Invertebrates and Pathogens Associated with Wild Ginger, *Hedychium gardnerianum* and *Hedychium flavescens* (Zingiberaceae), in New Zealand

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Contents

Summary

Project and Client

A survey of the fungi, bacteria, and invertebrate fauna associated with wild ginger, *Hedychium gardnerianum* (kahili ginger) and *Hedychium flavescens* (yellow ginger) (Zingiberaceae), in New Zealand was carried out between November 2006 and May 2007 by Landcare Research for a national collective of regional councils and the Department of Conservation.

Objective

- To survey the fungi, bacteria, and invertebrate fauna associated with wild ginger, *Hedychium gardnerianum* and *Hedychium flavescens* (Zingiberaceae), in New Zealand, and identify the herbivores (and their associated predators and parasitoids) and fungal and bacterial pathogens attacking wild ginger.

Methods

- A survey of the fungi, bacteria and invertebrate fauna associated with wild ginger in New Zealand was carried out between November 2006 and May 2007 by Landcare Research. Thirty *Hedychium gardnerianum* sites and four *Hedychium flavescens* sites were surveyed throughout the range of these species. To assist with identification of bacteria found, cultures of *Ralstonia solanacearum* were sourced from Hawai'i where it is being used as a biocontrol agent.

Results

- No specialist wild ginger invertebrates were found during the survey.
- The overall damage that could be attributed to invertebrate herbivory was minimal.
- The most obvious foliage damage appeared to be caused by the larvae of a range of moth species (especially leafrollers) and molluscs (slugs and snails).
- A sap-feeder, *Scolypopa australis* (passionvine hopper), was the only invertebrate species classed as 'abundant'.
- Thrips occasionally produce silvery-coloured patches on wild ginger foliage but probably have little effect.
- Generalist predators found on wild ginger include spiders, ladybirds, lacewings, earwigs, ants, and praying mantids.
- No specialist wild ginger pathogens were found during the survey.
- The overall damage attributable to diseases was minimal.
- A disease complex comprised of primary and secondary fungal pathogens was associated with low to moderate leaf necroses and damage.
- The ginger bacterium, *Ralstonia solanacearum*, was not isolated from plant materials collected during the survey.
- Bacterial isolates sourced from Hawai'i were identified as *Enterobacter* and not *R. solanaceanum* as expected. Enterobacter is known to sometimes overgrow *R. solanacearum* in culture and shows no promise as a potential biocontrol agent of wild ginger.

Conclusions

- Wild ginger is attacked by a wide range of native and introduced invertebrates in New Zealand but overall damage appears to be minimal and none of the herbivore niches on wild ginger are well utilised.
- Foliage feeders (most noticeably lepidopteran larvae, molluscs, and thrips) appear to be the most damaging invertebrates currently feeding on wild ginger in New Zealand.
- The diversity of generalist pathogens on wild ginger in New Zealand is low, and all of these pathogens were associated with minor disease damage to both ginger hosts.
- Although *Ralstonia solanacearum* is recorded as present in New Zealand on other hosts, the strain known to attack ginger does not appear to be established here.

Recommendations

- Given that invertebrate herbivore damage to wild ginger in New Zealand is minimal and no specialised pathogenic fungi or bacteria are known to be present on the weed in New Zealand, we recommend that a classical biological control programme for wild ginger should proceed.
- Given that the Hawaiian programme using *R. solacearum* is no-longer active, and that there may be better potential agents identified during surveys of wild ginger which are scheduled to be undertaken in its native range in coming years, we recommend that no further work be undertaken on *R. solanacearum* in the meantime.

1. Introduction

A survey of the fungi, bacteria and invertebrate fauna associated with the 2 species of wild ginger in New Zealand, *Hedychium gardnerianum* (kahili ginger) and *Hedychium flavescens* (yellow ginger) (Zingiberaceae), was carried out between November 2006 and May 2007 by Landcare Research for a national collective of regional councils and the Department of Conservation. Following a recommendation of a feasibility study investigating the prospects of biological control of wild ginger in New Zealand (Harris et al. 1996), 30 kahili ginger sites and 4 yellow ginger sites were surveyed.

2. Background

Wild ginger is regarded as a serious weed in New Zealand and a major threat to native forests (Craw 1990, Vervoort 1991). There are 2 species of wild ginger in New Zealand: kahili ginger (*Hedychium gardnerianum*) and yellow ginger (*Hedychium flavescens*). The 2 species are similar, with massive branching surface rhizomes and aerial stems up to 2 m tall. Leaves of yellow ginger are generally narrower than those of kahili ginger and its flowers are light cream in colour whilst kahili ginger flowers are lemon yellow with red stamens (Environment Bay of Plenty (EBOP) 2005).

Wild ginger can form dense colonies in native forests, with beds of rhizomes forming a dense layer up to a metre thick smothering young native plants and preventing native seedling establishment. New plants may develop from rhizome portions that have become detached from the parent plant, and a major source of spread is by people illegally dumping ginger rhizomes on roadsides or in the bush. Kahili ginger is also spread by birds such as tui and blackbirds, which disperse seeds. Yellow ginger does not produce seeds in New Zealand. Wild ginger prefers open, light-filled environments that are warm and moist, but will readily grow in partial or full shade beneath the forest canopy. Maximum growth occurs during spring and summer and the plant becomes semi-dormant during winter (Auckland Regional Council (ARC) 1999).

Kahili ginger is native to India, growing on the lower slopes of the Himalayas, while yellow ginger originates in Eastern India and Madagascar (EBOP 2005). Wild ginger was introduced to New Zealand about 130 years ago (Byrne 1992) and occurs mainly in the North Island with some coastal patches centred around human settlements in the South Island. It has spread widely since the early 1970s. Of the 2 species, kahili ginger has the widest distribution in New Zealand and is of primary concern. Kahili ginger has been introduced throughout the tropics and is now invasive in many forest ecosystems (Anderson and Gardner 1999), including forests in the Federated States of Micronesia, Cook Islands, French Polynesia, Hawai'i, New Zealand, La Reunion, South Africa and Jamaica (Invasive Species Specialist Group (ISSG) 2006). It is regarded as a weed in Brazil (R. Barreto, Federal University of Vicosa, Brazil, pers. comm.).

Chemical and mechanical control of wild ginger is labour intensive, expensive, time consuming, and often ineffective. These factors combine to make eradication unlikely. Biological control, if at least partly successful, offers some advantages over current control methods. Use of host specific biological control agents would reduce the effects of chemical herbicides on the environment, and, unlike current control methods, biological control agents act continuously and are self-dispersing. Several potentially host-specific pathogens have been documented from *Hedychium* species (Harris et al. 1996) and a thorough survey of the native range would find many more potential biological control agents. Such a survey is planned to be carried out in 2008 by CABI with funding from agencies in Hawai'i and the National Biocontrol Collective in New Zealand.

Harris et al. (1996) recommended monitoring the progress of a trial of a soilborne bacterium *Pseudomonas solanacearum* (now called *Ralstonia solanacearum*), a potential biocontrol agent being tested in an inundative biological control programme against invasive kahili ginger in the Volcanoes National Park, Hawai'i (Anderson and Gardner 1996). This bacterium is a soil-borne plant pathogen which had been isolated from three ornamental ginger species, kahili, yellow, and white ginger (*Hedychium coronarium*), in Hawai'i. It caused a significant bacterial wilt disease on all three hosts. Symptoms included yellowing, wilting, and necrosis of plant shoots and rotting of the perennial rhizomes, both of which resulted in plant death, hence its biocontrol potential. The disease is spread naturally via soil water and root-to-root transmission, and artificially through wounds and agricultural practices (e.g., infected nursery cuttings, irrigation, soil cultivation, contaminated equipment).

Despite good progress implementing *R. solanacearum* as an inundative biocontrol agent, current research activity in the Hawaiian programme (operated by Rob Anderson at United States Geological Survey (USGS) Hawai'i) has ceased indefinitely. Consequently, there are several critical knowledge gaps relevant for the New Zealand context. These gaps must be filled to help determine if *R. solanacearum* is a suitable agent to release against kahili ginger in New Zealand. Further information required includes:

- Determining how well this bacterium would grow, spread, and infect kahili ginger in the New Zealand climate; in particular, whether this strain is still pathogenic at low soil temperatures (New Zealand's mean annual average soil temperature is less than 16^{o}C).
- Determining the pathogenicity of the Hawaiian strain against New Zealand form(s) of wild ginger.
- Undertaking the genetic characterisation and identification of the Hawaiian strain used by Rob Anderson. So far, it has only been identified using traditional host range and phenotyping methods.
- Determining the host specificity and host range stability of this strain against the New Zealand non-target test list.

This information will be required before this bacterium could be prioritised for release in New Zealand. (Refer to Appendix 2 for additional information on this bacterium).

This report describes the results of a survey of the fungi, bacteria, and invertebrates associated with wild ginger in New Zealand. The main aims of the survey were to determine whether any specialist wild ginger fungi, bacteria, or invertebrates are already present in New Zealand; to determine whether any generalist pathogens or invertebrate herbivores are adversely affecting wild ginger in New Zealand; and to record the invertebrate parasitoids and predators associated with the herbivorous invertebrates on wild ginger.

3. Objective

To survey the fungi, bacteria, and invertebrate fauna associated with wild ginger, *Hedychium gardnerianum* and *Hedychium flavescens* (Zingiberaceae), in New Zealand, and identify the herbivores (and their associated predators and parasitoids) and fungal and bacterial pathogens attacking wild ginger.

4. Methods

4.1 Invertebrates

We surveyed the invertebrate fauna of wild ginger, *Hedychium flavescens* (yellow ginger) and *Hedychium gardnerianum* (kahili ginger), at 34 New Zealand sites, ranging from Kaeo in the north to Greymouth in the south, between November 2006 and May 2007 (Fig. 1 and Fig. 2). Thirty kahili ginger sites (Fig. 1) and four yellow ginger sites (Fig. 2) were surveyed. At each site, 10 collection locations were selected. A collecting tray, 80 cm x 80 cm, was placed under suitable parts of selected plants, and the foliage above the tray was hit five times with a solid stick. Most invertebrates that fell onto the tray were collected with an aspirator and preserved in 95% alcohol. Caterpillars (Lepidoptera) were collected live and placed with wild ginger foliage in ventilated containers to be reared to the adult stage for identification or to identify parasitoids emerging from the larvae.

