity. Moreover, *H. gardnerianum* is an extremely difficult biocontrol target for Hawai'i due to the cultural significance of closely related *H. coronarium*, which is used to make leis, so continued financial support from Hawai'i cannot be relied on (note that molecular studies indicate that, as in New Zealand, *H. gardnerianum* growing in Hawai'i also appears to be a hybrid of *H. gardnerianum* and *H. coronarium*; G. Houliston pers. comm.). This programme would benefit from increased and more reliable long-term funding.

Host-range testing is close to completion for one agent (a stem-mining fly *Merochlorops* cf. *dimorphus*), and is also at an advanced stage for a rhizome-boring beetle *Metaprodioctes* sp. The testing results to date indicate that there is a good chance both of these species are adequately host-specific to be introduced into New Zealand, although *Metaprodioctes* is unsuitable for Hawai'i because it attacks *H. coronarium*. If all goes well, the additional testing required for these two candidate agents could be completed in 1–2 years. Surveys have identified a range of other potential agents including: 1) a leaf-mining hispine beetle

Prionispa patra, which has potential for New Zealand but is a poor prospect for Hawai'i as it attacks *H. coronarium*; 2) other leaf-mining hispine beetles, especially *Gonophora pulchella* and *Chaeridiona* cf. *pseudometallica*; 3) a moth with gregarious larvae *Artona* sp.; 4) few fungal natural enemies have been found, but one, *Hyalotiella* sp., may have potential for use as a biocontrol agent. With additional funding, the potential for these species to be released against *H. gardnerianum* can be investigated.

Surveys of *H. gardnerianum* in New Zealand (Winks et al. 2007) found two pathogens present (a leaf spot *Mycosphaerella* sp. and a rhizome rot *Fusarium oxysporum*) which could also be further studied as to their potential to be developed into bioherbicides.

4.4 Knowledge gaps

The main knowledge gaps are predicting: a) the long-term ecosystem-level effects of *H. gardnerianum* in New Zealand and; b) whether biological control is likely to have sufficient impacts on *H. gardnerianum* infestations to nullify the adverse effects of *H. gardnerianum* invasion.

4.4.1 Predicting the long-term ecosystem-level effects of *H. gardnerianum* in New Zealand

Individual plant species may have major effects on ecosystem processes, and non-native invasive plants can produce ecosystems with altered composition and successional pathways that function very differently from the native ecosystems they replace (Williams & Karl 2002). Seedlings of large-seeded plants (seeds > 200 mg) were found under *H. gardnerianum* infestations in New Zealand, implying that forest may persist in invaded areas, but will become dominated by a few large-seeded species that are capable of regenerating through *H. gardnerianum*, while smaller-seeded species may become excluded (Williams et al. 2003). Displacement of native plant species that are host to a diverse indigenous arthropod community is likely to result in broader ecosystem level impacts because *H. gardnerianum* is attacked by a limited number of herbivorous arthropods in New Zealand (Winks et al. 2007). Exclusion of native plant diversity and biomass is therefore likely to reduce the biomass and diversity of arthropod species available for other trophic levels. However, the long-term consequences are difficult to predict and 'resolution of the effects of weeds such as *H. gardnerianum* requires long-term experiments' (Williams et al. 2003).

The potential distribution of *H. gardnerianum* in Northland has not been estimated precisely, but if left unchecked the rate of invasion is likely to increase: plant invasion data can be described by logistic curves (Williamson 1996), where the rate of invasion is initially slow, but increases rapidly due to exponential growth, and then declines until the carrying capacity is reached (Fig. 1). *Hedychium gardnerianum* currently infests c. 5,000 ha of native forests in Northland; likely to be a small fraction (<1%) of the area it is capable of invading, for example, in 2002 there were 275,568 ha of indigenous forest and 150,937 of indigenous scrubland in Northland, as well as 368,219 ha of plantation forestry (Ewers et al. 2006). *H. gardnerianum* could, and is highly likely to, become much more widespread (Fig. 1).

