

# **Assessing the risk of exotic herbivorous insects to New Zealand's native plants**

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# Abstract

Despite the presence of >1400 exotic insect species in New Zealand, relatively limited literature is available to describe their impact on native biodiversity. In this project, I use an integrative risk assessment to identify the risk posed to a range of native plant species from exotic herbivorous insects. To do this, I determine the interactions between 'assets' (i.e. native plants) and the 'hazards' (i.e. exotic herbivorous insects that have already established). Firstly, I use literature collated within the online Plant-SyNZ database of exotic insects present in New Zealand and their associated host plants to identify: i) the most common exotic herbivorous insects, ii) the plants with the highest numbers of exotic herbivores, and iii) quantify the associations between them. Secondly, I compare the potential threat, as recognised from the above findings, with the realized threat by undertaking field surveys of five common plant species (karamu, kawakawa, mahoe, karo and red matipo) across 14 Regional Parks within the Auckland region to obtain the frequency and abundance of insects. I investigated how insect traits, plant traits, and environmental variables interact to shape these systems. Polyphagous and o-oligophagous insect species within the families Ricaniidae, Flatidae, Thripidae (subfamily Panchaetothripinae), Pentatomidae, Aphididae, Diaspididae and Coccidae were identified as posing a high-risk to native plants. Additionally, if these species had many associations with cultivated plants, then they posed an even higher risk to native plants. Vulnerable native plants were phanerophytes (plants taller than 25-50cm whose shoots don't die back periodically to that height limit) which are found in coastal environments and are within the families Haloragaceae, Scrophulariaceae, Sapindaceae, Bignoniaceae, Solanaceae and Rutaceae. The passionvine hopper was the most widespread and abundant species collected across all plant species and most sites within the field surveys. This was an important finding as there is no literature available to describe the impact of the passionvine hopper on native plants. However, the large populations throughout the Auckland Region are very concerning in relation to the long-term implications of their feeding pressure on native plants. Future researchers must aim to carry out full risk assessments relating to the feeding pressure of the passionvine hopper on native plants and insects which fall into the identified high-risk groups.

**Keywords:** potential impact, realised impact, biosecurity, biological invasions, risk assessments

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# Table of Contents

<b>Abstract.....</b>	<b>ii</b>
<b>Acknowledgments .....</b>	<b>iii</b>
<b>List of figures .....</b>	<b>vi</b>
<b>List of tables .....</b>	<b>vii</b>
<b>1. General introduction.....</b>	<b>1</b>
1.1 Biological invasions .....	1
1.2 Risk assessments .....	2
1.3 Exotic herbivorous insects.....	5
1.4 Exotic insects and New Zealand’s flora .....	5
1.5 Knowledge Gaps .....	6
<b>2. Aims and thesis arrangement.....</b>	<b>8</b>
2.1 Chapter 1: Using historical data records to understand biotic associations .....	8
2.2 Chapter 2: Surveys of associations across the Auckland region.....	8
<b>Chapter 1: Using historical data records to understand biotic associations .....</b>	<b>9</b>
<b>3. Methods .....</b>	<b>9</b>
3.1 Statistical Analyses: Identifying high-risk exotic insects.....	15
3.2 Statistical analyses: Identifying vulnerable native plants.....	18
<b>4. Results .....</b>	<b>20</b>
4.1. Summary of potential hazards (exotic herbivorous insects) .....	20
4.2 Predicting risk based on insect traits from the historical records.....	26
4.3 Summary of potential exposed assets (plants) .....	31
4.4 Predicting vulnerability based on plant traits from the historical records.....	37
<b>5. Discussion.....</b>	<b>39</b>
5.1 High risk insect species.....	39
5.2 Predictors of high-risk insect species .....	42
5.3 Vulnerable plant species .....	50
5.4 Predictors of vulnerable plant species .....	51

<b>Chapter 2- Surveys of associations across the Auckland region</b>	<b>53</b>
<b>6. Methods</b>	<b>53</b>
6.1 Field survey technique	56
6.2 Statistical analyses of field survey data	56
6.2.1 Insect communities and environmental variables	57
6.2.2 The passionvine hopper ( <i>Scolypopa australis</i> )	59
<b>7. Results</b>	<b>64</b>
7.1 Insect composition	64
7.2 Passionvine hopper ( <i>Scolypopa australis</i> )	75
7.2.1 Predictors of the passionvine hopper abundance	80
<b>8. Discussion</b>	<b>83</b>
8.1. Insect composition	83
8.2 Passionvine hopper ( <i>Scolypopa australis</i> )	85
<b>9. General discussion</b>	<b>86</b>
9.1 Exotic herbivorous insects in New Zealand	86
9.2 Hazards (exotic insects)	86
9.2.1 Passionvine hopper ( <i>Scolypopa australis</i> )	87
9.3 Exposed assets (vulnerable native plants)	90
9.4 Limitations of the online database and field surveys	90
9.5 Future research	91
<b>References</b>	<b>93</b>
<b>Appendices</b>	<b>107</b>

# List of figures

Figure 1. Natural disaster framework adapted to apply to biological invasions.....	4
Figure 2. World map of the ecozones.....	11
Figure 3. Histogram of the number of plant species that exotic insect species were recorded on.....	22
Figure 4. Total number of native plant species that adventive insects are associated with against the total number of cultivated plant species.....	30
Figure 5. Number of combined associations between exotic insects and native plants.....	32
Figure 6. The total number of associations between adventive insect species and native plant species.....	33
Figure 7. The number of adventive insect species that have been recorded on native plant species.....	34
Figure 8. Map of the 14 survey sites across the Auckland Region.....	53
Figure 9. Principal Components Analysis using the redundancy analysis to show the association of environmental variables with sample sites.....	71
Figure 10. Principal Components Analysis using the redundancy analysis to show the association of insect community with sample sites.....	72
Figure 11. Principal Components Analysis using the redundancy analysis to show the association of insect community with plant species.....	73
Figure 12. Number of passionvine hoppers collected per plant species across the Auckland Regional Parks.....	76
Figure 13. Average number of passionvine hoppers found at each sample site across Auckland Regional Parks.....	78
Figure 14. The relationship between the mean number of passionvine hoppers collected per sample site and degrees latitude.....	81

# List of tables

Table 1. List of insect traits used as independent variables in the statistical analyses.....	10
Table 2. List of traits recorded against each plant species which were used in the statistical analyses .....	12
Table 3. Summary statistics of each multivariate/simple regression analysis performed to predict the number of native plant species that exotic insect species is associated with.....	16
Table 4. Summary statistics of each multivariate/simple regression analysis performed to predict the number of exotic insect species recorded on native plants.....	19
Table 5: Associations between exotic insects and native plans.....	23
Table 6. Number of native plant species that each insect species has been recorded on, grouped as family.....	24
Table 7: The top ten exotic insect species and the total (and %) number of native plant species they have been recorded on.....	25
Table 8. Multivariate regression analysis using insect family (grouped), feeding type and the number of cultivated host plant species to predict the number of native host plant species.....	27
Table 9. Multivariate regression analysis using insect order, feeding type and number of cultivated host plant species to predict the number of native host plant species.....	29
Table 10. Number of exotic insects associated with each native plant (“#”), excluding plants with <10 associations.....	35
Table 11. Number of exotic insect species associated with native plants which are classified as threatened, excluding plants with <4 associations.....	36
Table 12. Multivariate regression analysis using plant family (grouped), Raunkiær life mode and altitude band to predict the number of exotic insect species recorded on a native plant.....	38
Table 13. The number of plants sampled per site and plant species.....	54
Table 14. The environmental variables used in the PCA analyses.....	57

Table 15. List of environmental variables used as independent variables in the statistical analyses of the passionvine hopper abundance.....	59
Table 16. Test summary statistics of the various multivariate and simple linear regression analyses performed. Each row relates to the independent variables used to explain the number of passionvine hoppers collected.....	62
Table 17. Invertebrates collected from surveys across the Auckland region that were removed from analysis as they were either non-insects or were not herbivorous.....	64
Table 18. Number of herbivorous insects collected across all sites and plants, grouped as insect order.....	65
Table 19. Number of herbivorous insects identified to a lower taxonomic ranking than order, sorted by the abundant taxa.....	66
Table 20. Number of herbivorous insects collected at each sample site, excluding the passionvine hopper.....	67
Table 21. Number of herbivorous insects collected from each plant species.....	68
Table 22. The numerical codes from the PCA biplot analyses and the taxonomic identification it corresponds with.....	70
Table 23. Number of passionvine hoppers collected per plant species, sorted by the average number of passionvine hoppers collected per plant.....	75
Table 24. Number of passionvine hoppers collected per sample site, sorted by average per plant.....	77
Table 25. Multivariate regression analysis using weather conditions to predict the number of passionvine hoppers collected.....	80

# 1. General introduction

## 1.1 Biological invasions

Biological invasions are a major contributor to population declines and extinctions of native species in their invading regions (Fenoglio et al., 2021). Hence, invasive species are considered a significant threat to global biodiversity (Chabaane et al., 2015). Considerable environmental and economic costs can occur following the successful establishment of a non-native organism into a new region (Horton et al., 2021). This has introduced a need to understand the cause and impact of biological invasions, leading to the entirely new scientific discipline which is 'invasion biology' (Horton et al., 2021). This discipline involves identifying traits which predispose an organism to successfully establishing and spreading in non-native regions and causing significant damage (Horton et al., 2021).

Biological invasions are often facilitated by direct or indirect human actions (Meyerson et al., 2009). Therefore, the trajectories and outcomes of such events must be considered in the context of anthropogenic drivers, such as trade and travel which often facilitate the spread of exotic species (Meyerson et al., 2009). Global trade and recreational travel have increased and diversified tremendously in the last century and associated with these changes are new pathways for species to move outside of their native range (Liebhold et al., 2013). Technological advances in trade and travel such as containerized cargo, movement of nursery stock, changing trade routes (seaborne, airborne, railway) and increases in the volume of such processes are continuously creating new pathways for exotic species (Hulme, 2009; Liebhold et al., 2013). Additionally, travel times between different regions is becoming shorter, and this increases the likelihood of exotic species surviving transportation (Hulme, 2009).

For example, containers of ornamental plants being exported from Singapore to London take approximately 14 hours via air transport and 22 days via ship (Roques, 2010). Historically, such exports took several months via ship (Roques, 2010). A steep increase in the trade of live plants in the 21<sup>st</sup> century is evident (i.e. bonsais and Christmas trees), and this type of trade introduces pathways which bring about the direct translocation of exotic insects (Roques, 2010). These plants are particularly high risk as they are generally transported quickly, with contaminants still intact, into suitable receptor environments (Roques, 2010). An increase in the trade of plant material via the internet is less controlled, especially for plant seeds which are easily transported around the world (Roques, 2010). For example, exotic seed chalcid wasps (*Megastigmus* sp.) have repeatedly established throughout Europe via the seed trade (Roques, 2010) and are known to infest the seeds of native conifers (Roques &

Skrzypczyńska, 2009). Changes within the wood-trade sector, such as the use of solid-wood packaging, pallets and plywood, serve as potential sources of exotic insect introductions (Roques, 2010).

Internationally, biosecurity organisations have recognised that the key to effective biosecurity lies within the prevention of exotic species establishing (Goldson et al., 2016). Thus, analysing historical establishment events of non-native species and their associated biological and ecological traits increases the success of detecting high-risk organisms before they successfully establish, while also strengthening the understanding of trends which may be involved in invasions (Liebhold et al., 2013).

## 1.2 Risk assessments

Risk assessments are valuable tools used to assess the level of risk associated with non-native organisms outside of their natural range (Dahlstrom et al., 2011; Hayes, 2003; Probert, et al., 2020). However, conducting a comprehensive risk assessment on every exotic species is not feasible (Beever et al., 2007; Probert, et al., 2020). Therefore, biosecurity organizations need to allocate their limited resources towards the species which pose the highest risk to that region. Risk assessments may be carried out on species both pre- and post-border (Hayes, 2003). However, this process is made more difficult by the fact that some 'high-risk' species may never pass through all the invasion pathways and establish in a new region (Jay et al., 2003; Probert et al., 2020). Conversely, some species that have already arrived and established, never have a significant negative impact (Jay et al., 2003; Probert et al., 2020). Hence, the species which are likely to pass through each of the environmental filters within the invasion pathway need to be identified as well as the species that will cause the most damage in the invading region.

A range of risk assessment approaches have been proposed (Hulme et al., 2008; Jamieson et al., 2016; Jamieson et al., 2021; Pheloung et al., 1999) but very few are focused on the impact of invasion to native ecosystems.

One model which is used in New Zealand is the PRONTI (prioritised ranking of non-target invertebrates) model (Todd et al., 2015). PRONTI uses five selection criteria to identify native species which may be particularly vulnerable to the exotic species. The aim is to prioritise only the highly vulnerable species for full risk assessments. The five selection criteria are 1) identification of potential hazards posed by the exotic species to native species; 2) the potential degree of exposure of the native species to the exotic species; 3) the ecological

impact which could occur following exposure; 4) the economic, cultural and social value of each native species; 5) our ability to carry out tests with each native species. The first two criteria are the most important drivers of the model as they aid the identification of the potential 'hazards' and 'exposure'. Information relating to the exotic species' physiology, ecology, and behaviour in its native region is used for the selection criteria, such as the likelihood that the exotic species will occur in a particular location. The model then ranks each native species in order from highest to lowest predicted risk, providing a more effective risk assessment.

Another model is the integrative risk assessment proposed by Probert et al. (2020) (Figure 1) which has been adapted from a generalized natural disaster framework. The proposed risk assessment integrates both the 'asset' which is the native plant species and the 'hazard' which is the exotic insect species. The purpose of this framework is to identify those exotic species which are likely to have a significant negative impact in the invading region. The first step is to identify both the hazards and assets and then the specific interactions between them to determine vulnerability (i.e., 'exposure') and then severity of the impact ('damage state'). This information is used to inform biosecurity organizations so that they can prioritize their resources towards the species which are going to have the largest impact.

This thesis will be using the risk assessment proposed by Probert et al. (2020) (Figure 1) which has been modified by adding terms in red ink that are relevant for this thesis.

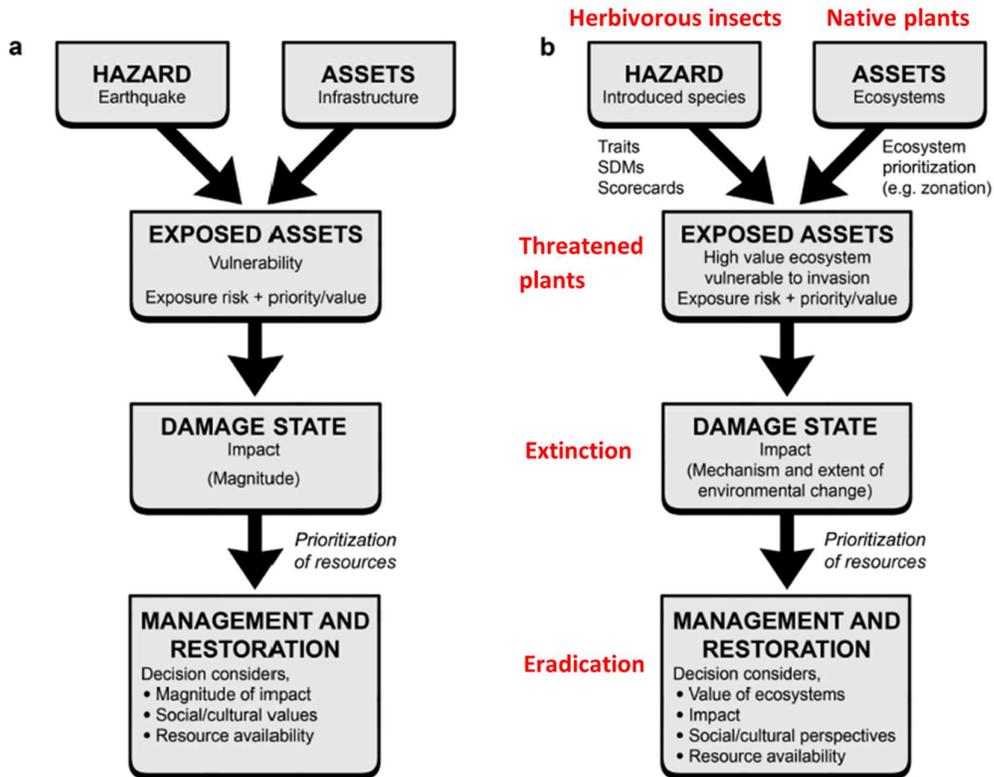


Figure 1. Natural disaster framework (a) adapted to apply to biological invasions (b) (adapted from Probert et al., 2020)

### 1.3 Exotic herbivorous insects

While the impact of invasive mammals is relatively well documented, and plants to a lesser extent, the impact of invasive insects has received disproportionately less attention (Anderson-Teixeira et al., 2021; Edney-Browne et al., 2018). This is concerning since insects comprise the majority of non-native animals which have established globally (Edney-Browne et al., 2018). Nonetheless, only a small percentage of these exotic insects will go on to cause significant ecological or economic harm (Epanchin-Niell, 2017), which I refer to as invasive or pests.

Herbivory is an important interaction that can strongly influence the way an ecosystem functions, especially when a combination of pressures are involved, such as pathogens or diseases (Johnson., et al 2016; Myers & Sarfraz, 2017). Around the world, exotic herbivorous insects occur in many forest/plant ecosystems and are known to kill plants, influence plant population densities, and reduce plant size, growth and seed production (Anderson-Teixeira et al., 2021; Boyd et al., 2013; Myers et al., 2017; Sjöman, et al., 2014; Straw, et al., 2016).

For example, the polyphagous Asian longhorn beetle (*Anoplophora glabripennis*) is a significant pest in the United States, Canada, and Europe (Boyd et al., 2013). This wood-boring insect can kill many species of broadleaved trees in its non-native region. Hence, it is considered a serious threat to tree landscapes (Boyd et al., 2013; Sjöman et al., 2014; Straw et al., 2016). Another example is the hemlock woolly adelgid (*Adelges tsugae*) and the emerald ash borer (*Agrilus planipennis*) which have both invaded North America and together are causing extreme declines of the native eastern hemlock (*Tsuga canadensis*) and ash trees (*Fraxinus* spp.) (Ellison et al., 2018; Herms & McCullough, 2014).

### 1.4 Exotic insects and New Zealand's flora

In New Zealand, there is a wealth of knowledge relating to the negative effects of exotic vertebrate herbivores (e.g. possums and deer) within native systems (Coomes et al., 2003; Sweetapple et al., 2013). However, existing literature on exotic insects in New Zealand primarily examines the impact realized within economically significant production systems (Boyd et al., 2013). For example, the Argentine stem weevil (*Listronotus bonariensis*) is an invasive insect which is widespread throughout New Zealand (McNeill et al., 2020). This weevil infests economically important crops (e.g. pasture, maize, sweetcorn, cereals and brassicas) causing significant economic losses to New Zealand (Barratt et al., 2016; Ferguson et al., 2019; McNeill et al., 2020; Popay et al., 2011). However, there is no literature available which

evaluates the risk of this species to New Zealand's native brassica species, most of which are threatened with extinction (Phillips et al., 2020). The focus on economically important pests is largely because invaders can impose significant costs in relation to market income (Epanchin-Niell, 2017). Hence, private decision makers generally choose to invest their money in management to reduce these impacts (Epanchin-Niell, 2017). Non-market values and ecosystem services impacts are relatively understudied and are often of greater value (Epanchin-Niell, 2017).

Very limited literature is available on the impact of exotic insects on New Zealand's native plants. This is concerning as more than 1,400 species of exotic insects have established within New Zealand, with herbivores representing the largest feeding guild (Edney-Browne et al., 2018). Indigenous vegetation in New Zealand is not 'immune' to the negative impacts of exotic insects. For example, the infamous painted apple moth (*Teia anartoides*) was first detected in New Zealand in 1999 (Cook et al., 2002). This species posed a major threat to New Zealand's native flora as it consumes an extremely wide range of plant species, including ribbonwood (*Hoheria populnea*) and kowhai (*Sophora microphylla*), both of which were susceptible to complete defoliation by its moth larvae (Cook et al., 2002).

The great white butterfly (*Pieris brassicae*) is another important example which was discovered in New Zealand in 2010. This butterfly was initially considered a low-risk organism to New Zealand because it can defoliate plants from the Brassicaceae family, but the use of insecticides would prevent such damage to brassica crops (Phillips et al., 2020). However, the Department of Conservation (DOC) recognized that New Zealand has 81 native Brassicaceae species, of which 66 are rare and threatened with extinction. Risk assessments by DOC suggested that New Zealand's native Brassicaceae species would be highly suitable hosts for the great white butterfly. The risk of multiple extinctions was high, so eradication started and was declared successful in 2016 (Phillips et al., 2020). This example serves as an important warning that exotic insects have the potential to severely impact native biodiversity in New Zealand.

## 1.5 Knowledge Gaps

Historical pest management of exotic insects in New Zealand has focused on those species which cause the most economic harm, such as species affecting the pastoral farming, beekeeping, horticultural, and forestry sectors (Goldson et al., 2015). However, an increase in understanding regarding the benefits of native plants to society is apparent (Boyd et al., 2013). Some plant species are integral components involved in maintaining the health of

ecosystems, such as the keystone species kauri (*Agathis australis*) within kauri forests (Boyd et al., 2013). In turn, these different ecosystems provide a wide array of ecosystem services (Boyd et al., 2013). Hence, research must focus on understanding the impact of exotic insects to native plants to best assist future pest management.

Under what circumstances herbivorous insects significantly affect plant populations remains relatively unknown (Myers et al., 2017). Hence, a research priority in biosecurity and ecology is to understand why some herbivorous insects become invasive and others do not (Boyd et al., 2013). It has long been recognised that there are physiological and biological traits which make some species more invasive than others, but the traits that make herbivorous insects more likely to invade native habitats is largely unknown (Peacock & Worner, 2008). To understand the factors involved in this, it is important to understand herbivory and the traits which influence the likelihood of a species reaching a high abundance (Boyd et al., 2013). It is also important to accurately predict which of these species are going to have the largest impact (Boyd et al., 2013). The ability to identify high-risk pests before they become a problem will increase New Zealand's preparedness to deal with future threats.

There are more than 670 species of herbivorous insects established in New Zealand (Edney-Browne et al., 2018). A number of these species have been recorded on native plants however, these interactions are very poorly studied (Martin & Paynter, 2015). Many of New Zealand's native plant species have evolved in isolation from these exotic insects (Anderson-Teixeira et al., 2021), meaning some of New Zealand's plant species will have no defence mechanism against the novel herbivores (Anderson-Teixeira et al., 2021). This highlights the importance of assessing the risk that these established insects pose to New Zealand's native flora.