We made a rapid visual inspection (generally less than 1 minute for each of the 10 collection locations at each site) of foliage, growing points, and stems for signs of invertebrates such as gall-formers, leaf miners, stem borers, and scale insects. We dug up the tuberous root system of 5 wild ginger plants to look for signs of invertebrates or their damage. At each site, we estimated by eye the amount of herbivore-related foliage damage and noted the likely cause of the damage (e.g., adult beetles, leafroller caterpillars).

Where feasible invertebrates were identified to species or genus level. When this was not feasible they were placed into groups of related species, e.g., Araneida (spiders). They were then ranked on a scale of abundance according to the total number of individuals collected and the number of sites at which they were present and were classed as rare, occasional, common, or abundant according to the definitions below:

rare: fewer than 5 individuals collected
occasional: 5–24 individuals collected, **or** present at fewer than five sites
common: 25+ individuals collected **and** present at five or more sites
abundant: 200+ individuals collected **and** present at 10 or more sites

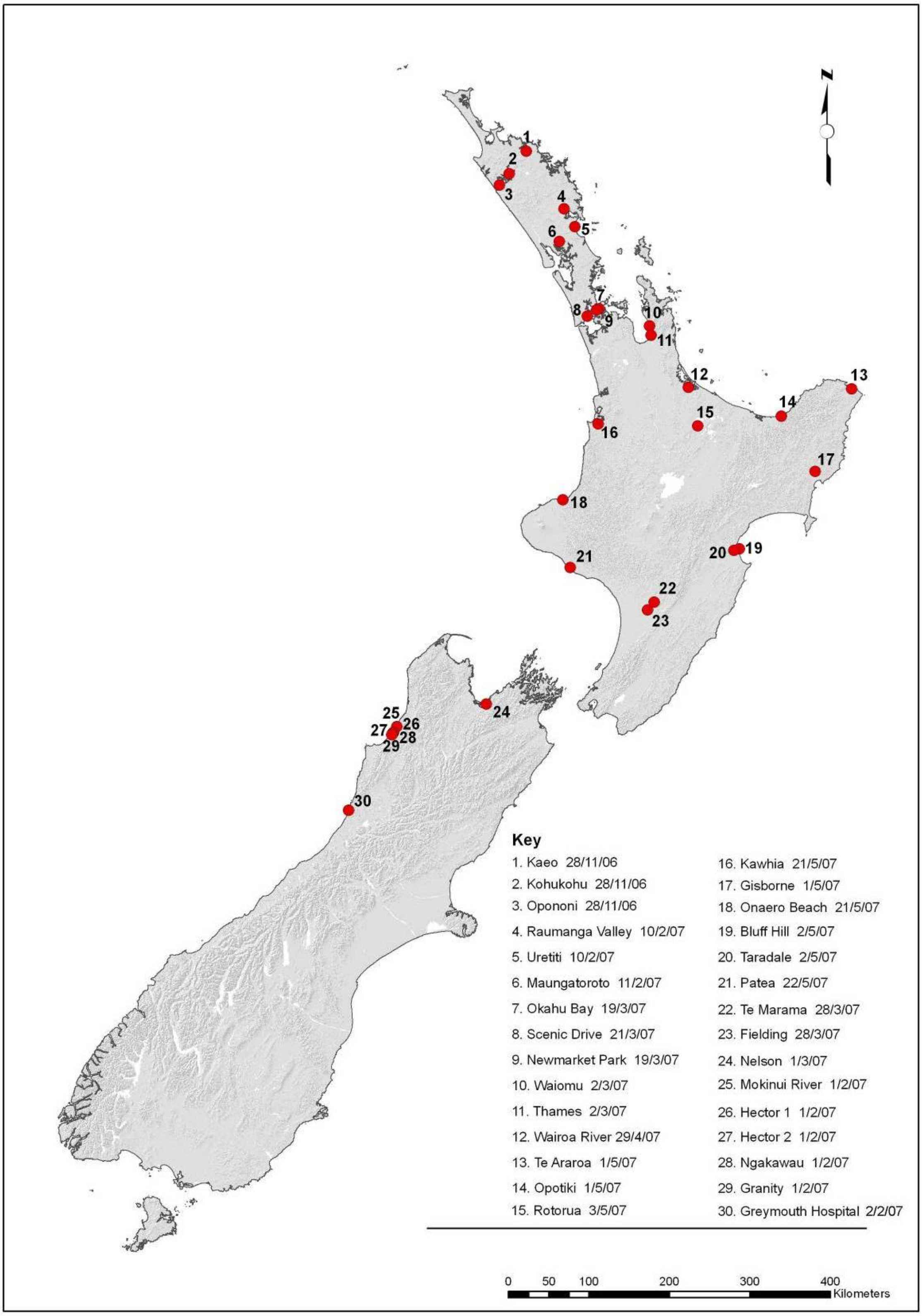

Fig. 1 *Hedychium gardnerianum* sites sampled for fungi, bacteria, and invertebrates (2006–07).

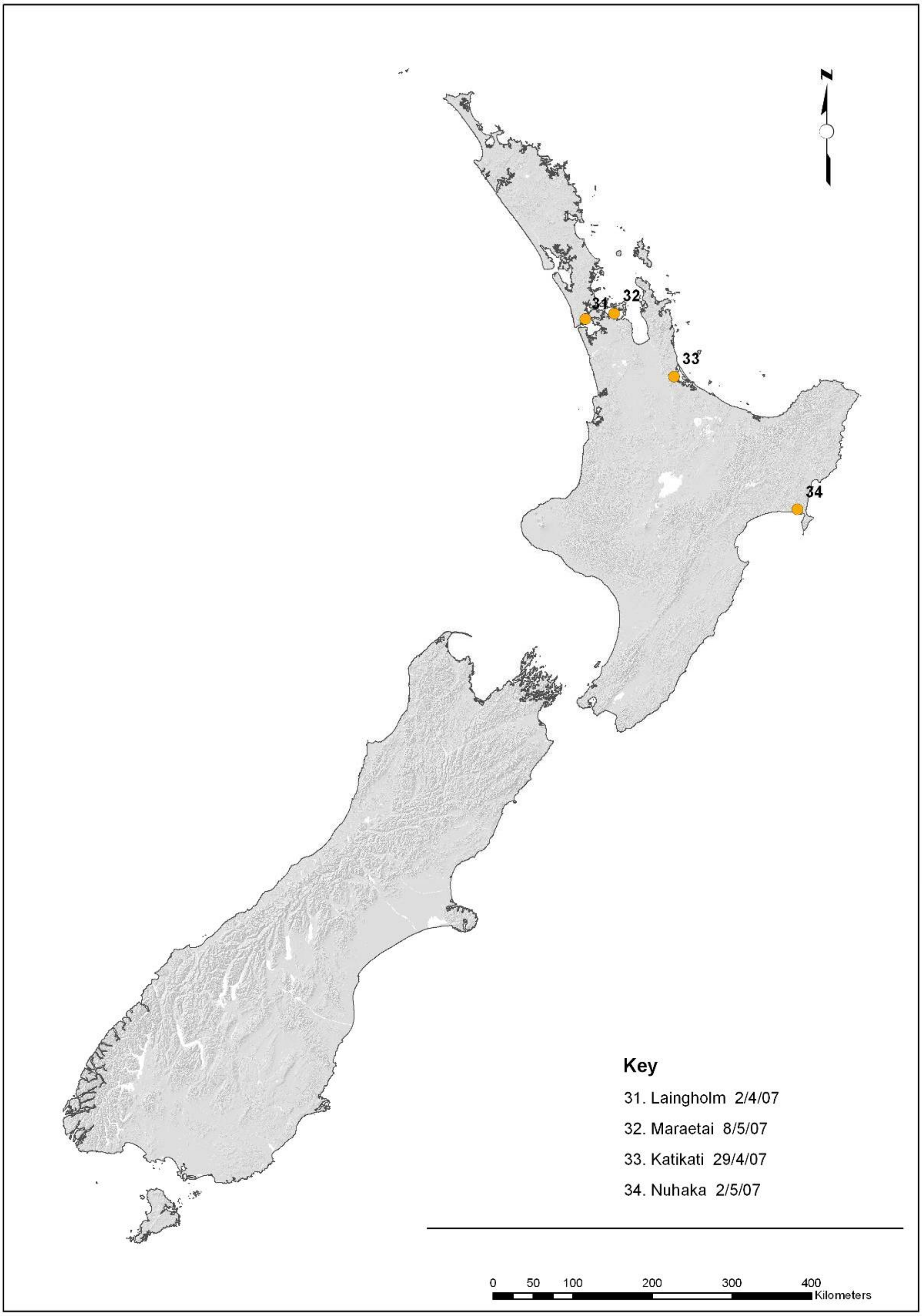

Fig. 2 *Hedychium flavescens* sites sampled for fungi, bacteria, and invertebrates (2006–07).

4.2 Fungi

Fungi associated with wild ginger were surveyed at the same 34 sites (Fig. 1 and Fig. 2) from which invertebrates were collected. At each site, plants at each of the 10 invertebrate collection points were inspected closely for signs of pathogen damage and other wild ginger plants in the area were examined more superficially for obvious disease symptoms. Diseased leaves, leaf petioles, stems, flowers, flower petioles, berries, or rhizomes/roots were placed in paper bags and kept cool in transit before processing. Collected material was examined within 5 days of collection.

