The lifecycle and epidemiology of the Tomato/Potato Psyllid (*Bactericera cockerelli*) on three traditional Māori food sources

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Abstract

The tomato/potato psyllid (*Bactericera cockerelli* (Sulc), TPP) is a species of Psylloidea first detected in New Zealand in 2006. Since its incursion the TPP has proved to be a major insect pest of solanaceous crops, particularly potatoes (*Solanum tuberosum*), tomatoes (*Lycopersicon esculentum)* and capsicums (*Capsicum* L.). The TPP is a vector of Zebra Chip Disease or liberibacter (*Candidatus* Liberibacter solanacearum syn. psyllaurous), a lethal plant disease related to Citrus greening disease (*Candidatus* Liberibacter asiaticus). Successive annual population outbreaks coupled with widespread liberibacter infection continues to challenge New Zealand's horticulture sector.

Three traditional Māori food sources, namely taewa (Solanaceae, *Solanum tuberosum* L. ssp. *andigena* and ssp. *tuberosum*), kūmara (Convolvulaceae, *Ipomoea batatas* (l.) Lam.) and poroporo (Solanaceae, *Solanum aviculare* G. Forst syn. *S. Laciniatum* (LINN.), are known to be susceptible to TPP infestation. Kūmara and taewa are annual summer plants present during the peak TPP development and population growth period. Poroporo flowers and fruits year-round and is therefore theoretically susceptible to infestation throughout the year and may serve as a potential overwintering host and food source for TPP.

Poroporo was assessed as an overwintering host of the TPP and the lifecycle progression of TPP was also compared on the three host plant species; taewa, kūmara and poroporo. The role of these three host plants in the annual lifecycle of this insect pest in the New Zealand environment.

The results showed that poroporo was not an important overwintering host of the TPP in the Manawatu/Rangitikei region; rather it can be viewed as an alternative or refuge host in the absence of the primary solanaceous host species and other volunteer weed host plants. The results indicated that taewa is a more suitable host of the TPP than poroporo and kūmara. In the same vein, poroporo is clearly more suitable as a host than kūmara. The relationship seen in this study in terms of host suitability can be pictorially represented as; Taewa> Poroporo> Kūmara

This study showed that all three host species are capable of supporting TPP and therefore each of the host species should be managed with a view to minimise the impact of TPP across seasons.

Acknowledgements

This thesis was undertaken in an attempt to amalgamate my undergraduate study in plant protection and my postgraduate study based on Māori natural resource development. It seemed all too convenient that in my first year of postgraduate study the tomato/potato psyllid (*Bactericera cockerelli*) arrived in the Manawatu District and infested the Massey University taewa (Māori potatoes, *Solanum tuberosum* ssp. *andigena*) seed bank managed by Dr Nick Roskruge. Fate some would say, and therein lies the conception of my thesis. The Tomato/Potato psyllid (TPP, *Bactericera cockerelli*) is an interesting insect, so small and some would think insignificant, it is hard to believe the impact this insect and Zebra Chip (*Candidatus* Liberibacter solanacearum syn. psyllaurous) disease has had on New Zealand horticulture.

I wish to first thank Dr Nick Roskruge, my supervisor and mentor, for without whom this thesis would not have been possible. Your knowledge, experience and endless patience have made this research possible. I am amazed by what you have accomplished and wish you well in your post-doctoral studies

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I thank the Tahuri Whenua network who have supported me throughout the duration of my research and have become almost like extended whanau. I will continue to support your kaupapa and actively participate in any venture you undertake.

I would also like to thank the researchers at Plant and Food Research for allowing me to attend various industry meetings and freely converse with those at the forefront of TPP research. Your work is invaluable. I am greatly looking forward to being part of your team in the coming year. I thank the Ministry for Science and Innovation (formerly known as the Foundation for Research, Science and Technology (FRST)) who funded my research, I cannot thank you enough for the support.

And to my ‘home’ of five years, Massey University Manawatu, my journey here has come to an end and I must move on. I would like to acknowledge the Institute of Natural Resources for their friendship and camaraderie.

God Bless.

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Chapter One

General Introduction

1.1 *Bactericera cockerelli* – Tomato/Potato Psyllid

The Tomato/Potato Psyllid (TPP, *Bactericera cockerelli*) is a new species of Psylloidea in New Zealand, first discovered in Auckland in 2006 (Teulon *et al*. 2009). It has since spread throughout New Zealand and is a major economic pest to the horticulture industry. Native to North America it is thought that the TPP was introduced to New Zealand possibly via Hawaii (Tomatoes New Zealand, 2009). Solanaceous crops are favoured by TPP particularly tomatoes and potatoes.

TPP feed by piercing plant tissues and sucking the contents of the phloem; host plants may appear weakened in response to high population infestations and reduced yields may eventuate. Serious plant damage results from the transmission of the bacterial disease "Zebra Chip (ZC) or Liberibacter; the causal agent *Candidatus* Liberibacter solanacearum (syn. Psyllaurous) is injected into host plants during feeding. TPP acquire the disease by feeding on infected host plants and it is transmitted vertically (plant to plant) (Brown *et al*. 2010) and horizontally (transovarially (adult to egg) or generationally) (Hansen *et al*. 2008). The disease is also harboured in infected potato seed tubers (Henne *et al*. 2010; Potatoes New Zealand, 2010). Reduced plant vigour and yield, chlorosis, plant death and discolouration of tubers (in potatoes) are symptomatic of Liberibacter infection. Psyllid yellows (PY) disease symptoms are also associated with *Ca*. L. Solanacearum; infected plants exhibit chlorotic leaves and slight tuber discolouration eventuates. Plants affected by PY may recover whilst ZC is lethal (Wen *et al*. 2009). It is estimated that since the arrival of TPP in New Zealand damage resulting from TPP infestation has cost the potato industry alone over NZ$60 million (Potatoes New Zealand, 2010).

1.1.1 Description

The TPP is a hemimetabolous insect which undergoes incomplete metamorphosis; the life history consists of eggs, nymphs and winged adults. The TPP belongs to the order Hemiptera which are typically classed as ‘sap sucking insects’ and includes the leafhoppers and aphids. Adult TPP are small grey or black winged cicada-like insects measuring approximately 4mm in length (Minchin, 2007). The abdomen is traversed by two distinct white stripes and the wings are transparent**.** The ovate shaped nymphs (immature stage) resemble scale insects (Plant and Food Research Ltd, 2009) however unlike scale insects TPP nymphs are mobile. Nymphs range in colour from tan, orange to green; typically the earlier stages (1-3) are tan-orange whilst more mature nymphs are green. At the third instar nymphs develop wing buds which appear more obvious at the fourth and fifth instars (MAF Biosecurity New Zealand, 2009). TPP lay ovate tan to orange coloured eggs borne on short stalks which change to green or brown within 2-3 days (*ibid*.). Eggs are laid on stems and leaves and are usually only noticeable when laid on the leaf margins.

Figure 1.1) TPP adults; transparent wings and white markings on the abdomen

(Source: Nansen, 2011)

1.1.2 Plant Damage

TPP feeding may cause weakened plants and reduced fruit/tuber size (Potatoes New Zealand, 2009); this type of damage is proportional to the level of psyllid infestation.

Major plant damage results from TPP transmitting the disease causing agent *Candidatus* Liberibacter solanacearum (Hansen *et al*. 2008), commonly referred to as Liberibacter or Zebra Chip (ZC). ZC affects both foliage and tubers/fruit

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Foliage symptoms include; chlorosis, leaf curling, stunting, flower abortion, fruit deformation (tomatoes) (EPPO, 2010), tuber discolouration (potatoes), “leaf scorching and eventual plant death” (Wen *et al*. 2009: 1102). In potatoes early ZC infection results in high set of small tubers whilst late infections cause tuber (medullary ray) discolouration known as Zebra chipping; reducing potato tuber quality and suitability for the process market (*ibid*.). ZC may also reduce seed tuber vigour (Henne *et al*. 2010).

PY disease is also vectored by TPP. It is thought this disease is closely related to ZC (Hansen *et al*. 2008; Brown *et al*. 2010; Nelson *et al*. 2010). PY symptoms in potatoes include; “pronounced yellowing of the foliage, stunting and slight vascular discolouration in the tubers” (Wen *et al*. 2009: 1102). In contrast with ZC, PY is “rarely lethal and recovery is possible” (*ibid*.).

The TPP is also thought to be a vector of *Candidatus* Phytoplasma australiense (phytoplasma) (Munyaneza, 2010), a disease causing agent responsible for the decline of the Tii Kouka (*Cordyline australis* (Forst. f.) Hook. f.) in New Zealand.

Damage resulting from the effects of TPP and associated disease complex has resulted in widespread economic losses to growers of solanaceous crops. Individual potato growers in Texas have reported losses of greater than $2.0 million annually (Centre for North American Studies, 2006). At present in New Zealand it is estimated that since its arrival in 2006 the TPP has collectively cost the potato industry alone over $60 million (Potatoes New Zealand, 2010).

1.1.3 Current state of research in New Zealand

TPP is a recent introduction into New Zealand and much of the information available is based on research undertaken overseas, particularly in the USA. Since its incursion huge efforts have been made by New Zealand scientists to learn more about the TPP and its effects in New Zealand. Funding has grossly limited the amount and depth of research needed here in New Zealand; the Ministry of Agriculture and Forestry (MAF), Biosecurity NZ, Sustainable Farming Fund, Plant and Food Research Ltd, Universities, the Foundation for Research, Science and Technology (FRST, now known as MoSI, Ministry of Science and Innovation), Horticulture Australia Ltd, McCains Food Ltd, Mr Chip Ltd, Bluebird Foods Ltd, Horticulture New Zealand particularly Potatoes New Zealand (PNZ) are major contributors to both funding and research nationally. Research and knowledge generated nationally is a collaborative effort of many of the above bodies. There are two major research schemes currently at work in New Zealand; the "Sustainable Psyllid Management project and Plant and Food Research Ltd's internal research programme" (Potatoes New Zealand, 2010: 1). The Sustainable Psyllid Management project includes;

- Insecticide field trials, spray programme development (including resistance management)
- National psyllid monitoring programme
- Biological control agents
- Spray application technology research (Potatoes New Zealand, 2010)

Other national research projects include;

- Psyllid population biology (PhD associate)
- Impacts of phytoplasma on potato production
- Screening of potato varieties for resistance
- Psyllid coordinator roles – including monitoring and technology transfer
- Psyllid workshops and extension materials (*ibid*.)

PNZ (Potatoes New Zealand) is a major means of communication between growers and research bodies within New Zealand presenting a series of update and discussion meetings, releasing regular newsletters and website updates. PNZ has also helped to establish a psyllid working group and national psyllid co-ordinator position which is currently occupied by Dr. Stephen Ogden.

1.2 TPP and Māori food sources

Three traditional Māori food sources are susceptible to TPP (Potatoes New Zealand, 2009); taewa (Solanaceae, *Solanum tuberosum* L. ssp. *andigena* and ssp. *tuberosum*), kūmara (Convolvulaceae, *Ipomoea batatas* (L.) Lam., sweetpotato) and poroporo (Solanaceae, *Solanum aviculare* G. Forst syn. *S. Laciniatum* (LINN.). All three crops belong to the Convolvulaceae or Solanaceae plant families, the only two families on which TPP complete their lifecycle (Tomatoes New Zealand, 2009). The Solanaceae are recognised as the preferred host family (Wallis, 1955). Kūmara and taewa are key cultivated crops and traditionally primary foods within the Māori diet. Poroporo is an uncultivated crop with many uses including; flavouring in hangi, a natural contraceptive and the ripe berries are eaten by children or processed as a jam (Roskruge, 2007). Taewa and kūmara are primarily summer annual plants and therefore susceptible to TPP population outbreaks during this season.

Taewa refers to the many varieties of potato cultivated by Māori during the 18th and 19th centuries; some of these varieties have survived through the times and continue to be grown today. TPP Infested taewa plants exhibit typical feeding damage symptoms as in conventional European potato varieties (e.g. Rua and Desiree). The 2008-2009 cropping season saw taewa crops throughout New Zealand including Palmerston North, Bulls, Hawke’s Bay and Gisborne claiming their yields were minimal and that the plants appear to have set many small marble sized tubers at plant maturity.

Kūmara is noted as a ‘poor host’ of TPP, although a study conducted by Martin (2008) found good evidence of the association of TPP with kūmara. In the cropping season of 2009/10 it was observed by Peter Wright at the Pukekohe Plant and Food Research Ltd station that TPP completed a full lifecycle (eggs-nymphs-adult) on Kūmara (Wright, pers. comms. 2010).

Poroporo fruits year-round (Te Ara, 2011) and therefore foliage is nearly always present providing a food source and breeding ground for TPP. Poroporo may thereby serve as a bridging host for TPP between seasons and potential inoculum for summer infestation. Potatoes New Zealand (2009) listed poroporo as a host of the TPP in New Zealand, the extent of seasonal infestations and the potential of the plant as an overwintering host is as yet unknown. As a solanaceous plant poroporo may be susceptible to Liberibacter and serve as a year-round source of disease inoculum.

1.2.1 TPP in a traditional context

Taewa is a major host of the TPP and the most serious issue facing the crop is declining seed tuber quality due to liberibacter especially regarding some of the rarer or relic varieties. For potatoes it has been shown by Henne *et al.* (2010) that when grown from liberibacter infected seed tubers, only 20-40% of tubers sprout dependent on individual seed tuber infection and cultivar. Low seed tuber and shoot vigour was noted. Delayed emergence can be expected and plant death may occur after a few weeks of growth (Potatoes New Zealand, 2010). As yet it is unclear if kūmara are susceptible to liberibacter. At this stage only solanaceous crops are recognised as vulnerable hosts to this disease.

Little is known about the role poroporo plays in the lifecycle of the TPP and disease carry over or harbouring. As a solanaceous plant it is possible that poroporo may harbour both TPP and Liberibacter and serve as an all year round source of the inoculum; contributing to their spread throughout the summer months to commercial crops. Due to these concerns increased poroporo control in cropping regions may contribute to the decline of the plant species in New Zealand.

1.3 Aim, objectives and research questions

“Little is known about the potato psyllid’s lifecycle in New Zealand” (Potatoes New Zealand, 2009^2: 2) and much of the literature available is based on information and data from the USA (*ibid*.). This research, in large, relates to commercially produced crops such as tomatoes, potatoes and capsicum. Inconsistencies exist within the literature pertaining to the life history of the TPP (Abdullah, 2008) especially in regards to lifecycle progression, oviposition preference (site and number of eggs laid) and if these factors are attributable to environmental factors and host plant suitability.

Kūmara and taewa are summer annual crops and therefore susceptible to psyllid outbreaks throughout the growing season. Poroporo is an evergreen plant and may play host to TPP throughout the year, potentially serving as an important overwintering or bridging host. The susceptibility of these traditional food sources to TPP attack and associated disease complex poses many problems to Taewa growers including adopting chemical sprays to control the TPP, potential seed tuber effects and reduced economic gains. Analysis of the TPP lifecycle on each of these food sources will yield information regarding plant host suitability and the lifecycle dynamics of the TPP on each host plant (e.g. length of each life stage, oviposition and mortality). A definite knowledge gap exists regarding these crops and acknowledgement of their national economic importance and intrinsic value, adds significance to this study.

This research assesses the progression of the TPP lifecycle on three traditional Māori food sources; taewa (*Solanum tuberosum* ssp. *andigena* & *tuberosum*), kūmara (*Ipomoea batatas*) and poroporo (*Solanum aviculare syn. S. laciniatum*.), in an attempt to yield information and data relevant in a national context but with a focus on traditional Māori food sources. Host preference and suitability were assessed; tables, graphs and basic statistics including mean, standard error and ANOVA tests (F-tests and Fisher least significant difference (LSD)) were calculated in relation to each host plant. Data regarding a number of lifecycle parameters was collected from the closed environment component of this study.

With regards to the open environment component of this research, population trends were recorded over time to allow the determination of the role of naturally occurring poroporo in the annual TPP lifecycle in New Zealand.

It is intended that this research will provide growers and users of kūmara, taewa and poroporo with an insight into the relationship between pest and host plant, and what can be expected in terms of pest populations and infestations within a single growing season. This information will inevitably assist growers in making informed decisions about the management and control of the pest.

1.3.1 Aim of the research

To compare the lifecycle progression of the tomato/potato psyllid (*Bactericera cockerelli* (Sulc)) in relation to the three host plant species; taewa, kūmara and poroporo. To ultimately identify the role of these plants and enable the determination of the significance of each host species in the annual lifecycle of this insect pest in the New Zealand environment.

1.3.2 Objectives

- To compare the lifecycle progression of the tomato/potato psyllid on each of the three host plant species; taewa, kūmara and poroporo,
- To determine host preference, suitability and significance of each host in the annual progression of the TPP lifecycle in New Zealand,
- To produce information and data relevant to New Zealand conditions regarding TPP lifecycle parameters.

1.3.3 Research questions

- Are taewa, kūmara and poroporo important host plants in the lifecycle progression of the tomato/potato psyllid (*B. cockerelli*) in the New Zealand environment?
- Is poroporo a significant overwintering host of the tomato/potato psyllid in New Zealand?

1.3.4 Limitations

The data collected for this thesis was collected throughout the winter of 2010 and over a single cropping season (2010-11); therefore trends comprising more than one year cannot be identified. The conclusions reached in this thesis are based on the research conducted within this time period. It would be favourable and furthermore verifiable to repeat the data collection over a 2-4 year period which may provide clearer trends and patterns in the annual TPP lifecycle.

The closed environment monitoring was not carried out in a fully controlled environment and therefore data collected from this study cannot be compared to other studies such as Abdullah (2008) due to the variation in results.

Only two natural poroporo populations were sampled for this thesis, ideally a number of strata should have been sampled to provide a representative subset of information regarding the relationship between host and insect.

1.4 Thesis organisation

This thesis consists of eight chapters in total followed by a number of appendices which are referred to throughout the thesis.