This project aimed to identify exotic insects which are potentially damaging to native plants and investigate which traits are predictive of a 'high-risk' insect. In this thesis, high-risk insects were species which were likely to attack many native plants. The implications of my findings could inform risk assessments and identify harmful insect pests prior to their establishment in New Zealand and/or identify insects which are having a significant, but currently unknown, impact within New Zealand's native ecosystems.

## **2. Aims and thesis arrangement**

This thesis has two data chapters which both overlap in their general introduction and background. Consequently, the thesis has a general introduction which serves both data chapters. However, there are two distinct methods, results, and discussion sections, and then a short general discussion to connect the data chapters.

Using the modified risk assessment proposed by Probert et al. (2020) (Figure 1), I identified the “hazards” (exotic herbivorous insects) and the “assets” (native plants) to determine the “exposed assets”.

### **2.1 Chapter 1: Using historical data records to understand biotic associations**

The aim of chapter one was to identify the associations between exotic herbivorous insects and native plants in New Zealand. To do this, I utilised an online database (Plant-SyNZ) which contains observations of insects on plants.

Using this database, I examined which exotic insect species’ pose a ‘high-risk’ to New Zealand’s native plants and determined a series of traits which may be influencing this ‘high-risk’ status. Similarly, I investigated which native plants are most ‘vulnerable’ to exotic insects and whether plant ecological traits influence the ‘vulnerable’ status of a plant species.

### **2.2 Chapter 2: Surveys of associations across the Auckland region**

The aim of chapter two was to survey insect species occurring on native plants, and to determine the frequency and abundance of ‘high-risk’ insect species identified from chapter one. This involved field work of both native and exotic insects on common plants throughout the Auckland Region.

# Chapter 1: Using historical data records to understand biotic associations

## 3. Methods

The basis for the first part of this thesis utilised the Plant-SyNZ database (<https://plant-synz.landcareresearch.co.nz/>). The database was developed by N.A. Martin initially, whilst at Crop and Food Research and is now managed by Landcare Research. The original purpose of the database was to assess the biodiversity of insect, mite, and nematode herbivores on New Zealand's native plants. It has since been expanded to include fungi and microorganisms, as well as predators and parasitoids of insect herbivores, and includes some information on exotic plant species. The database is continuously updated using mostly field observations, but also published information, taxonomic collections, and specialist knowledge (i.e. entomologists). It is also updated with newly discovered species, whether they be native or exotic to New Zealand. The database also contains photographs of plant damage, insects, fungi, and micro-organisms.

The first step was to extract all records of exotic herbivorous insects on native plants to create a specific dataset (see Appendix A). Against each insect species, I recorded ecological traits and taxonomic information (Table 1). These traits were taken from either within the Plant-SyNZ database or from the supplementary material of Edney-Browne et al. (2018). I used published literature to fill in the gaps where species information was missing. These traits were used in several statistical analyses to identify which traits are significant predictors of the number of associations with native plants.

I recorded all the ecological traits for each native plant species (Table 2) to create another dataset (see Appendix B). Traits were sourced from the ecological traits of New Zealand flora database (<https://ecotraits.landcareresearch.co.nz/>) which is managed by Landcare Research. Some plant species had missing information so where possible, this data was sourced using published literature. These traits were used in several statistical analyses to identify which traits are statistically significant predictors of the number of insects associated with a native plant.

Table 1. List of exotic insect traits used as independent variables in the statistical analyses to predict the number of associated native plants

<b>Independent variable</b>	<b>Levels</b>	<b>Detail</b>
Taxonomic group: Order, superfamily, family, genus	Insect taxonomic group	From Plant-SyNZ database
Ecozone (Edney-Browne et al., 2018)	Palaearctic	Biogeographical realm/ecozone of origin (Figure 2)
	Neotropic	“ ”
	Australasia	“ ”
	Afrotropic	“ ”
	Nearctic	“ ”
	Oriental	“ ”
	Oceania	“ ”
	Holarctic	All non-tropical parts of Europe, Asia, Africa north of the Sahara, and North America south to the Mexican desert region. Often subdivided into the Palaearctic and Nearctic subregions (Britannica, 2007)
Feeding type (Edney-Browne et al., 2018)	Polyphagous	Feeds on several different plant species
	O-oligophagous	Feeds on plants from the same order
	F-oligophagous	Feeds on species from the same family
	G-oligophagous	Feeds on species from the same genus
	Monophagous	Feeds on one plant species only
Body length (Edney-Browne et al., 2018)	Numerical: Natural log	Measured in dorsal view in mm
Cultivated plants (Landcare Research, 2007)	Numerical: Natural log (x+1)	The number of cultivated plants recorded on in New Zealand. The natural log (x+1) was used as several species had zero cultivated plants

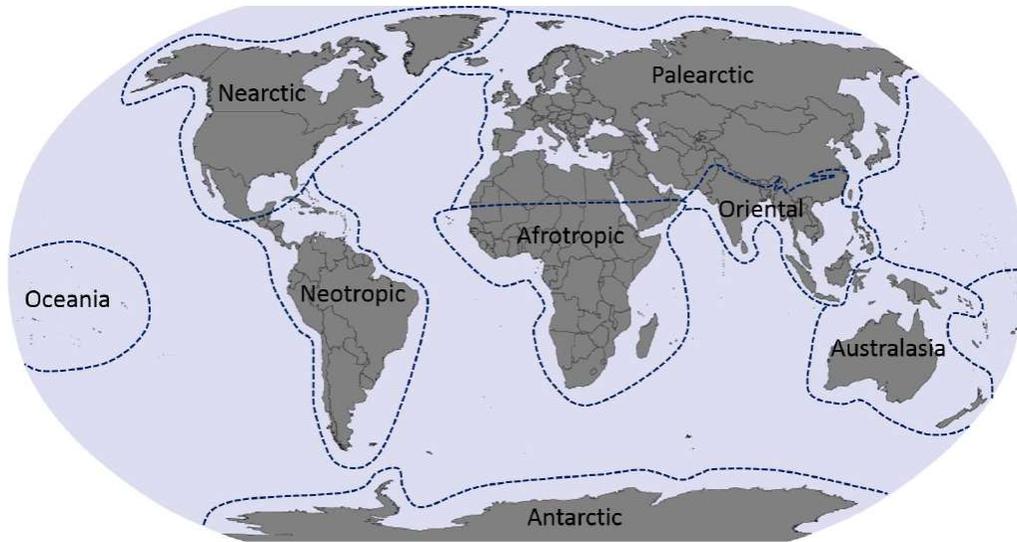


Figure 2. World map of the ecozones that were used to categorise the native ranges of the exotic insect species (World Wildlife Fund, 2015). The Holarctic zone is not in this figure however, this ecozone refers to all non-tropical parts of Europe, Asia, Africa north of the Sahara, and North America south to the Mexican desert region. Often subdivided into the Palaeartic and Nearctic subregions (Britannica, 2007). The Antarctic zone which includes both Antarctica and the Arctic were not relevant in this study.

Table 2. List of traits recorded against each native plant species which were used in the statistical analyses to predict the number of associated exotic insects

<b>Variable</b>	<b>Levels</b>	<b>Detail</b>
Taxonomic group: order, family	Plant taxonomic group	From Plant-SyNZ database
Raunkiær life mode (Landcare Research, 2022)	Chamaephyte	A woody plant whose resting buds are on or near the ground.
	Geophyte	Plants typically with underground storage organs, where the plants hold energy and water
	Hemicryptophyte	A perennial plant having its overwintering buds located at the soil surface
	Phanerophyte	Plants taller than 25-50cm which shoots don't die back periodically to that height limit
	Therophyte	An annual plant whose shoots/root system dies after seed production and complete entire life cycle within one year
Biostatus (Landcare research, 2011)	Native	A plant species found in New Zealand due to natural distribution and evolution
	Endemic	Same as above, however, is only found in New Zealand
Conservation status (De Lange et al., 2018)	At risk	Could become threatened if conservation management reduces and/or new threats arise, or population declines continue steadily
	Threatened	Greatest risk of extinction
	Not threatened	Taxa that are assessed and do not fit the above categories listed
Altitude band (Landcare Research, 2022)	Alpine	">1200m; tall grassland and low scrub - short, discontinuous vegetation" (Wardle, 1975)
	Coastal	"Transitional environments found within coastal watersheds, often influenced by

		marine and freshwater hydrology” (Lawrence, 2015)
	Lowland	“Below 400 m; lower belt of tall forest” (Wardle, 1975)
	Montane	“400-800 m; upper belt of tall forest” (Wardle, 1975)
	Subalpine	“800-1200 m; low forest and tall scrub” (Wardle, 1975)
Esler life mode (Landcare Research, 2022)	Annuals	“Returns to the seed stage at the end of a brief growth span of 12 months or less” (Esler, 1988)
	Ferns	“Spore producing apparatus” (Esler, 1988)
	Herbaceous perennials	“Live for >2 years and don’t accumulate woody tissue” (Esler, 1988)
	Monocot trees	“Agavoids, palms or bamboo-like reeds” (Esler, 1988)
	Parasites	“Dependent on other plants for nourishment” (Esler, 1988)
	Vines	“Vines are ascending plants dependent on other structures for support” (Esler, 1988)
	Woody species	“Distinguished from other groups of plants by secondary growth arising from the division of cells of the vascular cambium to form concentric cylinders of rigid tissue in the form of wood” (Esler, 1988)
Leaf form (Landcare Research, 2022)	Broad leaved	Leaves with a relatively flat surface
	Grass leaved	“Elongated structure arising at the node and consisting of a basal cylindrical sheath that encircles the stem or younger leaves” (Wheeler et al., 2002)
	Photosynthetic stems	Leaves reduced to brown scales and photosynthesis occurs in the stems
	Phyllodes	Flat expanded petiole that replaces the blade of a foliage leaf

	Scale-like	Small, flat, overlapping structures that store food and water. They are evergreens and do not drop their leaves
Pollination agents (Landcare Research, 2022)	Insects, birds, wind, water	From ecotraits website
Flowering season (Landcare Research, 2022)	Summer, spring, winter, autumn	From ecotraits website
Community (Landcare Research, 2022)	Shrubland, forest, open, wetland saline, wetland fresh, herbfield, scrub, tussockland, lowland, grassland, fernland,	From ecotraits website
Distribution around New Zealand (Landcare Research, 2022)	Widespread, local common, scattered, rare	From ecotraits website
Maximum mean plant height (m) (Landcare Research, 2022)	Numerical: Natural log	From ecotraits website

### 3.1 Statistical Analyses: Identifying high-risk exotic insects

Following statistical advice, several multivariate linear regression (MLR) and simple linear regression (SLR) models were performed in the R software environment using the “lm” function within the stats package (R Core Team, 2021). As there were many independent variables, several models were created to explore which insect traits were significant predictors of the number of associated native host plants which was the dependent variable (Table 3). The dependent variable was always in its natural log transformed state.

The first nine models (Table 3) returned a statistically significant p-value of  $<0.01$ . The models are listed in declining order of the adjusted R-squared value. The first two models had the highest adjusted R-squared value. Both models used feeding type and the number of cultivated host plants as the independent variables. However, the first model used family (grouped) and the second used order. Both these models were investigated in detail in the results section (Table 8 and 9).

Table 3. Summary statistics of each multivariate/simple regression analysis performed to predict the number of native plant species' that exotic insect species' were associated with. The dependent variable is the natural log transformed number of native host plants. Statically significant p-values (<0.05) are bold and values <0.10 have an asterix.

<b>Independent variables</b>	<b>Adjusted R<sup>2</sup></b>	<b>P-value</b>
Family (grouped) + feeding type + cultivated	0.49	<b>&lt;0.01</b>
Order + feeding type + cultivated	0.42	<b>&lt;0.01</b>
Cultivated plants	0.36	<b>&lt;0.01</b>
Family (grouped) + feeding type	0.35	<b>&lt;0.01</b>
Family (grouped)	0.28	<b>&lt;0.01</b>
Order + feeding type	0.19	<b>&lt;0.01</b>
Superfamily, feeding type	0.15	<b>&lt;0.01</b>
Feeding type	0.15	<b>&lt;0.01</b>
Order	0.10	<b>&lt;0.01</b>
Family	0.10	0.09*
Super family	0.05	0.16
Body size	0.00	0.25
Ecozone	-0.02	0.69

Model: Independent variables: Family (grouped), feeding type and cultivated plants (Table 8)

Insect family was one of the independent variables used in this MLR to explain the variation in the number of associated native plants. However, there were 55 families, which meant the results were very complex. To overcome this, I grouped all families together in a “low-risk” category if the family had an average of three or less native host plants.

The family Thripidae was subdivided up between the two sub-families (Panchaetothripinae and Thripinae) for the purpose of the regression models, because species of Panchaetothripinae were found on 6, 15 and 64 plants (possible higher-risk insects), whereas species of Thripinae were found on 1, 1, and 3 plants.

F-oligophagous feeders were selected as the intercept in this model because the average number of associated native plants from these insects was relatively low (2), compared to polyphagous feeders which was relatively high (10). Monophagous feeders had an average of one plant however, only two insects fell within this feeding group, whereas f-oligophagous feeders consisted of 32 insects. Thus, f-oligophagous feeders were the best group to compare all other feeding types with. The “low-risk” grouped families were also included in the intercept. This meant that all other insect families were compared to the ‘low-risk’ grouped families. All families and feeding types which were statistically significantly different from the intercept returned a p-value of <0.05. Whereas the numerical variable ‘cultivated plants’ returned a significant p-value if it was a statistically significant predictor of the number of associated plants.

Model: Independent variables: Order, feeding type and cultivated plants (Table 9)

The intercept for this model was Coleoptera and f-oligophagous. Coleoptera was selected because the average number of plants these insects were found on was two and was consequently the order which had the lowest average native plant associations. F-oligophagous feeders were chosen as the intercept for the same reasons mentioned in the previous model which used family (grouped) as the independent variable. All other categorical levels in this model were then compared to the intercept. Whereas cultivated plants returned a significant p-value if it was a statistically significant predictor of the number of associated plants.

## 3.2 Statistical analyses: Identifying vulnerable native plants

Several MLR and SLR models were fitted to explore which of the plant traits were significant predictors of the number of exotic insect associations (Table 4). The summary statistics of each model were used to inform which model needed to be investigated in more detail.

All models returned a statistically significant p-value, except for the model which used plant biostatus as a predictor. The first model used three independent variables and returned the highest adjusted R-squared value. This model is considered the best fit model as it has fewer independent variables than the second model which returned the same R-squared value. This is because it explained the highest variation in the dependent variable (number of associated exotic insect species) whilst also considering simplicity of the results. Additionally, when plant family (grouped) was swapped out of the first model for plant order (the fourth model in Table 4), the R-squared value drops 4% hence plant family (grouped) is the better taxonomic predictor.

Table 4. Summary statistics of each multivariate/simple regression analysis performed to predict the number of exotic insect species recorded on native plants. Statically significant (<0.05) p-values are bold.

<b>Independent variables</b>	<b>Adjusted R<sup>2</sup></b>	<b>P-value</b>
Family (grouped) + altitude + Raunkiær life mode	0.29	<b>&lt;0.01</b>
Family (grouped) + altitude + Raunkiær life mode + maximum mean height	0.29	<b>&lt;0.01</b>
Order + altitude + Raunkiær life mode	0.25	<b>&lt;0.01</b>
Family (grouped) + Raunkiær life mode + leaf form	0.24	<b>&lt;0.01</b>
Family + Raunkiær life mode + leaf form	0.24	<b>&lt;0.01</b>
Order + pollinator + altitude + Raunkiær life mode	0.23	<b>&lt;0.01</b>
Family (grouped) + Raunkiær life mode	0.22	<b>&lt;0.01</b>
Order + Raunkiær life mode	0.19	<b>&lt;0.01</b>
Order + Raunkiær life mode + leaf form	0.19	<b>&lt;0.01</b>
Raunkiær life mode + leaf form	0.14	<b>&lt;0.01</b>
Family (grouped)	0.13	<b>&lt;0.01</b>
Order + leaf form	0.12	<b>&lt;0.01</b>
Altitude	0.11	<b>&lt;0.01</b>
Raunkiær life mode	0.11	<b>&lt;0.01</b>
Order	0.10	<b>&lt;0.01</b>
Maximum mean height	0.09	<b>&lt;0.01</b>
Leaf form	0.09	<b>&lt;0.01</b>
Esler life mode	0.08	<b>&lt;0.01</b>
Pollinator	0.08	<b>&lt;0.01</b>
Community	0.05	<b>&lt;0.01</b>
Season	0.03	<b>&lt;0.01</b>
Distribution	0.02	<b>0.01</b>
Biostatus	0.00	0.84

Best fit model: Independent variables: Family (grouped), Raunkiær life mode and altitude band.

As there were 93 plant families, I grouped all families together in a “low-risk” category if the family had an average of <5 insect associations. The purpose of this was to reduce the complexity of the model results.

In this model, the grouped “low-risk” plant families are the intercept which all other families were compared with. The Raunkiær life mode ‘hemicryptophyte’ and the altitude band ‘alpine’ were also selected as the intercept. Hemicryptophyte plants were the intercept as they had a relatively low average number of insects associated with them (2), while also maintaining several plant records in the database. Alpine plants had a relatively low average of 1 insect association while also maintaining several records in the database. This meant that all other independent variable levels were compared to the intercept which were the low-risk plant variables. Any categorical variable levels which returned a significant p-value (<0.05) were therefore statistically significantly different from the intercept.

## 4. Results

### 4.1. Summary of potential hazards (exotic herbivorous insects)

The Plant-SyNZ database contained 171 herbivorous exotic insects which had been recorded on 376 native plants and contributed to a total of 1,166 associations. The insects were from six orders, 31 super families, 55 families and 136 genera. Only one species was from the order Isoptera, and this was *Kaloterme banksiae* which was recorded on *Lophozonia menziesii* (Nothofagaceae: Fagales). This association has been removed from future analysis. Most (67%) of the exotic insect species were only associated with 1-3 native plant species, while only 10% of the insects were recorded on >19 plant species (Figure 3).

Hemiptera was the order which had the most numerous insect species and number of combined associations (Table 5). Every other order had <30 insect species and <91 combined associations. Thysanoptera had the second highest number of associations with insects however, it only contained six species. Upon further inspection of the Thysanoptera species, the greenhouse thrip (*Heliothrips haemorrhoidalis*) is responsible for 64 of the 90 associations. The remaining insect orders contain species which have <14 associations with native plants.

In declining order (Table 6), Aphididae, Diaspididae and Coccidae are the families which have the most combined associations with native plants. However, the average number of associations per species is important to consider. For example, Aphididae has the highest number of combined associations, however 60% of these species are associated with <4 plants. This is because it is the family which also contained the most insect species within the Plant-SyNZ database. Ricaniidae is the family with the highest average associations as it only contained one species, the passionvine hopper (*Scolypopa australis*). The average association per species in Diaspididae and Monophlebidae were less than half that of the passionvine hopper. Nevertheless, these two families still had a relatively high average number of associations with native plants.

Out of all observations within the Plant-SyNZ database, 27 insect species contributed to 70% of all associations, and ten species contributed to 42% of associations (Table 7). The greenhouse thrip (Thysanoptera: Thripidae) is the only insect listed in the top 10 insects which is not from the order Hemiptera. Additionally, three of the top 10 species are from the family Diaspididae and three are from Coccidae.

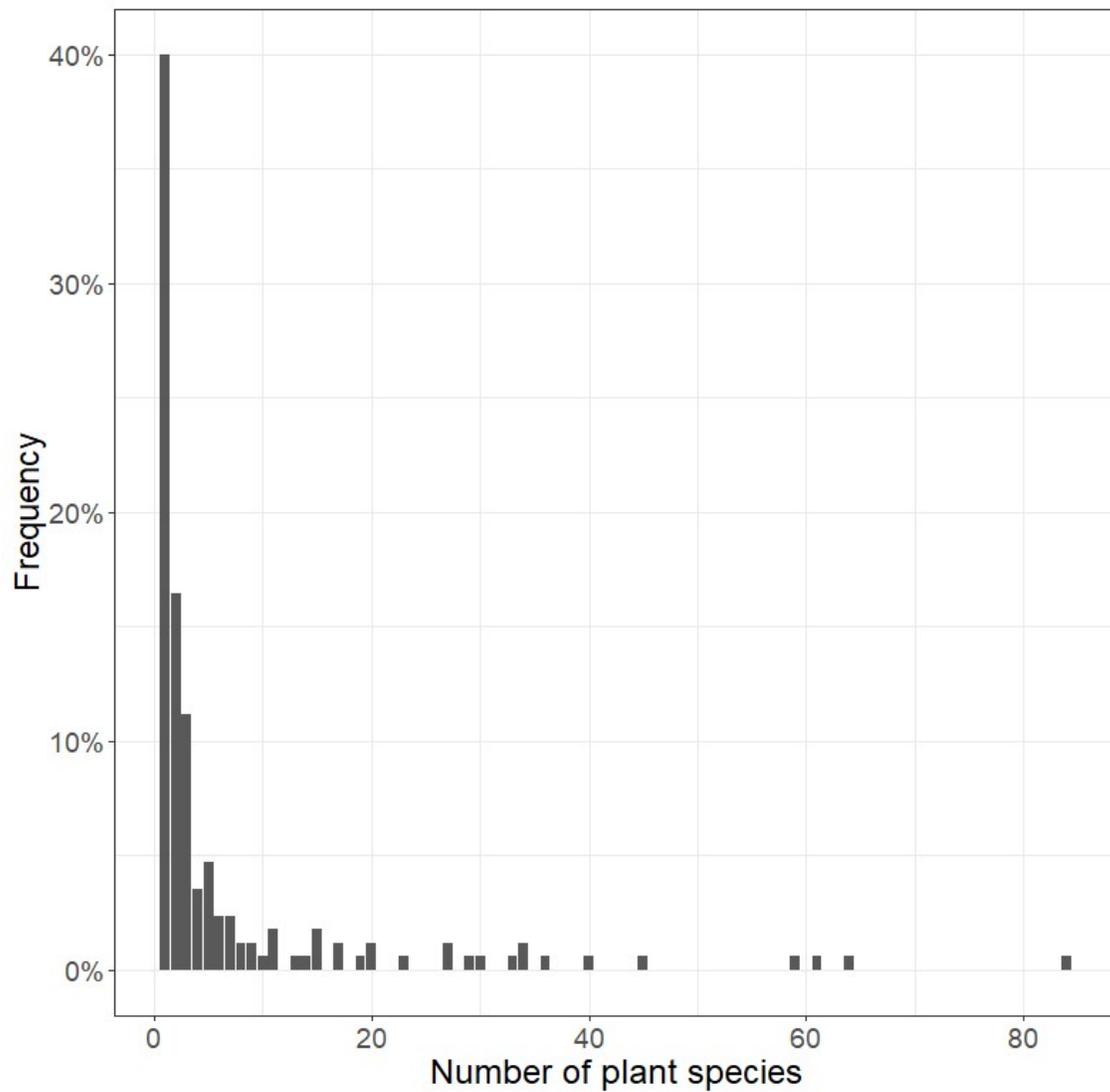


Figure 3. Histogram of the number of plant species that exotic insect species were recorded on based off the historical records within the Plant-SyNZ database. For example, 40% of exotic insect species were associated with only 1 native plant species.