In the laboratory, disease symptoms were recorded and photographed. Small pieces of tissue (c. 3 × 3 mm) were cut from the edge of diseased areas and surface sterilised by immersion in 2% hypochlorite for 1 minute followed by rinsing in 2 beakers of sterile water. The tissue fragments were blotted dry with sterile filter paper and placed on potato dextrose agar (Difco Labs, Detroit, MI, USA) with 0.02% streptomycin (Sigma, St Louis, MI, USA), in 9-cm Petri dishes. Plates were incubated under near-ultraviolet and white light (12 h photoperiod) at 22 ± 2°C (day) and 18 ± 2°C (night). An additional subsample of excised fragments of symptomatic tissues, not surface sterilised, was placed on moist blotting paper in a humid chamber for 1–3 days then necrotic areas were searched under a dissecting microscope for fungal reproductive structures.

Fungal colonies growing out of the tissue fragments and spores produced were identified to genus or species level using taxonomic literature, morphological and cultural characters, and molecular sequencing of fungal DNA (White et al. 1990).

Survey of bacteria on ginger in New Zealand

Bacteria associated with disease symptoms on ginger were assessed using a subsample of plant materials collected from seven surveyed sites (6 kahili ginger, 1 yellow ginger). As well as surveying for any pathogenic plant bacteria on ginger, we wished to determine if *R. solanacearum,* the bacterium successfully used for inundative biological control of kahili ginger in Hawai'i, was already present on ginger in New Zealand. Symptomatic rhizome, root, and shoot samples that resembled the described symptoms of *R.* infection in Hawai'i (i.e. unhealthy appearing patches of ginger where there is general dieback, wilt or yellowing of the shoots, and/or small water-soaked leaf lesions (Rob Anderson 2006 unpubl. data)) were processed to isolate bacteria, using standard microbiological plating methods (Janse 2005).

Small internal sections (<4 mm) of symptomatic tissues were excised at the leading edge of necroses, placed into a drop of sterile water, crushed with a sterile scalpel until the tissues and water were well mixed, and left for at least 5 minutes to allow the bacteria to diffuse into the water. A loopful of the mixture was then streaked onto a general isolation medium for bacteria [King's B, Sigma] and a semi-selective/diagnostic medium for *R. solanacearum* [Kelman's medium (Kelman 1954)]. Plates were incubated at 25^{o}C for up to 24, 48 and 72 hours.

Identification of Hawaiian isolates

To confirm the genetic identity of the *R. solanacearum* strain used in the biological control programme against kahili ginger in Hawai'i, 8 isolates stored by Rob Anderson were imported into Landcare Research's ICMP Quarantine laboratories in Auckland. This bacterium had been characterised phenotypically using biochemical and morphological methods (Anderson & Gardner 1999; Ishi & Aragaki 1963); however, since its original isolation and description in the 1960s, these traditional methods have been superseded by various molecular methods which use bacterial DNA to genotype and identify bacteria (Yu et al. 2003, Soulanoubat et al. 2002). Our genetic identification of the isolates used standardised molecular techniques (Janse 2005).

R. solanacearum has been divided into five races based on virulence and host range, and six biovars based on their biochemical properties (Hayward et al. 1994). Previous studies on the molecular diversity of *R. solanacearum* in Hawai'i genetically differentiated pathogenic *R. solanacearum* strains from edible ginger (*Zingiber officianale*) from other pathogenic races (Yu et al. 2003). Therefore, genotyping the kahili ginger strain of *R. solanacearum* might help determine if this strain is taxonomically distinct within race 4 of *R. solanacearum*. While better information about the phylogeny (relatedness) of the ginger biocontrol strain compared to the strains which attack non-target crops may also aid the assessment of its safety for release into the New Zealand environment.

Pathogenicity of New Zealand and Hawaiian isolates

In vitro assays were undertaken in the quarantine containment laboratory to assess the pathogenicity of bacteria isolated from plant materials in New Zealand. Hawaiian isolates were also included in this assay to complete the identification of this exotic strain (i.e. to confirm these isolates were the same pathogenic forms originally described from ginger). Surface sterilised sections of rhizome were excised from both edible and kahili ginger and placed on moist filter paper inside a petri dish or plastic sealed container. Three New Zealand isolates and 8 Hawaiian isolates were cultured on Kelman's medium for 48 hours at 25^{o}C, then inoculated onto the clean, cut surface of the excised rhizome tissue using a sterile scalpel. Inoculated plant sections were then placed inside temperature controlled incubators and incubated in darkness at 6 temperatures (18, 25, 28, 31.5, 35^{o}C). Each inoculation and temperature treatment was replicated three times. Disease symptoms were assessed after 3, 5, 7, and 10 days' incubation. As a positive growth control, each isolate was inoculated onto King's B agar plates and incubated at each temperature.

5. Results

5.1 Invertebrates

A full list of invertebrates associated with wild ginger, *Hedychium gardnerianum* and *Hedychium flavescens*, during this survey is presented in Appendix 1. None are specialists on wild ginger.

Herbivores

A total of 71 herbivorous invertebrate species was recorded from the 2 species of wild ginger during this survey. A further 10 groups of taxonomically related herbivorous species were recorded (where identification to species level was not feasible).

Invertebrates were collected from 30 kahili ginger sites and 4 yellow ginger sites, so it was only possible to calculate frequency categories (as described in the Methods section) for kahili ginger.

For kahili ginger only one herbivorous species, the passionvine hopper *Scolypopa australis* (Hemiptera: Ricaniidae) was classed as 'abundant'. A further 7 herbivorous species or taxonomic groupings were classed as 'common', 21 were 'occasional', and 46 were 'rare' (Appendix 1). Table 1 lists the abundant, common, and occasional herbivorous invertebrates collected from kahili ginger.

Twenty-two herbivorous species or taxonomic groupings were recorded from yellow ginger at the four survey sites. Six of these species were not recorded from kahili ginger (Table 1; Appendix 1).

Foliage feeders: Foliage damage attributable to invertebrate herbivory was minimal. Leaves that were more than 5% consumed were rare, and the overall amount of foliage consumed or damaged by herbivores was estimated to be less than 1%.

The larvae of a range of moth species, especially Tortricidae (leafrollers) and to a lesser extent Noctuidae, occasionally caused obvious damage to leaves. Leafroller larvae were sometimes found still inside 'rolled' leaves on the plant, but more commonly they were collected from the beating tray after being dislodged. Several moth larvae died while being reared to the adult stage; parasitoids emerged from some of these (Appendix 1). Very distinctive foliage damage (Fig. 3) consisting of neat rows of holes across a leaf was occasionally observed. It is thought that these holes form when a herbivore (possibly a caterpillar) chews through several layers of a tightly rolled new leaf.

Fig. 3 Wild ginger leaf showing rows of holes thought to be caused by damage while tightly rolled.

Foliage occasionally showed typical slug or snail damage and slime trails were sometimes visible.

Foliage-feeding thrips, banana silvering thrips (*Hercinothrips bicinctus*), and greenhouse thrips (*Heliothrips haemorrhoidalis*) were collected from 8 sites, at some of which they were numerous, producing distinctive silvery-coloured patches on the foliage.

Thirty-three species or related groups of herbivorous adult beetles were collected during the survey but foliage damage attributed to beetles was minimal. Many of these species might not have fed on wild ginger but used the foliage as shelter. For example, three weed biocontrol agents, *Agasicles hygrophila* (alligator weed beetle), *Lema cyanella* (Californian thistle leaf beetle), and *Longitarsus jacobaeae* (ragwort flea beetle) were found during the survey and it is highly unlikely that any of these would eat wild ginger.

Flower feeders: Damage attributable to invertebrates was rare on ginger flowers. However, *Thrips obscuratus* (New Zealand flower thrips), was commonly found during the survey and they are cause considerable damage to flowers of a wide range of plant species (Mound & Walker 1982). Moth larvae and *Forficula auricularia* (European earwigs), may also consume wild ginger flowers (http://www.extento.hawaii.edu/Kbase/////Crop/Type/chelisoc.htm).

Sap-feeders: *Scolypopa australis* (passionvine hopper) was the only sap-feeding invertebrate classed as ‘abundant’. A further 19 species or groups of sap feeders were found during the survey (Appendix 1). Damage caused by sap feeders, either directly by removing nutrients or indirectly by puncturing the plant and possibly allowing entry of pathogens, is very difficult to quantify.

Leaf miners: No leaf-mining invertebrates were found on wild ginger during this survey.

Stem borers: No stem-boring invertebrates were found on wild ginger during this survey.

Root/tuber feeders: Several invertebrate groups (e.g., amphipods, slaters, collembola, ants, and molluscs) were associated with wild ginger roots and tubers but none were considered to be causing noticeable damage to living tissues. Most were probably using the tubers for shelter.

Table 1 Herbivorous invertebrates collected from wild ginger at 34 New Zealand sites during 2006–2007.

Note: For kahili ginger, only "abundant", "common", and "occasional" species are listed here, except where the species was also found on yellow ginger. All species, including those classed as "rare", are listed in Appendix 1.