Chapter Two discusses the methodology used within this study to assess the suitability of poroporo as an overwintering host of the TPP and the lifecycle of the insect on the three host species for this research. The results of the study are presented in Chapter Three. Chapter Four presents an introduction and overview of the TPP including the biology, ecology and life history of the insect, followed by various management strategies commonly used by growers to control TPP. Chapter Five provides a discussion based on taewa, poroporo and kūmara; their history, intrinsic values to Māori and susceptibility to the TPP. Chapter Six describes ZC disease complex providing a discussion of the history and discover of the causal agents, plant symptoms and economic ramifications caused by this disease. Chapter Seven provides a discussion of the results found in this study and Chapter Eight presents a summary of the research and recommendations for future research regarding traditional Māori food sources and TPP.

Chapter Two

Materials and Methodology

2.1 Introduction

Kūmara (*Ipomoea batatas*), taewa (*Solanum tuberosum* ssp. *andigena* & *tuberosum*) and poroporo (*Solanum aviculare* syn. *S. laciniatum*.) are all susceptible to TPP attack and belong to the Convolvulaceae and Solanaceae families on which TPP breed (MAF Biosecurity New Zealand, 2009). All three host species may host TPP over the summer cropping season; poroporo foliage is present year round and therefore this host plant has the potential to serve as an alternative host for the TPP all year round.

Taewa crops appear to exhibit typical feeding damage and liberibacter symptoms as shown in conventional potato cultivars including psyllid yellows, high tuber set and low yields (Roskruge, pers. comms. 2010), but the most pressing issue facing this crop is possible low seed tuber vigour and disease carry-over. TPP and liberibacter have the potential to decimate taewa crop, due to the non-commercial nature of the crop for both seed and table produce. The 2008-09 cropping season was the first time the TPP and liberibacter were detected in taewa crops in New Zealand with devastating effects. Sites in Palmerston North, Bulls, Gisborne and Christchurch were affected by TPP and liberibacter. As yet it is unknown if kūmara and poroporo are susceptible to Liberibacter infection and PY, currently there is no literature available on this subject.

“Little is known about the potato psyllid lifecycle in New Zealand” (Potatoes New Zealand, 2008: 2); much of the literature available is based on information and data from the USA (*ibid*.) with particular focus on commercial solanaceous crops such as potatoes, tomatoes and capsicums. It is difficult and unreliable to relate this data to other host plants.

This trial consists of three separate components; open and closed environment monitoring and contained leaf samples to assess fecundity in relation to each of the three host species. The TPP lifecycle is affected by both environmental factors and host plant (species (Yang and Liu, 2009) and cultivar (Liu and Trumble, 2004)); the major factor manipulated for the purposes of this research is host plant species; three traditional host plants, kūmara (Owairaka red variety), taewa (Moemoe variety) and poroporo (*S. aviculare*) were assessed for their capacity to support the TPP lifecycle. Daily temperature in both the open and closed environment research components was collected and commented on in regards to TPP detection and lifecycle development. Open environment data was provided by local weather stations located close to the monitoring sites and the closed environment data was measured using a digital max/min thermometer. Variance in the TPP population used for this study was controlled through the use of a single biotype (group of organisms with the same genotype) to reduce any inconsistencies. The research within this proposal was achieved via experimental methods which involved extensive monitoring of the TPP lifecycle on each of the three host species. Two environmental settings were used during data collection; open environment (i.e. natural plant populations) and closed environment (glasshouse environment). These two environmental settings were utilized to further the assessment of poroporo as a host plant of the TPP and to generate new information and discussion points. Data relevant to lifecycle parameters such as; fecundity, survivorship and the length of each life stage and overall lifecycle in relation to each of the three host plants were collected and analyzed.

This research will yield information regarding host plant suitability and lifecycle dynamics of the TPP (e.g. length of each life stage, oviposition and mortality) each of these Māori food sources. A definite knowledge gap exists regarding these crops and in consideration of their national importance and intrinsic value, knowledge generation is required. Determining the role of each host plant may divulge data and information relevant to the management and possible control of the TPP in New Zealand.

2.1.1 Tahuri Whenua – National Māori Vegetable Growers Network

Tāhuri Whenua
National Maori Vegetable
Growers Collective

Tahuri Whenua, the National Māori Vegetable Growers Network, was established in 2002 and is responsible for representing Māori interests in the horticulture sector. The collective was established in response to growing interest in traditional horticulture and continuing production of indigenous crops and cultural practices (Tahuri Whenua, 2010²). The collective now has approximately 300 members including "landowners, crop producers, home gardeners, students, kaumatua, kuia, marae and kohanga" (ERMA, 2009). Dr. Nick Roskruge, the collective's chairperson, maintains a taewa seed tuber bank at Massey University where he is a senior lecturer in Horticulture and Māori Resource Studies. Dr. Roskruge is also a supervisor for this thesis.

The collective provides growers with information regarding traditional growing practices and crops including; kōkihi (New Zealand spinach, *Tetragonia tetragonoides* (Pallos) Kuntze), kaanga (Māori corn, *Zea mays* L.), kūmara (sweetpotato, *Ipomoea batatas* (L.) Lam.) and taewa (*Solanum tuberosum* L. ssp. *andigena*). Recent publications include a growers' guide to 'Pests and Diseases of Taewa Māori' and two further publications are in preparation regarding kamokamo and kūmara. The collective's major project is the 'Spud in a Bucket' "initiative aimed at promoting sustainability in New Zealand schools" (Tahuri Whenua, 2010). The initiative presents children with the opportunity to grow their own potato (Māori variety) plant in a bucket, as the name suggests. The children are responsible for maintaining the plant throughout the growing season including duties such as watering, weeding and assessing the lifecycle of the plant. The cropping season of 2010-2011 was the fifth season the project ran with approximately 60 schools and 3,800 students throughout New Zealand participating in the programme. In regards to TPP, Dr. Roskruge and I prepared a fact sheet in 2009 (see Appendix I) which included information regarding identifying the TPP, vectoring of diseases and a number of web links to refer to if any problems arose.

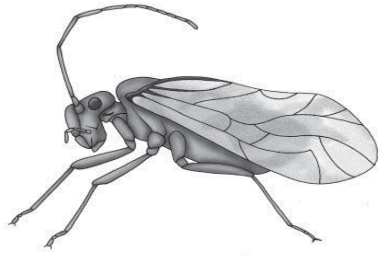
Tahuri Whenua meets twice annually across New Zealand including an annual general meeting (AGM) and a Hui-ā-rohe (regional meeting). These meetings allow members to bring issues forth, share information regarding their crops and notify the collective of any upcoming events in their areas. These hui are held at different locations around the country to showcase different areas and to share the travelling distances between the members. Being an active member and attending these meetings has allowed me to share information regarding the TPP with the growers network and also gather information from them on the status of their crops.

2.1.2 TPP identification

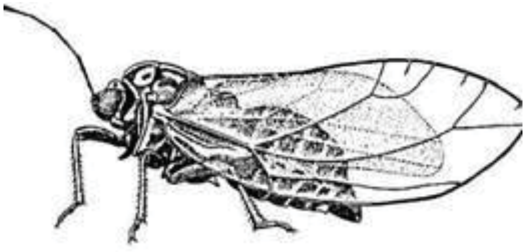
Identifying and confirming the presence of TPP requires careful observation of a number of morphological characteristics including wing venation and pattern and inner metatibial spur number on the hind legs. Through observing and monitoring the insect since 2008, recognizing the insect, signs and symptoms associated with TPP infestations has become a familiar task for me. No other Psylloidea species have been recognised as' insect pests' of the host plants utilized within this study (Martin, 1999). The Psylloidea are "generally narrowly host specific" (Hodkinson, 1974: 325) particularly as nymphs, whilst adult psyllids tend to be polyphagous (Capinera, 2008) and may feed on a range of host plants. Other psyllid species were detected during field monitoring; these events were noted.

TPP adults may be confused with winged adult psocids (Psocoptera) commonly known as barklice or booklice, which look similar in body shape and size as adult psyllids. At first glance the length of the antennae distinguish between the two, winged adult psocids possess longer antennae (Amateur Entomology Society, 2010) than the Psylloidea. This feature is obvious in the field with the naked eye. Psocid wings are held over the body much like a tent whilst TPP wings extend upwards past the posterior abdominal segment (see figure 2.1 below). (See section 2.2 for more information regarding TPP identification)

Figure 2.1) Left: Adult winged Psocid showing wings held over the body like a tent and Right: TPP wings which extend upwards of the TPP body.



(Australian Museum, 2010)



(SimplyKitchenGarden.com, 2011)

2.1.3 Plant monitoring techniques

At present universal monitoring techniques for TPP have not been developed; methods have been recommended by various research institutes (e.g. Plant and Food Research Ltd New Zealand), industry groups (e.g. Horticulture New Zealand and subsidiary product groups) and merchants (e.g. Fruitfed). These techniques are driven by the outputs required and focused on large outdoor or indoor commercially grown solanaceous crops particularly the tomato, potato and capsicum. The relationship between TPP and host differs for some plant species which also warrants adjusted monitoring techniques.

Taking these factors into account and the outcomes required during this study, direct observations of whole host plants were undertaken at regular intervals appropriate for each part of this study. All above ground plant parts and surfaces were sampled including “both sides of the leaf, petioles, axils and stems, apical leaves, blossoms and fruits” (Herzog and Kogan, 1980: 31). Insect counts and life stage information was recorded. This technique used within this study was used in both open and closed environment monitoring; open referring to natural plant populations occurring at the two monitoring sites and closed environment referring to a greenhouse environment. The only factor which changed throughout this study was the frequency of these monitoring events. The closed environment units were monitored daily at approximately 8.30-8.45am whilst the open environment sample units were monitored once weekly. The time was selected as TPP are less active at the low temperatures experienced during the early morning hours.

2.1.3.1 Survey period

Open environment sampling was initiated in early July 2010 and ceased late February 2011 whilst closed environment monitoring started early January 2011 and ceased late February 2011.

2.1.3.2 Sampling sites

Two different environmental settings were used to assess the potential of the host plant species as potential hosts for the TPP. Ten sample units of each host species were managed in glasshouse (temperature and light factors remained uncontrolled) conditions, whilst two natural populations of poroporo were assessed under natural (open environment) conditions. The latter two distinct populations were located in two study areas within the Manawatu-Rangitikei District; Bulls and Aokautere. The sample design for these two strata were completed on a by a case by case basis, dependent on availability of poroporo at each site, growth stage and plant health (see section 2.2.3.4 Monitoring technique and data collection for more information).

2.1.3.3 Open environment assessment

Only poroporo was monitored in an open environment situation. Population sampling was undertaken within two distinct strata (see Map 1 and 2) at Massey Hill Aokautere Palmerston North and Parewahawaha Marae in Bulls. The Massey Hill site consisted of a natural vegetation stand and the Bulls site poroporo was difficult to locate due to recent plant restoration work and the fact that the plant is classified as an agricultural weed.

The purpose of undertaking this component of the study was to observe TPP population dynamics on natural poroporo plants in the field to determine the potential of this host as an overwintering habitat for TPP.

2.1.3.4 Closed environment assessment

All three hosts; taewa, kūmara and poroporo were assessed as hosts of the TPP in a closed environment setting. Temperature was recorded daily using a digital min/max thermometer. The lifecycle analysis component of this study was assessed daily. Contained leaf samples were used to assess female fecundity.

Data collected included length (in days) of each life stage (oviposition, incubation, nymph development and adult) in reference to the three host species included in this study.

2.1.3.5 Contained leaf samples

Ten contained leaf samples of each host plant species allowed the assessment of female fecundity in relation to each host species. The plastic containers used within this trial were altered; a portion (approx. 4cm^2) of the upper surface (top or lid) was cut out and replaced by mesh cloth to allow air flow and a small toothed crimp clip attached (glued) on one side of the container to hold each sample leaf (Yang and Liu, 2009). Adult TPP were carefully released into these containers via the mesh opening. Each container was inoculated with one pair (one male, one female) of TPP adults with a new fresh leaf daily; the leaves removed from the containers were carefully assessed for egg numbers under a dissecting microscope (Abdullah, 2008; Yang and Liu, 2009). The containers were then placed into the glasshouse alongside the lifecycle assessment.

2.1.4 Assumptions

TPP were more likely to inhabit the Bulls site due to previous detection there in the 2008 and 2009 crop seasons, although during the taewa cropping season of 2010-11 the site was in a fallow phase as part of a rotation schedule for the site.

2.1.5 Inoculum and Biotype

The TPP biotype used in these experiments was collected at a Wanganui home garden from a number of eggplant (*S. melongena* L. cv. ‘Chinese lantern’) and tomato (*S. lycopersicum* L. cv. ‘Gardeners delight’) seedlings and reared on tomato plants (cv. ‘Moneymaker’). The name of the biotype is WAN11 or Wanganui 2011.

2.1.6 Seasonality

The closed environment monitoring was carried out during the summer months of the 2010/11 season due to the seasonality of taewa and kūmara, and the availability of seed tubers and propagative shoots. The summer temperatures provided conditions conducive to both TPP and host plant growth.

2.1.7 Environmental variables

The lifecycle of the TPP is susceptible to environmental changes; the most influencing factor being temperature. Optimal temperatures range from 21-27°C (Capinera 2001; Munyaneza 2010); temperatures above 32°C are detrimental to TPP leading to reduced egg-laying and hatching (Capinera, 2001). It is noted that 27°C is the optimal temperature for TPP growth (Cranshaw, 2001; Munyaneza, 2010). TPP growth ceases at 35°C (Cranshaw, 2001).

Other events which may affect TPP populations include; frosts, heavy precipitation and host plant factors including leaf drop events, host plant death (see sampling covariates for further information regarding host plant status) and other potential factors such as physical human interference, chemical use near the sampling sites and plant removal.

2.1.7.1 Open environment

The open environment sample units were exposed to natural environmental fluctuations; daily high and low temperatures were extracted from weather stations located close to each monitoring site. The rationale behind monitoring these plants during this period was to assess the potential of poroporo as an overwintering host of the TPP and therefore exposure to seasonal environmental changes was essential.

2.1.7.2 Closed environment

The closed environment sample units were assessed in a glasshouse to remove the effect external environmental factor. Temperature was not controlled and plants were subjected to natural daily light regimes. Sample lines were manually watered daily.

2.1.8 Disease complex

It was anticipated that Liberibacter may have had an effect on the host plants used within this study. Clean (disease free) colonies of TPP are difficult to establish especially when sampling or collecting TPP from the natural environment. New Zealand’s principal horticultural research and development group, Plant and Food Research Ltd (formerly known as Crop and Food Research and Horticulture Research New Zealand) has unsuccessfully attempted to establish clean TPP colonies for their own research purposes (Bourhill, 2010; Macdonald *et al.*, 2010).

Liberibacter has not (yet) been associated with poroporo and kūmara. Any signs and symptoms of the disease within this research were duly noted and the effects (if any) on the sample TPP populations were explained in context.

2.2 Insect Identification and sexing TPP

2.2.1 TPP identification

Four of the six Psylloidea families have been recorded in New Zealand; the Psyllidae, Calophyidae, Homotomidae and the Triozidae, the TPP belonging to the latter (Plant and Food Research Ltd, 2009²; Berry *et al*. 2010). Misidentification of psyllid species is possible as some of the native psyllid species resemble newly emerged adults particularly the Pittosporum psyllid (*Trioza vitreoradiata*).

The Triozidae are unique in possessing "trifurcate branching (see Figure 2.2) of the basal vain of the forewing, in contrast to other Psyllid families in New Zealand which have bifurcate branching" (Plant and Food Research Ltd, 2009²), for example the Dodonaea psyllid (*Psylla dodonaeae*) belongs to the Psyllidae family and possesses this bifurcate branching.

There are two distinct morphological characteristics which distinguish the TPP from other Triozidae in New Zealand; the possession of two inner metatibial spurs on the hind legs and forewing patterning which is "transparent with no colour patterns and the cubital cell is short and compact (see Figure 2.2)" (Plant and Food Research Ltd, 2009²). Binocular stereomicroscopes were used to identify insects on the yellow sticky traps retrieved from the field. Detection of other psyllid species was also recorded.

Figure 2.2) Showing metatibial spurs of the hind leg (left). Trifurcate branching of the basal vein and short cubital cell on the TPP forewing (right).

(Source: Plant and Food Research Ltd, 2009)

2.2.2 Sexing TPP

TPP were sexed based on the morphology of the posterior abdominal segment as expressed in literature available on this subject. The "apex of the female abdomen is rounded and more robust with a short ovipositor whilst the male abdomen has a more blunt appearance" (Abdullah, 2008: 62) (see below).

Figure 2.3) Male genitalia (Source: Brown, 2010)

Figure 2.4) Female genitalia (Source: Brown, 2010)

This trait was used throughout this study as a means of sexing adult TPP.

2.2.3 Beneficial insects

The presence of three major groups of beneficial insects was recorded within the open environment component of this study; which included the;

- Coleoptera: coccinelidae,
- Neuroptera: Hemebrionidae, and the
- Diptera: syriphidae,

These groups have been identified as major natural predators of the TPP in New Zealand (Boase, 2010; MacDonald *et al.* 2010). Pictorial identification cards (see appendix II) were made for use in the field to allow quick and accurate insect identification. Hand held magnifying glasses (hand lens) were also used.

2.3 Methods

2.3.1 Open environment monitoring

2.3.1.1 Study areas

Two strata of natural poroporo were assessed for their suitability as a host for the TPP within the Manawatu-Wanganui region; one at Aokautere near Massey University in Palmerston North and the other at Parewahawaha Marae in Bulls. The Manawatu-Wanganui region is the fourth largest outdoor vegetable crop growing region in New Zealand (Plant and Food Research Ltd, 2010); the largest of these crops being potatoes. With large potato growing areas such as Opiki and Ohakune located within the region, Manawatu-Wanganui region is the second largest potato producing region in New Zealand. Other solanaceous crops grown in the region include indoor tomato and capsicum crops. TPP was first noted in the region in the summer of 2008 (Teulon *et al*. 2009), little was known about the pest at this time and it went somewhat unnoticed in infested crops. Since then TPP have frequented the region during the summer months (*ibid*.) and in the view of potato growers around the region TPP has become a part of overall crop management. Crop monitoring and chemical spraying for this pest are now important control activities integrated into crop management plans. This annual influx of TPP ensured that insects were available for each of the components of this research

2.3.1.2 Site Selection

Two study areas (strata) were assessed in this study consisting of a total of 12 sampling sites. Both the Bulls and Palmerston North trials consisted of six plants; three mature shrubs and three juvenile plants. The two strata were located at Massey Hill in Palmerston North and Parewahawaha Marae in Bulls. The site at Bulls is located along a fence line which surrounds the marae gardens where taewa is a staple crop and it is expected that TPP will be more likely to occur at this site. During the 2010/2011 cropping season this site was not planted out in taewa due to rotational scheduling for the site, although many volunteer potatoes did emerge during the monitoring period. The Massey Hill (Aokautere) site is located approximately 150m north from the main Massey University Campus, Turitea.