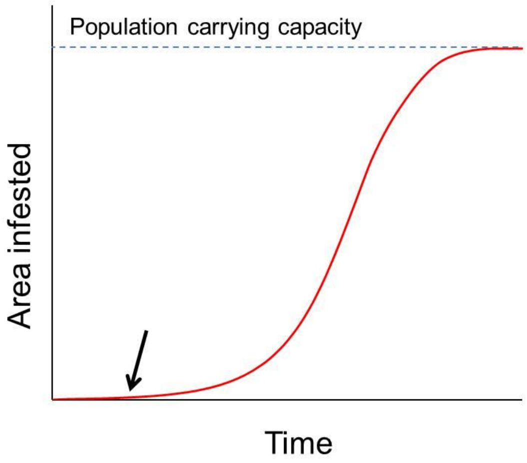

Figure 1. Logistical population growth. The arrow indicates the current area infested by *Hedychium gardnerianum* in Northland (5,000 ha) in relation to a population carrying capacity of 794,208 ha (i.e. the total area of indigenous forest, plantation forestry and indigenous scrubland, see text for details).

4.4.2 Predicting the potential impact of biocontrol against *H. gardnerianum* in New Zealand

It has been widely noted that invasive plant species usually lack the natural enemies associated with them in their native range and hypothesised that this might explain why they become invasive (Hierro et al. 2005). This hypothesis (often called the enemy-release hypothesis) is a central tenet of the use of biological control against invasive weeds. As well as forming dense monocultures, Byrne (1992) also noted that *H. gardnerianum* was found growing at very low light intensities in New Zealand. This contrasts with observations in the native range by Naik and Panigrahi (1961) who noted that *H. gardnerianum* is only found growing in sunlight and never as an undergrowth plant. The perceived vigour and ability of *H. gardnerianum* stands to colonise shady environments in New Zealand could potentially be due to an absence of damage caused by key specialist natural enemies.

A tool developed for predicting the impact of weed biocontrol based on plant traits (relative abundance in native versus exotic ranges, mode of reproduction and ecosystem invaded; Paynter et al. 2012) indicates that the impacts of biocontrol on plants that exhibit the same traits as *H. gardnerianum* have been, on average, moderate (reflecting a roughly 50:50 split between successful programs and failures). This assumes that *H. gardnerianum* is more abundant in New Zealand, compared with India: anecdotal reports (e.g. Djeddour & Shaw 2013; Fig. 2) indicate that *H. gardnerianum* does not form monocultures in the native range. It might be useful to quantify more rigorously the relative abundance of *H. gardnerianum* in New Zealand and India. This may be a good predictor of the potential impact of biological control (Paynter et al. 2012), assuming a successful biocontrol programme has the potential to reduce the biomass of *H. gardnerianum* stands in New Zealand to levels similar to that the native range.

Figure 2. Sampling *H. gardnerianum* in the native range (from: Djeddour et al. 2014).

It would also be desirable to know whether such a reduction is likely to achieve a desired goal of native plant regeneration. For example, Fowler et al. (2013) noted that for *Tradescantia fluminensis* Vell., another environmental weed in New Zealand, the threshold biomass above which native forest regeneration fails was 200 g m^{-2} (dry weight). The average biomass of *T. fluminensis* in New Zealand was 455 g m^{-2}, indicating that a mean reduction of >255 g m^{-2} (i.e. a >56% reduction in biomass) is required to restore native forest regeneration in areas invaded by *T. fluminensis.* In Brazil, where *T. fluminensis* is native, the mean biomass was 164 g m^{-2}, indicating that if biocontrol could reduce *T. fluminensis* biomass in New Zealand to levels similar to those recorded in the native range, then this should restore ecosystem function.

However, as noted in the introduction, another potential explanation for the invasiveness of *H. gardnerianum* growing in New Zealand is hybridisation: Although invasive *H. gardnerianum* growing in both New Zealand and Hawai'i is morphologically similar to *H. gardnerianum* growing in India, recent molecular work has indicated that it is a hybrid between *H. gardnerianum* and *H. coronarium* J. Koenig (G. Houliston, pers. comm.). Such hybrids may not occur naturally in the field in the native range so a survey comparing '*H. gardnerianum'* biomass in India and New Zealand may not be an appropriate comparison for making predictions about potential biocontrol impact.

Hybridisation is a factor that has explained wider ecological tolerance and invasiveness of other weed species (Ellstrand & Schierenbeck 2000). For example, in Britain *Rhododendron ponticum* colonizes areas much colder than those of its native range in Iberia. This wider ecological tolerance may be due to hybridization in Britain with the cold-tolerant *Rhododendron catawbiense* from North America (Milne & Abbott 2000). It might, therefore, be informative to compare growth rates and shade tolerance of New Zealand *H. gardnerianum*, *H. coronarium* and *H. gardnerianum* sourced from India. Moreover, knowing that New Zealand *H. gardnerianum* is a hybrid increases uncertainty regarding the impact of biocontrol as it can be harder to find agents that are capable of attacking hybrid weeds. For example, two subspecies and a hybrid subspecies of leafy spurge *Euphorbia esula* are recognised, and there is evidence that a biocontrol agent *Oberea erythrocephala* only attacks certain forms of the weed (Hansen et al. 2004). Similarly, biocontrol agent impacts against *Lantana camara* may be constrained by the presence of hybrids (Urban et al. 2011). However, testing of potential biocontrol agents to date has fortunately shown no issues with their willingness or ability to attack *H. gardnerianum* from New Zealand.