Taxon	Common Name	Feeding Site	*H. gardnerianum* Abundance class (Number of individuals)	*H. flavescens* Number of individuals
Phylum Mollusca	**Molluscs**			
Class Gastropoda	**slugs and snails**			
Cantareus aspersus Müller	brown garden snail	foliage	common (48)	9
unidentified molluscs		foliage	common (72)	1
Phylum Arthropoda				
Class Insecta	**Insects**			
Coleoptera	**beetles**			
Cerambycidae	**longhorn beetles**			
Psilocnaeia sp.		adults: foliage	rare (3)	1
Xylotoles sp.		adults: foliage	occasional (11)	1
Curculionidae	**weevils**			
Hylurgus ligniperda (Fabricius)		foliage	nil	1
Microcryptorhynchus sp.		foliage	nil	1
Peristoreus sp.		foliage	occasional (7)	
Scolopterus penicillatus White	four-spined weevil	foliage	occasional (6)	
Sericotrogus subaenescens Wollaston		foliage	nil	2
Stephanorhynchus curvipes White		foliage	occasional (15)	
Elateridae	**click beetles**			
Conoderus exsul (Sharp)	pasture wireworm	adults: foliage/flowers	occasional (11)	
Conoderus sp.		adults: foliage/flowers	rare (1)	1
Dermaptera	**earwigs**			
Forficula auricularia Linnaeus	European earwig	leaves/flowers/fruit/ insects	occasional (23)	24
Hemiptera	**bugs**			
Acanthosomatidae				
Rhopalimorpha sp.		sap feeder	occasional (6)	
Aphididae	**aphids**			
unidentified Aphididae		sap feeder	occasional (13)	

Taxon	Common Name	Feeding Site	*H. gardnerianum* Abundance class (Number of individuals)	*H. flavescens* Number of individuals
Aphrophoridae	**spittle bugs**			
Carystoterpa sp.		sap feeder	occasional (7)	
Philaenus spumarius (Linnaeus)	meadow spittle bug	sap feeder	occasional (8)	1
Cicadellidae	**leafhoppers**			
unidentified Cicadellidae		sap feeder	occasional (23)	
Cixiidae				
Koroana sp.		sap feeder	occasional (11)	
Delphacidae				
unidentified Delphacidae		sap feeder	occasional (10)	
Flatidae	**planthoppers**			
Siphanta acuta (Walker)	green planthopper	sap feeder	common (116)	32
Siphanta acuta (Walker) (egg batch)	green planthopper eggs		rare (1)	1
Lygaeidae	**seed bugs**			
Rhypodes sp.		sap feeder	occasional (5)	
Membracidae				
Acanthucus trispinifer (Fairmaire)		sap feeder	nil	4
Miridae	**mirid bugs**			
Sidnia kinbergi (Stål)	Australian crop mirid	sap feeder	nil	1
unidentified Miridae		sap feeder	common (45)	
Pentatomidae	**shield bugs**			
Cuspicona simplex Walker	green potato bug	sap feeder	occasional (5)	
Glaucias amyoti (Dallas)	New Zealand vegetable bug	sap feeder	rare (2)	1
Nezara viridula (Linnaeus)	green vegetable bug	sap feeder	common (79)	8
unidentified Pentatomidae		sap feeder	occasional (8)	1
Rhyparochromidae				
Stizocephalus brevirostris Eyles		seed/sap feeder	nil	1
Ricaniidae	**planthoppers**			
Scolypopa australis	passionvine hopper	sap feeder	abundant	37

Taxon	Common Name	Feeding Site	*H. gardnerianum* Abundance class (Number of individuals)	*H. flavescens* Number of individuals
(Walker)			(1031)	
unidentified Hemiptera (nymphs)			occasional (23)	
Lepidoptera (collected as larvae and reared to adult for identification)	**moths and butterflies**			
Tortricidae	**leaf rollers**			
Ctenopseustis obliquana (Walker) **<u>or</u>** *C. herana* (Felder and Rogenhofer)		foliage	occasional (5)	
unidentified Tortricidae		foliage	occasional (12)	2
Orthoptera	**crickets, grasshoppers, weta**			
Anostostomatidae				
Hemideina thoracica White	Auckland tree weta	foliage	rare (1)	2
Tettigoniidae	**long-horned grasshoppers**			
Caedicia simplex (Walker)	katydid		occasional (6)	
Thysanoptera	**thrips**			
Sub-Order Terebrantia				
Thripidae				
Heliothrips haemorrhoidalis (Bouche)	greenhouse thrips	foliage	occasional (28)	
Hercinothrips bicinctus (Bagnall)	banana silvering thrips	foliage	common (166)	
Thrips obscuratus (Crawford)	New Zealand flower thrips	flowers	common (196)	5

Predators and parasitoids

Predatory and parasitic species that may inhibit introduced biological control agents for wild ginger are recorded in Appendix 1.

5.2 Fungi

At all surveyed sites, all plants of both ginger species sampled had only low to moderate levels of disease. In the field, symptoms were usually sporadic and comprised superficial leaf necrosis (Fig. 4) that caused minor or insignificant damage to the weed. Most rhizome materials collected were asymptomatic apart from occasional necrotic rots which were not considered to be systemic (Fig. 5). Twenty-four fungal species were identified from these mild to moderate necroses. Three of these fungi were identified directly and solely from symptomatic plant tissues with the remainder being isolated from tissues into pure culture.

Fig. 4 Most commonly observed symptoms of leaf damage observed on wild ginger. Initial leaf spot lesions, shown on the left, progressed to the larger, 'streaked' leaf lesions shown on the right.

Fig. 5 Rhizome rot sampled from wild ginger

From 390 plant tissue samples plated, we obtained 292 fungal isolates (Table 2). Fungal colonisation ([total number of fungal isolates/number of tissue fragments] × 100), averaged across all tissue types (leaf flower, rhizome), was 75% as many tissues had no cultural isolates present. Mean fungal colonisation for wild ginger fell in the middle of the range recorded in previous Landcare Research fungal weed surveys. A further nine fungi were identified from the additional 64 tissue fragments incubated in humid chambers, but most were saprophytic species. However, a species of *Mycosphaerella* and a *Cercospora*-like fungus were observed directly sporulating on the surface of symptomatic leaf tissues. Both species may have been primary leaf pathogens; however, humid chamber samples were often overgrown with the saprophytic and secondary colonisation of *Botrytis* and *Alternaria*.

Table 2 Relative abundance of fungi collected from kahili and yellow ginger at 34 New Zealand sites during 2006–2007. (Sites= number of sites where each fungus present; Isolates = number of isolates; L= recorded from leaf/stem tissue; F= recorded from flower/fruit tissue; R = recorded from rhizome-root tissue); * = not isolated.)

			Kahili ginger			**Yellow ginger**		
Species	**Sites**	**Isolates**	**L**	**F**	**R**	**L**	**F**	**R**
Ascomycete fungi:								
Mycosphaerella sp*	1*	2*	+	-	-	+	-	-
Coelomycete fungi:								
Cercospora/ Pseudocercospora-like*	6*	6*	+	-	-	-	-	-
Colletotrichum acutatum	1	4	-	4	-	-	-	-
Colletotrichum boninense	1	6	6	-	-	3	-	-
Colletotrichum gloeosporioides	9	18	14	-	4	-	-	-
Coniothyrium sp.	1	1	1	-	-	-	-	-
Microsphaeropsis sp.	1	2	2	-	-	-	-	-
Pestalotiopsis sp.	2	2	1	-	1	-	-	-
Phoma spp. (3+ spp)	6	15	10+	-	2	3+	-	-
P. pinodella								
P. glomerata								
P. exigua								
Phomopsis sp.	12	23	21	-	-	2	-	-
unidentified species of Coelomycetes	14	37	27	-	5	1	-	4
Hyphomycete fungi:								
Acremonium strictum	2	7	5		3	1		
Alternaria alternata	10	36	25+	-	2	9+	-	-
Botrytis cinerea	1	3	3+	-	-	+	-	-
Cladosporium cladosporioides	5	11	10	-	1	-	-	-
Curvularia sp.	1*	1*	-	-	-	+	-	-
Cylindrocarpon destructans	1	3	-	-	3	-	-	-
Epicoccum purpurascens	9	29	22	5	-	-	-	-
Fusarium spp.	13	31	16	-	6	5	-	4

Species	Sites	Isolates	Kahili ginger			Yellow ginger		
			L	F	R	L	F	R
F. avenaceum	7	13	9	-	1	1	-	1
F. culmorum	3	5	-	-	3	-	-	2
F. lateritium	4	6	4	-	-	2	-	-
F. oxysporum	4	4	1	-	2	-	-	1
F. solani	1	2	2	-	-	-	-	-
F. tricinctum	1	1	-	-	-	1	-	-
Nigrospora oryzae	1	1	-	-	1	-	-	-
Paecilomyces sp.*	1*	1*	-	-	-	+	-	-
Penicillium spp.	4	4	3+	-	-	1+	-	-
Stemphylium sp.*	1*	1*	+	-	-	-	-	-
<u>Other fungi:</u>								
Aureobasidium pullulans	4	4	3	1	-	-	-	-
Sterile fungi (*Mycelia sterilia*)	15	38	30	-	3	5	-	-
Xylaria spp. and other endophytic types	7	8	3	-	3	2	-	-
Yeasts	1	6	1	3	2	-	-	-
		Sub totals:	203	13	36	32	-	8
Overall Totals	**34**	**292**		**252**			**40**	

* = fungi identified directly from excised leaf tissues in humid chamber; as these species were not isolated into pure culture they are not included in the number of isolates tally.
+ = fungi also observed sporulating on diseased tissues in humid chambers.

Over 40 recognisable taxonomic units (RTUs) were associated with disease symptoms on ginger, most being associated with the leaf necroses. Of these fungi, 29 were identified to genus and/or species level (Table 2). Many isolates were classified into RTUs belonging to the sterile fungi class Agonomycetes (*Mycelia sterilia*) or unidentified pycnidial fungi (Coelomycetes) which proved difficult to identify based on cultural and morphological characters alone. Many of the pycnidial fungi produced fruiting bodies (= pycnidia) in culture but did not develop further to produce diagnostic spores inside their pycnidia, and the sterile fungi do not form reproductive spores in culture. Identification of these fungi would require further cultural techniques to induce fertile pycnidia and/or molecular methods e.g., genetic ITS sequence data. Both approaches were beyond the resources of this project. However, as overall damage to both ginger species was insignificant, we do not recommend further taxonomic investigation of such isolates for biocontrol purposes.

The most frequently encountered group of fungi isolated from diseased leaf tissues were the Coelomycetous fungi which were generally associated with minor and superficial leaf lesions collected from all 34 sites. In pure culture, 111 Coelomycete isolates were obtained (Table 2); these were *Colletotrichum* spp. (31 isolates), *Microsphaeropsis* sp. (2 isolates), *Pestalotiopsis* sp. (2 isolates), *Phoma* spp. (at least 3 species, 15 isolates), and *Phomopsis* sp. (23 isolates), as well as a range of unidentified Coelomycetous isolates (37). Some of these isolates may represent the asexual (anamorph) stage of the *Mycosphaerella* fungus observed sporulating directly on the leaf tissues, as these leaf symptoms closely resemble other *Mycosphaerella–Cercospora* type leaf diseases on related Zingiberaceae hosts such as white ginger (*Hedychium coronarium*), cultivated ginger (*Zingiber officinale*), banana (*Musa*), and bird-of-paradise (*Strelitzia reginae*) (Fig. 6).