Each trial consists of six plants; three mature and three juvenile plants. The plants included in these trials were not selected using random methods and therefore it is necessary to outline the principle factors that determined their selection (Morris, 1955). Selection was based on;

- The sporadic nature of the presence of poroporo in the trial areas;
- The removal and control of poroporo in many areas due to its classification as an agricultural weed; and
- In attempts to locate 10 plants to sample in each trial unit only the number of plants used within this trial were found.

Due to the non-random allocation of sample units within the open environment sampling component of this research, statistical analysis undertaken will only relate to the strata in question (within strata) (Morris, 1955). Statistical tests such as ANOVA (analysis of variance) are no longer applicable in this situation (*ibid*.)

2.3.1.3 Monitoring technique and data collection

Plant sampling was carried out during the early morning when adult psyllids are less active. Whole plant counts were necessary for this study as TPP populations are clumped, both within the field and within individual host plants (Trumble, 2010). Direct observation of whole plants was carried out to ensure representative samples of the TPP population on each host were recorded.

Successive sampling at regular intervals (Varley *et al*. 1973) was undertaken weekly, during the winter months through to summer.

In all instances plants were sampled for the following;

Table 1: Insects monitored during open environment monitoring

Tomato/Potato Psyllid	**Beneficial Insects – Eggs and larvae**
-Eggs	-Hoverfly (Syriphidae)
-Nymphs; Stages 1-3 Stages 4-5	-Ladybird beetle (Coccinelidae)
-Exuviae	-Brown lacewing (Hemebrionidae)
-Adults	Other psyllid species

All above-ground plant parts and surfaces were sampled including "both sides of the leaf, petioles, axils and stems, apical leaves, blossoms and fruits" (Herzog and Kogan, 1980: 31). Insect counts were recorded.

Yellow sticky traps were used to indicate the presence of adults throughout the monitoring months; these numbers are included in the results and assessed in their entirety as there is no statistical relationship between trap catch and population abundance (Leather, 2005).

2.3.2 Closed environment monitoring

Closed environment monitoring involved observing and analyzing the TPP lifecycle on three traditional Māori food sources; taewa, Kūmara and poroporo. This was completed at the Massey University Seed Technology Department.

Each plant was infested with one pair of adult TPP (one female and one male). On infestation the sample units were monitored on a daily basis for the first oviposition event which then initiated the overall monitoring programme. These adults were contained and observed until mating occurred and then released onto the sample host plants. Once mated the adults were released onto the sample units for 24 hours. Ten sample units of 10 eggs each were allowed to remain on the host plants (Abdullah, 2008), the reminder (if any) were brushed off with a paintbrush. Areas containing these eggs were used for the life cycle component of this research and marked (using string tied to particular leaflet) to enable location during monitoring. A total of 100 eggs per host plant species were monitored throughout the component of the study.

Marked leaves containing eggs were observed daily to assess the progression of the TPP lifecycle throughout the monitoring period. Data regarding the TPP in relation to each of the host species was recorded including the length of each life stage. Survival of adults and nymphs was also noted.

The sample lines (host species) were covered with mesh covers (cloches, pore size 1.35mm^2) to ensure the inoculum remained on the plants.

2.3.2.1 Host plants

Ten plants of each host species were planted for use in this trial, taewa, kūmara and poroporo were potted at the Plant Growth Unit, Massey University, using ten litre pots with standard potting mix and a short term (3-4) month growth fertilizer mix. This fertiliser mix consisted of 150g of ‘short term’ mix and 150g of dolomite. Ten individual plants of each of the three host species were potted to provide sufficient plant material for the entire study. Five plants of each species were used in the lifecycle analysis component of the study whilst the remaining plants provided fresh leaf material for the fecundity and adult longevity study. Extra plants were housed in a clear plastic hot house to prevent natural infestation of TPP. To allow comparisons between the host species, kūmara and poroporo plants with “approximately the same foliage biomass as potato plants” (Davidson and Connor, 2003: 93) were used in this trial. The kūmara trial units were placed in the glasshouse prior to potato and poroporo due to differences in climatic requirements for growth needed for this research.

The moemoe variety of taewa was used in this study due to the availability of seed and its popularity with growers (Roskruge, pers comms. 2010). Taewa seed was provided by Dr. Nick Roskruge and Owairaka Red kūmara shoots (tipu) of the red variety purchased from Oderings, Palmerston North. Immature poroporo plants were uplifted from a single site on Massey Hill and potted for this study.

2.3.2.2 Inoculation

Artificial inoculation occurred in the glasshouse. TPP adults were sexed and separated into pairs (one male, one female) in clear plastic vials. Each of the host plants were inoculated with one pair of TPP adults. Each pair was released near the base of the host plants allowing them to jump up onto the host (Jamieson, 2010). The adults were allowed to mate and lay eggs for 24 hours and then removed (Abdullah, 2008). Ten sampling sites consisting of ten eggs in any one area on the sample plants were selected and used for the lifecycle component of this study.

A further 30 pairs of TPP were sexed and utilized in the fecundity component of this study. Each replicate (ten in total for each host species) was inoculated with freshly emerged pairs of TPP; this pair was assessed throughout the duration of the monitoring period until they perished.

2.3.2.3 Data Collection

Data regarding a number of lifecycle parameters was collected throughout the monitoring periods. In the open environment, population trends were recorded over time to allow determination of the role of wild poroporo in the annual TPP lifecycle in New Zealand. The closed monitoring component accounted for the bulk of the data collected for this study. Lifecycle data recorded included the following;

- On plant:
    - Pre oviposition period
    - Egg incubation
    - Nymph development
    - Nymph and egg survivorship

- Contained leaf samples
    - Pre mating period
    - Fecundity
    - Adult longevity (male and female)
    - Oviposition period

- Total development period (= Incubation period + Nymph development)

- Total lifecycle (= Total development period + Pre oviposition period)

Each lifecycle was measured in days (24 hour periods) lapsing at 8.30am on the morning when the trial replicates were monitored.

The ‘pre-oviposition period’ was measured from the time of “adult emergence to the oviposition of the first egg” (Abdullah, 2008: 63). Egg incubation was measured from the first oviposition event until the emergence of nymphs, whilst the nymph development period initiates from this point to the emergence of the first adults. Survivorship was noted and measured for nymphs and eggs as part of the on-plant lifecycle measurements. At the end of each life stage (e.g. egg, nymph, adult) those surviving insects were counted and noted; average survival was calculated over the ten replicates for each host species.

For the contained leaf samples the pre-mating period was recorded from the time of collection (of newly emerged adults) until mating was observed (Abdullah, 2008). Longevity was measured form the time of emergence till death for both adult male and female TPP. Fecundity was measured by daily recording of egg numbers over the oviposition period. This period was measured from the laying of the first egg to whichever occurred first; female death or last egg-laying event.

Total development time was calculated by adding the egg incubation period and nymph development together. Total lifecycle length was calculated by adding total development time and pre-oviposition period (*ibid*.).

2.4 Covariates

2.4.1 Sampling covariates

Table 2: Sampling covariates

Sampling Covariates	
Air temperature	Host plant growth stage
Time of day for sampling	Season
Rain (precipitation)	Wind direction
Host availability	Site proximity to known TPP infestation
Host plant health	Leaf mass

Many of the sampling covariates (refer to Table 2) are only applicable to the open environment monitoring component of this research as the closed environment component was carried out in a glasshouse thereby removing the effect of some of these covariates. Those covariates which do vary within this component are either measured or controlled through artificial means.

Daily high and low temperatures were recorded for both the open and closed environment components of this research. Open environment data for both the Palmerston North and Bulls sites were provided by Weather Underground (WU), an American based "commercial weather station which provides real time weather information via the internet" (Wikipedia, 2010). Weather information outside of the US is based on "information and observations from members with automated personal weather stations" (*ibid*.). In terms of validity, the Associated Press, an American news agency which operates "243 news bureaus and serves at least 120 countries, uses WU to prepare national weather summaries" (*ibid.*). Bulls weather information was retrieved from the IRANGITI2 weather station based in Aiken St, Bulls and the Palmerston North, data was collected by the MANAWAT1 site located in East St, Hokowhitu in Palmerston North the nearest station to the monitoring site. Closed environment data was recorded daily through the use of a 'Day/Night' thermometer to provide daily high and low temperatures.

The time of day for sampling was kept constant by undertaking monitoring at the same time for each monitoring event; (approx). 8.30am as this is when TPP are less active, making detection easier.

The open environment sample units were observed through their natural cycles during the monitoring period; events such as leaf drop and plant death were noted and commented on in terms of recorded results.

The closed environment plants were watered daily and requirements (fertilizer) for growth artificially provided at planting. For each of the species assessed within this component, plants of similar biomass were used for comparisons.

2.4.2 Site covariates

Table 3: Site covariates

Site Covariates	
Proximity to known TPP host plants	Public disturbance
Number of plants at each site	Air temperature
Air temperature	Vegetation cover
Occurrence of other Psylloidea species	Rainfall
Age of poroporo stands (young or mature)	Wind speed and direction
Health of poroporo stands	Sticky trap loss

The site covariates (refer to Table 3) are applicable to the open environment component of this study and were all measured throughout the duration of the monitoring period.

Seasonal fluctuations affect environmental conditions and the availability of host plant material, and the survival of TPP and other insects. Air temperature was recorded throughout the monitoring period.

Poroporo stand health was assessed on a weekly basis and leaf drop events noted as well as leaf regeneration. The number and age (juvenile or mature) of poroporo plants at each site was assessed at the beginning of the monitoring period. A juvenile plant was defined as possessing a single stem and less than one metre in height; larger plants that did not fit into these specifications were classified as adult plants. Host plant surveys were carried out twice during the monitoring period one in winter (July 2010) and again in summer (December, 2010) due to the plant growth habit (annuals, perennials etc.); recognized hosts of the TPP were noted.

The yellow sticky traps were fastened to host plants using plastic ties and bulldog clips where needed to lessen the probabilities of trap loss.

Vegetation cover at the two sites was distinctly different; the Massey Hill (Aokautere) monitoring site was enclosed by surrounding vegetation, this site is currently undergoing restoration planting. The Bulls site was quite exposed and poroporo was the predominant plant along the fence line of the Marae garden.

2.5 Analysis

All data was entered into Microsoft Excel and used in conjunction with Minitab to generate graphical displays, basic statistics (mean and standard error) and statistical tests (F tests and Fisher LSD) regarding population growth.

2.5.1 Closed environment data

For each of the recorded variables (life stage length, fecundity and survival) mean values were generated over the ten replicates for each host plant species; also the standard error for these values was determined using Minitab. F tests and Fisher LSD tests were undertaken to determine any significant relationships in terms of lifecycle parameters and the three host plants.

2.5.2 Open environment data

TPP population data was graphically presented as a time series graph showing numbers of TPP and their life stage over the monitoring period. A second graphical display integrates temperature into the time series graph to show the effect of temperature on TPP presence within the sample areas.

2.5.3 Contained leaf samples

For each host species average egg counts and standard error were calculated over the ten replicates. ANOVA tests (F-test and Fisher's LSD) were carried out to show any significant differences between oviposition behaviour in terms of each of the three host species.

Chapter Three

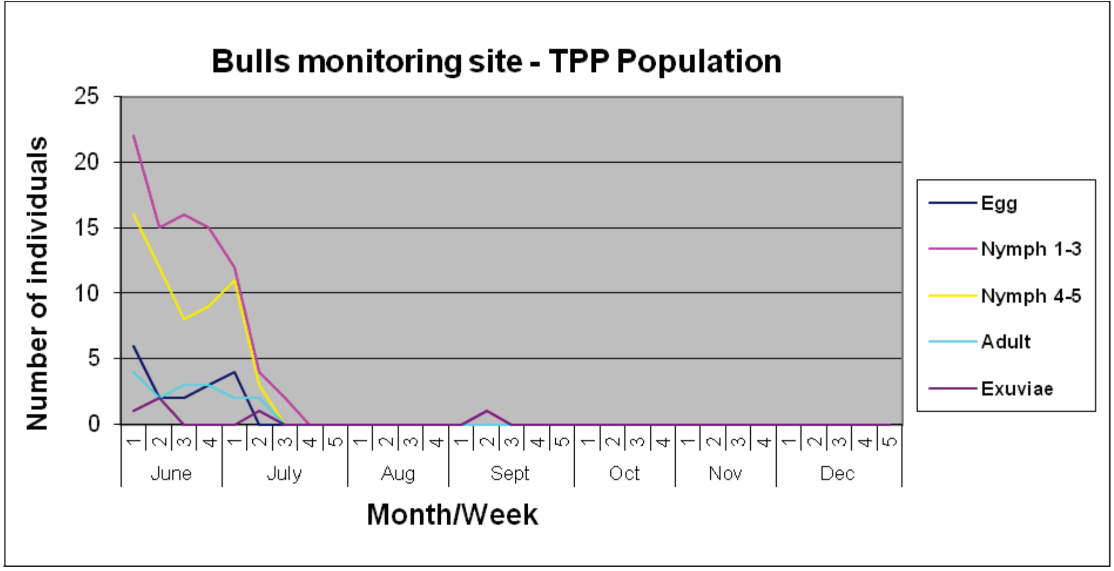
Results

This chapter contains the results and analysis of data obtained from the two components of this study; open and closed environment monitoring. Section A presents results from the open environment study, followed by Section B which includes the closed environment data and analysis and finally Section C which is based on the contained leaf sample results.

3.1 Section A: Open Environment Monitoring

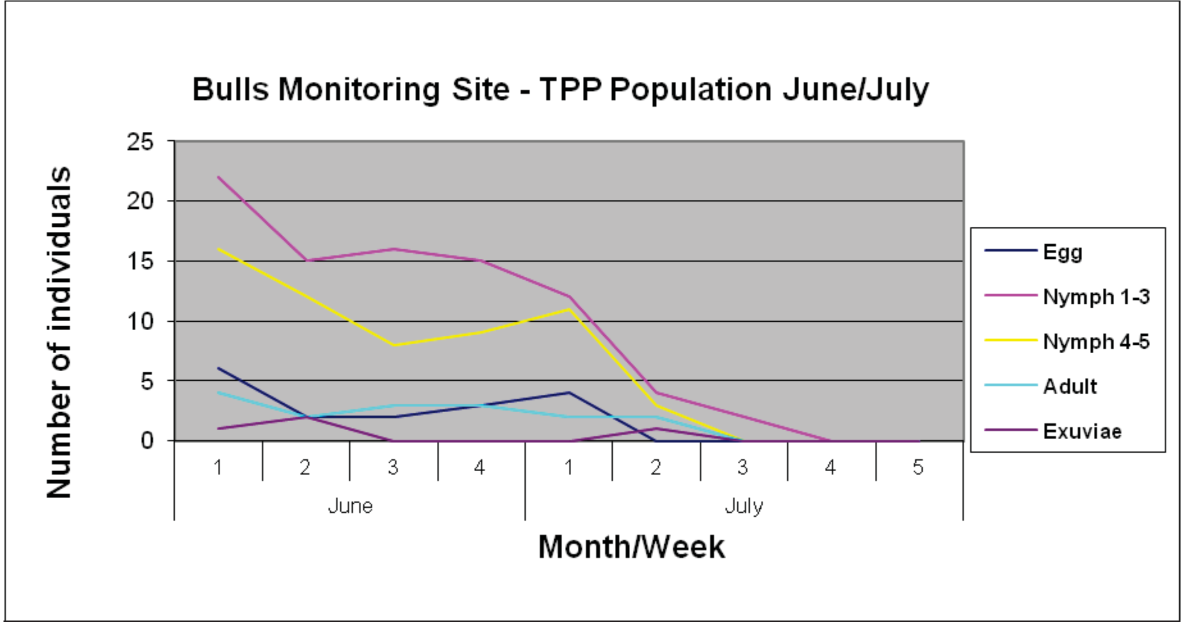
3.1.1 TPP and natural enemy detection - Bulls monitoring site

Figure 3.1a) TPP population over the monitoring period: Bulls



TPP were present at the Bulls site for the first two months of monitoring; from week one in June to week 4 in July (see figure 3.1a). After this point only one exuviae was detected; week two of September. Over this period the total TPP population was declining before dying out in week 4 of July.

Figure 3.1b) TPP population during June and July 2010: Bulls



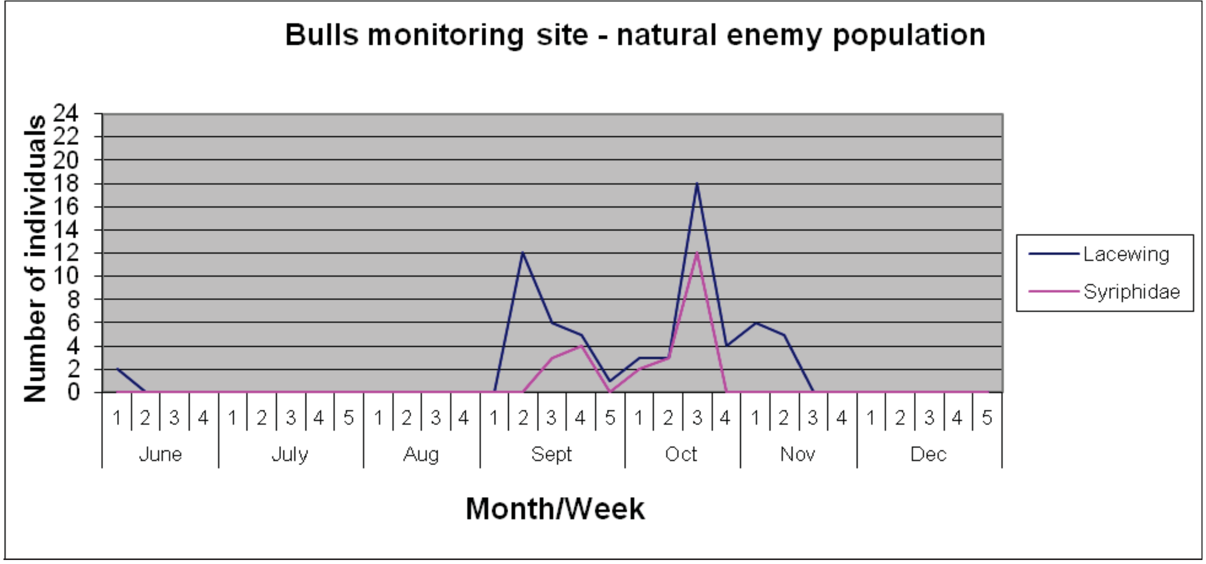
The initial egg population of six was the maximum over the entire monitoring period; declining to two eggs for the following two weeks. A small increase to four eggs was seen in week one of July before a decline to zero eggs the following week.