Table 5: Associations between exotic insects and native plants. “%”= the percentage of all associations with native plants

<b>Insect order</b>	<b>No. insect species</b>	<b>No. combined associations</b>	<b>%</b>	<b>Cumulative %</b>
Hemiptera	100	928	80%	80%
Thysanoptera	6	90	8%	87%
Coleoptera	29	63	5%	93%
Lepidoptera	26	60	5%	98%
Diptera	9	24	2%	100%

Table 6. Number of native plant species that each insect species had been recorded on, grouped as family. Only families with >9 associations with plants are included. Average association = the average number of associations with native plants per insect species

<b>Insect family (Order)</b>	<b>No. insect species</b>	<b>No. combined associations</b>	<b>Average association</b>
Ricaniidae (Hemiptera)	1	59	59
Diaspididae (Hemiptera)	9	236	26.2
Monophlebidae (Hemiptera)	1	20	20
Flatidae (Hemiptera)	3	51	17
Coccidae (Hemiptera)	10	160	16
Nolidae (Lepidoptera)	1	11	11
Thripidae (Thysanoptera)	6	90	10
Aphididae (Hemiptera)	47	303	6.4
Pentatomidae (Hemiptera)	3	16	5.3
Agromyzidae (Diptera)	3	15	5
Tortricidae (Lepidoptera)	4	18	4.5
Pseudococcidae (Hemiptera)	10	38	3.8
Aleyrodidae (Hemiptera)	4	15	3.8
Curculionidae (Coleoptera)	13	34	2.6

Table 7: The top ten exotic insect species and the total (and %) number of native plant species they have been recorded on.

Scientific name	Common name	Order	Family	Total plants recorded on	%	Cumulative %
<i>Hemiberlesia rapax</i>	Greedy scale	Hemiptera	Diaspididae	84	7%	7%
<i>Heliothrips haemorrhoidalis</i>	Greenhouse thrip	Thysanoptera	Thripidae	64	6%	13%
<i>Aspidiotus nerii</i>	Oleander scale	Hemiptera	Diaspididae	61	5%	18%
<i>Scolypopa australis</i>	Passion vine hopper	Hemiptera	Ricaniidae	59	5%	23%
<i>Lindingaspis rossi</i>	Black araucaria scale	Hemiptera	Diaspididae	45	4%	27%
<i>Coccus hesperidum</i>	Brown soft scale	Hemiptera	Coccidae	40	3%	30%
<i>Ceroplastes sinensis</i>	Chinese wax scale	Hemiptera	Coccidae	36	3%	33%
<i>Aulacorthum solani</i>	Foxglove aphid	Hemiptera	Aphididae	34	3%	36%
<i>Siphanta acuta</i>	Green planthopper	Hemiptera	Flatidae	34	3%	39%
<i>Saissetia coffeae</i>	Hemispherical scale	Hemiptera	Coccidae	33	3%	42%

## 4.2 Predicting risk based on insect traits from the historical records

The best fit MLR used to explain the variation in the number of native plants that exotic insects are associated with is seen below in table 8. Relative to the low-risk intercept, the families which are statistically significantly different are Ricaniidae, Flatidae, Thripidae (Panchaetothripinae), Pentatomidae, and Aphididae. These families returned t-values of  $>2.15$  so are predicted to be found on a statistically significantly higher number of native plants than the intercept. However, Monophlebidae, Diaspididae and Coccidae have p-values which are 0.06-0.09 so are close to being statistically significant. They also returned positive t-values, so the mean number of associated native plants was higher than the low-risk intercept.

Ricaniidae had a noticeably high coefficient estimate of 2.95. This figure is in the natural logarithm, so the exponent of this figure (19.11) identifies the expected increase in the dependent variable. This meant that a change from the “low-risk” families in the intercept to a Ricaniidae insect resulted in a predicted increase of 19.11 times the number of associated plants than the intercept. Whereas a change from the “low-risk” families to Flatidae insects, which has the second highest coefficient of 1.88, predicts an increase of only 6.55 times the number of associated plants than the intercept. Similarly, a change from the low-risk feeding type f-oligophagous to polyphagous was associated with a predicted increase of 1.75 times the number of plants.

O-oligophagous also returned a statistically significant p-value (0.05) and returned a higher positive coefficient estimate than polyphagous feeders, suggesting species in this group may be found on more plants than polyphagous insects. However, o-oligophagous had a high standard error, and the t-value was lower than that of the polyphagous insects. This means that the coefficient estimate is not precise. The lower precision surrounding the coefficient in o-oligophagous feeders is because only one insect within the database is o-oligophagous. Similarly, Ricaniidae and Monophlebidae had a high standard error (0.85) as they each had only one species featured in the database.

Cultivated plants returned a p-value of  $<0.01$ , so this independent variable was a statistically significant predictor of the number of plant associations. With an increase in one cultivated host plant, there was an estimated increase of 1.51 times the number of associated native plants. The t-value in this variable was the highest out of all other independent variables and it maintained the lowest standard error, so there is sufficient evidence that this variable is a statistically significant predictor of the number of native plants.

Table 8. Multivariate regression analysis using insect family (grouped), feeding type and the number of cultivated host plant species to predict the number of native host plant species ( $R^2 = 0.56$ , Adjusted  $R^2 = 0.49$ ,  $F(22, 147) = 8.52$ ,  $p = <0.01$ ). 'CE'= coefficient estimate and 'SE'= standard error. The independent variable "FT" = Feeding type. The independent variable "Family" has the insect order it corresponds with in brackets: H= Hemiptera, T= Thysanoptera, D= Diptera, L= Lepidoptera. Statically significant ( $<0.05$ ) p-values are bold and non-significant p-values which are  $<0.10$  are marked with an asterix.

Independent variables	CE	SE	t-value	P-value
(Intercept)	-0.12	0.18	-0.68	0.50
<b>Family:</b> "low-risk" families + <b>FT:</b> f-oligophagous				
<b>Family:</b> Ricaniidae (H)	2.95	0.85	3.48	<b>0.00</b>
<b>Family:</b> Flatidae (H)	1.88	0.50	3.79	<b>0.00</b>
<b>Family:</b> Panchaetothripinae (T)	1.21	0.52	2.34	<b>0.02</b>
<b>Family:</b> Pentatomidae (H)	1.08	0.50	2.15	<b>0.03</b>
<b>Family:</b> Aphididae (H)	0.49	0.16	3.02	<b>0.00</b>
<b>Family:</b> Monophlebidae (H)	1.49	0.85	1.74	0.08*
<b>Family:</b> Diaspididae (H)	0.65	0.34	1.95	0.06*
<b>Family:</b> Coccidae (H)	0.52	0.31	1.69	0.09*
<b>Family:</b> Aphrophoridae (H)	1.18	0.85	1.39	0.17
<b>Family:</b> Nolidae (L)	0.78	0.89	0.88	0.38
<b>Family:</b> Agromyzidae (D)	0.44	0.52	0.84	0.40
<b>Family:</b> Pieridae (L)	0.65	0.86	0.76	0.45
<b>Family:</b> Tortricidae (L)	0.27	0.43	0.63	0.53
<b>Family:</b> Pseudococcidae (H)	-0.18	0.30	-0.60	0.55
<b>Family:</b> Membracidae (H)	0.48	0.85	0.56	0.57
<b>Family:</b> Aleyrodidae (H)	-0.19	0.44	-0.43	0.67
<b>FT:</b> polyphagous	0.56	0.19	2.86	<b>0.00</b>
<b>FT:</b> o-oligophagous	1.71	0.86	2.00	<b>0.05</b>
<b>FT:</b> g-oligophagous	0.16	0.32	0.50	0.62
<b>FT:</b> Unknown	0.13	0.24	0.53	0.60
<b>FT:</b> monophagous	0.12	0.62	0.20	0.84
Cultivated	0.41	0.06	6.50	<b>0.00</b>

The MLR results seen in table 9 revealed that Hemiptera is the only insect order which is statistically significantly different from the intercept. Similarly, polyphagous feeders were the only feeding type which were statistically significant. Although, o-oligophagous feeders had a p-value of 0.06 so were close to being significant. A change to polyphagous feeders predicted an increase of 1.68 times the number of native plants from the intercept. While Hemiptera predicted an increase of 1.65 times the number of native plants. The number of cultivated host plants was also a statistically significant predictor of the number of native plants associated with. An increase of one cultivated host plant predicted an increase of 1.57 times the number of native plants.

Thysanoptera insects returned a near statistically significant p-value of 0.10 and a t-value of 1.68 so they were predicted to be found on more plants than the intercept. Additionally, the coefficient was larger than Hemiptera insects, so these insects had a higher predicted number of native plant associations. However, the standard error was relatively high (0.42) so the coefficient is not precise and this is a consequence of the high variation seen between the six thrip species.

This model returned a relatively high adjusted R-squared value of 0.42. This meant that 42% of the variation in the number of associated native plants was explained by insect order, feeding type and cultivated host plants. This is 7% lower than the best fit model which used insect family (grouped), feeding type and cultivated host plants.

Figure 4 illustrates the relationship between the number of recorded cultivated host plants and the number of native host plants, both variables are in their log normal state. The R-squared value of 0.43 suggested a moderate positive relationship between number of cultivated host plants and the total number of native host plants. There appeared to be high variability in the number of native host plants when there are <5 cultivated hosts, however there is a stronger positive association when the number of cultivated plants exceeded five. An increase of one cultivated plant resulted in an estimated increase of 1.2 native plants for exotic herbivorous insects, irrespective of feeding type or order.

Table 9. Multivariate regression analysis using insect order, feeding type and number of cultivated host plant species to predict the number of native host plant species ( $R^2 = 0.45$ , Adjusted  $R^2 = 0.42$ ,  $F(10, 159) = 13.26$ ,  $p = <0.001$ ). The independent variable “FT” = Feeding type. Statically significant ( $<0.05$ ) p-values are bold and non-significant p-values which are  $\leq 0.10$  are marked with an asterix.

Independent variables	Coefficient estimate	Std. Error	t value	P-value
(Intercept)				
<b>Order:</b> Coleoptera + <b>FT:</b> f-oligophagous	-0.17	0.25	-0.68	0.50
<b>Order:</b> Hemiptera	0.50	0.19	2.59	<b>0.01</b>
<b>Order:</b> Thysanoptera	0.68	0.41	1.68	0.10*
<b>Order:</b> Lepidoptera	0.13	0.27	0.47	0.64
<b>Order:</b> Diptera	0.06	0.35	0.17	0.86
<b>FT:</b> polyphagous	0.52	0.20	2.55	<b>0.01</b>
<b>FT:</b> o-oligophagous	1.75	0.92	1.91	0.06*
<b>FT:</b> unknown	0.17	0.25	0.68	0.50
<b>FT:</b> g-oligophagous	0.10	0.35	0.30	0.76
<b>FT:</b> monophagous	0.05	0.67	0.07	0.95
Cultivated	0.45	0.06	8.07	<b>0.00</b>

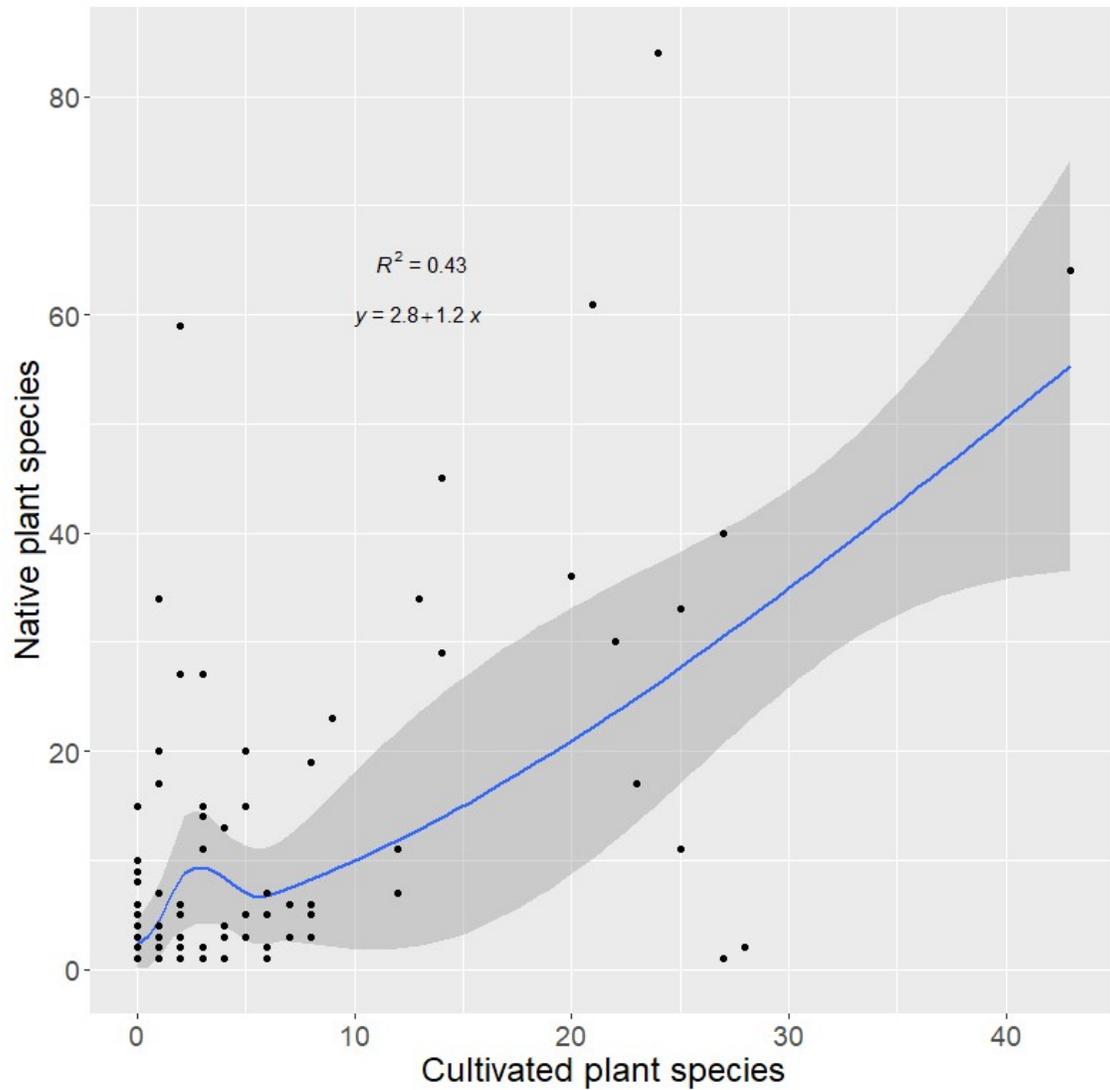


Figure 4. Total number of native plant species that exotic insects are associated with against the total number of cultivated plant species. Neither of the variables had been log transformed in this simple regression analysis.

### 4.3 Summary of potential exposed assets (plants)

There were 376 different native plant species which had records of exotic insects on them. The native plants were from 39 orders, 93 families and 187 genera. Apiales was the order with the highest number of associations, a total of 146, followed by Asterales and Lamiales, each had a total of 123 associations (Figure 5). The remaining plant orders had <80 associations in total. Hemiptera was always the most common insect order recorded on any plant order. Endemic plants had 632 more associations with exotic insects than the indigenous/non-endemic plants (Figure 6). However, the average number of insects recorded on each endemic plant species and indigenous/non endemic plant species were both three (Figure 7).

Although there were 376 plant species, only twenty-nine plant species accounted for 30% of all associations between native plants and exotic insects (Table 10). Twenty-one of these plant species were endemic and the remaining eight were native/non-endemic to New Zealand (i.e. they are found elsewhere in the world). Twenty-three of these plants fall within the 'not threatened' category under the conservation classification (De Lange et al., 2018), four are 'threatened', one is 'at risk' and one isn't assessed as the plant was only identified to genus level. The plants listed in table 11 are particularly vulnerable due to their threatened status in New Zealand. The conservation status of a plant is important to consider because a plant which has already been recognised as at risk of extinction, which also has many exotic insects feeding on it should be considered a vulnerable species.

Poroporo (*Solanum aviculare*) is concerning as it is the plant that has had the most exotic insects recorded on it and is classified as "threatened". It is further classified as "nationally vulnerable" which is only three stages before being declared extinct (De Lange et al., 2018). Pōhutukawa (*Metrosideros excelsa*) is also classified as threatened (nationally vulnerable) with 14 insects recorded on it. Tecomanthe (*Tecomanthe speciosa*) has ten insect associations and is categorised as nationally critical which is the classification before extinction is declared. If the insect species which are recorded on these plants are present in high abundances and/or the feeding pressure is great, this could direct these plant species further towards extinction.

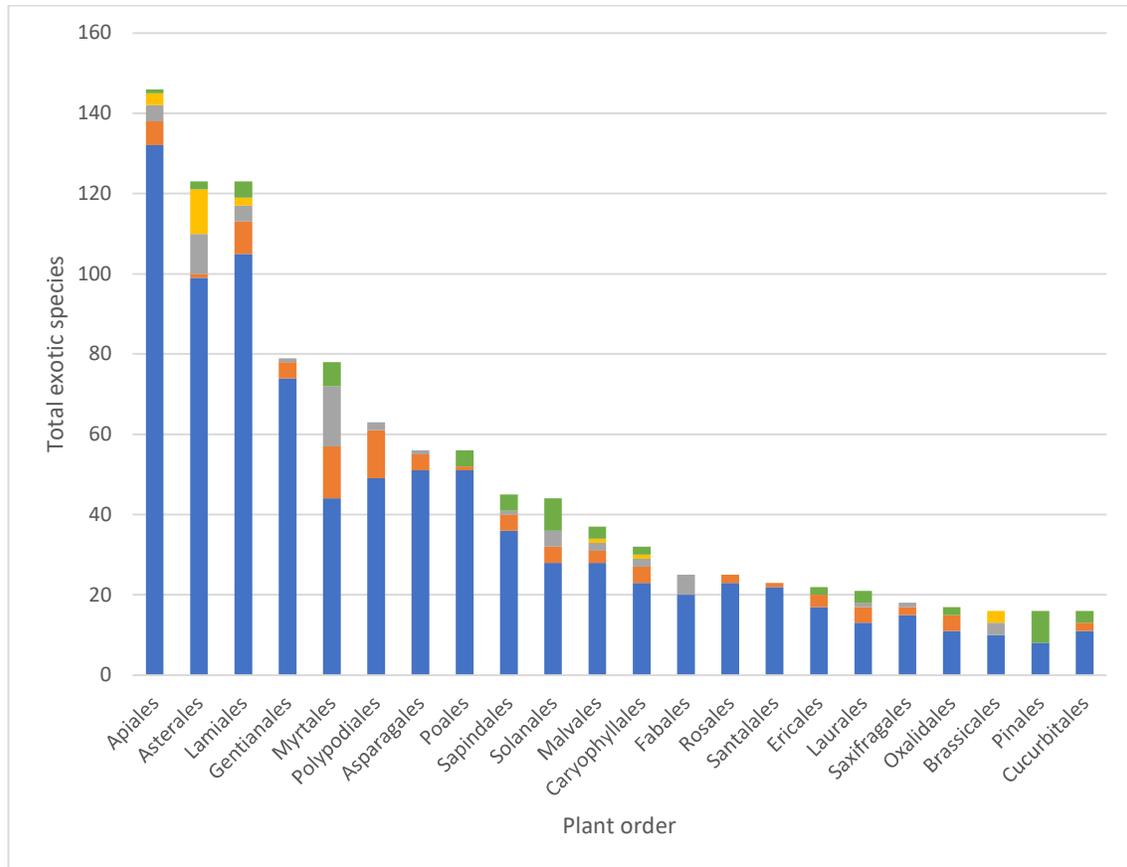


Figure 5. Number of combined associations between exotic insects and native plants grouped by insect order and plant order. As there were 39 plant orders, only orders which had more than 15 associations were included. Bars are stacks by insect order: Hemiptera (blue), Thysanoptera (orange), Lepidoptera (grey), Diptera (yellow), Coleoptera (green)

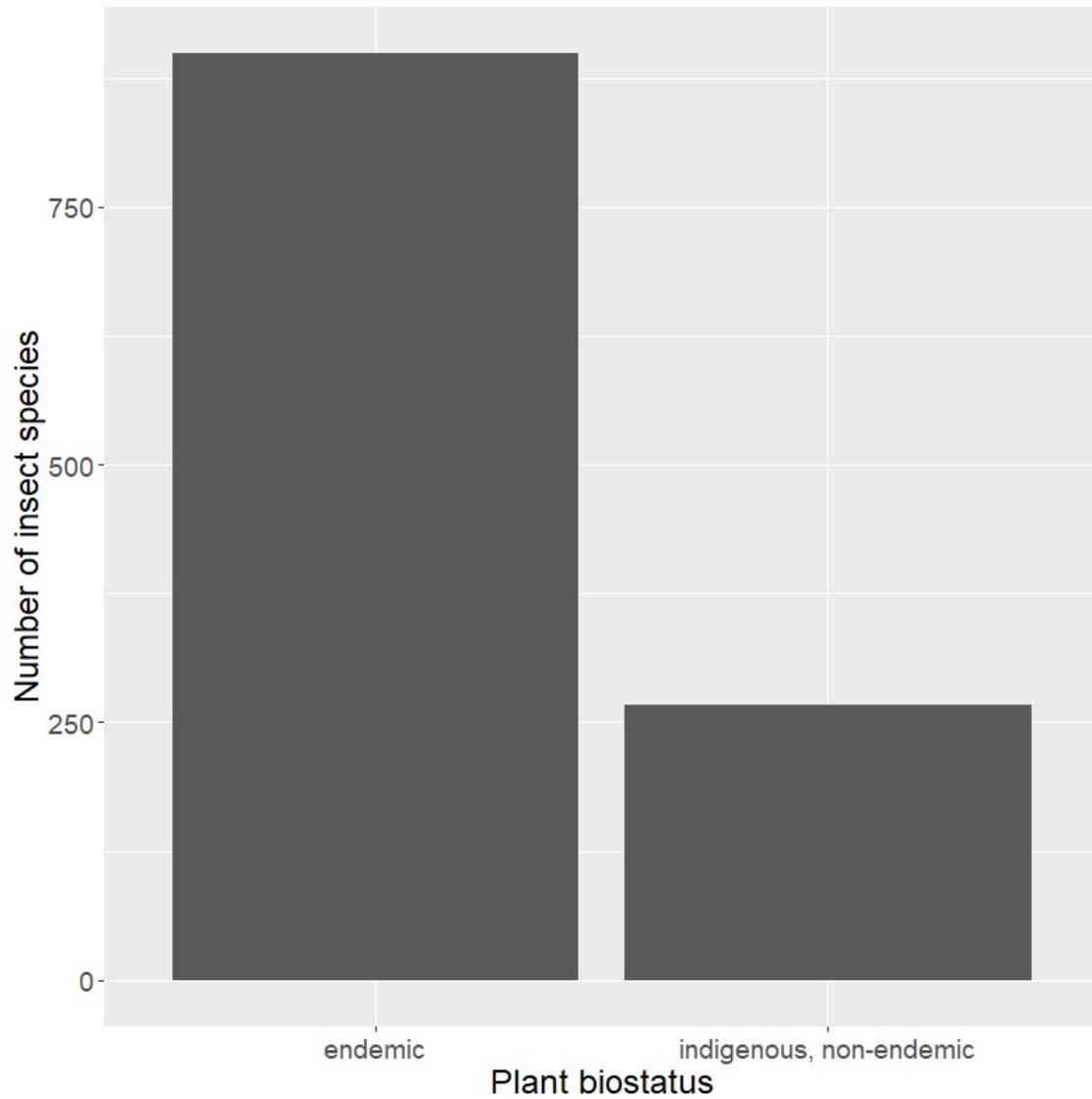


Figure 6. The combined number of associations between exotic insect species and native plant species grouped as plant biostatus