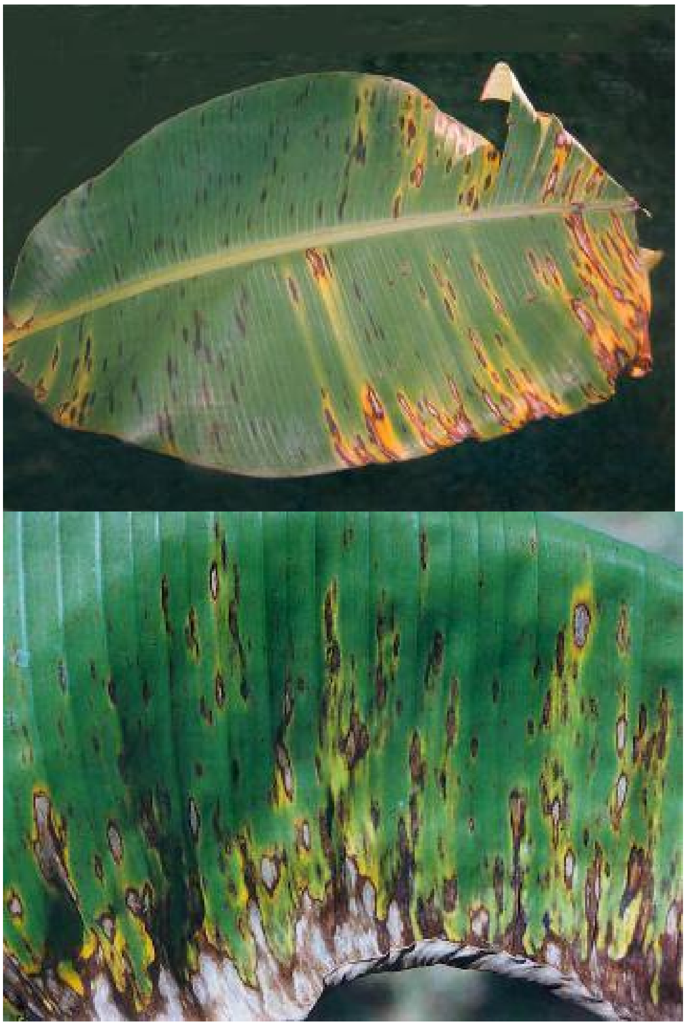

Fig. 6 Disease symptoms of *Mycosphaerella/Cercospora* infection on banana leaves.
Source: Liberto et al. 2006.

There are many case studies of where plant pathogenic species of *Colletotrichum, Microsphaeropsis, Phoma* and *Phomopsis* have been successfully explored for weed biocontrol. For example *Phomopsis* and *Microsphaeropsis* have been recently trialled against thistle species (Moran 2007, Ash *et al.* 2007), and *Phoma* against *Gaultheria* (Zhao & Shamoun 2006) and dandelion (Stewart-Wade & Boland 2004). Internationally host specific strains of *Colletotrichum* are now routinely used for weed biocontrol both in classical and inundative (mycoherbicide) systems. However, as overall damage caused by these Coelomycetous fungi to wild ginger was insignificant, we do not recommend further taxonomic investigation of such isolates for biocontrol purposes.

The remaining leaf isolates were Hyphomycetous species such as *Acremonium strictum, Botrytis cinerea,* and *Fusarium*; they were either weak or secondary pathogens (Table 2).

Disease damage on flower and fruit tissues was minimal, mainly comprising discolouration and browning. Because only saprophytic fungi, e.g., *Epicoccum purpurascens,* were obtained from the affected tissues, symptoms probably resulted from natural senescence. The main symptom on fruit was the appearance of irregular shaped tiny speckled lesions (>4mm diameter), from which *Colletotrichum* cf *acutatum* was isolated.

Although the rhizome and root tissues were surveyed primarily for the presence of the *R. solanacearum* bacterium in New Zealand, some minor fungal rots were observed (Fig. 5). Fungi associated with these symptoms were ubiquitous, soilborne root pathogens like *Cylindrocarpon destructans* and *Acremonium strictum*, all of which have broad host ranges and occur worldwide (Farr et al. 2007); therefore, they are of no potential use for biocontrol. A range of common soilborne *Fusarium* species were also identified from the rhizome rots, and although a *Fusarium* root rot disease has devastated cultivated ginger (Trujillo 1963), the symptoms associated with *Fusarium* spp. in New Zealand were not of the same serious magnitude.

The most common leaf damage on both ginger species was that associated with a Coelomycete disease complex (= a disease caused by more than 1 species acting synergistically), as this damage was observed on most leaves sampled from 26 of the 34 sites surveyed. Its initial symptoms were characteristic chlorotic yellow circular spots or elongated flecks, usually located at or near the leaf edge. As the lesions enlarged, the central tissues dried out, turning tan with a darker brown-red rim and bright yellow chlorotic halo (Fig. 4). As the disease developed, the lesions enlarged, spreading from the leaf margins inwards along the leaf veins towards the leaf midrib. This pattern of spread along the leaf veins made the overall leaf symptoms appear as large chlorotic yellow-brown streaks (Fig. 4). The entire area of infected leaf tissue turned tan-brown, finally becoming discoloured and dry, with large yellow transition zones between the borders and the green leaf tissue. A representative specimen exhibiting these symptoms was deposited in Landcare Research's PDD Herbarium collection at Auckland.

5.3 Bacteria

New Zealand survey

Several hundred isolates were obtained from the lower stem, rhizome, and root of both ginger species. All the bacterial colony forming units (CFUs) isolated onto Kings B medium were determined to be naturally occurring saprophytic soilborne or plant surface bacteria. However, on the semi-selective Kelman's medium 15 isolates appeared to be phenotypically similar to the non pathogenic forms of *R.* that occur in Hawai'i (Fig. 7). Molecular methods (DNA sequencing) were used to identify these bacteria which included species of *Erwinia* (isolate A16; see Fig. 8). Two of these isolates (A16 and A17) were selected for pathogenicity testing against ginger as they were originally isolated from a severe stem rot (Fig. 9).

Fig. 7 Hawaiian isolates cultured on Kelman's medium at 25°C

Identification of Hawaiian isolates

Molecular characterisation of the Hawaiian isolates did not confirm any of the 8 isolates as being *Ralstonia solanacearum*. Seven were identified as the same species of *Enterobacter*, (Fig. 8) which is taxonomically distant from *Ralstonia* and its relatives.

A previous study of the bacteria associated with ginger wilt in Hawai'i reported that two species of *Enterobacter* (*E. asburiae* and *E. cloaceae*) are frequently isolated from ginger rhizomes, and in fact overgrow *R. solanacearum* in culture. Alvarez *et al.* 2003). Therefore it also likely that these *Enterobacter* isolates overgrew Rob Anderson's *R. solanacearum* isolates at some point in the isolation and culturing process in Hawai'i.

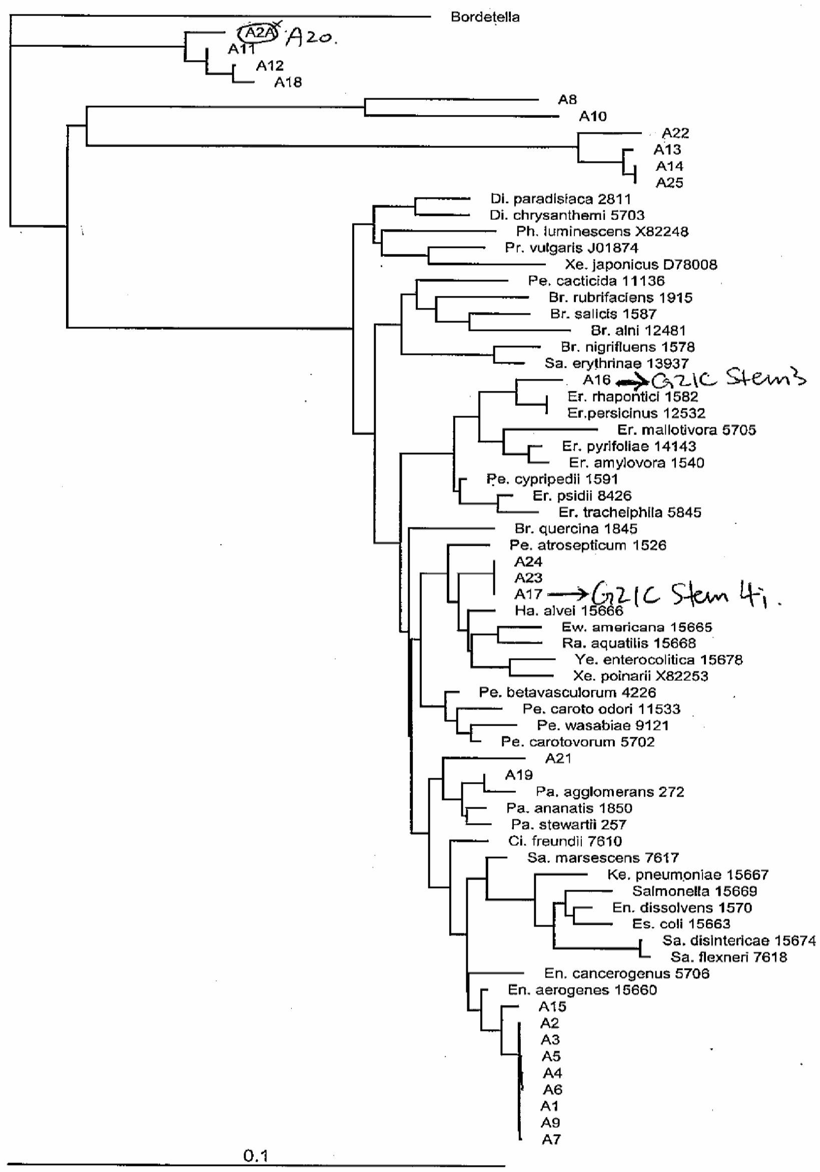

Fig 8 Genetic phenogram of bacterial isolates obtained from ginger in New Zealand and Hawai'i. (A1-7, A9 = isolates obtained from Rob Anderson identified as *Enterobacter;* NZ ginger isolates A8, A10- A25).