Pragmatically, it may be simplest to proceed with biocontrol and only investigate whether hybridisation is an important antagonistic factor if a biocontrol programme fails to succeed.

4.4.3 Economic data

In addition to the above knowledge gaps, better economic data on the costs of *H. gardnerianum* impacts and control would be useful when making a case for biological control. This is because the Environmental Protection Authority bases its decisions on whether the potential benefits of biological control outweigh the risks and economic data on the costs of *H. gardnerianum* is required in order to conduct a cost: benefit analysis (Hill et al. 2013).

5 Conclusions

Multiple studies in NZ and overseas have indicated that *H. gardnerianum* populations can invade undisturbed forest and inhibit the regeneration of native understorey plants. The long-term prognosis for New Zealand forests invaded by *H. gardnerianum* is not good: untreated *H. gardnerianum* patches appear capable of persisting indefinitely and forest will eventually become degraded as native plants senesce, die and are not replaced due to a lack of seedling regeneration under *H. gardnerianum*.

Although there are knowledge gaps regarding the long-term impacts of *H. gardnerianum* invasion, these impacts will clearly be detrimental and will increase as *H. gardnerianum* continues to spread. Therefore, urgent action appears justified: indeed, Williams et al. (2003) argued that prioritising the management of weed species should proceed even though their impacts are uncertain, while costs are still relatively low.

The negative impacts of *H. gardnerianum* can only be avoided if dense patches are controlled in a way that kills or inhibits *H. gardnerianum* selectively, so that native regeneration can occur. There are two options for improved management of *H. gardnerianum* in New Zealand. Either: a) increase expenditure on conventional control using herbicides; or b) increase investment in a biological control programme.

H. gardnerianum is now so widespread in New Zealand that the cost of widespread herbicide use would be astronomical (tens of millions of dollars) and would have to be an indefinite commitment as eradication is unlikely. Chemical control is therefore only likely to be affordable and environmentally safe in relatively small, intensively managed areas.

Biological control is potentially the most cost-effective method for widespread control of *H. gardnerianum*. Nevertheless, *H. gardnerianum* is considered a relatively difficult target because the candidate agent species discovered to date are difficult to rear and because the hybrid nature of New Zealand *H. gardnerianum* could potentially present additional complications. A biocontrol programme against a novel target weed such as *H. gardnerianum* is likely to cost in the region of c*.* $1–3 million, depending on the number of biocontrol agent species required to achieve control (Paynter et al. 2015) (note this is the estimated cost of developing agents up to the point that permission to release is obtained and mass-rearing and initial releases have occurred, and not counting funds spent on subsequent agent redistribution and impact monitoring). Surveys for candidate biocontrol agents of *H. gardnerianum* have already been conducted in India and testing of two candidate agent species is underway. A further investment of around $1,000,000 is likely to be required to get these agents to a stage where they could be released in good numbers. If additional agents are required to achieve sufficient control, we estimate it would cost another c*.* $640,000 per agent developed.

If suitable classical biocontrol agents cannot be established or fail to control *H. gardnerianum* in New Zealand, then the plant pathogens already present (see section 4.3, above) could potentially be bulked up and applied as mycoherbicides. This approach, however, requires considerable field testing and other research. Consequently, this technique is usually limited to targets that cause a sufficiently large problem to justify the high developmental costs. Moreover, although it has been argued that pathogens with broad host ranges can be used in mycoherbicides as long as the risks to non-target plants are understood (Bourdôt & Saville 2010), this is more appropriate for weeds that are problematic in agricultural areas (where the diversity of other species is limited) than for environmental weeds such as *H. gardnerianum*. A bioherbicide that could damage New Zealand native species would be of limited use against *H. gardnerianum* in native forests with high biodiversity values.

6 Recommendations

Biological control has potential to provide cost-effective control, and a programme is underway funded by a consortium of New Zealand and Hawai'ian funding bodies. Additional funding for biocontrol could safeguard this programme, which is at risk due to the lack of promising agents for Hawai'i, and could enable work to be expanded on other candidate agents for New Zealand.

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