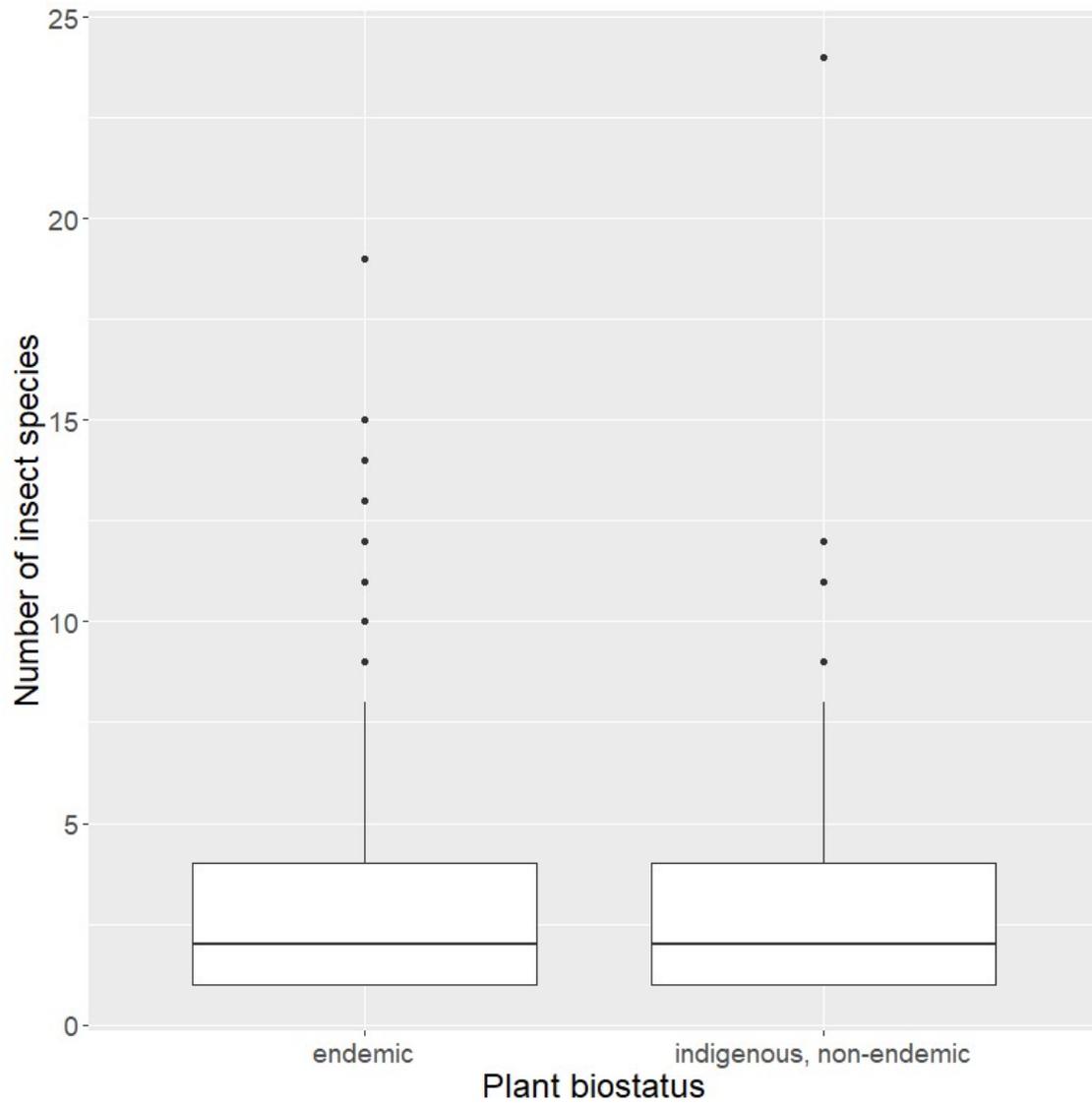


Figure 7. The number of exotic insect species that had been recorded on native plant species grouped as plant biostatus

Table 10. Number of exotic insect species associated with each native plant species, excluding plants with <10 associations. Species in bold were sampled in the field survey section in chapter two of this thesis. “CS” is the conservation status: T= Threatened, AR= At risk, NT= Not threatened. “C%” is the cumulative percentage of all associations

Scientific name	Common name	CS	No. insects	C%
<i>Solanum aviculare</i>	Poroporo	T	24	2%
<i>Myoporum laetum</i>	Ngaio	NT	19	4%
<i>Vitex lucens</i>	Puriri	NT	19	5%
<i>Veronica stricta</i>	Koromiko	NT	15	7%
<i>Metrosideros excelsa</i>	Pöhutukawa	T	14	8%
<i>Hoheria populnea</i>	Lacebark	NT	14	9%
<i>Haloragis erecta</i>	Fire weed	NT	14	10%
<b><i>Pittosporum crassifolium</i></b>	<b>Karo</b>	<b>NT</b>	<b>13</b>	<b>11%</b>
<i>Pittosporum eugenioides</i>	Lemonwood	NT	13	12%
<i>Leptospermum scoparium</i>	Manuka	AR	12	13%
<i>Pseudopanax lessonii</i>	Coastal five finger	NT	12	14%
<i>Muehlenbeckia complexa</i>	Pohuehue	NT	12	16%
<i>Dodonaea viscosa</i>	Akeake	NT	12	17%
<i>Kunzea ericoides</i>	Kanuka	T	11	17%
<i>Melicope ternata</i>	Wharangi	NT	11	18%
<i>Coprosma grandifolia</i>	Shining karamu	NT	11	19%
<i>Cordyline australis</i>	Cabbage tree	NT	10	20%
<i>Pittosporum tenuifolium</i>	Kohuhu	NT	10	21%
<b><i>Coprosma robusta</i></b>	<b>Karamu</b>	<b>NT</b>	<b>10</b>	<b>22%</b>
<i>Plagianthus divaricatus</i>	Ribbonwood	NT	10	23%
<i>Tecomanthe speciosa</i>	Tecomanthe	T	10	24%
<b><i>Myrsine australis</i></b>	<b>Red matipo</b>	<b>NT</b>	<b>10</b>	<b>25%</b>
<i>Phormium tenax</i>	Flax	NT	9	25%
<i>Veronica sp.</i>	<i>Veronica sp.</i>	NA	9	26%
<b><i>Melicytus ramiflorus</i></b>	<b>Whitey wood</b>	<b>NT</b>	<b>9</b>	<b>27%</b>
<i>Schefflera digitata</i>	Patē	NT	9	28%
<i>Apium prostratum</i>	NZ celery	NT	9	28%
<i>Solanum laciniatum</i>	Porporo	NT	9	29%
<b><i>Piper excelsum</i></b>	<b>Pepper tree</b>	<b>NT</b>	<b>9</b>	<b>30%</b>

Table 11. Number of exotic insect species associated with native plants which are classified as threatened, excluding plants with <4 associations.

<b>Scientific name</b>	<b>Common name</b>	<b>Conservation status</b>	<b>No. insect species</b>
<i>Solanum aviculare</i>	Poroporo	Nationally Vulnerable	24
<i>Metrosideros excelsa</i>	Pōhutukawa	Nationally Vulnerable	14
<i>Kunzea ericoides</i>	Kanuka	Nationally Vulnerable	11
<i>Tecomanthe speciosa</i>	Tecomanthe	Nationally Critical	10
<i>Lepidium oleraceum</i>	Cook's scurvy grass	Nationally Endangered	8
<i>Korthalsella salicornioides</i>	Dwarf mistletoe	Nationally Critical	7
<i>Lophomyrtus bullata</i>	Ramarama	Nationally Critical	5
<i>Scandia rosifolia</i>	Koheriki	Nationally Critical	5
<i>Metrosideros robusta</i>	Northern rata	Nationally Vulnerable	4
<i>Syzygium maire</i>	Swamp maire	Nationally Critical	4
<i>Metrosideros bartlettii</i>	Bartlett's rata	Nationally Critical	4
<i>Olearia traversiorum</i>	Chatham Island akeake	Nationally Vulnerable	4

#### 4.4 Predicting vulnerability based on plant traits from the historical records

The results from the MLR revealed that the plant families Haloragaceae, Scrophulariaceae, Sapindaceae, Bignoniaceae, Solanaceae and Rutaceae were statistically significantly different from the low-risk intercept (Table 12). All of these families had positive t-values  $>2.21$  so they were predicted to have more insect associations than the intercept. However, Haloragaceae was the family which was predicted to have the highest number of insect associations with an increase of 6.36 times (exponent of 1.85) the number of insects than the intercept. However, Solanaceae followed by Sapindaceae had the highest t-values for family so are the groups which have the greatest evidence of a significant difference from the intercept. Meliaceae, Labiatae and Malvaceae were close to being statistically significant (p-values 0.08- 0.10).

Phanerophyte was the only Raunkiær life mode which was statistically significantly different from the intercept. A change from Hemicryptophyte plants to Phanerophyte plants meant there was a predicted increase of 1.8 times (exponent of 0.59) the number of insect associations. Coastal and lowland were also statistically significant however, coastal had the highest t-value of 5.31 whereas lowland returned a t-value of -1.98. Coastal is therefore the only altitude band which was statistically significantly higher than the intercept, with a predicted increase of 1.58 times (exponent of 1.58) the number of insect associations. Overall, these independent variables explained 29% of the variation in the dependent variable.

Table 12. Multivariate regression analysis using plant family (grouped), Raunkiær life mode and altitude band to predict the number of exotic insect species recorded on a native plant ( $R^2 = 0.34$ , Adjusted  $R^2 = 0.29$ ,  $F(25, 349) = 7.09$ ,  $p = <0.001$ ). “CE”= model coefficient estimate. RLM”= Raunkiær life mode. “Alt”= altitude band. Statically significant ( $\leq 0.05$ ) p-values are bold and non-significant p-values which are  $\leq 0.10$  are marked with an asterix.

Independent variables	CE	Std. Error	t value	P-value
(Intercept)				
<b>Family(g):</b> grouped <5				
<b>RLM:</b> Hemicryptophyte				
<b>Alt:</b> Alpine	0.30	0.15	1.98	0.05
<b>Family(g):</b> Haloragaceae	1.85	0.73	2.54	<b>0.01</b>
<b>Family(g):</b> Scrophulariaceae	1.80	0.70	2.58	<b>0.01</b>
<b>Family(g):</b> Sapindaceae	1.73	0.50	3.45	<b>0.00</b>
<b>Family(g):</b> Bignoniaceae	1.54	0.70	2.21	<b>0.03</b>
<b>Family(g):</b> Solanaceae	1.50	0.42	3.60	<b>0.00</b>
<b>Family(g):</b> Rutaceae	1.10	0.41	2.71	<b>0.01</b>
<b>Family(g):</b> Meliaceae	1.24	0.70	1.77	0.08*
<b>Family(g):</b> Labiatae	0.81	0.49	1.64	0.10*
<b>Family(g):</b> Malvaceae	0.44	0.27	1.66	0.10*
<b>Family(g):</b> Piperaceae	1.05	0.70	1.51	0.13
<b>Family(g):</b> Violaceae	0.97	0.70	1.39	0.17
<b>Family(g):</b> Corynocarpaceae	0.94	0.70	1.34	0.18
<b>Family(g):</b> Ripogonaceae	0.80	0.70	1.15	0.25
<b>Family(g):</b> Loganiaceae	0.65	0.70	0.93	0.35
<b>Family(g):</b> Acanthaceae	0.44	0.70	0.63	0.53
<b>RLM:</b> Phanerophyte	0.59	0.11	5.38	<b>0.00</b>
<b>RLM:</b> Chamaephyte	0.23	0.23	1.04	0.30
<b>RLM:</b> Geophyte	0.13	0.32	0.40	0.69
<b>RLM:</b> Therophyte	0.10	0.30	0.32	0.75
<b>RLM:</b> Unknown	0.00	0.12	-0.04	0.97
<b>Alt:</b> Coastal	0.46	0.09	5.31	<b>0.00</b>
<b>Alt:</b> Lowland	-0.20	0.10	-1.98	<b>0.05</b>
<b>Alt:</b> Unknown	0.14	0.15	0.90	0.37
<b>Alt:</b> Montane	0.09	0.09	0.97	0.33
<b>Alt:</b> Subalpine	-0.09	0.11	-0.80	0.43

## 5. Discussion

### 5.1 High risk insect species

Not all established exotic insect species go on to become invasive (Probert et al., 2020). Instead a small percentage of species will be considered invasive, and the remaining species will have much less of an impact on the native environment (Probert et al., 2020). It is therefore not surprising that out of 171 exotic insect species within the Plant-SyNZ database, only 15% (27 out of 171) contributed to 70% of all associations with native plant species. These 27 insect species are associated with 11-84 different native plant species. These are the species which should be considered high-risk to native plants. They show a high degree of polyphagy, being found on many native plant species and contribute to a huge percentage of all associations with native plants.

A common theme amongst the below top 10 high-risk exotic insect species (listed in order of declining risk status) is their invasive status among non-native plants. All, except the green planthopper, have been found to have a significant negative impact either on cultivated plants or ornamental plants. If an insect is considered a pest on non-native plants which are present in New Zealand, this could suggest they pose a high-risk to native plants.

#### Greedy scale (*Hemiberlesia rapax*) Diaspididae: Hemiptera.

The greedy scale is globally recognized as an invasive species and is an important pest of kiwifruit (*Actinidia deliciosa*) orchards hence, most literature relates to its impact within cropped systems (Blank et al., 1990; Blank et al., 1996). I found no literature relating to the greedy scale's impact on New Zealand's vegetation. This species is very polyphagous and has associations with 84 native plant species, which is characteristic of Diaspididae insects, so it is concerning that no attention has been given to its impact on native plants.

Out of all 84 native plant species that the greedy scale was associated with, nine of these species were indigenous (non-endemic) and the remaining 75 were endemic species. Of these host species, five were nationally vulnerable and seven were nationally critical. Forty-six percent of all associations between the greedy scale and native plant species occurred within the families Myrtaceae, Compositae, Rubiaceae, Araliaceae, Malvaceae and Pittosporaceae so these may be families which are preferred hosts of the greedy scale.

#### Green house thrip (*Heliethrips haemorrhoidalis*) Thripidae: Thysanoptera.

This was the only species within the top 10 insects which wasn't a Hemipteran. Globally, the greenhouse thrip is a pest of many plant species (Trueman et al., 2001) and in New Zealand, is an important pest of avocado (*Persea americana*) (Stevens et al., 1999). It also attacks citrus trees (*Citrus*) where it feeds on the leaves and the fruit (Rivnay, 1935). Research on the susceptibility of plants to attack by this species revealed that the greenhouse thrip prefers plant species with leaves which are coriaceous with one or both surfaces being smooth (Brown & Simmons, 2006). Plant species which evaded thrip damage commonly had glandular trichomes (Brown & Simmons, 2006). Native plants which fall under the former description may be those which are most vulnerable to this species.

#### Oleander scale (*Aspidiotus nerii*) Diaspididae: Hemiptera

This is a cosmopolitan pest predominantly found in tropical and subtropical regions (Einhorn et al., 1998). The main reason for its global pest status is due to its impact on lemon (*Citrus limon*) and olive trees (*Olea europaea*), but also ornamental plants (Einhorn et al., 1998). In New Zealand, it is a key pest on kiwifruit (Edwards et al., 2008; Morales, 1988). This scale insect damages plants by sap-sucking which weakens the plant, causes discoloration of leaves and serious fruit deterioration (Einhorn et al., 1998).

#### Passionvine hopper (*Scolypopa australis*) Ricaniidae: Hemiptera

A phloem-feeding insect which is considered a serious pest of kiwifruit in New Zealand (Charles & Allan, 2004; Sullivan et al., 2021). This species also produces honeydew which promotes the growth of sooty moulds (Sullivan et al., 2021). There is no research available on the impact of the passionvine hopper (PVH) on native plants in New Zealand, though there are two studies which look at host preference of native plants.

#### Black araucaria scale (*Lindingaspis rossi*) Diaspididae: Hemiptera

Henderson (2011) reported that this species was becoming more common in natural habitats in New Zealand with the number of native host plants reaching 20. This number has since reached 40 according to the Plant-SyNZ database. As this is a scale insect, plant damage occurs via their sucking mouthparts to access plant sap and heavy infestations are likely to cause tissue damage (Hegde et al., 2020). Affected portions of the plant dries up which can spread and ultimately lead to plant collapse, depending on the host plant species (Hegde et al., 2020). For example, this scale insect is a known pest of commercially grown roses. Heavy infestations of this species have proven to cause some plants to dry up completely and die

(Hegde et al., 2020). In New Zealand, it is known to infest apple orchards and causes significant injury (Timlin, 1964).

Brown soft scale (*Coccus hesperidum*) Coccidae: Hemiptera

This is a recognized pest species in New Zealand which required the introduction of a biological control agent in 1921 (Hodgson & Henderson, 2000). It is a serious pest on ornamental plants (indoor and outdoor) and to a lesser extent fruit orchards such as avocado, citrus, tamarillo (*Cyphomandra betacea*), grape (*Vitis vinifera*) and kiwifruit (Hodgson & Henderson, 2000). It is found in low densities on various introduced perennials, shrubs and trees (i.e. *Pinus radiata* and *Prunus* spp.) (Hodgson & Henderson, 2000). By 2000 it had 22 known native host species and by 2022 it had 40 known native hosts, according to the Plant-SyNZ database. Sap-sucking produces honeydew and results in black sooty mould fungus (Hodgson & Henderson, 2000). In 2000 it was considered the most common and widespread of the exotic soft scales in New Zealand (Hodgson & Henderson, 2000). It is found on the Kermadec Islands, as well as the Chatham Islands and is widespread throughout both the North and South Islands (Hodgson & Henderson, 2000). If this species is also common on native plants the impact of feeding could be significant.

Chinese wax scale (*Ceroplastes sinensis*) Coccidae: Hemiptera

This soft scale is a commercial pest of citrus and feijoa (*Feijoa sellowiana*) and produces honeydew resulting in the growth of sooty moulds (Hodgson & Henderson, 2000; Lo et al., 1996; Ting-Kui et al., 1994). It prefers a more temperate climate according to its current distribution (Ting-Kui et al., 1994). In New Zealand, it is present throughout the North Island and as far south as Nelson in the South Island (Lo et al., 1996) but it prefers warmer regions, generally Northland to Gisborne (Hodgson & Henderson, 2000). This species has been recorded on garden natives and forest margins which have been disturbed by humans or in open native ecosystems such as mangroves or bracken (Hodgson & Henderson, 2000).

Foxglove aphid (*Aulacorthum solani*) Aphididae: Hemiptera

A polyphagous aphid native to Europe with a near cosmopolitan distribution (Miller et al., 2009). It is of great economic importance due to extreme polyphagy and its ability to transmit at least 45 plant viruses (Miller et al., 2009). It appears that most damage to plants occurs via the transmission of viruses rather than direct feeding damage, or at least more literature is available on the transmission of viruses and less on the direct impact of feeding damage by this aphid (Ashby et al., 1979; Damsteegt & Hewings, 1986; Damsteegt & Voegtlin, 1990;

Kyriakou et al., 1983). Potato (*Solanum tuberosum*) is the most important crop which is seriously affected by this aphid in New Zealand (Lowe, 1967).

#### Green planthopper (*Siphanta acuta*) Flatidae: Hemiptera

A sap-sucking planthopper native to Australia (Withers, 2001). Damage by this insect is caused either by the direct removal of nutrients or by puncturing the plant (Waipara et al., 2005). This species is mainly discussed within the literature in relation to its abundance and presence on weedy plants (Harman et al., 2008; Waipara et al., 2005; Winks et al., 2004).

#### Hemispherical scale (*Saissetia coffeae*) Coccidae: Hemiptera

A sap-feeding, honeydew producing scale insect which is an important pest known to affect several cultivated crops, such as citrus and guava (*Psidium guajava*) (Saikia et al., 2019). In New Zealand, it has been observed in low numbers on grapevines, is a minor pest on ornamental shrubs in warmer regions (i.e. Auckland and Northland) and has also been found in remnant native forests on native plants (Hodgson & Henderson, 2000). It is recorded from Northland in the North Island to the Otago Lakes in the South Island (Hodgson & Henderson, 2000).

## 5.2 Predictors of high-risk insect species

In this project the response variable was the 'number of native plants that an exotic insect species was recorded on' and this was examined through a number of variables (e.g. taxonomic group, feeding type). Species of Hemiptera had the most interactions with native plants. In the Plant-SyNZ database, one-hundred insect species are Hemiptera and there were a combined 928 different interactions with native plant species, 80% of all interactions. This was a very large number in comparison to all other orders, with the second highest number, 90 associations, occurring in Thysanoptera species. However, 56 of the 100 Hemipteran species were only associated with 1-3 plants. Thus, Hemiptera as a predictor for the number of native plant associations was not sufficient on its own. Thysanoptera insects were interesting as there were only six species in the database but combined, they had the second highest number of interactions.