Pathogenicity of New Zealand and Hawaiian isolates

None of the bacterial isolates (*Erwinia* from New Zealand, and *Enterobacter* from Hawai'i) produced consistent signs of disease on either ginger species, at any of the incubated temperatures. Pathogenic strains would have produced lesions across the replicate rhizomes and temperature treatments, but this characteristic was not observed for any bacterium. A very few inoculated rhizomes did show rot lesions after 3 days' incubation (Fig. 9), but because fungal mycelium was present by days 7 and 10, these symptoms were probably caused by latent secondary fungal pathogens already present in the tissues at the time of collection. Control growth plates confirmed all bacteria were viable. As pathogenicity was not confirmed for any tested bacterial isolate, the New Zealand isolates hold no future potential for biocontrol and nor do any of the exotic *Enterobacter* isolates.

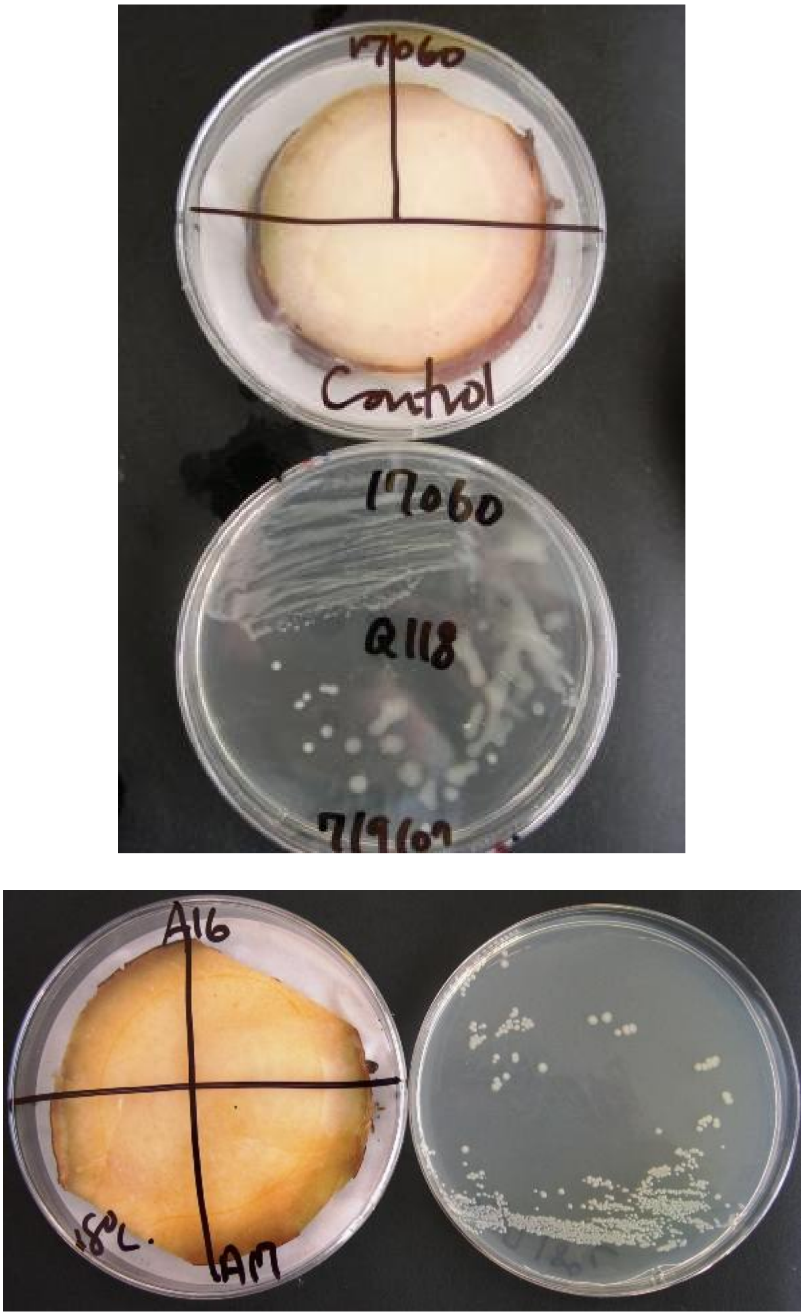

Fig. 9 Pathogenicity *in vitro* assay showing excised Kahili ginger sections inoculated with bacterial isolates.

Top: no symptoms after being inoculated with *R. solanacearum*; Bottom: minor rot symptoms after being inoculated with a NZ isolate of *Erwinia* (A16), but these symptoms caused by latent secondary fungal pathogen, *Fusarium oxysporum*.

6. Conclusions

6.1 Invertebrates

A wide range of native and introduced invertebrates is associated with wild ginger in New Zealand; however, we found no specialised, wild ginger feeding invertebrates during this survey. While foliage feeders (particularly lepidopteran larvae, molluscs, and thrips) appear to be the most damaging invertebrates currently feeding on wild ginger in New Zealand, damage caused by invertebrate herbivory could not be considered significant. The overall amount of wild ginger foliage that appeared to have been consumed or damaged by herbivorous invertebrates at our survey sites was estimated to be less than 1%.

The combined effect of generalist predators such as spiders, earwigs, ants, and praying mantids could inhibit the effectiveness of some potential invertebrate biological control agents for wild ginger; in particular, the parasitoids identified during this survey would probably affect some potential lepidopteran biological control agents. For example, *Meteorus pulchricornis* is known to have an extremely large host-range (attacking hosts from eight lepidopteran families in New Zealand; Berry & Walker 2004).

Specialised wild ginger biocontrol agents are unlikely to encounter significant competition from resident herbivores as none of the herbivore niches on wild ginger are well utilised in New Zealand; indeed, some (e.g., leaf-mining and stem-mining) do not appear to be utilised at all. Therefore, there is considerable scope for the introduction of host-specific invertebrate biocontrol agents that could markedly reduce the vigour of wild ginger in New Zealand.

6.2 Fungi

Very few fungal pathogens have been reported on either kahili ginger or yellow ginger in their invasive ranges worldwide (Farr et al. 2007). Our New Zealand survey also found few primary pathogens on both hosts, and none of those identified is likely to be a specialised ginger pathogen. Therefore, no species identified has much biocontrol potential, particularly because cumulative damage to both hosts was low and did not halt the invasion and spread of either ginger species.

6.3 Bacteria

The bacterial survey did not detect any isolates of *R. solanacearum*, nor any other plant bacterium that was a primary disease agent of wild ginger in New Zealand. The Hawaiian isolates obtained from Rob Anderson were identified as an *Enterobacter* species, probably originating as cultural contaminant overgrowing *R. solanacearum* at some point in the isolation and culturing process in Hawaii. No further assessment of *R. solanacearum*'s biocontrol potential in New Zealand can be undertaken unless fresh isolates can be obtained from infected ginger plants at the inoculated sites in Hawai'i. Given that the Hawaiian programme using *R. solanacearum* is no-longer active, and that there may be better potential agents identified during surveys of wild ginger which are scheduled to be undertaken in its native range in coming years, we recommend that no further work be undertaken on *R. solanacearum* in the meantime.

7. Recommendations

In light of our conclusions that invertebrate herbivore damage to wild ginger in New Zealand is not serious, and that no specialised pathogenic fungi or bacteria are known on the weed in New Zealand, we recommend that:

A classical biological control programme for wild ginger should proceed as follows:
(a) Survey herbivorous invertebrates and pathogens associated with wild ginger in its native range.

(b) Prioritise potential biocontrol agents according to their potential to damage wild ginger and the likelihood of adequate host-specificity.

(c) Undertake host-range tests with selected invertebrates and pathogens on plant species of importance to New Zealand.

(d) Introduce host-specific invertebrates and pathogens to New Zealand as classical biocontrol agents if acceptably safe candidates can be identified.

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Appendix 1 Invertebrates associated with wild ginger, *Hedychium gardnerianum* and *Hedychium flavescens*, at 34 New Zealand sites (2006–2007)

Key: Definitions of frequency categories

rare: fewer than 5 individuals collected in total
occasional: 5–24 individuals collected, **or** present at fewer than five sites
common: 25+ individuals collected **and** present at five or more sites
abundant: 200+ individuals collected **and** present at 10 or more sites

Note: *Invertebrates were collected from 30* H. gardnerianum *(kahili ginger) sites but just 4* H. flavescens *(yellow ginger) sites; therefore, frequency categories could be calculated (using the definitions above) only for* H. gardnerianum.