Stage 1-3 nymph numbers peaked at 22 in the first week of June. From this point numbers declined over the next two weeks to 15/16. All stage 1-3 nymphs had died out at week 4in July; the last TPP remaining at the site. Stage 4-5 nymph numbers peaked at 16 in week one of June; during week four of June and week one of July an increase in stage 4-5 nymphs was seen which may have been due to the progression of some stage 1-3 nymphs to stage 4. At week three of July no stage 4-5 nymphs remained at the site.

Adult numbers remained low throughout the monitoring period peaking at four in week one of June and declining to three. At week three of July the adult TPP population was no longer present at the site. No adult TPP were noted on the yellow sticky traps throughout the monitoring period.

Exuviae numbers were low throughout at the Bulls site, peaking at two at week two of June. Exuviae were detected sporadically throughout the monitoring period in July and September due to variation in individual stage 4-5 nymph maturity

Figure 3.1c) Natural enemy population over the monitoring period: Bulls

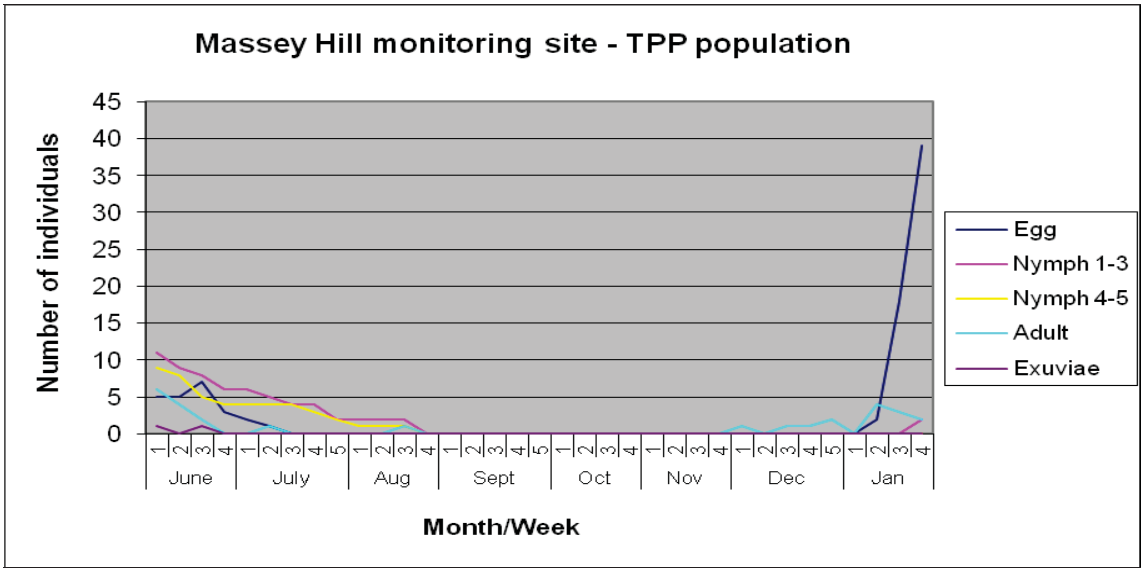


Throughout the monitoring period only lacewing and syriphidae were seen at this monitoring site, no ladybird beetle or other psyllid species were noted, either on the yellow sticky traps or on the individual monitoring sites.

Only two lacewing larvae (June week one) were noted at the Bulls monitoring site when TPP were present. It wasn't until September (week one) when lacewing and syriphidae larvae were seen at the Bulls site again. Therefore it can be said that natural enemies did not have a significant effect on the TPP population at this site

3.1.2 TPP and natural enemy detection - Massey Hill monitoring site

Figure 3.1d) TPP population over the monitoring period: Massey Hill

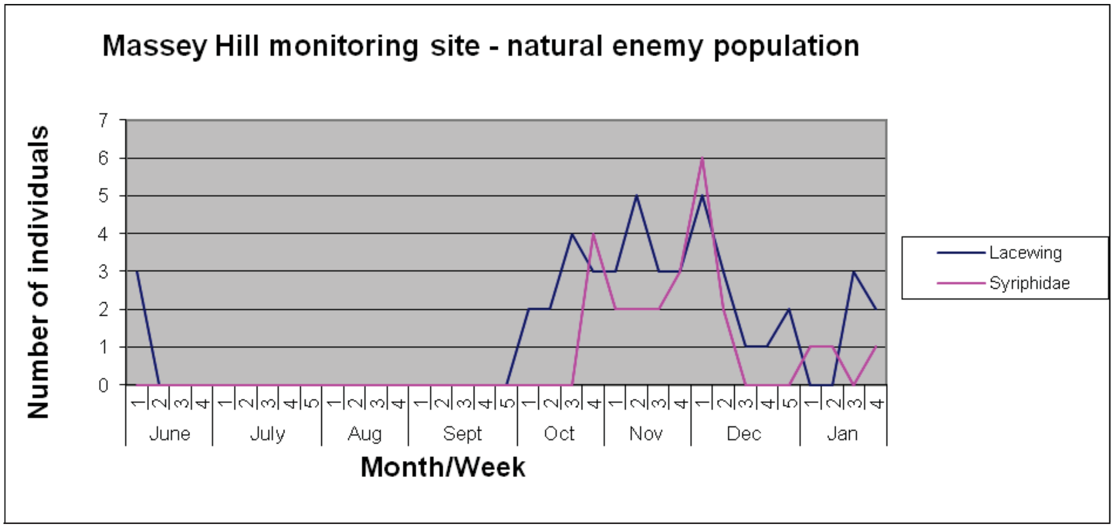


Egg numbers were initially low at only five at week one of June; a small spike was seen at week three of June where egg numbers reached their maximum at seven for the monitoring period. From this point egg numbers decreased to zero at week three of July. Egg numbers began to rise again in the second week of January which greatly increased to 39 the following week.

Both 1-3 and 4-5 nymph stages followed the same pattern of decline over the first three months of monitoring. Stage 1-3 nymphs peaked at 11 in week one in July and tapered off to zero over the following twelve weeks. One stage 1-3 nymph was seen at week four of January (2011). Stage 4-5 nymph numbers were at their maximum at nine at week one in July, no increases were seen throughout the following 11 weeks when the population reached zero in week three of August. Adult numbers were low throughout the period. At the initiation of monitoring, six adults were noted; no adults were detected after week four of June until week one in December (2011) where one adults was detected. In week two of January four adults were detected, three in week three and two in week four. The influx of eggs was most likely due to the presence of adult TPP.

Exuviae numbers did not exceed one, only two were seen over the entirety of the monitoring period one in week one and again in week three of June. Therefore the decline in total nymph numbers is not likely to be attributed to stage 5 nymphs progressing to adults.

Figure3.1e) Total Natural enemy population over the monitoring period: Massey Hill site



The above graph shows the total natural enemy population for the Massey Hill monitoring site (i.e. a summation of the two poroporo populations at the Massey Hill site location). Three lacewing larvae were detected at week one of June thereafter no lacewing were seen until week one of October. Syriphidae larvae were first detected in week three of September. TPP returned to the site in week one of December through to week four of January (the end of the monitoring period), throughout this period natural enemy were lower than initially seen October and November.

3.1.3 Plant factors affecting TPP detection

The most significant plant factors which influenced the detection of TPP and natural enemies at the two monitoring sites were leaf drop and plant death. The tables below show these events, the date and sampling unit to which they occurred.

Table 4: Bulls monitoring site plant factors affecting insect detection

Month	Week	Site	Event
July	3	Massey Hill	All leaves browning and wilting
	5	Bulls	High level of leaf drop and wilt
		Massey Hill	High level of leaf drop
		Bulls	Leaf browning and wilting
August	3	Massey Hill	Lower leaves browned off/ middle leaves yellowing and top still green. Fruit brown and rotting
		Massey Hill	Leaves completely browned off
		Bulls	High level of leaf drop. Only leaves at the rear of the plant remain
October	2	Bulls	Leaf drop and juvenile plant death
December	2	Bulls	All sampling sites sprayed off by Marae Growers using Roundup.
	3	Bulls	No leaves, only plant skeleton remains. Monitoring ceases

Plant factors which may have affected the detection of TPP were first recorded at week three in July and thereafter. At the Massey Hill monitoring site leaf wilt and browning coincided with the total decline of stage 4-5 nymph numbers at this site.

Figure 3.1f) Bulls: Monitoring plant 3 in week three of December

Table 5: Massey Hill monitoring site plant factors affecting insect detection

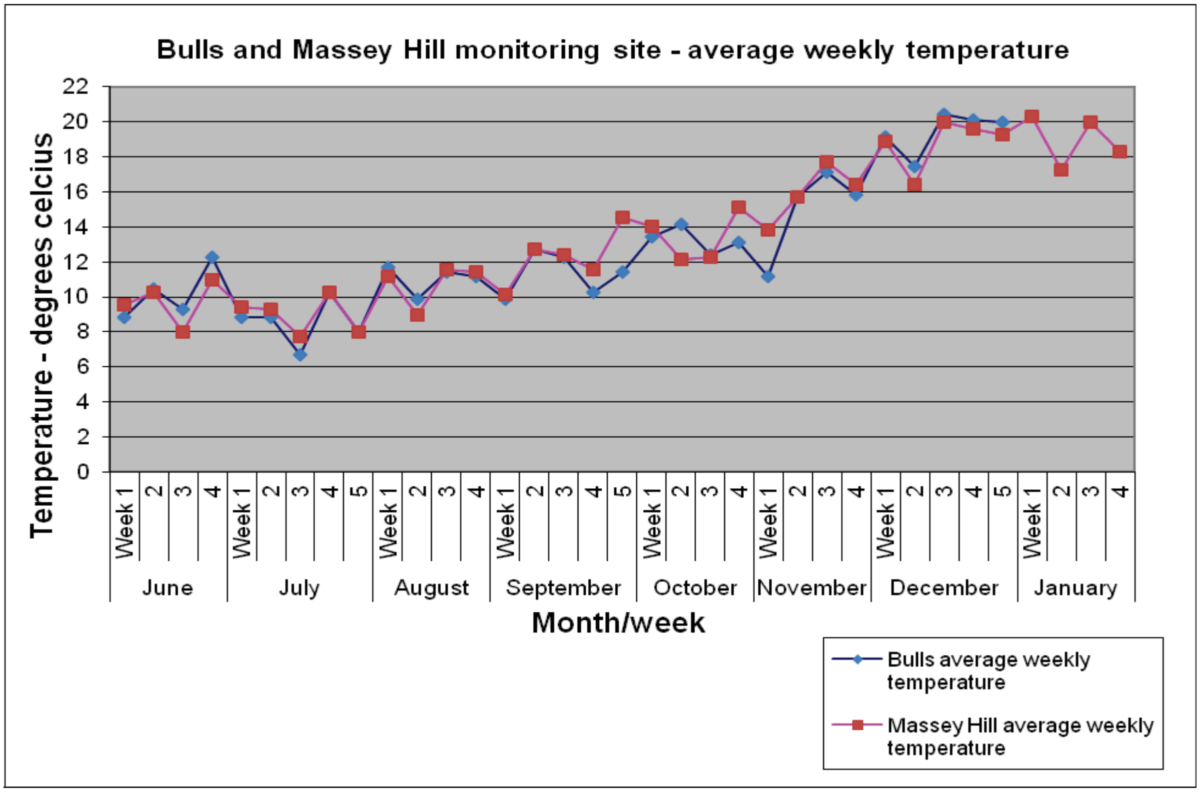
Month	**Week**	**Plants**	**Event**
July	4	3,4,5	Plants 3, 4 and 5 dying off due to frost
August	2	3,4,5	Plants 3,4 and 5 dead

As shown above plants 3, 4 and 5 were detrimentally affected by frost in week four of July and by week two in August these plants had died off. These three plants were the juvenile plants; plants of this age are particularly susceptible to frosts (Te Mara Reo, 2009). The death of these plants had no effect in the decline of TPP at the Massey Hill site as the mature plants remained healthy throughout the monitoring period.

Juvenile plant death was also noted at the Bulls site in week two of October.

3.1.4 Temperature

Figure 3.1g) Comparison of average weekly temperature at the Bulls and Massey Hill monitoring sites

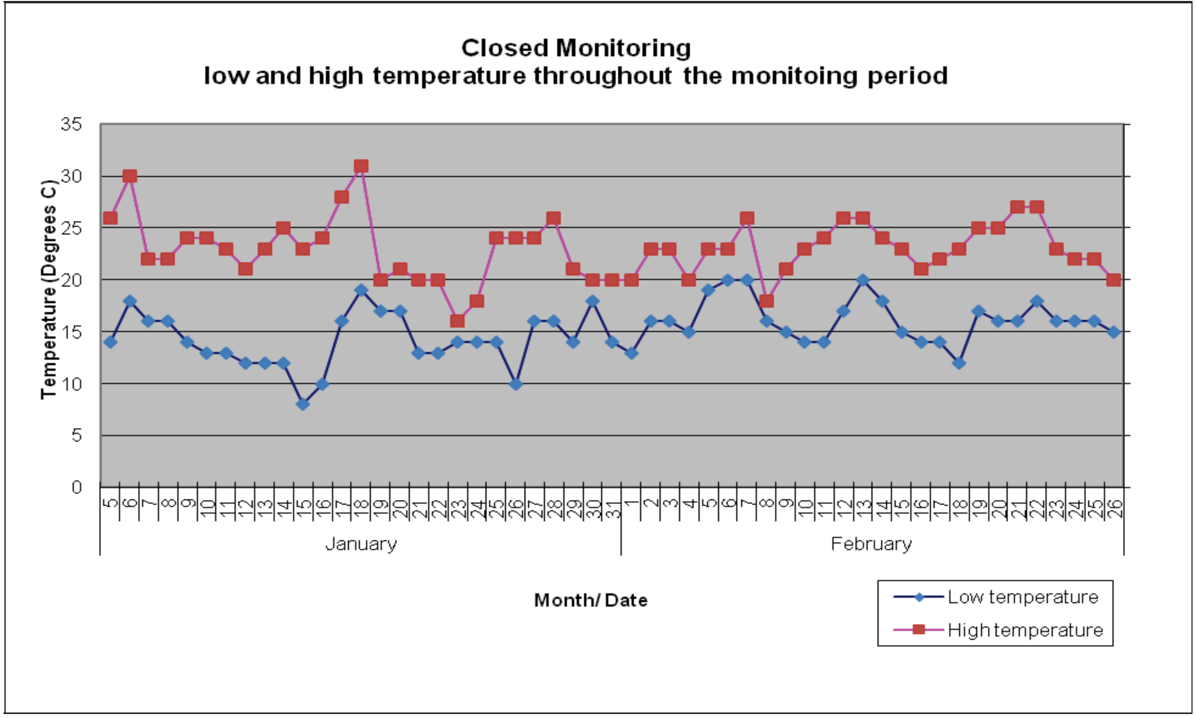


The temperature range for both sites from week one in June to week four in July was 7°-12.5°C below the functional range of 15-32°C and (just) above the development threshold of 7ºC (Biosecurity, 2009). TPP development would have continued but at a slower rate than if the temperature was 26/27°C the optimum temperature for TPP growth.

3.2 Section B: Closed Environment Data

3.2.1 Temperature

Figure 3.2a) Daily low and high temperatures during the closed environment monitoring period



3.2.2 On-plant development data

Table 6: Lifecycle parameters of B. cockerelli fed either on taewa, poroporo or kūmara under glasshouse conditions

	Development time (days ± SE)					
Stage	Taewa	Poroporo	Kūmara	LSD$_{(0.05)}$	F$_{(2,27)}$	P
Pre oviposition	7.1 ± 0.31a	8.2 ± 0.44a	8.7 ± 1.11a	2.064	1.32	0.283
Egg incubation	5.9 ± 0.23a	6.8 ± 0.33a	11.3 ± 1.34b	2.347	12.8	<0.001
Nymph development	14.5 ± 0.43a	15.8 ± 0.51a	19 ± 2.24a	-	2.95	0.069
Total development	20.4 ± 0.3b	22.6 ± 0.58b	30.3 ± 3.49a	5.996	6.33	0.006
Total lifecycle	27.5 ± 0.56b	30 ± 0.89b	39 ± 4.4a	7.583	5.13	0.013

Equations: Total development period = Incubation period + Nymph development (Abdullah, 2008),
Total lifecycle = Total development period + pre oviposition period (Abdullah, 2008)
Means (over ten replicates) in the same row followed by the same letters are not significantly different at *P* =0.05 (LSD: Minitab 16, 2010)

Table 7: Survival of B. cockerelli egg and nymphal life stages fed either on taewa, poroporo or kūmara under glasshouse conditions

		Survivorship (# ± SE)				
Stage	Taewa	Poroporo	Kūmara	LSD $_{(0.05)}$	$F_{(2,27)}$	P
Egg	9.7 ± 0.15a	7.9 ± 0.54b	2.6 ± 0.56c	1.29	68.88	<0.001
Nymph	8.6 ± 0.34a	5.8 ± 0.63b	1.6 ± 0.34c	1.326	59.43	<0.001

Means (over ten replicates) in the same row followed by the same letters are not significantly different at *P* =0.05 (LSD: Minitab 16, 2010)

3.2.2a Pre oviposition period

Pre oviposition was lowest on taewa at 7.4 ± 0.31 days, followed by poroporo at 8.2 ± 0.44 days and highest on kūmara at 8.7 ± 1.11 days. The relationship between pre oviposition period and the three host species is not significant.