The variables which best predicted the number of native plant associations for an exotic insect were taxonomic family (grouped), feeding type and the number of recorded cultivated host plants. Polyphagous insects in the families Ricaniidae, Flatidae, Thripidae

(Panchaetothripinae), Pentatomidae and Aphididae were the insects which were high-risk (in order of highest to lowest risk). These were the insects which were statistically significantly different from the “low-risk” intercept. They all returned a t-value of  $>2.15$  so were predicted to be found on more plants than the intercept. Additionally, the risk-status of these insects increased with an increase in the number of cultivated host plants. Monophlebidae, Diaspididae and Coccidae returned p-values which were nearly statistically significant (0.06-0.09) and returned positive t-values. Monophlebidae had only one insect featured in the database with 20 associations with native plants, hence it had a relatively high standard error and a t-value  $<1.98$ . Though these three families were not statistically significant, this doesn't mean all insects in these families are low-risk. Insects in these families should be monitored as they tend to be found on many native plants compared to the intercept. Additionally, Diaspididae and Coccidae insect species each featured in the top 10 high risk insect species three times.

Insects which were o-oligophagous and polyphagous returned a statistically significant p-value. However, there was only one species in the Plant-SyNZ database which was o-oligophagous, and it was recorded on eight plants. Hence, the accuracy of the coefficient estimate of o-oligophagous insects is questionable. However, an insect species which falls within any of the mentioned high-risk families above which is also o-oligophagous and successfully established should be assumed to maintain the ability to attack several native plants and not overlooked. Polyphagous insects had the highest t-value of all the feeding groups as well as the lowest standard error, so this was a reliable predictor of a high-risk insect.

The second-best fit model used to explain the variation in the number of native plants that an exotic insect is associated with was insect taxonomic order, feeding type and cultivated plants. However, this model explained 42% of the variation in the dependent variable, 7% less than the best fit model which used family (grouped), feeding type and cultivated plants as the independent variables. This model revealed that Hemiptera was the only order and polyphagous was the only feeding type which was statistically significant different from the low-risk intercept. Additionally, the number of cultivated host plants was a statistically significant predictor of the number of native plant associations. However, order is a high taxonomic identification and there was great variation in the dependent variable between species of Hemipteran insects, hence this is not the best fit model.

#### Invasive Hemiptera insects

For the Plant-SyNZ database, Hemiptera had the greatest number of species and the most interactions with native plants. Globally, numerous species of Hemiptera are well recognized as pests of plants, with many examples of their negative economic impacts (Firake et al., 2022; Mi et al., 2020; Tiwari et al., 2018; Yan et al., 2021).

The scale insects within the super family Coccoidea contain some of the most serious pests that attack many plants globally, feeding almost exclusively on plant phloem (Mansour et al., 2017). An example is the soft scale (Coccidae: *Saissetia oleae*) which is globally regarded as a serious pest, particularly on olive and citrus by the direct consumption of sap as well as indirect feeding damage via the production of honeydew (Mahzoum et al., 2020; Mansour et al., 2017). It is very polyphagous, feeding on an estimated 150 different plant species from various families (Mahzoum et al., 2020). It is also the 11<sup>th</sup> high-risk species within the Plant-SyNZ database, with a recorded 30 associations with native plants.

The soybean aphid (Aphididae: *Aphis glycines*) has invaded parts of the United States and much of Canada and been a major source of economic loss within soybean production systems (Ragsdale et al., 2011). Consequences of feeding injury include a reduction in plant height, pod set, seed numbers and size (Ragsdale et al., 2011)

#### Invasive Thysanoptera insects

Thrips are often considered preadapted to an invasive lifestyle due to their small body size and their ability to live within cryptic habitats (Morse & Hoddle, 2006). For these reasons, thrips are frequently intercepted at borders globally (Morse & Hoddle, 2006). However, it is estimated that only 1% of all known thrip species have gained a pest status (Morse & Hoddle, 2006). Hence, it is important to identify which species of thrips are likely to be the significant pests. The two species which are considered high-risk insects are the greenhouse thrip (*Heliothrips haemorrhoidalis*) and the banana silvering thrip (*Hercinothrips bicinctus*) due to the number of native plant associations in the Plant-SyNZ database. The greenhouse thrip has previously been identified as an economic pest in New Zealand (Froud & Stevens, 2002; Jamieson et al., 2008). Despite its pest status, very limited information relates to impact on native plants. However, Van Epenhuijsen (2006) found that this thrip caused serious damage to foliage of some manuka plants. Additionally, Martin (2017) found that it caused significant damage to the leaves of seedlings and saplings of NZ honeysuckle (*Knightia excelsa*).

Thysanoptera was the second highest taxonomic order in terms of associations with native plants. However, there were only 6 species within the order that appeared within the database. Those insects that did appear, varied widely in the number of associated native plant species.

This variation contributed to its statistically non-significant result in the second best fit MLR model which used order as the taxonomic predictor. However, a statistically non-significant result does not mean that all thrips will be low risk. Three of the thrips within this order were from the subfamily Thripinae and were found on 1-3 plants, so are low-risk insects. A fourth was found on six plants and the remaining two were found on 15-64 plants. These three higher-risk insects were from the subfamily Panchaetothripinae. In the MLR analyses using order, feeding type and cultivated plants, Thysanoptera had the highest standard error of all the orders (Table 9). This was because of the large variation in this family among a small number of insects. Thus, Thysanoptera is not a sufficient predictor of the number of associated native plants. However, subfamily (Panchaetothripinae) provided a better indication of the thrips which could pose a high-risk to native plants. Additionally, thrips within this subfamily that have many cultivated plant associations and are polyphagous are probably the insects which will pose the greatest risk to native plants.

#### Family: Ricaniidae

Ricaniidae (Hemiptera) polyphagous insects were significant predictors of the number of associated native plants and was the family which was highest-risk to native plants. However, this result should be interpreted with caution as only one species fell within this family. This was the PVH which was predicted to be associated with 19.11 times more plants than the intercept.

Ricaniidae includes planthoppers which are mainly distributed throughout the tropics and the PVH is the only one present in New Zealand (Fletcher, 2008). New Zealand has a complex climate which varies from warm subtropical in the far north to a cooler temperate climate in the south and extreme alpine conditions in mountainous areas (Mackintosh, 2001). This is probably what prevents species of Ricaniidae from successfully establishing in New Zealand. However, Australia's Ricaniidae species which extend into the southern temperate regions of Australia should be considered high-risk due to the similar climatic conditions which increase the likelihood of establishment (Fletcher, 2008).

#### Flatidae

The predicted number of native host plants of Flatidae species was 6.55 times more than the intercept. This is the largest family within the superfamily Fulgoroidea (Kim et al., 2001). There were three species of Flatidae in the Plant-SyNZ database. The green planthopper (*Siphanta acuta*), the grey planthopper (*Anzora unicolor*) and an unidentified Flatidae species. Two of the three Flatidae species were found on 15-34 native plants which suggests they are

extremely polyphagous. The last species is the unidentified Flatidae species which has been recorded on two native plants. There are no native species of Flatidae to New Zealand and those occurring here are all of Australian origin (Larivière et al., 2010). Flatidae insects feed on vascular plant phloem and are widely dispersed in New Zealand (Larivière et al., 2010). The grey planthopper has been recognized as a pest of economic importance which transmits fire-blight and various diseases in fruit trees (Larivière et al., 2010; Martin, 2017).

### Panchaetothripinae

It was not surprising that Panchaetothripinae was a statically significant predictor of the number of associations with native plants. Especially considering one thrip species was listed second in the top 10 insects, with 64 associations. Morse & Hoddle (2006) state that thrips which are generally considered invasive are those which are highly abundant in their native range, have high levels of vagility, whether this occurs naturally or is human assisted, and are generally closely associated with human activity (i.e. cropped systems). They also suggest that high-risk thrips are ones which can adapt their life cycle, so it is in synchronization with the new region, lack obligate diapause, are polyphagous and maintain multivoltine (producing >1 brood per year). Species with high fecundity and short lifespans are generally considered good invaders, additional predisposition to parthenogenesis benefits many invaders given there are limited mates following dispersal (Morse & Hoddle, 2006). Species within the genera *Frankliniella*, *Scirtothrips*, and *Thrips* in the subfamily Thripinae exhibit some or all of these biological traits (Morse & Hoddle, 2006). However, the genera *Scirtothrips* and *Thrips* contain the low-risk Thysanoptera species according to the Plant-SyNZ database. These genera are considered invasive overseas (Morse & Hoddle, 2006), so it is surprising that they are not exhibiting extreme polyphagy on native plants in New Zealand.

The subfamily Panchaetothripinae contains the three thrips which are found on the highest number of native and non-native host plants (including cultivated and naturalised plants). The three low-risk thrips within the subfamily Thripinae were recorded on 1-3 native plant species and 0-2 non-native plant species. Hence, polyphagous thrips in the subfamily Panchaetothripinae which have many associations with non-native plants could suggest they are high-risk to native plants. Alternatively, the two genera *Heliethrips* and *Hercinothrips* could be species which are high-risk to New Zealand's plants as these are the two thrips which are found on >14 native plants.

### Pentatomidae

These insects are commonly known as stink bugs or shield bugs. Pentatomidae is the fourth largest family within the suborder Heteroptera (Grazia et al., 2015) with eight subfamilies (Panizzi et al., 2015). These insects feed by the insertion of stylets into plant tissue to suck up nutrients which causes wilt in plants and often abortion of fruits and seeds (Čokl, 2008; Panizzi et al., 2015). Like most other herbivorous insects, feeding can transmit plant pathogens which ultimately increases damage (Panizzi et al., 2015). As these species generally feed on several economic plant species, they are regarded as key pests (Panizzi et al., 2015). The green vegetable bug (*Nezara viridula*) was the Pentatomidae insect which had the most associations, with 7 native plants.

It is interesting that this family was identified as high-risk to New Zealand's plants as the polyphagous brown marmorated stink bug (*Halyomorpha halys*) is from this family and is considered very high-risk to New Zealand (Vandervoet et al., 2019). This status is mainly due to the expected impact on field crops where it is anticipated to attack almost any cropped plant in New Zealand (Vandervoet et al., 2019). The MLR identified that risk status increases with an increase in the number of cultivated host plants so I would expect that the ability to attack many cultivated plants increases the number of native plants it will attack if successfully established.

### Aphididae

Aphids are predisposed to invasion due to their small size (1.5-3.5mm long), parthenogenetic reproduction and high reproductive rates so they have proven to be a problem for biosecurity in New Zealand (Teulon & Stufkens, 2002). There was only one Aphididae species in the top 10 high-risk insects and this was the foxglove aphid (*Aulacorthum solani*) which is a known pest of potato (Teulon & Stufkens, 2002).

As of 2002, there were c. 110 Aphididae species in New Zealand while only 12 indigenous species had been described (Teulon & Stufkens, 2002). Exotic aphids are known to damage economically important plants by direct feeding and the transmission of viruses (Teulon & Stufkens, 2002). However, it is much more difficult to quantify their impact on plants within native ecosystems hence the lack of literature available on this issue (Teulon & Stufkens, 2002). Nevertheless, Teulon & Stufkens (2002) report observations of large populations of aphids on several native plant species, suggesting feeding impact could be high when this occurs.

### Monophlebidae

Monophlebidae contains an estimated 237 species of scale insects from 44 genera which feed exclusively on plant sap (Peri & Kapranas, 2012). They usually colonize all parts of the plant and feeding causes tissue discolouration, early fruiting and reduced plant vigour (Peri & Kapranas, 2012). Indirect feeding impacts include honeydew extraction which reduces plant photosynthesis (Peri & Kapranas, 2012).

This family was considered nearly statistically significant in the statistical analyses so should be a family considered of medium risk. However, like Ricaniidae, only one species from this family is present in New Zealand (Martin, 2018). This was the cottony cushion scale (*Icerya purchasi*), native to Australia. It is highly polyphagous and feeds on >200 plant species globally (Hoddle et al., 2013). It is known to threaten endangered flora overseas (Causton et al., 2004) as it promotes mortality and degradation of native/endemic plants (Hoddle et al., 2013). In New Zealand, it was considered an important pest on trees and shrubs (including citrus) until biological control agents were introduced to control its populations (Martin, 2018).

Whether the cottony cushion scale is a unique species with an exceptional polyphagous ability, or whether the whole family should be considered high-risk is questionable. Species within this family which are polyphagous and have many associations with cultivated plants are the ones which should be considered high-risk future invaders. Additionally, species falling within this criteria which are present in southern temperature regions in Australia or regions with a similar climate pose the highest risk to New Zealand as establishment is more likely (Fletcher, 2008).

### Diaspididae

This family was considered nearly statistically significant in the statistical analyses however, three insects featured in the top 10 high risk species. Hence, this family should be considered high risk. These are the armoured scale insects, and they had a total of 236 interactions with native plants which was shared over nine exotic insect species in the Plant-SyNZ database.

Diaspididae contains upwards of 2,500 described species (Mansour et al., 2017). Internationally, these are the most commonly introduced insects which is attributed to their small size and camouflaging ability (Mansour et al., 2017). Unlike other scale insects (Families: Coccidae and Pseudococcidae) which are phloem-feeders, Diaspididae insects will feed on parenchyma tissue of hosts (Mansour et al., 2017).

As of 2011, there were 29 exotic species in New Zealand and eight of these were of Australian origin (Henderson, 2011). Several exotic Diaspididae species in New Zealand have proven to

be important pests of economic crops, resulting in significant economic losses (Charles & Henderson, 2002; Tyson et al., 2005). Feeding causes deformation of plant parts, spotting on foliage, leaf loss, decreased plant health and mortality (Tyson et al., 2005). The extent of damage in relation to the size of Diaspididae populations often appears out of proportion compared to other Coccoidea species (Charles & Henderson, 2002). The increased damage by Diaspididae insects is probably due to their unique digestive system which allows them to re-inject excess plant matter with a toxic effect to the plant (Charles & Henderson, 2002).

Henderson (2011) stated that only four of the exotic species in New Zealand have invaded natural ecosystems and the damage within these systems is minimal, however there is no reference to back up this statement. The four species includes the three listed in the top 10 high-risk species, as well as the latania scale (*Hemiberlesia lataniae*) which was the 12<sup>th</sup> high-risk exotic insect species. While there is research relating to exotic Diaspididae within cropped systems in New Zealand, none of these papers aimed to identify the risk to native plants (Charles & Henderson, 2002; Lo & Blank, 1989; Morales, 1988; Timlin, 1964).

### Coccidae

This family should also be considered high risk to native plants due to its near statistically significant value and because it featured in the top 10 high risk insect list three times. These are the soft scales which contain many species of insects that have globally gained an invasive status (Miller et al., 2009). The exotic species in New Zealand are generally of world-wide distribution and are of some economic importance, particularly on introduced crops and cultivated garden plants (Hodgson & Henderson, 2000). There have been several biocontrol agents imported to control pests of Coccidae including the brown soft scale (*Coccus hesperidum*) and the black scale (*Saissetia olea*) due to their impact on several plant species which are cultivated in New Zealand (Hodgson & Henderson, 2000).

### Cultivated Plants

Forty-nine percent of the variation in the number of plants an insect species is recorded on was explained by the number of cultivated host plants, family (grouped) and feeding type. Hemiptera, but more specifically the families Ricaniidae, Flatidae, Thripidae (Panchaetothripinae), Pentatomidae and Aphididae, should be considered higher-risk insects to native plants if they are associated with many cultivated plants. This supports the idea that insects which are pests in cropped systems may also be pests in native vegetated systems. This is interesting as most of the insects from the top 10 high risk insect species are considered pests within cropped systems. However, there is minimal research available on these species

in native ecosystems. If an economic pest is likely to feed on many native plants, then studies on their impact in native ecosystems should also be priority, not just their impact on economically significant crops.

### Non-significant variables

The independent variables 'insect ecozone' and 'body size' were not statistically significant predictors of the number of native plant associations. This was surprising as I had expected that insects which originated from regions which shared similar flora would be found on many native plants. For example, there are limited instances of successful insect invasions on native trees within the southern hemisphere as the main source of trade and travel is from the northern hemisphere and those insects are poorly adapted to the plant taxa within the southern hemisphere (Nunez-Mir et al., 2017). Additionally, insect body size has previously proven a statistically significant variable explaining an exotic insect's ability to successfully establish outside of its native range. This has been found to be the case in ants, where smaller ants have greater establishment success (Lester, 2005; McGlynn, 1999). Thrips are generally considered successful invaders, and this is attributed in part to their small body size (Morse & Hoddle, 2006). Hence, it was surprising that body size was not a statistically significant variable in my analysis. Although, the regression models in this project were testing for the risk-posed to native plants rather than establishment success. Establishment success doesn't guarantee an insect will attack native plants, nor have a large impact if it does (Probert et al., 2020).

## 5.3 Vulnerable plant species

There were 376 native plant species within the Plant-SyNZ database from 39 different orders. Apiales, Asterales and Lamiales were the most vulnerable orders as each had >120 associations with exotic insects. Hemiptera insects were always the insects which made up the largest portion of associations per plant order. This was not surprising as Hemiptera contributed to the most associations with native plants.

Twenty-nine native plant species make up a total of 30% of all associations with exotic insects (Table 10), hence they are considered the most vulnerable plant species. Four of the top 29 plants are categorised as 'threatened' by the New Zealand Threat Classification System. Three of these species (Poroporo *Solanum aviculare*, pohutukawa *Metrosideros excelsa* and Kanuka *Kunzea ericoides*) are considered 'nationally vulnerable' and the fourth (Tecomanthe *Tecomanthe speciosa*) is considered 'nationally critical'. Manuka (*Leptospermum scoparium*)

features on this list and is categorised as 'at risk-declining'. These are the plants which are of highest concern as their populations are already declining and feeding pressure from several exotic insect species could be encouraging further decline. Additionally, the remaining plant species in table 11 are the species which are classified as 'threatened' by the New Zealand Threat Classification System and should be considered moderately vulnerable. All other plants have <9 exotic insect species recorded on them and are considered less vulnerable.

As the top 29 plant species had a high number of exotic herbivorous insects recorded on them, five of these plants were selected for sampling chapter 2. However, the rationale behind the plant species chosen will be discussed further in the discussion section of chapter 2.

## 5.4 Predictors of vulnerable plant species

In this statistical analysis, the dependent variable was the 'number of exotic insect species which were recorded on each native plant species'. This was examined through several variables (e.g. plant taxonomic group, Raunkiær life mode and mean maximum plant height). The best fit MLR model was the one which used plant taxonomic family (grouped), altitude band and Raunkiær life mode. This model revealed that plants which were phanerophytes in the families Haloragaceae, Scrophulariaceae, Sapindaceae, Bignoniaceae, Solanaceae and Rutaceae (in order of declining vulnerability) were most vulnerable to exotic insects. Additionally, when these plants are found in coastal environments, they were even more vulnerable. This model explained 29% of the variation in the independent variable which is a relatively low predictive outcome. This suggests that the traits identified as statistically significant in the best fit models do not predict a vulnerable plant with great certainty. However, the models do provide sensible rules for plants which may be more vulnerable to exotic insects. Additionally, a combination of the identified traits as well as a plant which is classified as 'threatened' is probably a good indication that a plant is vulnerable.

### Non-significant variables

Plant biostatus was not a statistically significant predictor of the number of exotic insect associations. There is a common view that the reason exotic insects have such a reportedly low impact on native plants in New Zealand is due to high endemism (Brockherhoff et al., 2010). Consequently, New Zealand's plants are so distinct from host plants in the invaders native region that they maintain a degree of resistance (Brockherhoff et al., 2010). However, insects which are not host specific (i.e. polyphagous) are less affected by this concept and these are the insects which are more represented in the exotic insects which successfully establish.

Thus, the high endemism resistance theory is probably not strong or at least explains why polyphagous insects are the high-risk species.

# Chapter 2- Surveys of associations across the Auckland region

## 6. Methods

This section involved collecting insects to characterise the composition of insect fauna across various native plants within the Auckland Region. A permit was obtained (CS112) via Auckland Council to collect insects from the Regional Parks.

Fourteen sites were sampled across the Auckland Region (Figure 8). The percentage of exotic cover at each of the Regional Parks was obtained from the landcover database (Pairman, 2014). The sampling sites were selected based on this information to ensure sure they were spread across the disturbance gradient. This was decided upon as I intended to test whether exotic cover influenced insect composition.

The plants sampled in this section were selected as they were the plants which had a high number of exotic insect associations as per the historical data records from the Plant-SyNZ database. However, I had to consider practicality of finding plants. The plants had to be relatively common as I intended to compare insect composition on the same plant species across all sites. For example, poroporo (*Solanum aviculare*) was the plant which had the highest number of exotic species recorded on as per the online database. However, this species is uncommon and finding two plants per site was not feasible. Hence, the plant species' selected for sampling were karo (*Pittosporum crassifolium*), mahoe (*Melicytus ramiflorus*), kawakwa (*Piper excelsum*), karamu (*Coprosma robusta*) and red matipo (*Myrsine australis*). They all had >9 exotic insect associations and are relatively common so they were found across most sampling sites.

At each sampling site, the goal was to sample two of each plant species so that a total of 10 plants were sampled per site. However, this was not always possible as some plant species weren't located at every site, so some sampling sites had less than 10 plants sampled (Table 13).

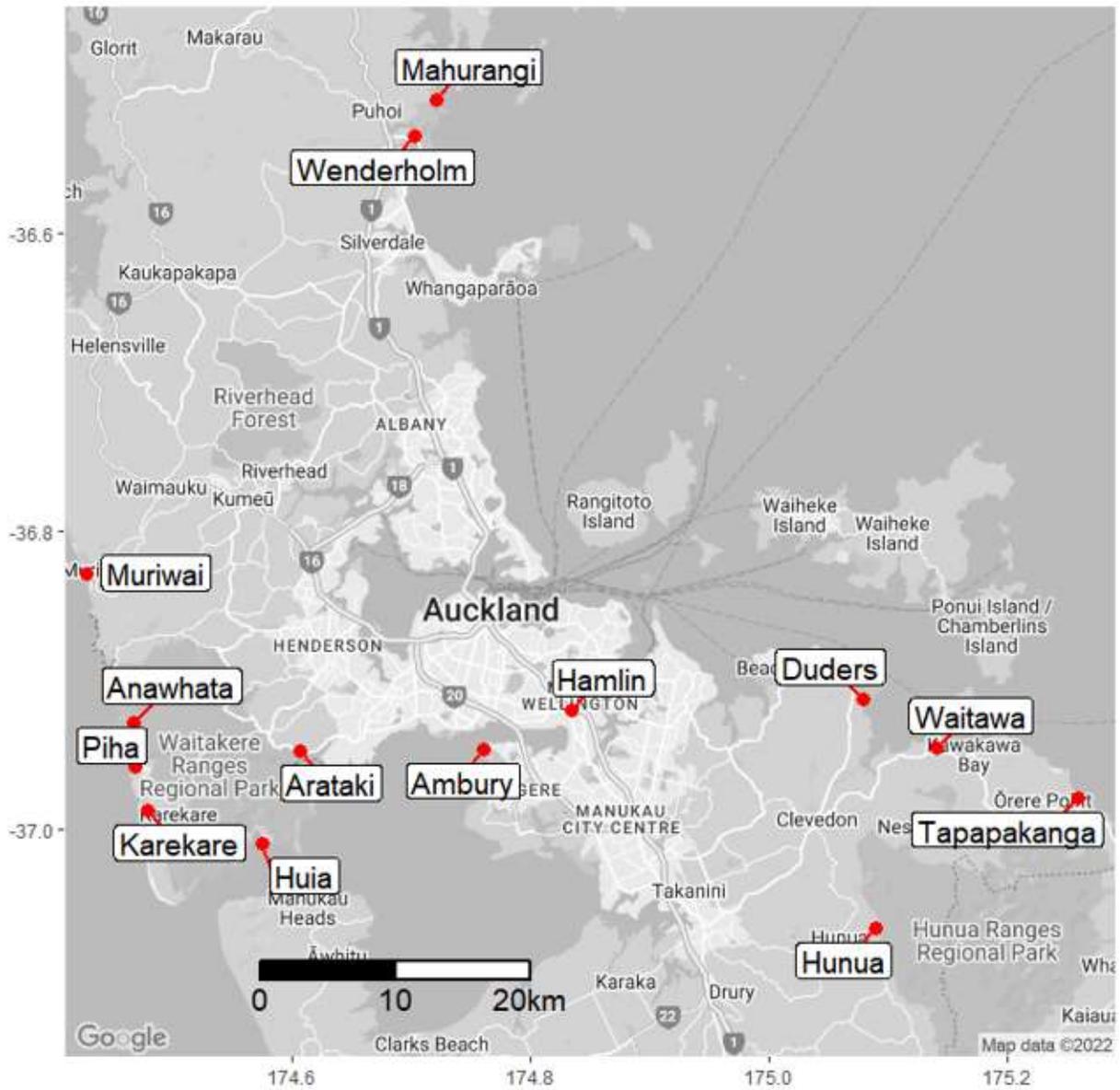


Figure 8. Map of the 14 survey sites across the Auckland Region.