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Phylum Mollusca	**molluscs**				
Class Gastropoda	**slugs and snails**				
Cantareus aspersus Müller	brown garden snail	herbivorous	common (48)	9	4,6,12,14,17,19,20,21,32,34
unidentified molluscs		herbivorous	common (72)	1	2,3,4,6,7,8,11,12,13,16,32
Phylum Arthropoda					
Class Crustacea					
Amphipoda					
unidentified Amphipoda		saprophytic	occasional (10)		13,18
Isopoda	**slaters**				
unidentified Isopoda		saprophytic	common (59)	82	5,10,12,13,14,15,16,17,18,27,31,32,33
Class Arachnida					
Acarina	**mites and ticks**				
Anystidae					

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Anystis sp.	**whirlygig mite**	predatory	common (38)	5	4,11,15,17,19,20,22,24,31,34
Oribatida	**oribatid mites**				
unidentified Oribatida		fungivorous	occasional (6)	8	15,16,17,20,22,23,24,31,34
Araneida	**spiders**				
unidentified Araneida		predatory	abundant (711)	111	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20, 21,22,23,24,25,26,27,30,31,32,33,34
Pseudoscorpiones	**pseudoscorpions**				
unidentified Pseudoscorpiones		predatory	rare (4)		3,23
Class Diplopoda	**millipedes**				
unidentified Diplopoda		saprophytic	occasional (5)		13
Class Chilopoda	**centipedes**				
unidentified Chilopoda		predatory	rare (2)		13
Class Collembola	**springtails**				
unidentified Collembola		saprophytic	common (143)	10	10,13,15,16,17,18,23,24,25,27,31,33
Class Insecta	**insects**				
Blattodea	**cockroaches**				
Celatoblatta sp.			rare (2)		1
Celeriblattina sp.		saprophytic	occasional (5)	1	10,11,34
Drymaplaneta semivitta (Walker)	Gisborne cockroach	saprophytic	rare (2)		1,12
Parellipsidion sp.		saprophytic	rare (3)		1,2

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
unidentified Blattodea		saprophytic	common (48)	21	1,2,3,6,7,9,10,11,14,17,20,24,27,31,34
Coleoptera	**beetles**				
Anthicidae	**ant beetles**				
Sapintus pellucidipes (Broun)			rare (4)	3	8,10,12,16,31,33
Anthribidae	**fungus weevils**				
Euciodes suturalis Pascoe		fungivorous	rare (1)		2
Sharpius brouni (Sharp)		fungivorous	rare (3)		2,10,17
Carabidae	**ground beetles**				
Notagonum sp.		predatory	rare (1)		22
unidentified Carabidae (larva)		predatory	rare (1)		27
Cerambycidae	**longhorn beetles**				
Bethelium signiferum (Newman)	wattle longhorn	herbivorous	rare (2)		5,10
Oemona hirta (Fabricius)	lemon tree borer	herbivorous	rare (3)		1,11
Psilocnaeia sp.		herbivorous	rare (3)	1	2,12,32
Spilotrogia fragilis (Bates)		herbivorous	rare (1)		3
Spilotrogia sp.		herbivorous	rare (1)		26
Xylotoles sp.		herbivorous	occasional (11)	1	4,5,6,9,11,12,23,33
Chrysomelidae	**leaf beetles**				
Agasicles hygrophila Selman and Vogt	alligator weed beetle	herbivorous	rare (1)		6

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Eucolaspis sp.	bronze beetle	herbivorous	rare (3)		2,6
Lema cyanella (Linnaeus)	Californian thistle leaf beetle	herbivorous	rare (1)		5
Longitarsus jacobaeae (Waterhouse)	ragwort flea beetle	herbivorous	rare (1)		4
Peltoschema sp.		herbivorous	rare (1)		1
Coccinellidae	**ladybirds**				
Adalia bipunctata (Linnaeus)	two-spotted ladybird	predatory	occasional (5)		22,23
Coccinella undecimpunctata Linnaeus	eleven-spotted ladybird	predatory	rare (1)		20
Diomus notescens (Blackburn)		predatory	rare (1)		17
Diomus sp.		predatory	rare (1)	1	17,33
Halmus chalybeus (Boisduval)	steely-blue ladybird	predatory	common (119)	95	4,5,6,8,9,10,11,12,17,19,24,31,32,33,34
Illeis galbula (Mulsant)	fungus-eating ladybird	fungivorous		1	32
Rhyzobius sp.		predatory	rare (1)		30
Scymnodes lividigaster (Mulsant)	yellow-shouldered ladybird	predatory		1	32
Scymnus loewi (Mulsant)		predatory	occasional (37)	1	17,34
Serangium maculigerum Blackburn		predatory	rare (1)		9
Stethorus sp.		predatory	rare (2)		15,21
Corylophidae	**hooded beetles**				
Arthrolips oblonga (Broun)		fungivorous	rare (1)		10

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Sericoderus sp.		fungivorous	occasional (13)	2	4,15,17,19,21,23,32,34
Cryptophagidae	**cryptic beetles**				
Atomaria lewisi Reitter			rare (1)		24
Micrambina sp.		pollen/ fungus feeder	common (164)	5	4,7,10,11,12,13,14,17,21,24,32,33
Paratomaria sp.		pollen/ fungus feeder	common (60)	2	4,9,10,11,23,24,33
unidentified Cryptophagidae			common (831)		4,5,6,9,10,11,24
Curculionidae	**weevils**				
Aneuma sp.		herbivorous	rare (3)		11,23
Hylurgus ligniperda (Fabricius)				1	34
Irenimus sp.		herbivorous	rare (2)		22
Listronotus bonariensis (Kuschel)		herbivorous	rare (2)		17
Microcryptorhynchus sp.		herbivorous		1	32
Microtribus huttoni Wollaston		herbivorous	rare (4)		3,26,30
Pactola sp.		herbivorous	rare (1)		4
Peristoreus sp.		herbivorous	occasional (7)		27,11
Phlyctinus callosus Boheman	garden weevil	herbivorous	rare (2)		21
Scolopterus penicillatus White	four-spined weevil	herbivorous/ pollen feeder	occasional (6)		11
Sericotrogus subaenescens Wollaston		larvae and adults in dead wood		2	31
Sitona discoideus	sitona weevil	herbivorous	rare		20

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Gyllenhal			(1)		
Stephanorhynchus curvipes White		herbivorous/ pollen feeder	occasional (15)		10,11
Stephanorhynchus lawsoni Sharp		herbivorous/ pollen feeder	rare (1)		11
Tysius bicornis (Fabricius)		pollen feeder	occasional (11)		11
Dermestidae	**hide beetles**				
Trogoderma sp.		pollen feeder	rare (1)		6
Elateridae	**click beetles**				
Conoderus exsul (Sharp)	pasture wireworm	herbivorous	occasional (11)		4,5,6,10
Conoderus sp.		herbivorous	rare (1)	1	5,33
Metablax cinctiger (White)		herbivorous	rare (1)		6
Ochosternus zealandicus (White)		herbivorous	rare (1)		6
Erotylidae	**handsome fungus beetles**				
Loberus depressus (Sharp)		fungus/ pollen feeder	rare (2)	3	27,32
Loberus nitens (Sharp)		fungus/ pollen feeder	rare (3)		21
Latridiidae	**mildew beetles**				
Aridius bifasciatus (Reitter)		fungivorous	occasional (8)	20	15,17,19,27,33,34
Aridius costatus (Erichson)		fungivorous	rare (1)	1	17,33
Aridius nodifer (Westwood)		fungivorous	rare (3)		24,19
Melanophthalma sp.		fungivorous	abundant (241)	147	5,7,10,11,12,14,15,17,18,20,22,23,24,28,32,33,34

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Melandryidae	**leaping beetles**				
Hylobia sp.		herbivorous	rare (1)		21
Monotomidae					
Monotoma sp.		fungivorous		1	32
Mycetophagidae	**fungus beetles**				
Litargus vestitus (Sharp)		fungivorous	common (34)	5	4,5,9,10,11,17,20,21,32,33
Nitidulidae	**sap beetles**				
Aethina nigra (Reitter)		pollen feeder	rare (1)		9
Carpophilus sp.		saprophytic	rare (1)	2	10,33
Epuraea scutellaris (Broun)		herbivorous	rare (1)		17
Oedemeridae	**lax beetles**				
Parisopalpus nigronotatus (Boheman)	spotted lax beetle	adults: nectar larvae: in dead and rotting wood	occasional (6)		6
Thelyphassa lineata (Fabricius)			rare (1)		16
Phalacridae	**bald beetles**				
Phalacrus uniformis frigoricola Thompson		fungivorous	rare (2)		5,10
unidentified Phalacridae			occasional (8)		10,11
Scirtidae	**marsh beetles**				
unidentified Scirtidae		predatory	common (26)	16	3,6,9,11,17,22,26,30,32,33

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Silvanidae	**flat beetles**				
Cryptamorpha desjardinsi (Guérin)	Desjardin's flat beetle	fungivorous	occasional (19)	4	2,3,4,7,9,10,17,18,33,34
Staphylinidae	**rove beetles**				
Anotylus brunneipennis (MacLeay)		predatory	rare (1)		12
Astenus guttula Fauvel		predatory	rare (2)	2	17,20,33,34
Sagola sp.		predatory	rare (1)		12
Tachyporus nitidulus (Fabricius)		predatory	rare (1)		17
unidentified Staphylinidae		predatory	occasional (19)		4,10,11,17,25
Tenebrionidae	**darkling beetles**				
Lorelus sp.		herbivorous	rare (1)		11
Zopheridae	**false darkling beetles**				
Bitoma rugosa Sharp		herbivorous	rare (1)		15
Dermaptera	**earwigs**				
Forficula auricularia Linnaeus	European earwig	omnivorous	occasional (23)	24	10,12,14,15,17,18,23,31,32
Diptera	**flies**				
Tachinidae	**bristle flies**				
Trigonospila brevifacies (Hardy)	Australian leafroller tachinid	parasitoid	rare (2)		22,27
Hemiptera	**bugs**				
Acanthosomatidae					
Rhopalimorpha sp.		sap feeder	occasional (6)		8

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Anthocoridae					
unidentified Anthocoridae		predatory	common (76)	9	4,6,9,10,11,13,14,15,16,17,18,21,32,33,34
Aphididae	**aphids**				
unidentified Aphididae			occasional (13)		4,9,11,17,19
Aphrophoridae	**spittle bugs**				
Carystoterpa sp.		sap feeder	occasional (7)		1,30
Philaenus spumarius (Linnaeus)	meadow spittle bug	sap feeder	occasional (8)	1	25,30,34
Cicadellidae	**leafhoppers**				
unidentified Cicadellidae		sap feeder	occasional (23)		4,10,11
Cicadidae	**cicadas**				
unidentified Cicadidae		sap feeder	rare (2)		4,5,26
Cixiidae					
Oliarus oppositus (Walker)		sap feeder	rare (1)		6
Koroana sp.		sap feeder	occasional (11)		30
Coreidae					
Acantholybas brunneus (Breddin)		sap feeder	rare (2)	1	4,31
Delphacidae					
Ugyops pelorus Fennah		sap feeder	rare (1)		27
unidentified Delphacidae		sap feeder	occasional		4,16