3.2.2b Egg incubation

Egg incubation was 5.9 ± 0.23 days on taewa and 6.8 ± 0.33 days on poroporo. Kūmara had by far the longest egg incubation period at 11.3 ± 1.34 days; this was significantly higher than the other two hosts.

3.2.2c Nymph development

Nymph development was 14.5 ± 0.43 days on taewa, 15.8 ± 0.51 on poroporo and 19 ± 2.24 on kūmara. The relationship between nymph development and the three host species is not significant.

3.2.2d Survival

Egg survival

The relationship between egg survival and host species is significant. Egg survival was highest on taewa at 9.7 ± 0.15; poroporo 7.9 ± 0.54 and kūmara 2.6 ± 0.56.

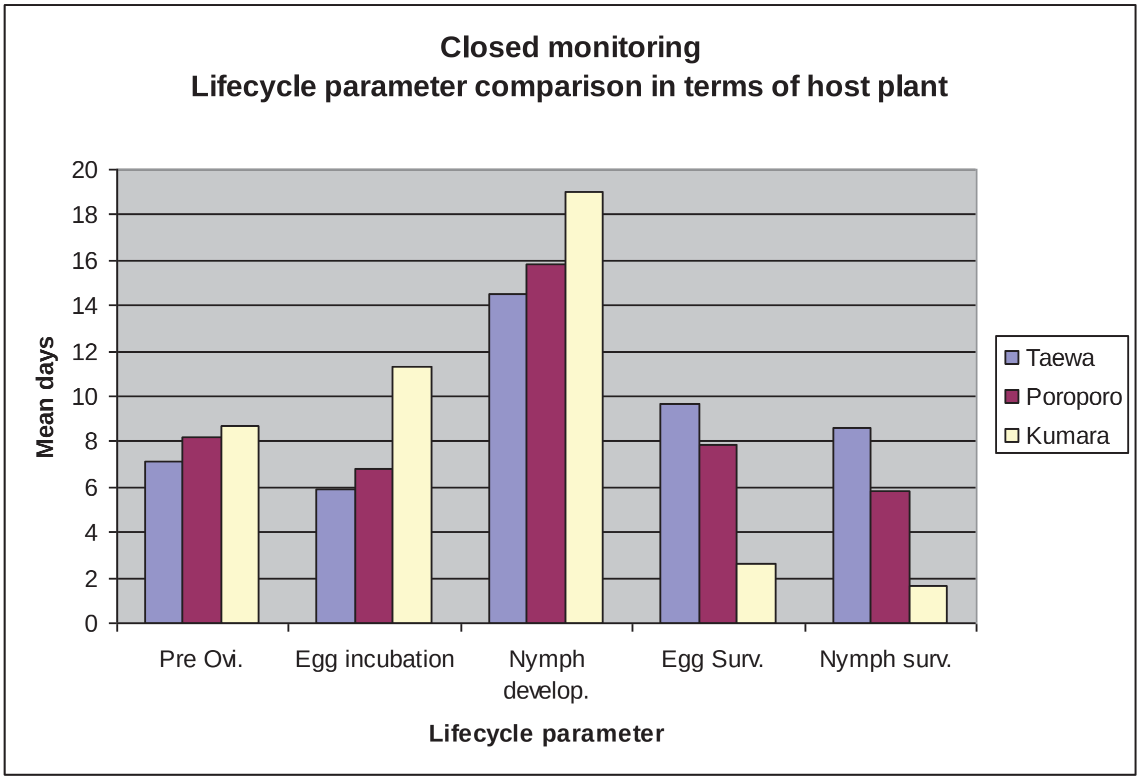
Nymph survival

As with egg survival the relationship between nymph survival and host species is significant, where each of the three hosts differed significantly from the other. Nymph survival was highest on taewa at 8.6 ± 0.34; poroporo at 5.8 ± 0.63 and kūmara lowest at 1.6 ± 0.34.

3.2.2e Total development and Total lifecycle calculations

The total development and total lifecycle calculations both show the same trend; both calculations for taewa and poroporo are similar but differ significantly to kūmara. Both development periods are significantly longer on kūmara in comparison to taewa and poroporo.

Figure 3.2b) Mean lifecycle parameter length (days) for the on-plant measurements for each of the three host species



3.3 Section C: Contained leaf samples

Table 8: Female reproductive parameters and longevity of B. cockerelli adults fed on taewa, poroporo or kūmara under glasshouse conditions

Development time (days ± SE)						
Stage	Taewa	Poroporo	Kūmara	LSD (0.05)	$F_{(2,27)}$	P
Pre mating	5.9 ± 0.3b	7.7 ± 0.37a	8 ± 0.42a	1.074	9.41	0.001
Fecundity	180.1 ± 15.3a	139.7 ± 11.78b	54.4 ± 7.31c	34.66	28.87	<0.001
Oviposition period	20.4 ± 0.81a	20.7 ± 0.99a	16.5 ± 1.36b	3.124	4.74	0.017
Male	20 ± 0.88a	17 ± 1.15ab	14.2 ± 1.76b	3.819	4.86	0.016
Female	27.8 ±1.36a	26.4 ± 1.68a	21.6 ± 1.65b	4.552	4.3	0.024

Means in the same row followed by the same letters are not significantly different at *P* =0.05 (LSD: Minitab 16, 2010)

3.3a Pre mating period

Pre mating period was shortest on taewa at 5.9 ± 0.3, followed by poroporo at 7.7 ± 0.37 and highest on kūmara at 8 ± 0.42. Taewa differed significantly from poroporo and kūmara.

3.3b Female fecundity

Mean female fecundity was significantly higher on taewa at 180.1 ± 15.3 than both poroporo (139.7 ± 11.78) and kūmara (54.4 ± 7.31). Poroporo also differed significantly from kūmara.

3.3c Longevity

Male

Male longevity was highest on taewa at 20 ± 0.88 days, followed by poroporo at 17 ± 1.15 days. Longevity was significantly lower on kūmara at 14.2 ± 1.76 days than on taewa and poroporo.

Female

Female longevity was highest on taewa at 27.8 ± 1.36 days, followed by poroporo at 26.4 ± 1.68 days. Like male longevity, female longevity was significantly lower on kūmara at 21.6 ± 1.65 days. Longevity was greater for females than males across all three host species.

3.3d Oviposition period

The oviposition period was similar on taewa (20.4 ± 0.81 days) and poroporo (20.7 ± 0.99 days); oviposition period on kūmara was significantly lower at (16.5 ± 1.36 days).

Figure 3.3a) Contained leaf sample - mean lifecycle parameter length (days) for each of the three host species

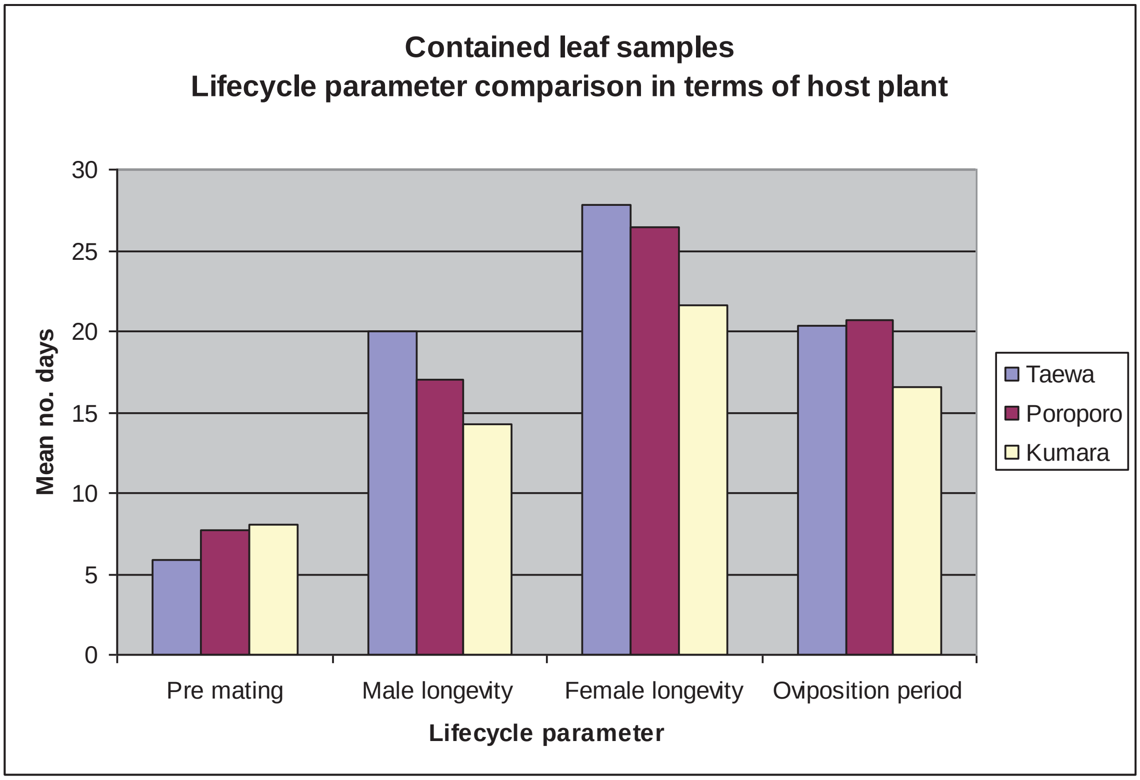
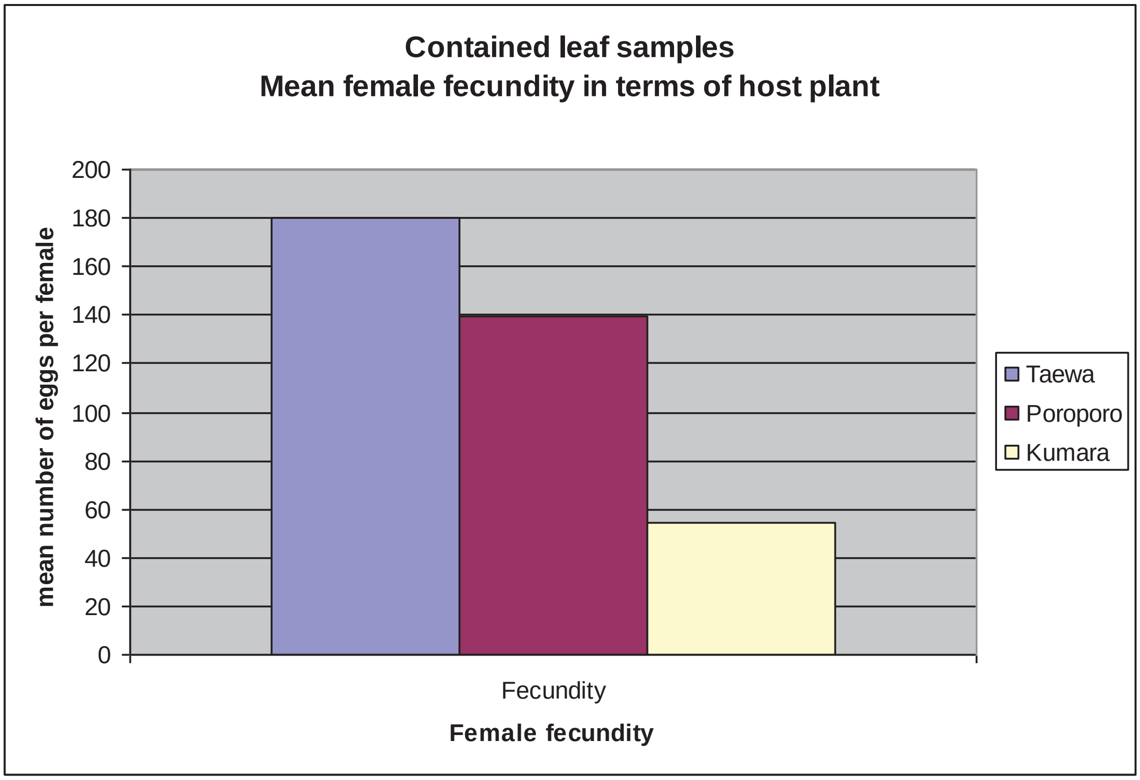


Figure 3.3b) Contained leaf samples- mean female fecundity for each of the three host species



Chapter Four

Bactericera cockerelli – Tomato/Potato Psyllid (TPP)

4.1 Hemiptera: Psylloidea

The TPP belongs to the order Hemiptera which are typically referred to as the 'piercing and sucking' insects; included in this order are aphids and leafhoppers. There are over 2,500 described Psylloidea species worldwide (Resh and Cardé, 2003). Collectively the Psylloidea are commonly referred to as the 'jumping plant lice' or 'psyllids'. The Psylloidea were previously thought to comprise a single family, the *Psyllidae,* now a common name for a family within the superfamily. Recent reclassifications have since divided the Psylloidea from six (White and Hodkinson, 1985) to eight families (Burckhardt, 1987). Psyllids belong to the sub-order Sternorrhyncha considered to be the most 'primitive' of the Hemiptera ('true bugs') (Zipcodezoo.com, 2010). Adult psyllids are small terrestrial insects which resemble small cicadas; the immature stages are similar to scale insects.

4.2 Biology and Ecology

4.2.1 Host range

Adult TPP are polyphagous feeding on hosts from many plant families whilst the nymphs are generally monophagous and remain on the host to which they are borne, due in the most part to their motility capabilities. As the insect's name suggests the TPP is a major pest of solanaceous plants. Key hosts include major solanaceous crops such as tomatoes, potatoes, capsicum (*Capsicum* L.) and eggplant (*Solanum melongena* L.) (Trumble, 2010). Many solanaceous weeds are also hosts of the TPP including the nightshade (Solanaceae) family.

TPP have also been recorded on many other plants including members of the following plant families:

> “*Amaranthaceae, Asclepiadaceae, Asteraceae, Brassicaceae, Chenopodiaceae, Convolvulaceae, Fabaceae, Lamiaceae, Lycophyllaceae, Malvaceae, Menthaceae, Pinaceae, Poaceae, Polygonaceae, Ranunculaceae, Rosaceae, Salicaceae, Scrophulariaceae, Violaceae and Zygophyllaceae”* (Food and Environmental Research Agency, 2009).

Many of the susceptible hosts within these plant families are considered as unsuitable hosts and may only be resting hosts. TPP are not known to breed on these hosts. The TPP is said to “breed on three plant families, the Lamiaceae (Mint Family, only in green houses), Convolvulaceae and the Solanaceae” (MAF Biosecurity NZ, 2009).

Non-solanaceous weeds known to harbour TPP in the USA include; pigweed (Amaranthaceae), lambsquarter (*Chenopodium* spp.) and members of the mallow (Malvaceae) family (Trumble, 2010). Lesser known hosts include the radish (*Raphanus sativus*), beans *(Phaseolus* spp.), corn (*Zea mays*), and sugar beets (*Beta vulgaris* L.). Non-crop hosts include the; dandelion (*Taraxacum* sp.), spruce (*Picea* Mill.), milkweed (*Euphorbia* sp.), violets, *Dactylis* sp. grasses, the larkspurs (*Delphinium*) *(ibid.)*, lucerne (*Medicago sativa*) and thorn apple (*Datura stratonium*) (Potatoes New Zealand, 2009).

4.2.1a Host specifity

Psyllids are “generally narrowly host specific” (Hodkinson, 1974: 325) particularly in the larval stages (Burckhardt and Lauterer, 1997), many are either monophagous or oligophagous. Nymphs are more host specific than the adults (Resh and Cardé, 2003) and tend to feed only on a particular plant genus, species (*ibid*.), growth stage (immature or mature plants), structure (e.g. leaf or stem) or surface (Capinera, 2008). Adult psyllids tend to be polyphagous (*ibid*.) and may feed on a range of host plants but their development is restricted to a particular species of plants, usually those that the nymphs feed on (*ibid*). Hodkinson (1974) noted that the term host plant in reference to the Psylloidea should be restricted to those hosts which support the development of the psyllid species in question. “The hosts of phylogenetically close psylloids are usually closely related as well” (Burckhardt and Lauterer, 1997: 99).

4.2.2 Feeding habits

Host plant selection is by taste (chemo-gustatory) (Resh and Cardé, 2003; Hodkinson, 1974) rather than smell (olfactory). Psyllids possess specialised piercing and sucking mouthparts typical of the Hemiptera, where the “maxillae and mandibles are modified into needle like stylets which lie within a grooved labium” (Capinera, 2008: 595). Psyllids feed by penetrating plant tissues with the stylet and sucking cell contents (Resh and Cardé, 2003). Psyllids inject solidifying saliva during feeding which forms a “protective sheath around the mouthparts” (Resh and Cardé, 2008: 957). This act of injection is a crucial step in the transmission of diseases (Trumble, 2010).

Nymphs and adults excrete a white granular substance called ‘psyllid sugars’ (see following page) or honeydew which is a key sign of psyllid feeding. Honeydew attracts other insects such as ants and the “growth of black sooty mould fungi which can impede photosynthesis and reduce plant vigour” (Resh and Cardé, 2008: 957).

Figure 4.1) ‘Psyllid sugars’

(Source: Brown, 2010)

4.2.3 Disease transmission

Psyllids are common vectors of plant diseases (Hodkinson, 1974) for example *Diaphorina citri*, the Asian citrus psyllid vectors citrus greening disease (syn. Citrus huanglongbing, *Candidatus* Liberibacter asiaticus) in citrus. Injection of salivary compounds is also damaging to host plants (Hodkinson, 1974). The TPP is a major vector of the disease *Candidatus* Liberibacter solanaecerum syn. psyllaurous commonly referred to as Zebra chip (ZC) and is also a possible vector of *Candidatus* Phytoplasma australiense (phytoplasma). The Liberibacter pathogen is carried within the stylet and is transmitted to susceptible hosts when the stylet penetrates host tissues and solidifying compounds are injected (Trumble, 2010). In order for TPP to transmit ZC, infected psyllids need to feed on a host plant for a period of at least one hour (Trumble, 2010; Munyaneza, 2010). The association of these diseases with the TPP will be discussed in depth in chapter five.