Table 13. The number of samples per site and plant species

<b>Date sampled</b>	<b>Site</b>	<b>Mahoe</b>	<b>Red matipo</b>	<b>Karo</b>	<b>Karamu</b>	<b>Kawakawa</b>
10-01-22	Ambury	2	0	2	1	0
12-01-22	Anawhata	2	2	2	2	2
13-01-22	Arataki	2	2	0	0	0
15-01-22	Duders	2	2	0	2	2
18-01-22	Hamlin	2	2	2	2	2
19-01-22	Huia	2	2	0	2	2
27-01-22	Hunua	2	0	0	2	2
14-02-22	Karekare	2	0	2	2	2
14-02-22	Mahurangi	2	2	2	2	2
15-02-22	Muriwai	2	0	2	2	2
17-02-22	Piha	2	2	2	2	2
22-02-22	Tapapakanga	2	2	0	2	2
23-02-22	Waitawa	2	2	1	2	2
23-02-22	Wenderholm	2	2	2	2	2
	<b>Total</b>	<b>28</b>	<b>20</b>	<b>17</b>	<b>25</b>	<b>24</b>

## 6.1 Field survey technique

Using standardised sampling with beat sheets and sweep nets, I collected insects from a total of 114 plants from 14 of the Auckland Regional Parks. Twenty sweeps through the foliage of each plant occurred. A beat tray was held under the foliage, and I manually shook the branch 20 times to dislodge the slower moving insects and ones which cling to branches. The branch selected was the one which held the most foliage. For both sampling methods, insects were transferred into a zip lock bag with ethanol and preserved for later identification in the laboratory.

Sampling occurred over the hotter months (January-February) of the year 2022 and sampling always began between 1100-1300 NZST. This was generally the hottest time of the day and when insects were most active. All plants were sampled on days with similar environmental conditions (i.e. similar temperature and humidity).

In the laboratory, insects were sorted to taxonomic order, and then a mix of lower taxonomic levels. I identified 47% of all insects to species level, 32% to order, 7% to infraorder, 6% to family, 4% to morphospecies, 2% to super family and 2% were classified as 'unknown'.

All insects were preserved in ethanol vials following identification with a code that corresponded to the sample information. The number of insects per taxonomic group were tallied up within this same database (see Appendix C).

## 6.2 Statistical analyses of field survey data

Non insects and non-herbivorous insects are not analysed further as this was outside the scope of this thesis, so they were excluded from my database. However, a summary of these invertebrates can be seen in table 17.

Using only the herbivorous insect dataset, I created summaries of the frequency and abundance of insects per site and plant species, as well as the total number of insects per taxonomic identification and per insect order. The purpose was to identify whether there were any trends or patterns, such as an unusually abundant species or group of insects. The passionvine hopper (PVH) was very abundant and no other insect identifications came close to being collected in such high numbers. I found that the PVH effected the results of the statistical analyses of insect composition so much that it was analysed by itself in a separate section under results.

To identify if there was a statistically significant difference between the number of insects collected (excluding the PVH) per plant species, a one-way ANOVA was performed. This model used the natural log (x+1) transformed number of insects collected per sample as the dependent variable. The independent variable was the plant species sampled. The one-way ANOVA test was fitted using the aov function in the stats package (R Core Team, 2021) within R studio.

### 6.2.1 Insect communities and environmental variables

As there were several insect taxonomic groups and environmental variables involved in the field surveys, it was important to reduce the dimensionality of the data. A PCA (principal component analysis) was used to achieve this as its purpose is to summarise the linear relationship between the composition of insects which are explained by a set of independent variables. Using the Vegan (Oksanen et al., 2013) package in R studio, a PCA using the rda function was employed to extract and summarise the differences among insect composition in relation to the plant species and environmental variables at each site. Six environmental variables were examined and are described in table 14. Three PCA biplots were generated, and the first plot displayed the relationship between the sample sites and the environmental variables at each site, the second plot showed the relationship between insect composition and the sample site. The third plot illustrated the relationship between insect composition and the plant species.

Table 14. The environmental variables used in the PCA analyses.

<b>Variables</b>	<b>Detail</b>
Hectares of native land cover (Pairman, 2014)	Hectares of native landcover within a 1km radius from the carpark at each site
Hectares of exotic land cover (Pairman, 2014)	Hectares of native landcover within a 1km radius from the carpark at each site
Number of plants sampled per site	A number between 4-10
Temperature (°C) (Thorsen, 2022)	The temperature measured at the closest time to when sampling began
Wind speed (km/h) (Thorsen, 2022)	The speed measured at the closest time to when sampling began
Humidity (%) (Thorsen, 2022)	The humidity measured at the closest time to when sampling began
Plant species sampled	Karo, karamu, mahoe, red matipo, kawakawa

### 6.2.2 The passionvine hopper (*Scolypopa australis*)

The PVH was the insect species which was collected the most. If this species was included in the previous PCA analyses, no relationship would be visible between all other insect identifications as the PVH was an outlier collected in huge amounts. Hence, the PVH was analysed separately.

Using the Stats (R Core Team, 2021) package in R studio, I performed a one-way ANOVA using the aov function to identify if there was a statistically significant difference between the number of PVHs on each plant species. As there were several samples which had zero PVH collected, I used the natural log (x+1) transformed number of PVHs as the dependent variable and the plant species was the independent variable.

Several SLR and one MLR analyses were performed to identify whether there were any environmental variables which influenced the number of PVH collected. In these models, the natural log (x+1) transformed number of PVH collected per sample was the dependent variable. There were numerous environmental conditions used as the independent variables and these are outlined below in table 15. The regression analyses were performed on R studio using the lm function within the Stats package. When 'weather' was used as the independent variable, the intercept level was 'more clouds than sun' as it had the lowest average number of PVH collected. All other levels within the 'weather' variable were compared to this intercept.

Table 15. List of independent variables used in the statistical analyses to predict the number of passionvine hoppers collected

<b>Independent variables</b>	<b>Levels</b>	<b>Details</b>
Latitude (Google maps, 2022)	Numerical	Taken from the car park of the Regional Park
Longitude (Google maps, 2022)	Numerical	Taken from the car park of the Regional Park
Weather (Thorsen, 2022)	Mild	Two to four degrees Celsius above the mean
	Passing clouds	Mainly sunny means sunny with some cloudy periods
	Overcast	Sky condition when greater than 9/10ths of the sky is covered by clouds
	Partly sunny	Sky condition when between 3/10ths and 7/10ths of the sky is covered however, used to emphasize the presence of daytime sunshine
	More clouds than sun	More than half cloud cover but with some breaks in the cloud. It can also be described as cloudy with some sunny periods
	Warm	Four to seven degrees Celsius above the mean
Temperature at sampling time (°C) (Thorsen, 2022)	Numerical	The temperature at the time sampling began
Lowest temperature (°C) (Thorsen, 2022)	Numerical	This is the lowest temperature reached on the sampling day
Highest temperature (°C) (Thorsen, 2022)	Numerical	This is the highest temperature reached on the sampling day
Wind speed (km/h) (Thorsen, 2022)	Numerical	Wind speed at the time sampling began
Humidity (%) (Thorsen, 2022)	Numerical	The humidity at the time sampling began

Hectares of exotic cover (Pairman, 2014)	Numerical	Hectares of native landcover within a 1km radius from the carpark at each site
Hectares of native cover (Pairman, 2014)	Numerical	Hectares of native landcover within a 1km radius from the carpark at each site
Plant height (m)	Numerical	Eyeball estimate of plant height

Table 16 displays the summary statistics of the different SLR and MLR models fitted. Several models returned a statistically significant p-value. However only two of these models provided sufficient evidence that the independent variables influenced the number of PVHs collected. The second model listed in table 16 used 'weather' as the independent variable and returned an adjusted R-squared value of 0.31, this is the best fit model. The third model in table 16 used latitude as the independent variable. This returned an adjusted R-squared value of 0.13, this is the second-best fit model. The reasoning behind these two models being the best fit, and not the first model which returned the highest adjusted R-squared value, are discussed in detail the results section.

Table 16. Test summary statistics of the various multivariate and simple linear regression analyses performed to predict the abundance of the passionvine hopper. Each row relates to the independent variables used to explain the number of passionvine hoppers collected. Only the p-value and the adjusted R-squared value are shown. Statistically significant p-values (<0.05) are bold and near significant (<0.10) have an asterix.

<b>Independent variables</b>	<b>Adjusted R-squared</b>	<b>P-value</b>
Weather + latitude	0.35	<b>0.00</b>
Weather	0.31	<b>0.00</b>
Latitude	0.13	<b>0.00</b>
Wind speed	0.06	<b>0.01</b>
Humidity	0.04	<b>0.02</b>
Longitude	0.02	0.06*
Plant species	0.02	0.20
Temperature at sampling	0.01	0.20
Hectares of exotic cover	0.00	0.28
Plant height	-0.00	0.46
Hectares of native cover	-0.01	0.53

## 7. Results

### 7.1 Insect composition

A total of 2,507 invertebrates were collected from 114 plants and 14 sites. After the removal of non-insects and insects which were not herbivorous (Table 17), there were 1,422 herbivorous insects left for analysis.

The most abundant order collected throughout the field surveys was Hemiptera followed by Diptera and Coleoptera (Table 18). The exotic PVH was the most abundant insect (Table 19), with a total of 587 individuals collected, which is 41% of all herbivorous insects collected. From here onwards, the PVH will be analysed in its own section. Excluding the PVH, Hymenoptera was the taxonomic identification which was collected the most frequently, being collected from 57 out of 114 samples. Followed by Diptera which was collected from 53 samples. However, these groups were identified to a high taxonomic level, so these identifications contain several different species.

Wenderholm, Mahurangi, and Waitawa were the sites which had the highest number of insects collected, excluding the PVH. Hamlin had the lowest number of insects with only 20 collected. The greatest number of insects were collected from karamu (24% of all insects collected), and the least from red matipo (17%). However, a one-way ANOVA revealed that there was not a statistically significant difference in the total number of insects collected between the plant species sampled ( $F(4, 109) = [0.89]$ ,  $p = 0.47$ ).

Out of the insects identified to species level, the native Australasian green shield bug (*Glaucias amyoti*) was the most frequently collected (excluding the PVH). Fifty-three percent of the 34 insects collected were from Mahurangi and Hunua and 62% percent of them were collected from karamu. The endemic pittosporum psyllid (*Trioza vitreoradiata*) was only found at half of the 14 sites sampled. Only one specimen was collected off karamu in Muriwai, the remaining pittosporum psyllids were always found on karo. The most common exotic insect identified to species level (excluding the PVH) was the pittosporum shield bug (*Monteithiella humeralis*). However, there were only 15 collected and 10 of them were found at Ambury from one karo tree, the remaining were found on karo at Mahurangi, Hamlin and Karekare.

Table 17. Invertebrates collected from surveys across the Auckland region that were removed from analysis as they were either non-insects or were not herbivorous.

<b>Invertebrate identification</b>	<b>No. insects</b>
Arachnids	523
Psocodea	231
Blattodea	95
Gastropoda	80
Steelblue ladybird ( <i>Halmus chalybeus</i> )	79
White fly ladybirds ( <i>Serangium maculigerum</i> )	34
Marsh beetles (Family: Scirtidae)	12
Ladybirds (Family: Coccinellidae)	11
Collembola	6
Yellow shouldered ladybirds ( <i>Apolinus lividigaster</i> )	5
Fungus eating ladybirds ( <i>Illeis galbula</i> )	3
Manotodea	2
Minute hooded beetles (Family: Corylophidae)	2
Assassin bugs (Family: Reduviidae)	2

Table 18. Number of herbivorous insects collected across all sites and plants, grouped as insect order (excluding the passionvine hopper). Caterpillar/larvae are the only category which are not listed as order as they were identified to morphospecies.

<b>Order</b>	<b>No. insects</b>
Hemiptera	198
Diptera	177
Coleoptera	170
Hymenoptera	134
Caterpillar/larva	51
Unknown	34
Lepidoptera	31
Neuroptera	20
Thysanoptera	12
Orthoptera	6
Phasmatodea	2

Table 19. Number of herbivorous insects identified to a lower taxonomic ranking than order, sorted by the abundant taxa

<b>Insect ID</b>	<b>Order</b>	<b>Total</b>
Passion vine hopper ( <i>Scolypopa australis</i> ) <b>Exotic</b>	Hemiptera	587
Cucujiformia: Polyphagan beetles	Coleoptera	103
Caterpillar/larva	Unknown	51
Australasian green shield bug ( <i>Glaucias amyoti</i> ) <b>Native</b>	Hemiptera	34
Unknown	Unknown	34
Miridae: Plant bugs	Hemiptera	31
Curculionoidea: Weevils	Coleoptera	29
Pittosporum psyllid ( <i>Trioza vitreoradiata</i> ) <b>Endemic</b>	Hemiptera	25
Formicidae: Ants	Hymenoptera	25
Chrysomelidae: Leaf beetles	Coleoptera	16
Pittosporum shield bug ( <i>Monteithiella humeralis</i> ) <b>Exotic</b>	Hemiptera	15
Cerambycidae: Longhorn beetles	Coleoptera	5
Karamu leaf beetle ( <i>Pleuraltica cyanea</i> ) <b>Endemic</b>	Coleoptera	4
Tipulidae: Crane flies	Diptera	4
Green planthopper ( <i>Siphanta acuta</i> ) <b>Exotic</b>	Hemiptera	3
Mordellidae: Tumbling flower beetles	Coleoptera	2
Psylloidea: Psyllids	Hemiptera	2
Tri-horned treehopper ( <i>Acanthuchus trispinifer</i> ) <b>Exotic</b>	Hemiptera	2
Cicadoidea	Hemiptera	1

Table 20. Number of herbivorous insects collected at each sample site, excluding the passionvine hopper.

<b>Sample site</b>	<b>Number of insects collected</b>
Wenderholm	117
Mahurangi	96
Waitawa	92
Hunua	72
Huia	72
Duders	65
Tapapakanga	57
Arataki	46
Anawhata	44
Ambury	41
Piha	40
Muriwai	37
Karekare	36
Hamlin	20

Table 21. Number of herbivorous insects collected from each plant species, excluding the passionvine hopper.

<b>Plant species</b>	<b>Total insects</b>
Karamu	204
Karo	166
Kawakawa	139
Mahoe	184
Red matipo	142

There were three strong patterns based on the environmental variables and the sample site (Figure 9).

- i) Several sites (Waitawa, Tapapakanga, Hunua, Hamlin, Muriwai, and Ambury) were associated with increased hectares of exotic vegetation cover, longitude, and the highest wind speed (km/h).
- ii) Arataki, Anawhata and Karekare are on the opposite ends of the biplot and are consequently associated with higher levels of native vegetation cover. These sites also had highest low temperature recorded for the day compared to all other sites sampled and not surprisingly the highest temperature of the day recorded.
- iii) Wenderholm and Mahurangi are associated with highest combined plant height and latitude.

The PCA analysis in figure 10 shows a clustering of several insect identifications in the centre of the biplot, suggesting that most insect taxa are found across all sites. Two other patterns emerge, which appear to be based on the abundance of certain insect groups at certain sites.

- i) First, the high proportions of Cucujiformia beetles, 51% of the total for this taxa, at Waitawa.
- ii) Second, the high proportions of Diptera, 49% of the total for this taxa, at Huia and Wenderholm.

Finally, the PCA biplot in figure 11 shows the clustering of insects in relation to the plant species they were collected from. In general, there are few patterns in terms of their insect composition. The insects clustered around the center of the graph were collected relatively equally on all plant species.

- iii) Cucujiformia beetles are associated with karamu as 54% were collected from this plant. Sixty-two percent of the Australasian green shield bugs (*Glaucias amyoti*) were collected from karamu
- iv) Pittosporum psyllids (*Trioza vitreoradiata*) are associated with karo with 96% or 24 insects being collected from this species. One hundred percent of the pittosporum shield bugs (*Moteithiella humeralis*) (15 insects) were collected from karo.
- v) The morphospecies caterpillar/larvae were associated with kawakawa as 53% were collected from this plant species.

Table 22. The numerical codes from the PCA biplot analyses and the taxonomic identification it corresponds with the following figures (Figure 10, 11).

Code on PCA biplots	Insect identification
1	Caterpillar/larvae
2	Coleoptera
3	Longhorn beetles (Cerambycidae)
4	Tumbling flower beetles (Mordellidae)
5	Weevils (Curculionoidea)
6	Leaf beetle (Chrysomelidae)
7	Karamu leaf beetle ( <i>Pleuraltica cyanea</i> )
8	Polyphagan beetles (Cucujiformia)
9	Diptera
10	Crane flies (Tipulidae)
11	Hemiptera
12	Plant Bugs (Miridae)
13	Australasian green shield bug ( <i>Glaucias amyoti</i> )
14	Pittosporum shield bug ( <i>Monteithiella humeralis</i> )
15	Psylloids (Psylloidea)
16	Pittosporum psyllid ( <i>Trioza vitreoradiata</i> )
17	Green planthopper ( <i>Siphanta acuta</i> )
18	Cicadoidea
19	Tri-horned treehopper ( <i>Acanthuchus trispinifer</i> )
20	Hymenoptera
21	Ants (Formicidae)
22	Lepidoptera
23	Neuroptera
24	Orthoptera
25	Phasmatodea
26	Thysanoptera
27	Unknown

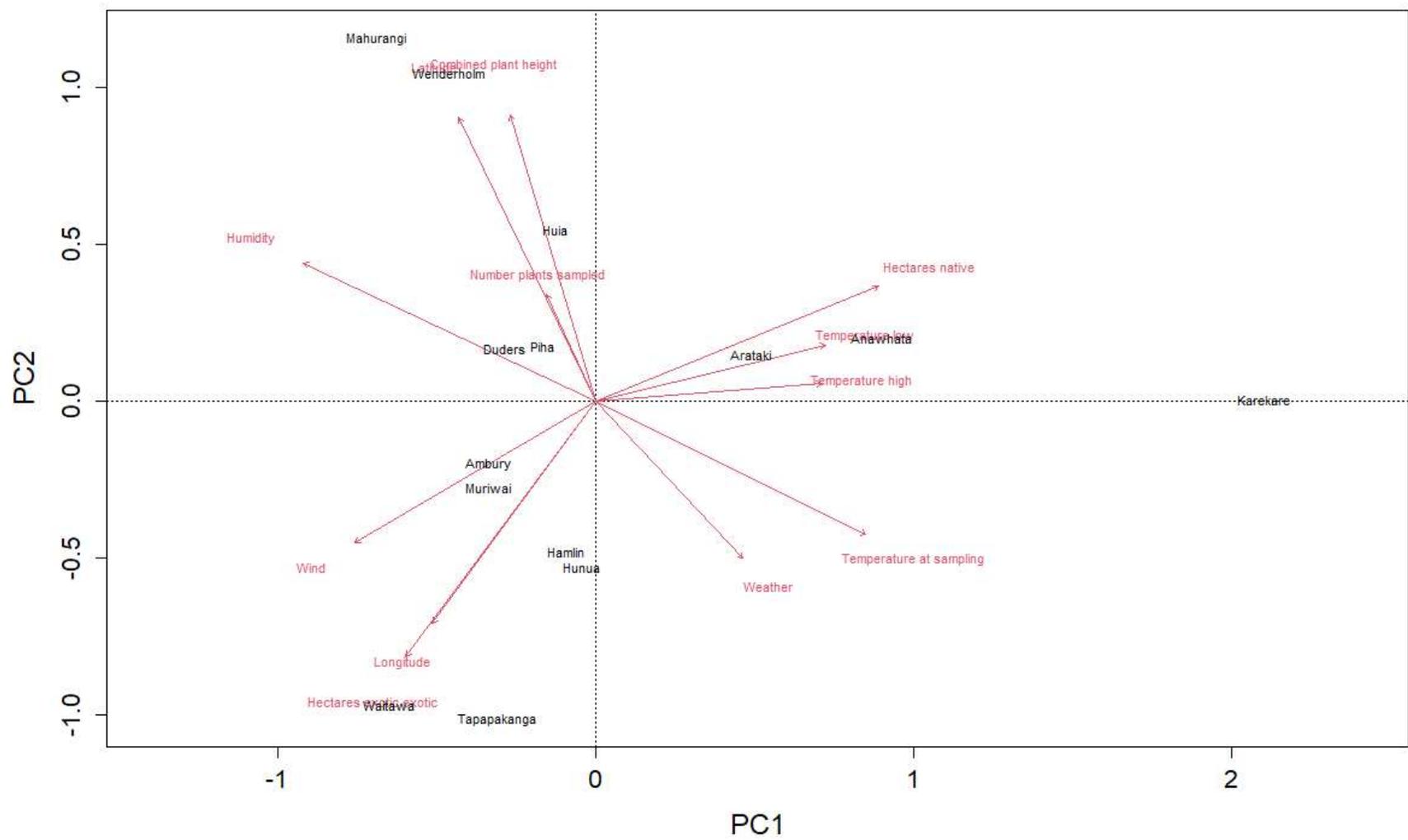


Figure 9. Principal Components Analysis using the redundancy analysis to show the association of environmental variables (red) with sample sites (black).