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
			(10)		
Derbidae					
Eocenchrea maorica (Kirkaldy)			rare (1)		11
Flatidae	**planthoppers**				
Siphanta acuta (Walker)	green planthopper	sap feeder	common (116)	32	1,3,4,5,6,8,9,10,11,12,13,14,15,17,18,20,21,26,27, 30,31,32,33
Siphanta acuta (Walker) (egg batch)	green planthopper eggs		rare (1)	1	20,33
Lygaeidae	**seed bugs**				
Arocatus rusticus (Stål)		sap/seed feeder	rare (2)		27
Nysius sp.	wheat bug	sap/seed feeder	rare (1)		20
Rhypodes sp.		sap/seed feeder	occasional (5)		2
Membracidae					
Acanthucus trispinifer (Fairmaire)		sap feeder		4	32
Miridae	**mirid bugs**				
Chaetedus sp.		sap feeder	rare (1)		25
Chinamiris sp.		sap feeder	rare (2)		5
Deraeocoris maoricus Woodward		predatory	rare (3)		9,27,30
Sidnia kinbergi (Stål)	Australian crop mirid	sap feeder		1	33
unidentified Miridae			common (45)		1,4,5,6,9,11,25,27,30

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Nabidae	**damsel bugs**				
Nabis sp.		predatory	rare (1)		4
Pentatomidae	**shield bugs**				
Cuspicona simplex Walker	green potato bug	sap feeder	occasional (5)		9
Glaucias amyoti (Dallas)	New Zealand vegetable bug	sap feeder	rare (2)	1	9,33
Nezara viridula (Linnaeus)	green vegetable bug	sap feeder	common (79)	8	4,5,6,8,9,10,11,12,13,14,17,19,21,32,33,34
unidentified Pentatomidae			occasional (8)	1	5,9,12,14,24,32
Psyllidae					
unidentified Psyllidae		sap feeder	rare (4)		27
Rhyparochromidae					
Brentiscerus putoni (White)		sap/seed feeder	rare (1)		17
Stizocephalus brevirostris Eyles				1	31
Ricaniidae	**planthoppers**				
Scolypopa australis (Walker)	passionvine hopper	sap feeder	abundant (1031)	37	4,5,6,7,8,9,10,11,12,13,14,16,17,20,24,25,27,31, 32,33,34
unidentified Hemiptera			occasional (23)		2,5,8,10,27,30
Hymenoptera	**bees, wasps, ants**				
Braconidae	**parasitic wasps**				
Meteorus pulchricornis Wesmael		parasitoid	rare (1)		4

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Dryinidae					
unidentified Dryinidae		parasitoid of *Siphanta acuta* nymphs	rare (1)		18
Formicidae	**ants**				
Iridomyrmex sp.		omnivorous	rare (2)	1	4,33
Monomorium fieldi Forel		omnivorous	occasional (44)	1	4,5,24,30,32
Monomorium sp.		omnivorous	rare (2)		27
Ochetellus glaber (Mayr)		omnivorous	occasional (9)	6	5,11,32
Pachycondyla sp.		omnivorous	rare (2)		10,11
Paratrechina sp.	garden ant	omnivorous	occasional (24)	5	1,2,5,7,11,15,17,24,32,33
Pheidole vigilans (Smith)		omnivorous	rare (1)		7
Prolasius advena (Smith)	small brown bush ant	omnivorous	rare (3)		12,14
Technomyrmex albipes (Smith)	white-footed house ant	omnivorous	common (65)	3	1,2,3,4,5,7,10,11,17,20,32,34
Tetramorium bicarinatum (Nylander)		omnivorous	rare (4)		2,5,15
Platygastridae					
Aphanomerus pusillus Perkins		egg parasitoid of *Siphanta acuta*	rare (2)	53	18,24,33
Aphanomerus sp.		egg parasitoid of *Siphanta acuta*	rare (3)		12,23,24
Vespidae	**social wasps**				
Polistes chinensis Fabricius	Asian paper wasp	omnivorous	rare (2)	1	12,14,33
Polistes humilis (Fabricius)	Australian paper wasp	omnivorous	rare (1)		16

Taxon	Common name	Feeding mode	*H. gardnerianum* Abundance class and (Number of individuals)	*H. flavescens* Number of individuals	Collection sites
Lepidoptera (collected as larvae and reared to adult for identification)	**moths and butterflies**				
Geometridae	**looper moths**				
unidentified Geometridae		herbivorous	rare (3)		10,26
Noctuidae	**armyworms, cutworms**				
Thysanoplusia orichalcea (Fabricius)			rare (2)		2,5
unidentified Noctuidae		herbivorous	rare (4)		8,17,30
Pieridae					
Pieris rapae Linnaeus	cabbage white butterfly		rare (1)		21
Psychidae	**bag moths**				
unidentified Psychidae			rare (1)		4
Tineidae					
unidentified Tineidae		saprophytic	rare (1)		13
Tortricidae	**leaf rollers**				
Cnephasia jactatana Walker	black-lyre moth	herbivorous	rare (1)		9
Ctenopseustis obliquana (Walker) **or** *C. herana* (Felder and Rogenhofer)		herbivorous	occasional (5)		4,6,23,27
Planotortrix notophaea Turner		herbivorous	rare (1)		22
unidentified Tortricidae		herbivorous	occasional (12)	2	3,4,6,23,27,31,34

Taxon	**Common name**	**Feeding mode**	***H. gardnerianum* Abundance class and (Number of individuals)**	***H. flavescens* Number of individuals**	**Collection sites**
Mantodea	**praying mantids**				
Miomantis caffra Saussure	African praying mantis	predatory	occasional (8)		4,5,10,12,14,17,20
Neuroptera	**lacewings**				
Micromus tasmaniae (Walker)	Tasmanian lacewing	predatory	occasional (13)	1	1,2,4,5,17,27,32
Orthoptera	**crickets, grasshoppers, weta**				
Anostostomatidae					
Hemideina thoracica White	Auckland tree weta	omnivorous	rare (1)	2	11,31
Tettigoniidae	**long-horned grasshoppers**				
Caedicia simplex (Walker)	katydid	herbivorous	occasional (6)		4,11,27,30
Conocephalus sp.	field grasshopper	herbivorous	rare (4)		4,5,10
Psocoptera	**book lice**				
unidentified Psocoptera		saprophytic and fungivorous	common (98)	11	1,2,3,4,5,8,9,10,11,13,14,15,17,19,21,22,23,24,26, 30,33,34
Thysanoptera	**thrips**				
Sub-Order Terebrantia					
Thripidae					
Heliothrips haemorrhoidalis (Bouche)	greenhouse thrips	herbivorous	occasional (28)		4,5,15,20
Hercinothrips bicinctus (Bagnall)	banana silvering thrips	herbivorous	common (166)		4,14,17,19,20,35
Thrips obscuratus (Crawford)	New Zealand flower thrips	herbivorous	common (196)	5	4,5,6,10,11,23,24,32
Sub-Order Tubulifera					
unidentified Tubulifera		fungivorous	rare (1)	1	23

Appendix 2 Further background on *Ralstonia solanacearum*

Ralstonia solanacearum consists of a large and complex group of strains all with different distributions, host ranges, virulence, physiology, and biochemistry (Hayward et al. 1994). Considered as a plant pathogen, these strains have been divided taxonomically into five races mainly differentiated by host specificity (Hayward et al. 1994). Race 1 affects a wide range of unrelated crop species including tomato, peanut, edible ginger, and olive. Race 2 is limited to musaceous hosts e.g., banana; Race 3 infects potato in cooler temperate climates; Race 5 infects mulberry, and Race 4 includes those infecting the ornamental and edible ginger strains (Yu et al. 2003).

Despite *R. solanacearum*'s reported broad host range, some races and strains, including the ginger race 4, have been shown to be host specific. For example, Anderson and Gardner (1999) found the strain used as a biological control agent for kahili ginger had a narrow host range: it did not cause systemic bacterial wilt on important non target native species nor indeed on closely related hosts like yellow and white ginger. These results enabled this strain to be inoculated in the field on kahili ginger populations invading and threatening the Ohia-Lehua *Metrosideros* rain forest in the Volcanoes National Park. A recent evaluation of the biocontrol efficacy of *R. solanacearum* at these field sites has shown a negative effect on the fitness and survival of kahili ginger by reducing the number of fruiting stems, seedling recruitment, and rhizome biomass (Rob Anderson, 2006, unpubl. data). For example a 57% reduction in flowering stems was observed in inoculated field plots in Hawai'i.

Whilst disease spread to date has been relatively slow (estimated at 1 linear meter per year through unassisted soilborne transmission), the bacterium has been successfully formulated into a mass-produced alginate based inoculum (Rob Anderson, 2006, unpubl. data). The rate of infection is vastly improved when this inoculum is applied to wounded rhizomes where it can then systemically infect the plants. Once applied, the formulated bacterium can also survive in soil and continue to spread and cause disease in subsequent seasons (an inherent advantage over chemical control methods which have to be applied each season). Recent observations of faster rates of spread and infection (up to 30 m outside the application zone) have led to speculation that the bacterium is also spread by insects e.g., *Drosophila* spp., birds, and mammals (Rob Anderson, 2006, unpubl. data).

Although conventional control measures such as application of chemical herbicide can effectively control kahili ginger (e.g., Escort, metsulfuron-methyl, can deliver 100% mortality (Harris et al. 1996)), *R. solanacearum* was being developed as an alternative, self-perpetuating control tool for remote areas where implementing conventional controls annually is difficult and where chemicals cannot be used because they damage non-target native plants.