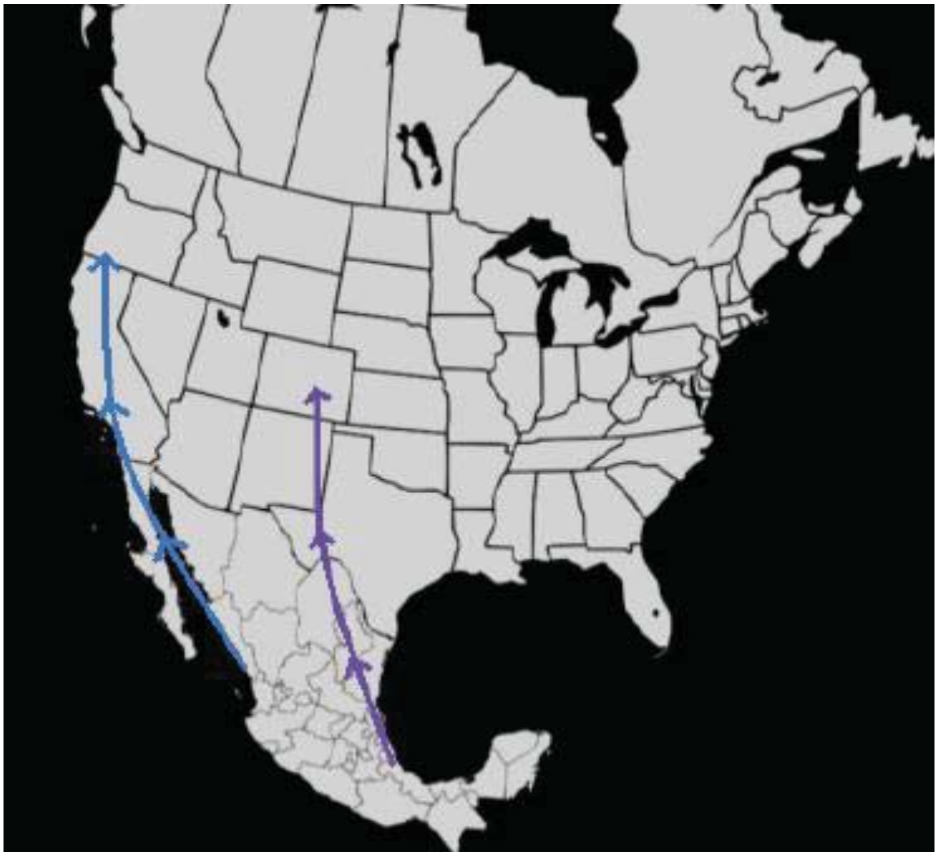
4.2.4) Behaviour

Adult psyllids jump backwards when disturbed hence the common name; jumping plant lice (Resh and Cardé, 2003). Local dispersal occurs via jumping or flying and long distance movements via air currents, records have shown some adults being carried “8 miles (12.87 km) on wind currents” (Hodkinson, 1974: 324). Some species exhibit migratory movements, moving onto alternative hosts during the winter months (overwintering) and returning to the primary hosts as conditions improve. These movements may involve localized or long distance migration. In the USA it is noted that TPP overwinter in California, Arizona, Northern Mexico and Southern New Mexico (Munyaneza *et al*. 2009) and return to summer feeding grounds in the Northern states (see figure 4.2).

As a multivoltine (many generations per year) species TPP are prone to population outbreaks during favourable conditions. The first outbreak was reported in 1940 in California and another in 1970 in the Midwestern USA (Abdullah, 2008). Since 2001 outbreaks “have been noted in tomato and potato crops each year in the western and north-western US states and Canada” (*ibid*.).

Mating behaviours are exhibited by some species where the females of some species stridulate (Resh and Cardé, 2003) as grasshoppers and crickets do, rubbing two structures or surfaces against one another producing a shrill noise (*ibid.*). Other species display darting movements or flicker their wings (*ibid.*). Male TPP produce a drumming sound on the leaves and females emit sex pheromones (Brown; 2010).

Figure 4.2) Proposed migration pattern of TPP in its home range of North America



(Source: Brown, 2010)

4.3 Lifecycle

TPP are hemimetabolous, undergoing incomplete metamorphosis. The life history of hemimetabolous insects includes eggs to nymphs to winged adults, notably lacking a pupae stage as seen in complete metamorphosis (holometabolous). Adults and nymphs tend to exploit the same environment and host plants. The TPP life history consists of egg; five nymph instars (see below) and a winged adult stage. Adults emerge from mature fifth instar nymphs, shedding a small papery exuviae. Sclerotization (hardening of the exoskeleton) occurs within 24-48 hours causing adults to change colour from tan to black (Brown, 2010). The psyllid lifecycle is “usually highly synchronised with host plant phenology” (Hodkinson, 1974: 325). The wings are colourless and fully expanded ten minutes after hatching (*ibid.*).

Figure 4.3) Left: ¹the complete lifecycle of the TPP including the egg, five nymph stages and winged adult. Right: ²Magnified image of the five nymph stages.

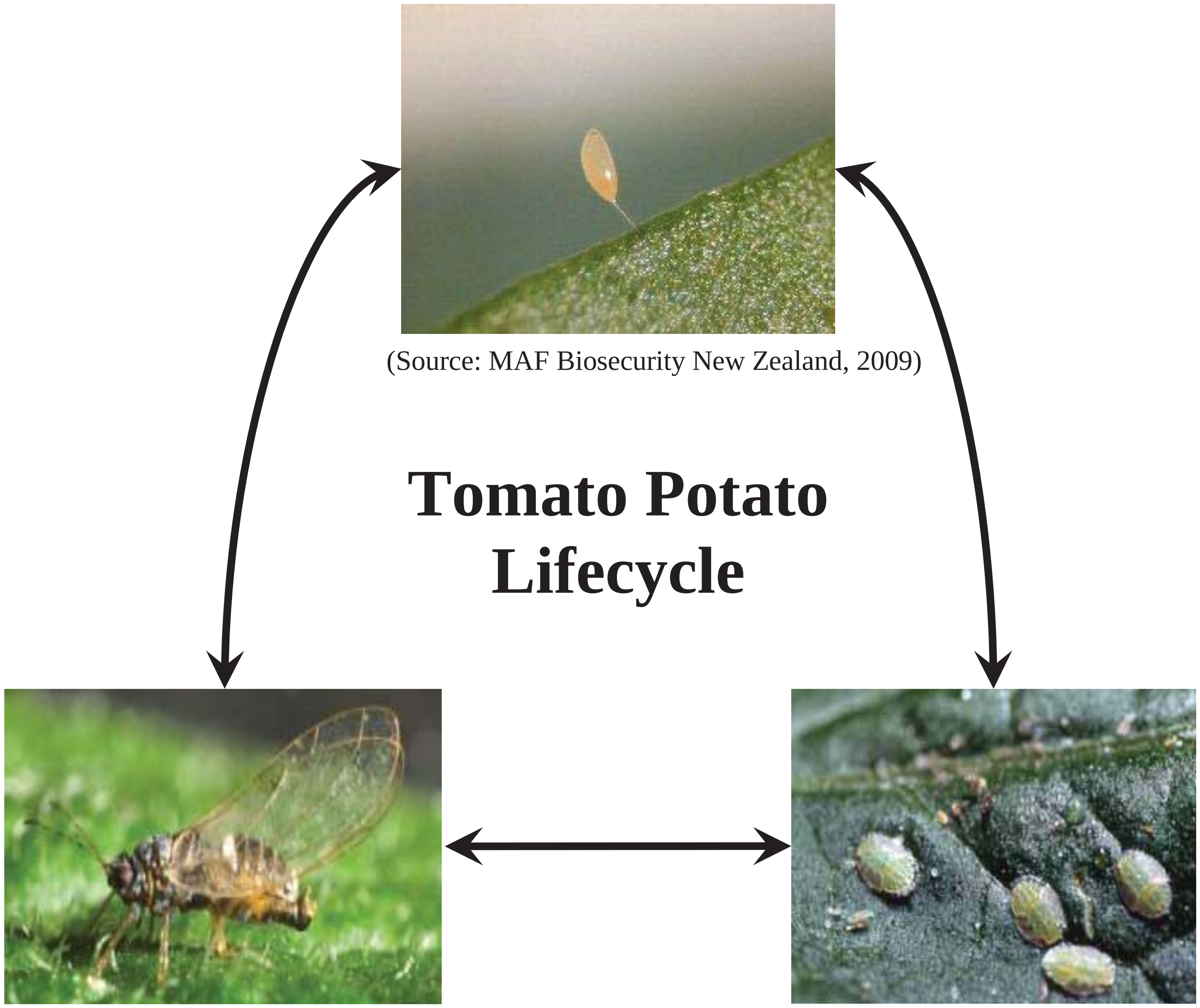
(Source¹: MAF Biosecurity New Zealand, 2009) (Source²; Brown, 2010)

The eggs are yellow when first deposited changing to orange with age (Lehman, 1930). Eggs are laid on leaf and stem surfaces and are commonly found on leaf margins (Lehman, 1930; Horticulture New Zealand, 2009). The eggs are elevated off the plant surface by a short stalk or pedicel, through which water is derived (Resh and Cardé, 2003; Brown, 2010) It has been reported that an adult female may lay anywhere between 75 (Abdullah, 2008; Lehman, 1930) to 1000 eggs (Potatoes New Zealand, 2009²). Abdullah (2008:60) reported an "average of 231.8 eggs per female with a range of 184-258". Lehman (1930: 312) noted that "adult females on average lay 75 eggs". On hatching, the first instar is orange, changing to green at the fourth instar stage (Lehman, 1930; MAF Biosecurity New Zealand, 2009), although nymphs may be a combination of tan-orange and green. External wing buds appear at the third instar stage and become more apparent during consecutive moults (MAF Biosecurity New Zealand, 2009). Newly emerged adults vary in colour from orange-green, changing to brown on the day after and black on the third day (Lehman, 1930). The wings are colourless and fully expanded ten minutes after hatching (*ibid*.).

Yang and Liu (2009) demonstrated that the TPP lifecycle varies in response to host plant; their research shows that TPP perform better on eggplant (*Solanum melongena* L) than bell pepper (*Capsicum annum* L.).

Figure 4.4) Tomato/Potato Psyllid lifecycle at an average temperature of 18°C

Eggs hatch after 3-9 days



(Source: MAF Biosecurity New Zealand, 2009)

Mating occurs 2-3 days after emergence. On emergence Psyllids are yellow changing to brown after 2-3 days and onto black or grey with white stripes after 5 days.
(Source: Plant and Food Research Ltd, 2009)

There are five instars during the nymph stage of the TP Psyllid lifecycle. At an average temperature of 18° the nymphal stage is completed in 12-21 days (MAF Biosecurity New Zealand, 2009).
(Source: Horticulture New Zealand, 2008)

4.3.1 Reproduction

Reproduction is sexual (Hodkinson, 1974; Resh and Cardé, 2003) although "parthenogenesis may occur when only females are present" (Hodkinson, 2009; Brown, 2010) Females are sexually viable at the end of the teneral (soft bodied) stage (Brown, 2010) and may also mate multiple times (Brown, 2010).

It has been shown that TPP development is also affected by host plant. Yang and Liu (2009) showed that TPP lifecycle development was "shorter and survivorship greater when fed on eggplant as opposed to capsicum" (pp. 1663). Furthermore egg incubation and daily oviposition rate were higher on eggplant suggesting that eggplant is a better host than capsicum for the TPP (*ibid*.). This study will reveal, if any, the suitability or adequacy of each of the three hosts (taewa, poroporo and Kūmara) in terms of supporting TPP lifecycle development.

4.3.2 Favoured Conditions

Development is temperature dependent, with an optimum temperature of 27ºC and functional range of 15-32ºC (MAF Biosecurity New Zealand, 2009). At an average temperature of 18ºC a complete lifecycle could be completed in 33 days (*ibid.*); therefore it is feasible to expect up to 2-5 generations per cropping season (*ibid.*). TPP are frost intolerant (sub zero temperatures) and capable of withstanding high temperatures. It is thought that the TPP seeks shade or moves to the inner parts of the plant in high temperatures (*ibid.*).

TPP favour warm but not hot conditions (Capinera, 2001). Optimal temperatures range from 21-27°C (Capinera 2001; Munyaneza 2010), temperatures above 32°C are detrimental to TPP leading to reduced egg-laying and hatching (Capinera, 2001). It is noted that 27°C is the optimal temperature for TPP growth (Cranshaw, 2001; Munyaneza, 2010). TPP growth ceases at 35°C (Cranshaw, 2001). It is also thought that heavy precipitation is detrimental to TPP populations (*ibid*.). Oviposition is at its optimum in temperate climates (Brown, 2010).

Environmental conditions influence the incidence and development of TPP outbreaks especially during late spring – early summer as these factors affect the size of overwintering populations, migration patterns (wind patterns) and the availability of susceptible hosts along the migration path (Cranshaw, 2001).

4.4 Native Range and Migration

TPP are native to the Rocky Mountain region of North America including; “Colorado, New Mexico, Arizona, Nevada, Utah, Wyoming, Idaho, Montana, Alberta and Saskatchewan” (Munyaneza *et al.* 2009; 514).

TPP are migratory insects; annual patterns have emerged from several reports in the TPPs native range of North America. In late spring TPP migrate north bound from overwintering grounds in California, Arizona, Northern Mexico and Southern New Mexico (Munyaneza *et al.* 2009). Overwintering hosts include native *Lycium* species (e.g. wolfberry (*Lycium barbarum)* and matrimony weed (*Lycium halimifolium*) (Cranshaw 2001; Capinera 2001; Trumble, 2010). TPP can be found in Utah, Colorado and Wyoming in mid to late June (summer) (Cranshaw, 2001); and Oregon and Washington in late July (summer) (Cranshaw, 2001) where ‘early solanaceous weeds or potatoes are common hosts” (Munyaneza *et al.* 2009: 516). Migration is largely achieved via wind borne dispersal (Capinera, 2001: 344).

Little is known about the migratory behaviours of the TPP in New Zealand.

4.5 Taxonomy

The TPP is currently classified as *Bactericera cockerelli,* after previously being known as *Paratrioza cockerelli* and *Trioza cockerelli.* The current classification is based on a number of morphological characteristics which many of the *Bactericera* genera share. These characteristics are not exclusive to the genera rather they define the Triozidae family, this has (in some views) led to the misclassification of some Triozidae Psylloidea including TPP.

The TPP has also been classified as *Trioza cockerelli* (Maryanski-Nadaachowski and Glowecka, 1993) in the genus *Trioza*. This genus has been classified under two families; the Triozidae and Triozinae (Burckhardt and Lauterer, 1987), currently the genus belongs to the former. *Paratrioza cockerelli* is the final taxonomic classification sometimes referred to within the literature, belonging to the families Triozidae and Psyllidae *(ibid.)*

Table 9: Three taxonomic classifications of the TPP

	P. cockerelli	***T. cockerelli***	***B. cockerelli***
Kingdom	Animalia	Animalia	Animalia
Phylum	Arthropoda	Arthropoda	Arthropoda
Class	Insecta	Insecta	Insecta
Order	Hemiptera	Hemiptera	Hemiptera
Suborder	Homoptera	Homoptera	Homoptera
Superfamily	Psylloidea	Psylloidea	Psylloidea
Family	Triozidae/ Psyllidae	Triozidae/Triozinae	Triozidae
Genus	*Paratrioza*	*Trioza*	*Bactericera*
Species	*Paratrioza cockerelli*	*Trioza cockerelli*	*Bactericera cockerelli*

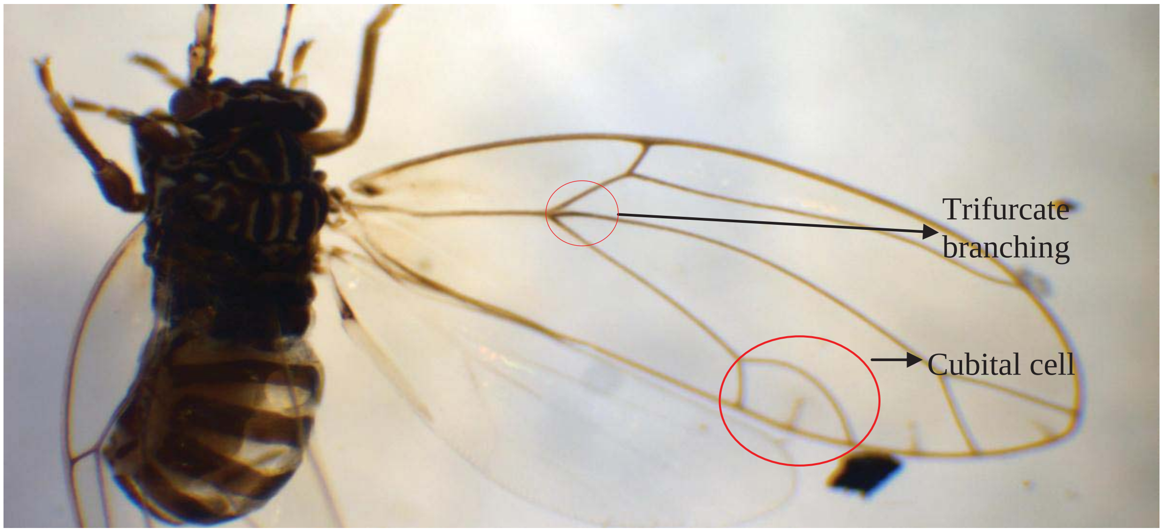
New Zealand literature refers to the TPP as *B. cockerelli* (Hemiptera: Triozidae) (Plant and Food Research Ltd, 2009²) this differs from some American publications which refer to the pest as *B. cockerelli* (Hemiptera: Psyllidae) (Al-Jabr, 1999; Liu and Trumble, 2004; Liu, Johnson and Trumble, 2006; Al- Jabr and Cranshaw, 2007; Abdullah, 2008; Yang and Liu, 2009), *P. cockerelli* (Hemiptera: Psyllidae) (Crawford, 1911) or *T. cockerelli* (Hemiptera: Triozidae) (Pletsch, 1947). The most popular classification in American literature is *B. [=Paratrioza] cockerelli* (*Sulc*) (Hemiptera: Psyllidae) (Liu, Johnson and Trumble, 2006; Liu, Trumble and Stouthamer, 2006; Al-Jabr and Cranshaw, 2007 Yang and Liu, 2009). It is widely accepted that the above three names are synonymous and all refer to the TPP.