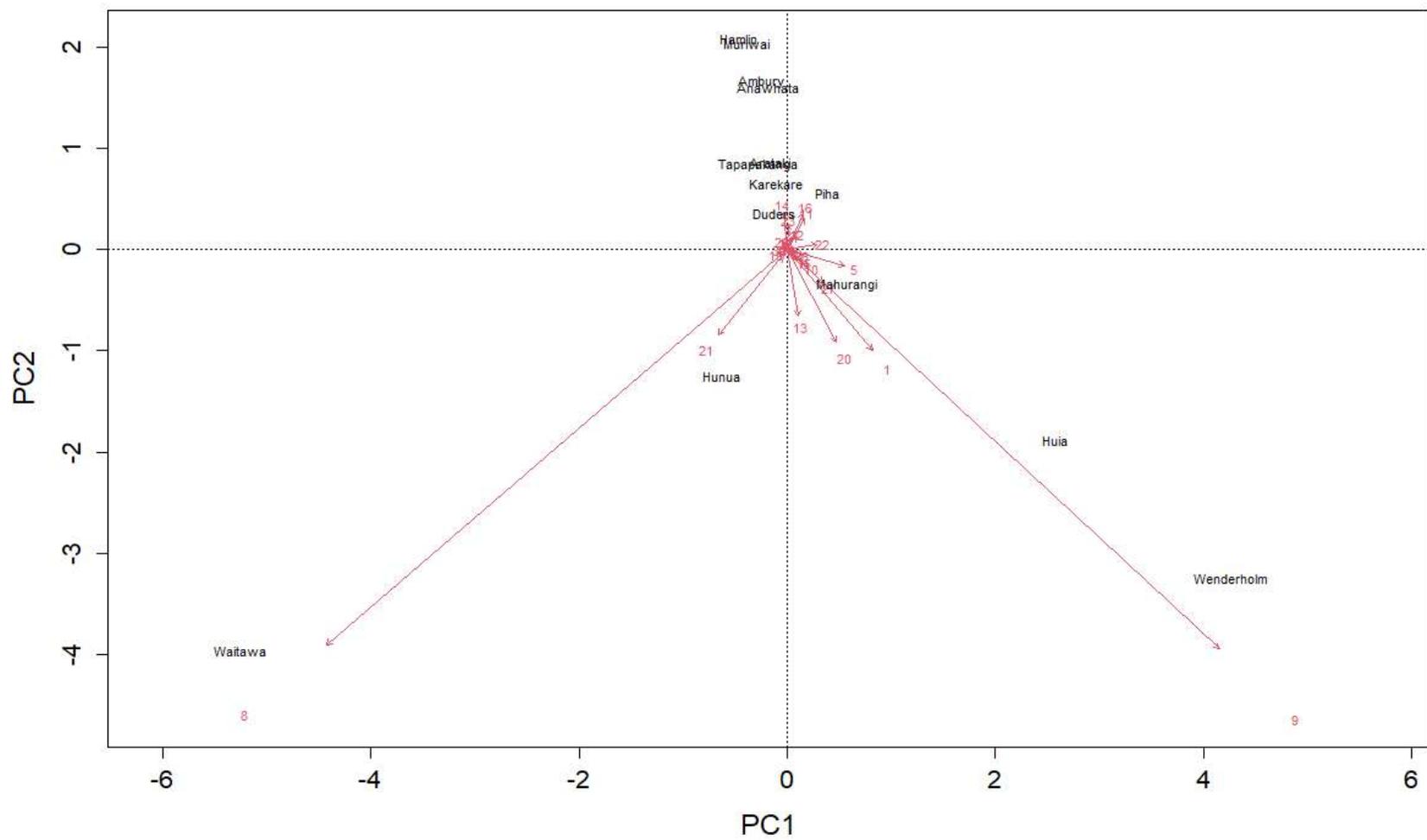


Figure 10. Principal Components Analysis using the redundancy analysis to show the association of insect community (red) with sample sites (black).

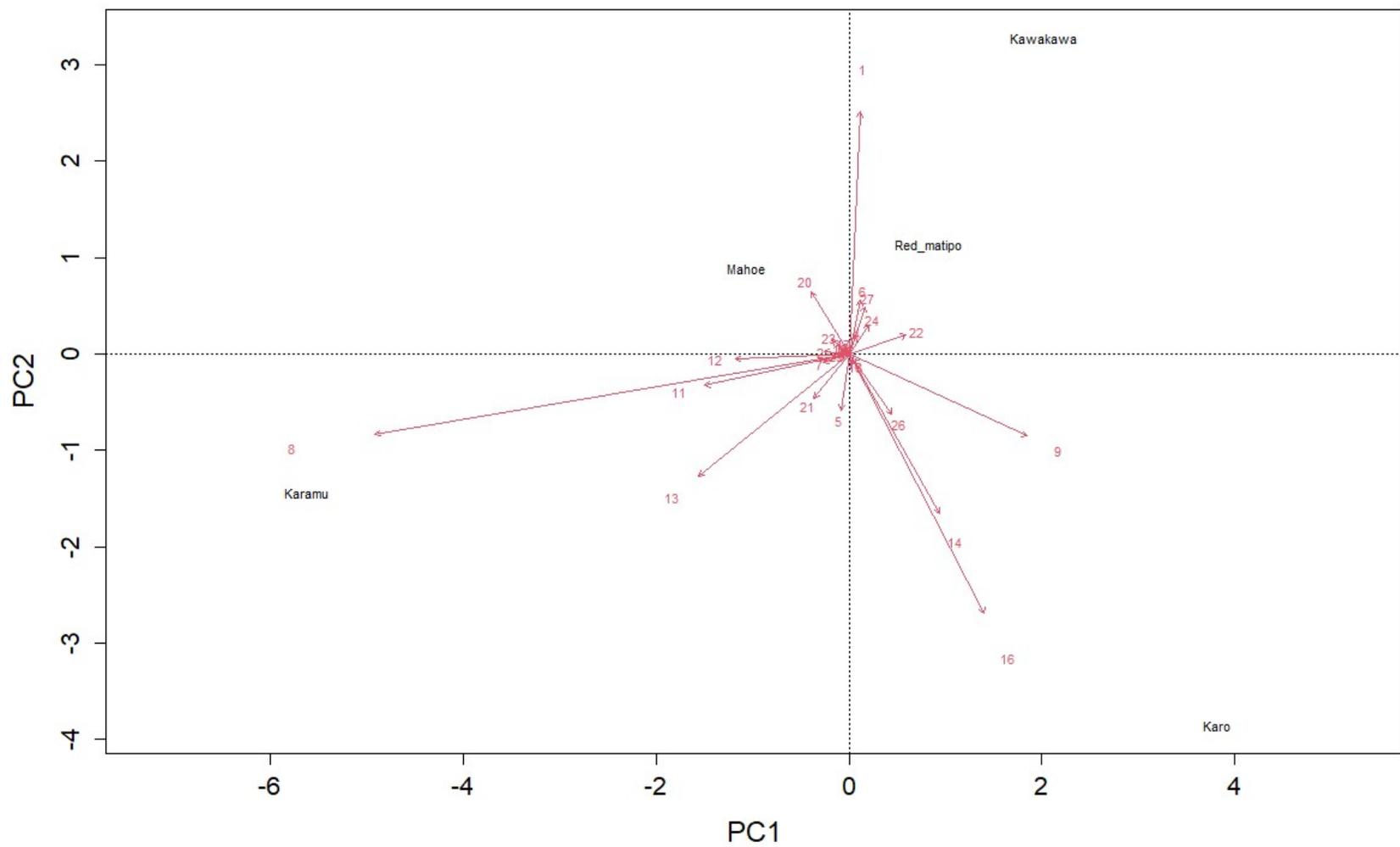


Figure 11. Principal Components Analysis using the redundancy analysis to show the association of insect community (red) with plant species (black).

## 7.2 Passionvine hopper (*Scolypopa australis*)

The most frequent and abundant herbivorous insect was the exotic PVH, with a total of 587 individuals collected across all samples. It was collected from all plant species and all sites except for Ambury, Wenderholm and Hamlin. To put this in perspective, the second most abundant insect identification below order was the infraorder Cucujiformia (Polyphagan beetles) with 103 collected. However, this taxonomic group was identified to a high level, hence this group contains several different insect species. The second most abundant insect identified to species level was the Australasian green shield bug, with a total of 34 insects (Table 19).

Out of the 114 plants which were sampled, the PVH was collected from 64 plants, making this species the most frequently collected. By comparison, the next most frequent insects were Hymenoptera which were collected from 57 of the 114 samples and Diptera which were collected from 53 of the samples. However these are high taxonomic identifications, so it is not surprising these groups of insects were collected frequently. The PVH was collected from 17 mahoe plants which made this species the most common host (Table 23). However, it is important to consider the same number of plants weren't sampled across all plant species. The PVH was most abundant on mahoe, with a total of 248 insects collected from this plant species. This was 118 more insects than kawakawa, which was the plant it was second most abundant on. The mean number of PVH collected per plant didn't vary greatly, however there were several outlier samples which contained many PVH (Figure 12). For example, one sample collected from mahoe had a total of 112 PVH. A one-way ANOVA was performed to compare the effect of the plant species on the number of PVHs collected. The results revealed that there was a non-statistically significant difference in the mean number of PVHs collected between the five plant species sampled ( $f(4, 109) = [1.52]$ ,  $p\text{-value} = 0.20$ ).

The average number of PVH collected was highest at Tapapakanga and Huia (Table 24). Both sites had more than three times the number of PVH collected than at Waitawa, which was the third most abundant site. One sample collected from Huia was an outlier which had a total of 112 PVH collected. Tapapakanga also had one sample with an unusually high number of PVH collected, of 58. Ambury, Wenderholm and Hamlin were the only sites which had no PVH collected.

Table 23. Number of passionvine hoppers collected per plant species, sorted by the average number of passionvine hoppers collected per plant

<b>Plant species</b>	<b>No. PVH collected</b>	<b>Average per plant</b>	<b>No. plants collected from</b>	<b>Total plants sampled</b>
Mahoe	248	9	17	28
Red matipo	103	7	13	20
Kawakawa	130	5	13	24
Karamu	92	4	14	25
Karo	14	1	7	17

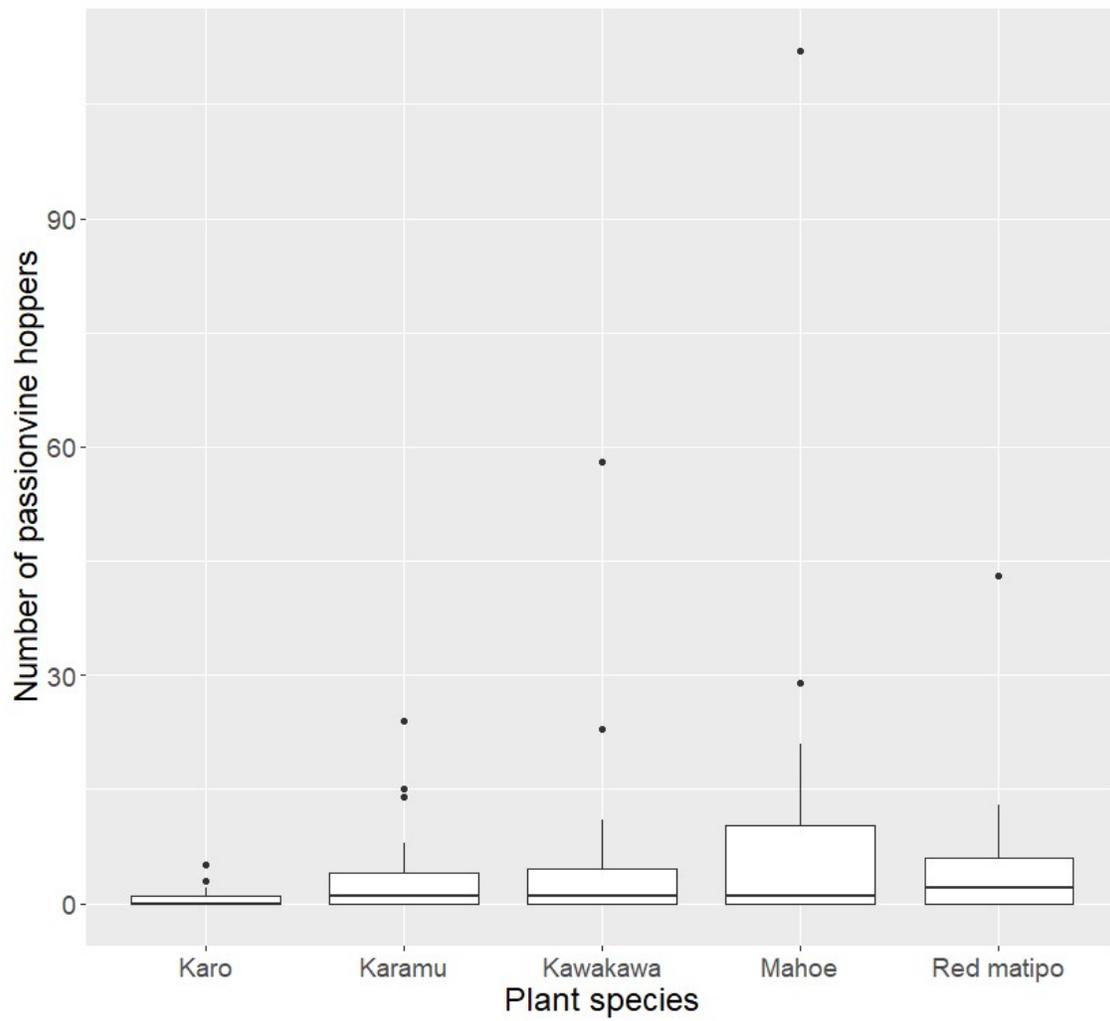


Figure 12. Number of passionvine hoppers collected per plant species across the Auckland Regional Parks

Table 24. Number of passionvine hoppers collected per sample site, sorted by average per plant

<b>Site</b>	<b>Total collected</b>	<b>Average collected per plant</b>	<b>Number of plants sampled</b>
Tapapakanga	187	23	8
Huia	164	21	8
Arataki	32	8	4
Waitawa	52	6	9
Hunua	38	6	6
Anawhata	37	4	10
Piha	30	3	10
Muriwai	25	3	8
Karekare	10	1	8
Mahurangi	9	1	10
Duders	3	0	8
Ambury	0	0	5
Wenderholm	0	0	10
Hamlin	0	0	10

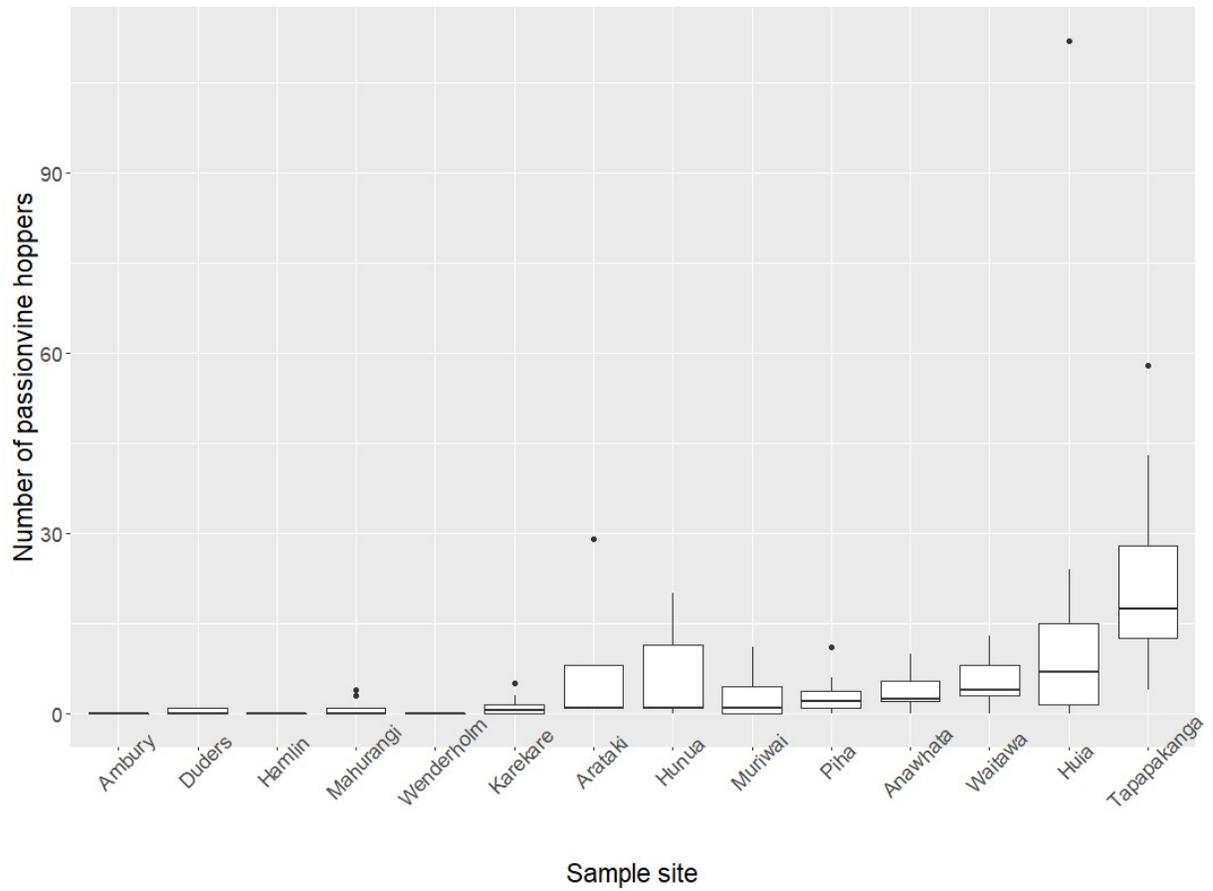


Figure 13. Average number of passionvine hoppers found at each sample site across the Auckland Regional Parks

### 7.2.1 Predictors of the passionvine hopper abundance

The best fit regression model to explain the variation in the number of PVHs which were collected, was the SLR model which used weather as the independent variable ( $R^2 = 0.34$ , Adjusted  $R^2 = 0.31$ ,  $F(5, 108) = 11.09$ ,  $p = <0.001$ ). Weather conditions explained 31% of the variation in the number of PVHs which were collected. The mean number of PVHs collected when the weather was categorised as either 'partly sunny', 'overcast' or 'passing clouds' were statistically significantly different than the intercept which was when the weather was categorised as 'mild' (Table 25). If the weather was categorised as 'partly sunny', the number of PVHs were predicted to multiply by 32.79 (the exponent of 3.39) compared to the intercept. Consequently, this was the weather state which was predicted to have the highest number of PVHs collected, followed by the statistically significant weather conditions 'overcast' and 'passing clouds'.

The second-best fit model was the one which used latitude as the independent variable. However, the adjusted R-squared value was low ( $R^2 = 0.13$ , Adjusted  $R^2 = 0.13$ ,  $F(1, 112) = 17.23$ ,  $p = <0.001$ ). This model revealed that a decrease in one degree latitude was associated with the number of PVHs multiplying by 25.28. This means that there are predicted to be more PVHs at lower latitudes than at higher latitudes (also seen in Figure 14).

When these two independent variables (weather and latitude) are combined into the same MLR, the adjusted R-squared value is 0.35 (Table 16). This is only 0.04 higher than the best fit model which used only weather as the independent variable. Hence, the model using only weather as the independent variable to explain the number of PVHs collected was the best fit.

Table 25. Multivariate regression analysis using weather conditions to predict the number of passionvine hoppers collected ( $R^2 = 0.34$ , Adjusted  $R^2 = 0.31$ ,  $F(5, 108) = 11.09$ ,  $p = <0.001$ ). “CE”= coefficient estimate. Statically significant p-values ( $<0.05$ ) are bold.

Independent variables	CE	Std. Error	t value	P-value
(Intercept) Mild	0.39	0.29	1.35	0.18
Partly sunny	3.49	0.53	6.61	<b>0.00</b>
Overcast	1.75	0.41	4.31	<b>0.00</b>
Passing clouds	0.90	0.36	2.48	<b>0.01</b>
More clouds than sun	0.57	0.37	1.53	0.13
Warm	0.45	0.53	0.85	0.39

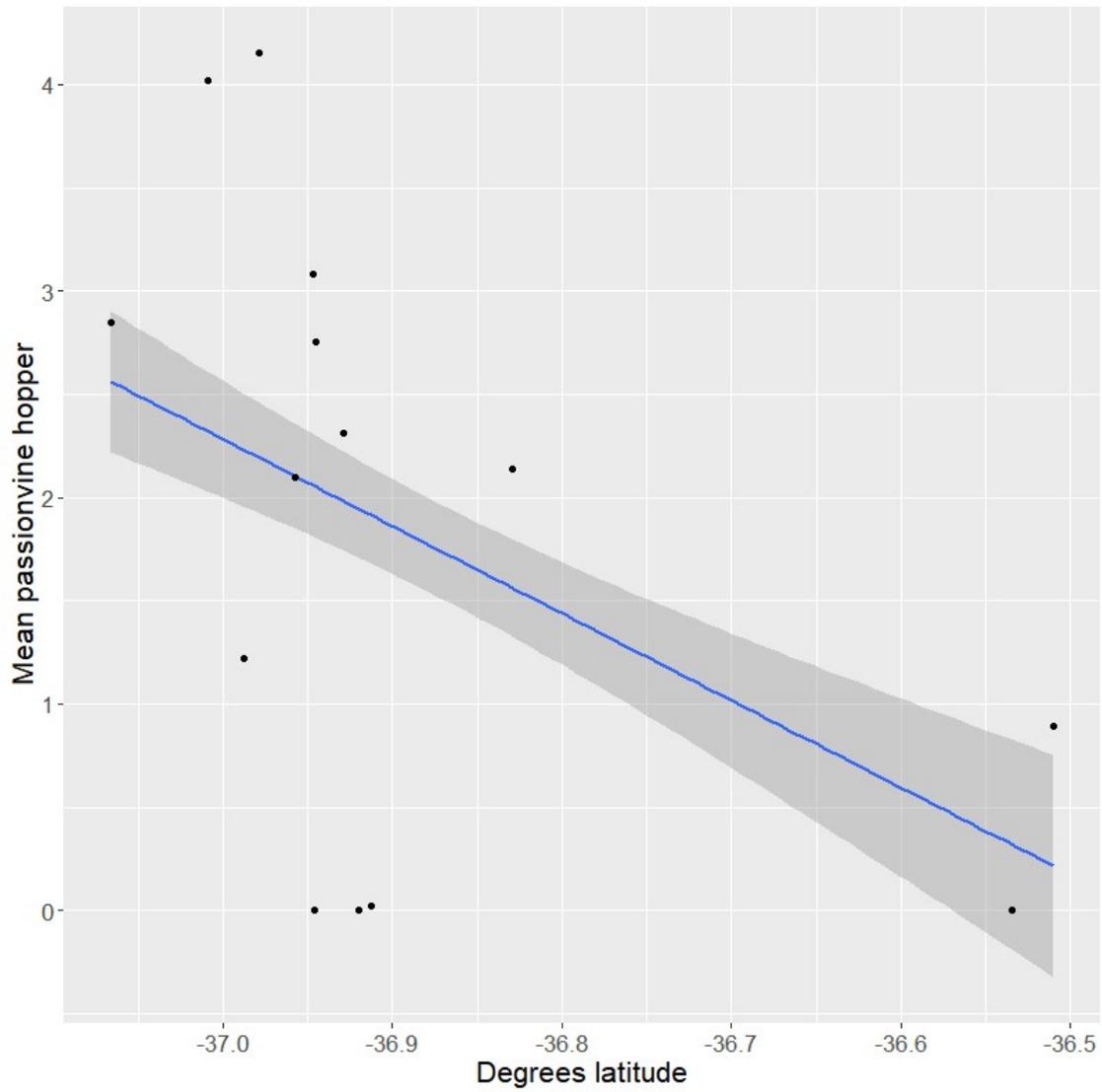


Figure 14. The relationship between the log (x+1) transformed mean number of passionvine hoppers collected per sample site and degrees latitude.