4.6 Distinguishing TPP from other Psylloidea in New Zealand:

The number of Psylloidea species thought to inhabit New Zealand varies from author to author and tends to increase with time. Ferris and Klyver (1932) identified 25 species; Tuthill (1950) identified 51 species within 6 genera, and the latest work by Pamela Dale (1985) found 81 species within 11 genera and 8 subfamilies (Dale, 1985).

Four of the six Psylloidea families have been recorded in New Zealand; the Psyllidae, Calophyidae, Homotomidae and the Triozidae, the TPP belonging to the latter (Plant and Food Research Ltd, 2009²). The Triozidae is distinguished from the other three families in New Zealand by the forewing venation in having "trifurcate branching of the basal vain of the forewing, in contrast to other Psyllid families in New Zealand which have bifurcate branching" (*ibid.*; Berry *et al*. 2010). (See figure 4.5 below).

Figure 4.5) TPP wing showing trifurcate branching of the basal vein of the forewing and cubital cell



(Source: Plant and Food Research Ltd New Zealand, 2010)

The *Bactericera* genera posses two inner metatibial spurs on the hind legs; this characteristic distinguishes the genera from others in New Zealand. *Trioza adventicia* (Eugenia psyllid) along with two undescribed species resemble the TPP in having two metatibial spurs on the hind legs; these species are distinguishable from the TPP in the appearance of the forewings. The forewings of the TPP are "transparent with no colour patterns and the cubital cell is short and compact" *(ibid.)*. One further characteristic which sets the TPP apart from other Trioza is the lack of well developed genal processes and long setae on the dorsal surfaces of the head and body *(ibid.)*.

Figure 4.6) Inner metatibial spurs of TPP

(Source: Plant and Food Research Ltd New Zealand, 2010)

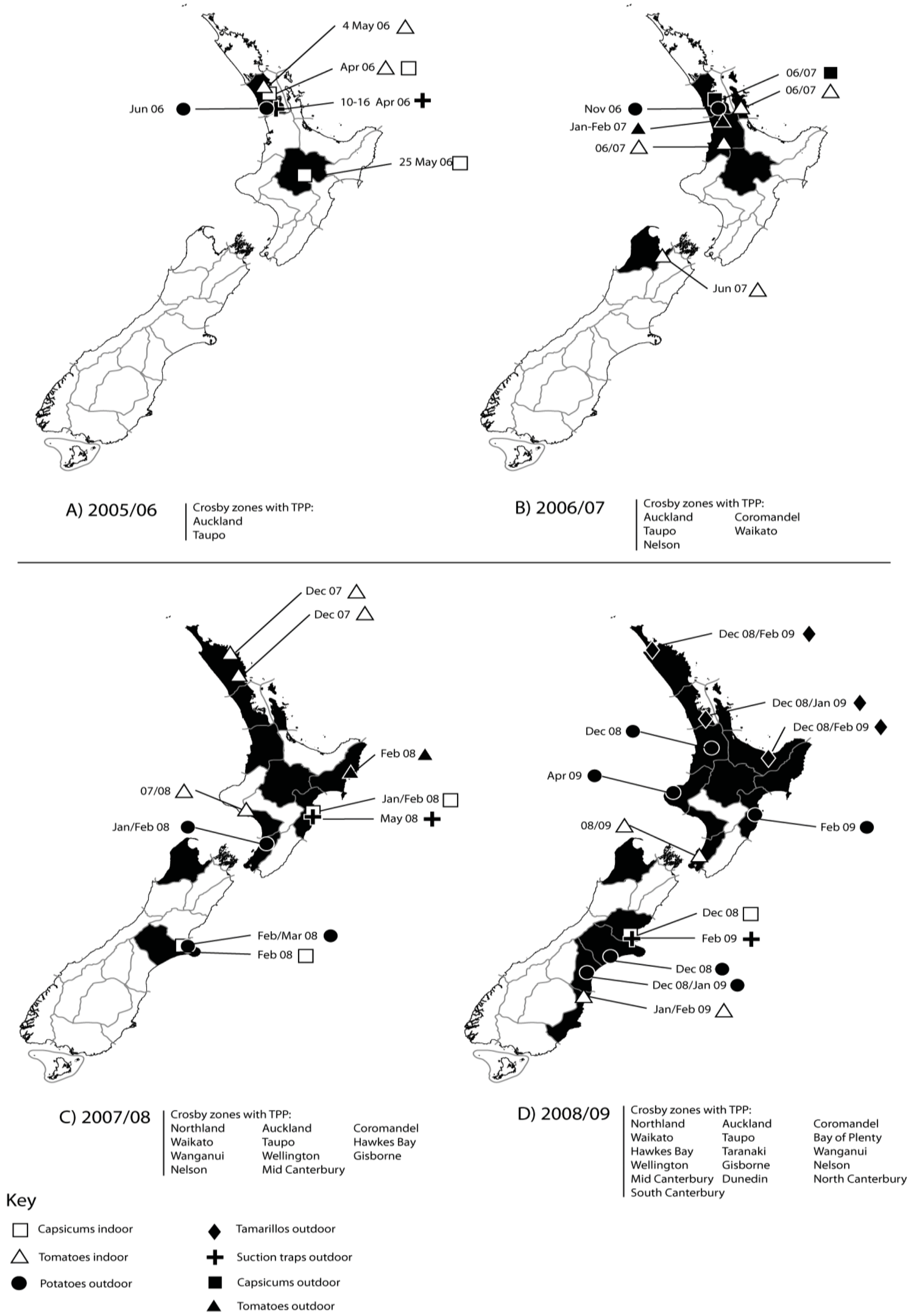
4.7 The Distribution and dispersal of the TPP in New Zealand

The TPP was officially recorded in New Zealand in May/June 2006 (Teulon *et al.* 2009) although it is thought the pest "probably arrived in the summer of 2005-06" (Teulon *et al*. 2009: 136). The TPP is said to have been introduced to New Zealand from its native range in North America, possibly via Hawaii (Tomatoes New Zealand, 2009). Since 2006 the TPP has spread throughout crop growing areas in the North and South Islands.

In the 200-/06 summer TPP were found on indoor capsicum and tomato crops, and outdoor potato crops in Auckland including Pukekohe (Tuelon *et al*. 2009). In the same year TPP were found on indoor capsicums in Taupo. Identification of the pest was undertaken by MAF Biosecurity NZ (MAFBNZ) and the US Department of Agriculture Systematic Entomology Laboratory *(ibid.)*. In the 2006/07 season it was noted that TPP had spread throughout the Waikato, Coromandel, the first South Island record of the TPP was also recorded this season in Nelson on greenhouse tomatoes *(ibid.)*. 2007/08 saw the spread of the TPP increase, into Northland, Wanganui, Wellington and Mid Canterbury. The spread continued into 2008-09 season, much of the North Island was infested including Taranaki, Bay of Plenty and North and South Canterbury *(ibid.)*. Through my own monitoring this was the first season the TPP was seen in the Manawatu District and infesting taewa (Māori potato) crops. The TPP is now considered widespread throughout New Zealand. *Figure* 4.7(pp 54) illustrates the distribution of the TPP throughout New Zealand

It is likely that the TPP spread via a "combination of natural and human mediated dispersal" (Teulon *et al*. 2009: 136), including migration, infested plant materials and human contact. The TPP is a migratory pest. In its home range of North America, the TPP is said to "migrate from its overwintering and breeding grounds in western Texas, southern New Mexico, Arizona, California and Northern Mexico northbound to escape high temperatures in late spring" (Munyaneza *et al.* 2009: 514). Therefore it is likely that some localised or long flight migration may have taken place in New Zealand and assisted in the dispersal of the TPP throughout New Zealand. Lack of strict hygiene practices has also encouraged the spread of TPP via human means. There are some instances in New Zealand whereby growers have received plant seedlings infested with TPP (Teulon *et al*. 2009). Attachment to inanimate goods or materials has further facilitated the spread of TPP throughout New Zealand *(ibid.)*.

Figure 4.7) Distribution of the TPP since its incursion in New Zealand



(Source: Teulon *et al*. 2009: 138)

4.8 TPP Management and Control

The TPP is proving to be a challenging insect to manage in New Zealand and overseas. It is advised that an integrated approach be adopted in attempting to control this insect, utilizing various chemical, mechanical and biological methods and the adoption of an integrated pest management (IPM) strategy.

Pre-planting practices include utilizing clean seed (virus free for tuber crops) or clean seedlings, and the removal of any alternative host plants within the crop growing area (Bioforce Ltd *et al*. 2008; Fruited, 2009) Crop monitoring should be initiated early in the season and yellow sticky traps erected. Post planting, alternative host removal should continue and crop monitoring initiated. Insecticide application should be initiated only when justified to reduce the incidence of resistance; chemical rotation is essential (Plant and Food Research Ltd, 2009). Post planting crop residues should be destroyed (i.e. burnt) appropriately and continued removal of alternative hosts which may serve as overwintering or bridging hosts (Bioforce Ltd *et al*. 2008).

4.8.1 Monitoring

Crop monitoring is the first step in controlling the TPP, crop scouting and the use of yellow sticky traps aid in the detection of TPP and determination of further control options. Universal monitoring techniques have not yet been developed or TPP and very little is known about monitoring and economic thresholds worldwide (Trumble, 2010). Various techniques have been developed in New Zealand since the arrival of the TPP, but clear guidelines have not yet been specified and methods used are updated as new knowledge becomes available. Identification training may be required for those who have not previously worked with TPP.

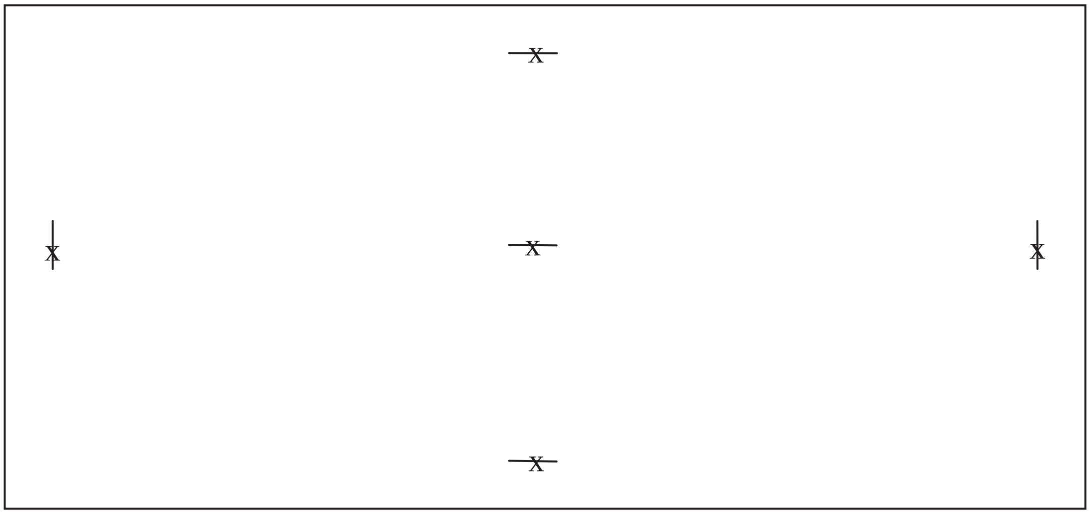
4.8.2 Sticky Traps

Sticky traps are useful as population indicators (i.e. reporting incidence of the TPP) but should not be used in control or management decision making (i.e. economic thresholds, chemical application indicators). There is currently no correlation between trap count and TPP crop population (Trumble, 2010). Neon green, neon orange and standard yellow coloured sticky traps are most effective in trapping TPP adults (Al-

Jabr and Cranshaw, 2007), currently yellow sticky traps are used by research bodies and commercial growers in New Zealand.

Sticky traps are best placed in the north, south, east and west positions of the crop field and one trap in the middle of the field (see *Figure 4.8*); set into the row at or just above plant canopy height (Hart and Mckennie, 2009). Traps need to be changed and assessed weekly. Examination of the catch should be completed within a few days of trap collection as the insects will deteriorate making identification difficult (*ibid.*). Traps should be placed at a rate of at least one per hectare. Additional traps may be placed facing prevailing winds or on the headlands as these positions are usually the first site for TPP influx (Potatoes New Zealand, 2009; Hart and Mckennie, 2009).

Figure 4.8) Outdoor potato crop sticky trap placement map



(Adapted from Potatoes New Zealand, 2009 and Heinz-Watties, 2008)

Trap numbers should be recorded every week; this will identify key periods of TPP infestation. Trap counts are insufficient alone in indicating the size of the infestation and the life stages present within the crop, therefore plant scouting is also required (Potatoes New Zealand, 2009).

4.8.3 Plant Scouting

Crop scouting involves intensive sampling of whole plants to yield information regarding the presence and abundance of the various TPP life stages within the field.

Liberibacter and psyllid yellow symptoms may also be detected and removed whilst plant scouting.

Fields should be sampled in a W or M pattern throughout the crop, sampling at least five whole plants per hectare (Fruitfed, 2009; Potatoes New Zealand, 2009). Individual plants should be assessed from top to bottom concentrating on the underside of the leaves for the nymphs and leaf edges for the eggs. The abundance of each life stage should be recorded (i.e. eggs, nymph and adult). Nymph counts should be separated into either small, medium or large, experienced scouts may distinguish between the five instars. The bulk of TPP population can be located in the middle regions of a potato or tomato plant (Trumble, 2010).

TPP infestations begin in the outermost rows of the crop moving inwards in a concentric pattern (*ibid*.). Controlling the first generation of TPP is integral to achieving effective control within the whole crop; this reduces the incidence and chances of secondary (and consecutive) inoculum from breeding, causing localized outbreaks (*ibid*.).

4.8.4 Chemical control

Many chemicals (see Appendix III) are now available for the control of TPP in New Zealand. Initially the use of broad spectrum insecticides for the control of aphids and potato tuber moth were advised for the control of TPP until specialist chemicals were released in 2009-2010 (i.e. Sparta). Neem oil (Azadirachtin), sun spray oil and Tamaron (Methamidophos) were popular products in 2008 and 2009 but their effectiveness was called into question as the control elicited was not as desirable as hoped.

Chemical control is reactive or curative where chemicals are applied on detection of TPP (Capinera, 2001). Achieving good plant coverage is essential in controlling TPP, ensuring that the undersides of the leaves are sprayed to control nymphs. Chemicals should be used only when justified, at the correct application rates and rotated to prevent the development of resistance (Plant and Food Research Ltd, 2009: Trumble, 2010). Chemicals must also be used in a selective manner to conserve beneficial organisms.

Appendix III contains a list of the chemical products available for the control of TPP in 2011, both here in New Zealand and overseas. It is important to point out that rates and application methods acceptable overseas may not comply with legislation in New Zealand, consult national guidelines or the most current edition of the New Zealand Novachem Agrichemical Manual before utilising these products. All of these chemicals in Appendix III have been trialled as appropriate controls for the TPP.

4.8.5 Biological control

Many insect families have been identified as natural enemies of the TPP (see below); conservation of these insects should be taken into consideration as part of an IPM plan.

- *Chrysopa* (lacewings)
- Araneae (true spiders)
- *Geocoris* spp. (lygaeidae, seed bugs)
- Coccinellidae (ladybirds)
- Syriphidae (hover fly)
- *Orius tricolor* (minute pirate bug)
- *Tamarixia* (eulophid wasp, parasitoid)
- *Nabis* spp.
- Staphylinidae (rove beetles)
- Neuroptera (lacewing)
- Parasitic wasps (Hymenoptera)

(Cranshaw, 2001; Macdonald *et al.* 2010; Trumble, 2010)

The most effective biological control agents (BCA) are the *Chrysopa* (lacewings) which attack all TPP nymph stages (Trumble, 2010). Biological control is not economically viable in the face of increased chemical control but should be incorporated into an overall IPM programmes.

4.8.6 Tips for TPP Control

- Monitor crops
- Calibrate sprayers
- Use soft selective chemicals

- Rotate between insecticides and allow a 6 week break before reapplying the same insecticide group
- Consider including oils with insecticides for egg control.

(Trumble, 2010)

4.8.7 Cultural control

Principal cultural control methods involve adjusting the timing of planting activities and the removal of crop residues and alternative host control in and out of season. The latter two methods will remove any bridging hosts for the TPP.

4.9 Chapter summary

B. cockerelli is a new species of Psylloidea in New Zealand and since its detection in 2006 has caused widespread damage through the spread of Liberibacter or Zebra Chip disease. TPP is a polyphagous multivoltine insect, susceptible to population outbreaks when environmental conditions allow. Environmental conditions in New Zealand are particularly conducive (Munyaneza, 2009) to TPP development and for this reason TPP has become a major problem in New Zealand. Due to the severity and economic ramifications TPP presents to growers attitudes and actions have turned to methods to control the insect, particularly chemical controls although the validity and efficacy of some of the products available on the New Zealand market are questionable. It is advised that a number of strategies should be adapted in attempting to control TPP; an integrated approach is favourable where chemical, mechanical and biological control techniques complement one another and provide the most benefit to growers.