## 8. Discussion

### 8.1. Insect composition

The aim of this section was to characterise the composition of native and exotic insects found on different native plant species across the Auckland region. The PVH was the most frequently collected and most abundant insect species across all plants and most sites. There were relatively few other exotic species, although 53% of my taxa were identified to higher levels.

Overall, only a few strong environmental gradients were apparent across the landscape, and these did not have a strong influence on insect abundance. Additionally, there were no strong patterns between insect composition across the different plant species which were sampled.

Excluding the PVH, the most abundant exotic insect species was the Pittosporum shield bug (*Monteithiella humeralis*). This species was always associated with karo which is not surprising considering it is known to breed on *Pittosporum* (Martin, 2016). The total Pittosporum shield bugs collected was only 15 which suggests it may not be an insect which is high-risk in terms of it feeding on many native plants. However, as it was exclusively collected from karo, feeding pressure may be high on *Pittosporum*. Ten out of the 15 Pittosporum shield bugs were collected from the Ambury sampling site. This site had a large concentration of karo growing together which was not seen to this degree at any other sites. This was probably why most of these shield bugs were collected from this site. All other sites either had no occurrences or very low numbers of this species. This could suggest that feeding pressure is highest in environments where there are dense patches of *Pittosporum* growing together. Vandervoet et al., (2019) set up traps in sites around Auckland to collect stink bugs (Pentatomidae) and found 20 out of the 25 traps had no Pittosporum shield bugs, three traps had <5, while there were two sites which had 12-28 collected. They suggested this pattern was influenced by the vegetation available surrounding each trap. Although, Vandervoet et al., (2019). hadn't characterised the surrounding vegetation, it's possible that there were denser populations of *Pittosporum* nearby the trap that influenced higher abundances.

A portion of the insects identified as "caterpillar/larvae" will be the endemic kawakawa looper (*Cleora scriptaria*: Lepidoptera) which is a common herbivore of kawakawa (Hodge et al., 2000). More than half of the insects in this morphospecies category were found on kawakawa, illustrated in the PCA biplot (Figure 11), so this is a fair assumption to make. Some of these insects may also be larvae of insects which are not in the order Lepidoptera as they can often look similar in the earlier life stages (Hodge et al., 2000).

Wenderholm and Mahurangi were the sites which had the most insects collected however, the variation between samples at each site was high. For example, 58 insects were collected from one sample at Wenderholm while the remaining eight samples had 2-13 insects collected. The PCA analyses revealed most insect groups were collected relatively equally across all sites with very few patterns emerging (Figure 10). The Cucujiformia beetles were highly associated with Waitawa and the Diptera insects were associated with Huia and Wenderholm. Additionally, the PCA analyses illustrating the association between insect composition and plant species revealed few weak patterns. The Cucujiformia beetles and Australasian green shield bugs were associated with karamu, Pittosporum psyllids and Pittosporum shield bugs with karo and finally the caterpillar/larvae morphospecies with kawakawa.

The polyphagan beetles (Infraorder: Cucujiformia) were chiefly collected from Waitawa and karamu. However, this relationship is driven by the fact that just under half of all these insects were collected from one outlier sample which was a single karamu plant from Waitawa. If the field surveys were repeated, the same association with Waitawa and karamu may not be apparent. This comment is further driven by the fact that only nine polyphagan beetles were collected from all other samples at Waitawa. Additionally, the second karamu plant at this site had no polyphagan beetles collected from it.

Diptera was the other group of insects which was far off center on the PCA biplot. It was highly associated with Wenderholm and to a lesser degree Huia with 49% of all the Diptera insects collected from either site. Wenderholm had one outlier sample where 43 Diptera insects were collected and then all other samples at this site had <3 collected. This is a similar relationship to the polyphagan beetles which were chiefly found at Waitawa where one outlier sample is driving a strong association with a particular site. Huia was less of an outlier as one sample had 10 diptera collected from it and another had 21. These insects may be more likely to be found at Huia in relatively high numbers compared to the other sites if the surveys were repeated.

The field surveys I carried out already consisted of a high sampling effort with a total of 114 samples collected from 14 different sites throughout the Auckland Region. However, the high variation in insect composition between samples is important as it highlights the need for an even higher sampling effort to identify if there are any patterns occurring.

## 8.2 Passionvine hopper (*Scolypopa australis*)

The PVH was the most frequent and abundant insect species collected during the field surveys. This is an exotic species which has arrived from Australia and was found on all five of the sampled plant species. The only variables which appeared to influence populations of the PVH were weather and latitude. If the weather was categorised as 'partly sunny', the abundance of the PVH was likely to be highest, followed by 'overcast' and 'passing clouds'. The three sites which had no PVH collected, were the sites which had the weather conditions classified as 'more clouds than sun' and 'mild'. These were weather conditions which predicted a low PVH abundance. As weather continuously differs, this would not be a good predictor of patches of vegetation which may be under immense feeding pressure from the PVH. However, this is a very important finding to consider for future studies involving the PVH. Weather conditions vary greatly between days, and throughout the day. Hence, weather needs to be considered when studying the PVH. For example, if sampling occurs on days when there are more clouds than sun, then the abundance of the PVH could be underestimated, and possibly its impact.

Lower latitudes predict less PVH. However, latitude only explained 13% of the variation in the number of PVH collected. This is probably because sampling occurred within the Auckland region, so latitude did not vary greatly. A widespread study would provide more insight into the importance of latitude. I would expect this would be an important predictor because previous widespread studies suggest that populations are highest in warmer regions of New Zealand, from North Cape to the warmer parts of Nelson, in the South Island (Cumber, 1966). However, temperature wasn't a statistically significant predictor of the abundance of the passionvine hopper in my field surveys. This could be because the temperatures were relatively similar across all sampling days. Lower temperatures south of Nelson have previously been suggested as not suitable to the PVH, so the South Island is probably a region which is less likely to be vulnerable to the PVH. As latitude is fixed at each location (whereas weather conditions are not) this would be a better predictor of the population of the PVH within a certain locality, and the associated feeding pressure arising from such high populations.

Overall, my results suggest that the PVH is a generalist species capable of surviving and reaching high numbers on many plant species and across various environmental gradients. It does not appear to be sensitive to the different environmental conditions (i.e. hectares of exotic vegetation cover, humidity) experienced throughout the Auckland Region, except for weather and to a much lesser extent, latitude.

## 9. General discussion

### 9.1 Exotic herbivorous insects in New Zealand

There is a major gap within the literature relating to the impact of exotic insects on New Zealand's native plants (Boyd et al., 2013; Epanchin-Niell, 2017), despite several overseas examples of significant ecological harm following insect herbivore invasion (Anderson-Teixeira et al., 2021; Boyd et al., 2013; Myers et al., 2017; Sjöman et al., 2014; Straw et al., 2016). Preliminary assessments to identify high-risk insects that require full risk assessments is crucial to efficiently allocate New Zealand's limited biosecurity resources (Probert et al., 2020). Hence, the aim of this thesis was to identify the "hazards" (exotic herbivorous insects) and the "exposed assets" (native plants).

Using the risk assessment framework proposed by Probert et al. (2020), I have identified several traits and taxonomic groups which suggest an exotic herbivorous insect is at high-risk of attacking many native plants. Likewise, I have identified ecological traits and taxonomic groups which suggest a plant species may be vulnerable to exotic herbivorous insects.

### 9.2 Hazards (exotic insects)

Insects which are likely to pose a high-risk to native plants are those which are polyphagous, have higher numbers of cultivated plants as hosts, and are in the families Ricaniidae, Flatidae, Thripidae (Panchaethripinae), Pentatomidae, Aphididae, Diaspididae and Coccidae. These are the insects that are likely to have associations with many native plant species in New Zealand. This does not necessarily mean the feeding damage of these insects is significant, but rather that these insects fall within a high-risk category due to their extensive native plant host range.

The number of cultivated host plants was statistically significant and explained the highest variation in the number of native plants that an exotic insect was associated with. This is interesting as most of the insect species in the top 10 high-risk insect list are considered pests within cropped systems. For example, in New Zealand the greedy scale (*Hemiberlesia rapax*) and oleander scale (*Aspidiotus nerii*) are key pests of kiwi fruit (Blank et al., 1996) and are often found attacking other subtropical cultivated plants (Morales, 1988). This finding could be attributed to the "spillover" effect (Borremans et al., 2019). Biological spillover is the "movement of subsidized enemies across agricultural-to-natural habitat edges" (Borremans et

al., 2019). This process is mainly discussed within the literature in relation to pathogen spillover between different host species (Borremans et al., 2019), and to a lesser extent in vertebrates (Rand et al., 2006). However, it also relates to insect invasions in native vegetated systems, despite a lack of literature available on the topic. For example, several broadly distributed exotic aphid species, such as the green peach aphid (*Myzus persicae*) and the pea aphid (*Acyrtosiphon pisum*), attack various crops (e.g. oilseed rape, sugar beet, tobacco, red clover and lucerne) while also documented attacking numerous native plant species in the United Kingdom (Tscharntke et al., 2005).

Ecosystem boundaries are places where spillover is most common (Borremans et al., 2019; Tscharntke et al., 2005), such as with avian vertebrate predators where nest predation and parasitism at habitat edges in fragmented environments is highest (Rand et al., 2006). Multiple empirical studies have identified that anthropogenic land-use systems are likely key subsidies that encourage the movement of generalist invaders into neighbouring habitats (Rand et al., 2006). Hence, the rationale for sampling across the disturbance gradient in the field survey section (chapter 2) of this thesis to investigate this process. Rand et al. (2006) explains that the abundance, diversity and potential impact of predatory insects increases with an increase in the area or diversity of native habitat which surrounds cultivated crop fields. Although this paper is referencing native predatory insects and their impact on native insect prey, this process also applies to exotic herbivorous insects and their native host plants. Natural ecosystems near cropped land may provide alternative resources for exotic insects during some portions of the growing season (Rand et al., 2006) and aid their dispersal into native ecosystems.

### 9.2.1 Passionvine hopper (*Scolypopa australis*)

Following field surveys from the five native plants across the Auckland Region, I have identified the PVH as an insect which should be considered very high-risk. This species is found on all the five plant species sampled, across 78% of the sampling sites and was very abundant, suggesting feeding impact may be significant. Additionally, the online database revealed the PVH was recorded on 59 native hosts so there are potentially 59 plant species which may be under immense feeding pressure from this insect.

In my field surveys, the abundance of the PVH could have been greater. Although adults are relatively large and are easy to see/catch in sweep nets, nymphs can be missed as they cling to plants and are more difficult to dislodge (Logan et al., 2002). Hence, the abundance of the

PVH was probably underestimated as there are still many nymphs present during early summer.

The PVH is an Australian planthopper which arrived in New Zealand c. 1870 (Tomkins et al., 2000) and is widespread throughout New Zealand, with an extensive plant host range (Marshall et al., 2003). It has a one-year life cycle, with nymphs hatching late in spring and adults appearing from summer to early winter (Logan et al., 2017). Like other Hemipteran species, it uses its piercing and sucking mouth parts to suck out sap in the phloem. It uses its long stylets to pierce the rostrum of a plant and will inject saliva via one tube and the second tube sucks plant juices into the insect. Additional to direct feeding damage, this species produces huge amounts of honeydew which covers plant leaves and favours sooty mould growth. This inhibits photosynthetic activity and is detrimental to plant growth (Moir et al., 2008). Furthermore, when the PVH feeds on the poisonous endemic tutu (*Coriaria arborea*), it secretes a toxic honeydew. Honeybees which ingest this honeydew include it into honey which is poisonous to humans (New, 2006). The PVH is also a major pest on kiwifruit as the sooty mould growth decreases marketability of fruit. Thus, most literature focuses on the impact of the PVH within economically significant production systems (Charles & Allan, 2004; Logan et al., 2020; Marshall et al., 2003; Tomkins et al., 2000).

This planthopper was an unusually unique species as it was so much more abundant than all other insects collected across Auckland. This is a very important finding as this insect is not host specific, having been found on 59 native plants according to the Plant-SyNZ database and it was recorded in extremely high numbers in some samples within the field surveys. It has previously been stated that it is not unusual to find hundreds of PVHs on individual plants during the summer months whether they be exotic or native plant species (Larivière et al., 2010). This is exactly the pattern I had found in my field surveys where some plants had a huge quantity collected. Tomkins et al. (2000) found populations of PVH are highest in patches of non-native vegetation, such as weedy vegetation or home gardens, which were adjacent to kiwifruit orchards. This suggests the PVH may be more prevalent in regions that are near exotic vegetation cover and/or cropped systems. However, hectares of exotic cover were not a statistically significant predictor of the number of PVH collected at each sampling location. Instead, the results suggest that the PVH attacks practically any plant and is found in most environments.

The only variables which were statistically significant predictors of PVH abundance, albeit with a low percentage of variation explained, was latitude and weather. Lower latitudes predicted large populations of PVH as well as if the weather was categorised as 'partly sunny', 'overcast'

or 'passing clouds'. Low latitudes in New Zealand are generally hotter than higher latitudes which is concurrent with previous work relating to the preferred climate of the PVH. The PVH is not predicted to be found further south than Nelson and if it is, their populations are very low. Weather was a qualitative categorisation which was specific to conditions at the time of sampling. This suggests that the presence and abundance of the PVH is affected by weather conditions, which are subject to constant change. Apart from latitude, I could not identify stable environmental conditions, such as plant height or hectares of exotic vegetation cover, which affected the presence and/or abundance of the PVH. Instead, it appears that the PVH is unaffected by most environmental variables and will be present and found in large abundances at almost any site.

The large populations of the PVH throughout the Auckland region are concerning in relation to the long-term implications of feeding pressure on native plants. The PVH was collected in very large numbers, was present on every plant species, 56% of individual plants, and at 79% of sites. Since this species appears to show no host specificity, at least between the five native plants sampled, it's likely the PVH will feed on most native plants. It is known to cause debility of cropped or ornamental plants (Marshall et al., 2003), so a similar affect probably occurs between native plants. Particularly in patches of vegetation where the PVH is present in high numbers. This will be most concerning when it feeds on plants of high conservation concern. Fortunately, there are only two plants which are associated with the PVH, per the online database, that are classified as 'at risk' under the threat classification system and none which are classified as 'threatened'. However, this doesn't mean that PVH doesn't have associations with threatened plants. Instead, it could be that threatened plants are so rare that observations on these plants are also rare. Alternatively, the PVH may prefer to maintain associations with plant species which are common. Plants which are rare or declining in numbers probably require more effort to find. Thus, it serves the PVH to maintain associations with plant species which are very abundant and often found in high concentrations.

Using the records from the Plant-SyNZ database, the PVH is associated with plants from 47 different genera, 43 different families and 24 orders. Suggesting that this species is very polyphagous and not host specific. Occasionally, herbivorous exotic species will maintain relationships with closely related plants to their native host species. However, the PVH does not appear to follow this pattern. Furthermore, all plants sampled were endemic, so they are not found in the PVHs native region of Southern Australia.

There are very limited studies which focus on the PVH and its interactions with New Zealand's native plants. I could only source two papers which aimed to identify native host preference of

the PVH, however both were based off the same experimental study and did not occur in natural environments (Logan et al., 2002; Sandanayaka & Logan, 2003). Both papers identified that mahoe is the preferred native host of the PVH and has the highest survival rate when on this plant species. My field surveys did not reveal a statistically significant difference between the mean abundance of the PVH on different plant species, suggesting mahoe may not be a preferred plant compared to the other four plant species sampled. However, mahoe was the plant which had the highest number of PVHs overall, one sample even had 112 PVHs collected from it. Experimental studies often do not mirror the natural conditions which usually influence natural populations, so could be why my results varied from these previous studies in relation to host specificity.

### 9.3 Exposed assets (vulnerable native plants)

Phanerophyte plants within the families (in order of declining vulnerability) Haloragaceae, Scrophulariaceae, Sapindaceae, Bignoniaceae, Solanaceae and Rutaceae, and which are found in coastal altitude bands were the most vulnerable plant species to exotic herbivorous insects. However, any plant species listed in the top 29 plants list, or which are classified as 'threatened' with >3 exotic insect associations should be considered vulnerable.

Coastal environments in New Zealand are naturally frequently disturbed (Sullivan et al., 2005) and are generally very fragmented with only small remnants of its former cover remaining (Awimbo et al., 1996). Anthropogenic disturbance, such as coastal land development and edge effects from adjoining land use (i.e. commercial pine forests and grazing stock), are generally linked with coastal forests (Singers et al., 2018; Sullivan et al., 2005). Associated with a highly disturbed environment is the greater risk of invasion, as has often been proven with exotic plants invading coastal environments (Singers et al., 2018). Exotic insect spill over could be occurring from adjacent anthropogenic land use into these highly disturbed coastal ecosystems and would explain its identification as an environment which predicts plant vulnerability.

### 9.4 Limitations of the online database and field surveys

The results from the Plant-SyNZ database must be interpreted with caution. A record of an insect on a plant doesn't guarantee that an insect is attacking that plant species. The records

in the database may also be limited to biases in insects collected by the contributors of the database.

None of the top 10 insect species identified from the online database were collected in the field surveys, except for the PVH and the green planthopper. This is most likely a result of biases relating to the method of sampling, or it could be that the smaller bodied insects are not very abundant. However, methods such as sweeping and beating typically don't target taxa such as scale insects, however, they do collect the majority of other taxa on plants. I did not focus my sampling on scale insects because they are very difficult to identify and there are few experts available in New Zealand to assist.

COVID-19 restrictions meant that field work was delayed, and lab closures meant that the identification of insect specimens was restricted. In particular, there was limited access to identification resources (taxonomic collections and experts). More identifications would have been achieved in normal situations, particularly with the use of the insect collections and staff help. Identification to species level is a difficult and enormous task, mainly because of the specialist knowledge required, and the lack of resources to help identification (e.g. taxonomic keys, photos, guides). As this project was under time constraints, it wasn't possible to identify each insect to species level. However, special effort was made to identify the order which was most abundant (Hemiptera) to lower taxonomic groups, which was often family. Insects which were collected in large numbers or had distinguishing features were identified to species level. Hence, the PVH was the focus of the discussion. It was found in much higher numbers than all other taxonomic identifications and on all plant species which were sampled. There will probably be 'hidden' exotic species which were collected but not identified to species level. However, I don't expect that these hidden species will be high-risk insects. This is mainly because special attention was given to insects collected in large quantities which looked like they were of the same species.

Variation in insect numbers was high despite a large sample effort. There were some small-scale patterns (i.e. shield bugs predominantly collected from karo) however, they were collected in such low numbers and frequency. It is difficult to know if patterns were hidden, and more sampling was required to see these patterns, or whether there were no hidden patterns at all.

## 9.5 Future research

The insect traits identified in this thesis should be used to inform which exotic insects require full risk-assessments in relation to native plants and/or future studies on the impact of feeding.

Additionally, the top 10 insects were associated with an unusually high number of native plant species. These are also insects which should be the focus of future research in relation to their impact on native plants. The most significant finding was the abundance and frequency at which the PVH was collected. This species was so abundant that future research should focus on quantifying the feeding impact of this species to native plants. The plant traits which suggest a plant is vulnerable should be used to inform which plant species require the most attention in relation to the feeding impact of the passionvine hopper.

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# Appendices

## Appendix A

### Supplementary Data File

#### Description:

The accompanying Excel spreadsheet includes the exotic herbivorous insects which were recorded on native plants as per the Plant-SyNZ database. The following column headings of this spreadsheet represent the number of plant species that each exotic insect species has been recorded on. However, it has been divided up based on the biostatus of the plant: “endemic plants”, “native (non-endemic plants)”, “total native/endemic plants”, “naturalised plants”, “cultivated plants” and “total non-native/endemic plants”. Against each insect species, I have recorded ecological traits and taxonomic information. These traits were taken from either within the Plant-SyNZ database or from the supplementary material of Edney-Browne et al. (2018). However, some information was missing for insect species, so I used published literature to fill in the gaps where species information was missing, and these references are listed under the column titled “references”.

#### File name:

Appendix\_A\_exotic\_insects.xls

## **Appendix B**

### **Supplementary Data File**

#### **Description:**

The accompanying Excel spreadsheet shows the native plants which had exotic herbivorous insects recorded on them as per the Plant-SyNZ online database. The column heading “exotic insects” represents the total number of exotic insect species which have been recorded on each plant species, as per the Plant-SyNZ database. Against each plant species, I recorded ecological traits and taxonomic information. Traits were sourced from the ecological traits of New Zealand flora database (<https://ecotraits.landcareresearch.co.nz/>) which is managed by Landcare Research. Some plant species had missing information so where possible, this data was sourced using published literature and the references are listed under the column titled “references”. The column headings in this sheet: “category” represents the conservation status of each plant species (i.e. not threatened, at risk, threatened); “Status” refers to the specific conservation status of each plant species (i.e. threatened, nationally vulnerable).

#### **File name:**

Appendix\_B\_native\_plants.xls

## **Appendix C**

### **Supplementary Data File**

#### **Description:**

The accompanying Excel spreadsheet shows the raw data from the field surveys. Columns B-DK represent each sample collected in the field surveys. Rows 1-13 contain the sample information (i.e. plant species sampled, site, plant height, temperature). Rows 14-41 contain the insect identification and the number of insects collected per sample.

#### **File name:**

Appendix\_C\_field\_surveys.xls