Chapter Five

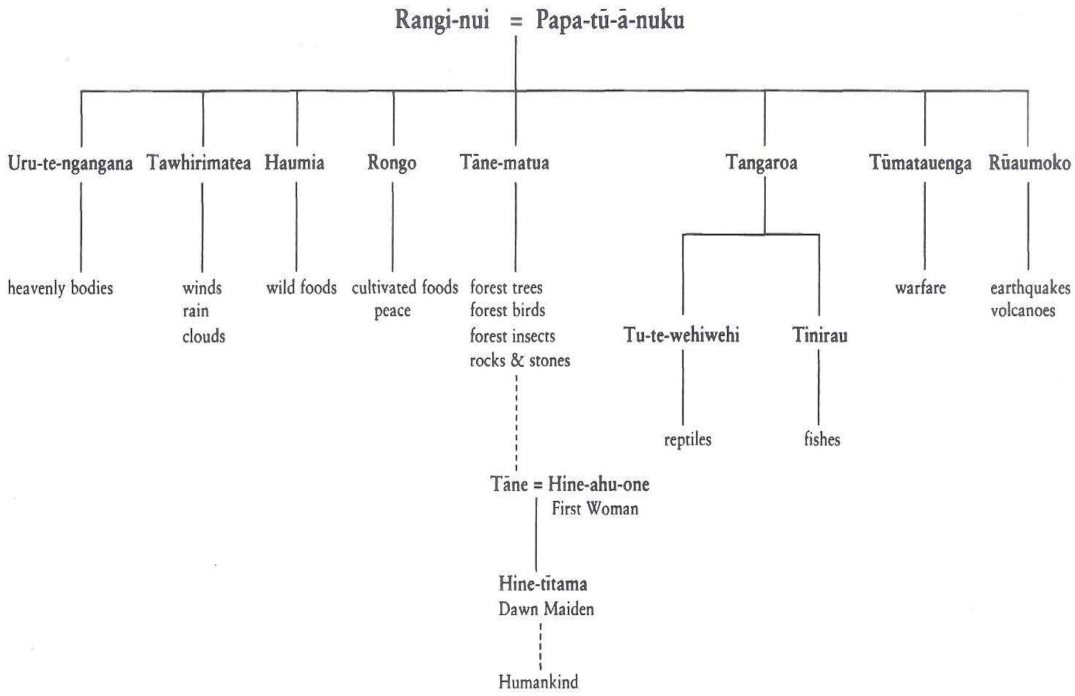
Māori Food Sources: History and Susceptibility to TPP

5.1 Māori Horticulture

It is clear that early Māori were horticulturists. This is supported by whakapapa which binds the people back to Ranginui and Papatūānuku, the primal parents, and their many (>70) offspring particularly Rongo-mā-tane (syn. Rongo-marae-roa) and Haumia-tiketike; kaitiaki (guardians) of cultivated and uncultivated crops respectively (Roskruge, 2007). Māori share intrinsic links with the physical, natural and spiritual realms; these links extend themselves to include all natural resources including foods. This relationship implies that all things are interconnected and from this stems the Māori worldview and value system which includes concepts such as; mauri, tikanga, tapu, noa and kaitiakitanga. It is these ancestral links and the Māori value system that shaped and formed traditional horticultural practices and Māori culture in a broader sense.

Horticulture, in a traditional sense, was an important component of daily life, not only for the survival and sustenance of the people but as a means of trade and mana (prestige) where the quantity and quality of the yield/harvest reflected the mana of the grower. Like many other indigenous peoples in the world Māori lived in a subsistence economy (Te Ara, 2011), whereby hunting, gathering and barter were important to their survival. Traditional horticulture consisted of both cultivated and uncultivated crops for example, kūmara (*Ipomoea batatas*) and aruhe (bracken fern rhizome, *Pteridium esculentum*) respectively. Food production was a part of daily life for the Māori community and supplemented hunting, fishing and other food gathering practices (Roskruge, 2007) necessary for their survival. Crops brought to New Zealand by Māori include taro (*Colocasia esculenta*), hue (*Lagenaria siceraria*), kūmara (*Ipomoea batatas*), aute (*Broussonetia papyrifea*), uwhi (yams, *Dioscorea* spp.) and Tī Kouka (*Cordyline australis*) (Roskruge, 2007).

Figure 5.1) Māori whakapapa from the ancient ancestors to humans



(Source: Roberts *et al.* 2004:5)

Figure 5.2) Poroporo

Figure 5.3) Young kūmara plant in the field

Figure 5.4) Taputini variety of kūmara

Figure 5.5) Taewa field at Ohakea

Figure 5.6) Moemoe variety tubers

5.2 Taewa Māori (*Solanum tuberosum* spp. *andigena*)

The many varieties of Māori potato are collectively known as taewa, peruperu, riwai, or parareka (Roskruge, 2007) by Māori. The variation in names is based on tribal dialect and geographical differences, for example taewa is used by Taranaki iwi and Parareka used by Ngāti Porou (*ibid.*). For the purposes of this research the term taewa will be used from this point forward.

Taewa were once an essential part of day to day survival from the 18th and 19th centuries and throughout the colonisation period. On introduction in 1769 (New Zealand Department of Agriculture, 1978) the potato was recognised as a low input high yielding crop; this saw the potato displace kūmara as the principal carbohydrate (Best, 1976; Roskruge, 1999).

5.2.1 Origin and History

The Māori potato, of which varieties belong to two subspecies of *Solanum tuberosum*, ssp. *tuberosum* and ssp. *andigena* , "is an annual, herbaceous perennial plant which has its origins in South America specifically the Andean region" (Roskruge, 1999:9). South America is considered as the home of the potato with both native and modern varieties originating from the upper and lower regions of the country respectively. Dr. Roskruge, Senior Lecturer in horticulture and Māori Resource Studies at Massey University is an advocate and what some consider a kaitiaki of the many taewa Māori varieties. Dr. Roskruge conducted research into the origins of the Māori potato at the International Potato Centre (Centro Internationale de la Papa – CIP), through DNA profiling and comparing this with the gene bank at CIP it was found that some of cultivars of the Māori potato have their origins in Peru and the correct botanical classification for the Māori varieties is *Solanum tuberosum* ssp. *andigena*, while the conventional 'European' potato is classified as *Solanum tuberosum* ssp. *tuberosum*. Passing traders and whalers from ports in Peru or South America may have traded with Māori during the 17th and early 18th centuries (Richards, 1993). Another theory is that the first introduction of the potato to New Zealand may lie in unrecorded trading visits to and from South America (Roskruge, 2007).

The introduction of the potato to New Zealand is a very contentious issue to say the least and many people have theories and opinions. Accounts of ‘outside’ contact before Captain Cook in 1779 are at best, sketchy. Cook, himself took the possibility of outside contact lightly, in part due to Māori not being as forthcoming with information as he would have liked (Richards, 1993). It is unanimous however amongst Māori and historians alike that taewa were not bought to Aotearoa (New Zealand) with Māori during their migration events from the ancestral lands of Hawaiiki.

Ships en-route from Europe travelling past “Amsterdam and along the north-east coast of Australia” (Richards, 1993:20), may have drifted into the vicinity of New Zealand. Historical records provide evidence of Māori contact with European voyagers who were marooned in New Zealand (Richards, 1993); accounts of looting ships and eating the crew exist in Māori history during this era. It is possible that these well stocked ships may have led Māori to the potato and initiated its cultivation (*ibid*.).

Another theory is that a Captain Stivers gifted the potato to Māori around 1766 in the Bay of Islands (Richards, 1993) and the name taewa being a transliteration of Stivers. This theory may be plausible as records exist of a Captain Stuyvers or Stuivers who was part of the Dutch East Indian company’s trading with China (Richards, 1993). The production of ‘white’ potatoes by Māori was recorded by Marion du Frense which dates back to 1793 (Richards, 1993).

Traditional Māori accounts of the potato lie in mythology and ancestry. The “Ngā Rauru people of South Taranaki grew a taewa variety known as Tatairongo, named after their ancestor Te Keke Tatairongo, who obtained the variety from the netherworld (Te Ao Po)” (Roskruge, 1999:7). It is likely that “Māori developed some cultivars by sowing true seed from potato berries available to them and making selections from seedlings’ (Harris, 2001:38), it is thought that some of the Māori varieties originated via this method (Harris, 2001).

5.2.2 Cropping History

On introduction, taewa played a major role in the subsistence of Māori communities. It is said that taewa eventually replaced kūmara and aruhe (bracken fern rhizome) as the main carbohydrate in the Māori diet (Best, 1976; Roskruge, 1999) and that taewa yields were larger than kūmara and aruhe collectively (Best, 1976). Cameron (1964: pp101) claimed that the potato could be;

> *"Grown on any moderately fertile soil. Large yields of crops could be obtained earlier and more reliably, even in high-lying or cold districts, while in warmer areas more than one crop could be grown each year. Potatoes could be grown successfully with less labour, and harvested crops stored with much less difficulty than could kūmara".*

These characteristics were appealing to Māori and contributed to the rapid expansion of taewa cultivation and production. Māori grew to rely on the taewa not only for survival, but as a means of trading commodity and for monetary gain. Trading facilitated the distribution of the potato amongst Māori throughout New Zealand.

In 1803 a vessel form New South Wales purchased "seven to eight tonnes of 'very fine' Māori grown potatoes" (Roskruge, 1999:10). These tubers were considered to be of very high quality which may be due to a lack of plant pathogens and diseases found in the potatoes' home range at that time period. The large scale production of taewa saw a change within Māori society and attitude; traditional subsistence farmers had become commercial horticultural producers (Roskruge, 1999; Harris, 2001). It was suggested that the introduction and continued production of the taewa led to a "decline in the physical fitness of the Māori race" (Harris, 2001: pp 45) due to lower physical demands and the displacement of traditional crops such as kūmara. Not only were the kūmara and aruhe replaced by the taewa but wild foods provided by native forests seemed less important as did the forest itself (Harris, 2001). Large areas of forest were cleared by Māori to make way for taewa production, early European accounts of "constant fires burning in old cultivations" (Cameron, 1964: 105) and native forests were common. It is recognised that this clearing of forested land led to the "destruction of the Waipunga and Mohaka valleys" (Cameron, 1964: 105). By 1840 the potato was considered a staple food (Roskruge, 1999).

5.2.3 Taewa in the 21st century

Modern taewa production has been reduced to crops being grown “mainly by Māori families and numerous non-Māori enthusiasts maintaining Māori potato collections” (Harris, 2001: pp 74). The focus for taewa has now shifted to scouting for appropriate traditional and contemporary growing knowledge and investing in scientific research. Modern day research institutes and societies have stepped in to aid in the restoration and preservation of traditional horticultural practices. Massey University established a taewa seed bank in 1999; many varieties are grown and then distributed throughout marae, iwi and hapū (Roskruge, 2005). This project ensures the availability of seed annually and provides a source of growing information. The seed bank is an annual project which culminates in a community harvest and hangi.

Scientists at Plant and Food Research Ltd and Massey University are working together “researching traditional knowledge on growing and storing the potato, developing best practice protocols for cultivation, establishing a virus-free seed stock and developing postharvest management systems to ensure quality is maintained” (O’Connor, 2004).

5.2.4 Taewa and TPP

As a summer annual crop, taewa are highly susceptible to TPP attack and liberibacter infection, especially due to their presence during the period of peak TPP infestation and population outbreak. The 2008/2009 cropping season was the first that TPP was seen in Taewa crops throughout New Zealand including Palmerston North, Gisborne and Christchurch. TPP went largely undetected in the crop during this season due to growers being unaware of the pest and the fact that symptoms did not present themselves until the latter stages of the season, when premature browning and plant death occurred almost overnight. Unbeknown to growers the affected crops were infested with TPP and showed symptoms of heavy feeding damage and early liberibacter infection. On harvest it was discovered that the plants had set many tubers which were typically pebble sized; many too small to use as seed for the following season. In October 2009 at the Tahuri Whenua annual general meeting (AGM) held at Rata Marae (Ngāti Hauiti), much interest was generated based on presentations regarding the TPP. Information and advice was provided to those members who crops were facing problems; this was the first time information was provided to the growers' network regarding TPP. Since the realisation that TPP poses a serious risk to taewa crops growers have become wary and undertake measures to safeguard their crops via chemical, mechanical and cultural means. The major problem facing taewa is the potential effects of liberibacter in seed tuber crops and declining seed tuber quality especially regarding some of the rarer or relic varieties (Roskruge, 2010, pers.comms). For potatoes it has been shown by Henne *et al*. (2010) that in crops grown from liberibacter infected seed tubers only 20-40% of the tubers will sprout, dependent on individual seed tuber infection and cultivar. Low seed and shoot vigour was noted. Delayed emergence can be expected and plant death after a few weeks of growing (*ibid*.). Reduced seed vigour coupled with marble sized tubers threatens the perpetuation of the crop.

5.3 Kūmara (syn. sweetpotato, *Ipomoea batatas*)

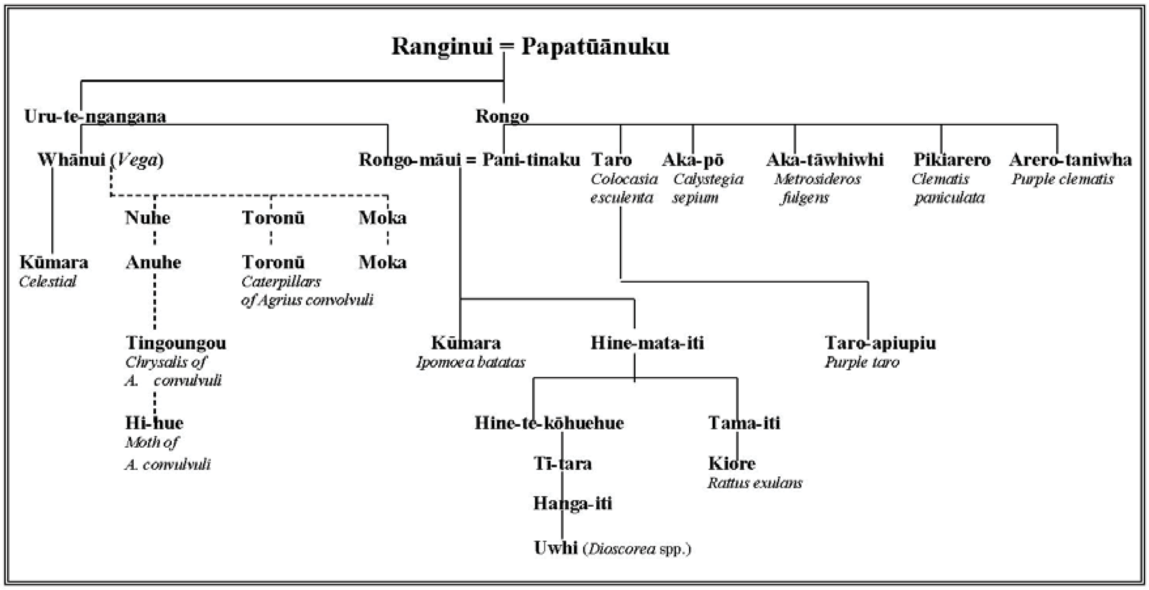
Traditionally kūmara (*Ipomoea batatas*) was by far the "most important of the cultivated food products" (Best 1976:99) for Māori; it was believed to yield more than the hue and taro collectively (Best, 1976). Māori brought kūmara with them through migration from the ancestral land Hawaiiki. Kūmara is a tropical crop, requiring warm soil and frost free conditions for optimum growth. Kūmara is semi- drought tolerant if the plant is at an advanced stage of growth, however yield and quality are affected if drought conditions are prolonged (New Zealand Department of Agriculture, 1978).

5.3.1 Origin

The history of the kūmara and its introduction into New Zealand is "inextricably interwoven with Māori whakapapa, history and people" (New Zealand Department of Agriculture, 1978:5). Kūmara was the "major vegetable before the introduction of the potato in 1769 and maize in 1772" (*ibid*.).

Whakapapa links the kūmara back to Rongo-mā-tane (deity or kaitiaki of cultivated crops) and Uru-te-ngangana (deity or kaitiaki of heavenly light and division); many accounts exist in relation to the traditional origin of kūmara. In accordance with the traditions of Ngāti Porou (North Island East Coast tribe), Te Whanau a Apanui (Eastern Bay of Plenty tribe), Ngāti Awa (Eastern Bay of Plenty tribe) and Tuhoe (inland Eastern Bay of Plenty tribe) iwi; Rongo-mā-tane is the kaitiaki of the cultivated crops and Pani-tinaku is the mother of the kūmara. Whanui, son of Uru-te-ngangana, is the parent of the kūmara and due to their celestial origins kūmara was not available for man. Rongo-maui is responsible for bringing the kūmara into the realm of man; after being denied kūmara seed by his father Whanui, Rongo-maui stole a tuber and hid it in his ure (penis). He then impregnated his wife who gave birth to kūmara in a nearby stream; it is said this is how the kūmara came into the realm of man. Pani is thus considered as the mother of kūmara.

Figure 5.7) Kūmara whakapapa



(Source: Roskruge, 2007: 31)

5.3.2 Cropping history

Kūmara is a sub-tropical crop and therefore had to be adapted to conditions in New Zealand. The temperate climate in New Zealand means that kūmara doesn’t commonly flower and vegetative propagation (Roskruge, 2007) is necessary. Traditionally “pieces of tubers with shoots” (Roskruge, 2007: 5) were cut and planted; cut face always facing north, or the crop was doomed to fail (Berridge, 1913). Due to their celestial origin and whakapapa associated with the kūmara, specific tikanga were undertaken “at all phases of cultivation from planting to storage” (New Zealand Department of Agriculture; 1978:1). Well ventilated underground storage pits were used to store the yield after harvest (*ibid*.).

New Zealand’s marginal environment necessitated the adaption of kūmara to prevailing conditions. As a tropical plant kūmara needed to be “converted from a tropical perennial to a temperate annual plant, requiring an enforced winter dormancy period” (Yen, 1990: 37); this was accomplished by creating storage pits suited to keeping kūmara over the winter period. Both food stock and winter ‘seed stock’ were kept in these storage pits (Yen, 1990). The advent of storage for kūmara was “the single most important factor in the extension of kūmara as far south as 45 degrees latitude” (Yen, 1990: 37).

5.3.3 Kūmara and TPP

Kūmara is a recognised host of the TPP in New Zealand (Potatoes New Zealand, 2009) but little is known about this insect-host relationship. Kūmara is noted as being a ‘poor host’ of the TPP. In the cropping season of 2009-10 it was observed by researchers at Pukekohe that TPP completed a full lifecycle (eggs-nymphs-adult) on kūmara (Wright, 2010, pers. comm.). As a non-solanaceous plant, kūmara may not be susceptible to ZC or PY. This is yet to be confirmed.

5.4 Poroporo (*Solanum aviculare* syn. *lacinatum*)

Poroporo or pōporo refers to all of the following plants; *Solanum aviculare*, *S. laciniatum*, *S. nigrum* and *S. nodifolium* in Māori tradition (Te Mara Reo, 2009). Poroporo is native to New Zealand and Australia where it is known as ‘kangaroo apple’. The two, *Solanum aviculare* and *S. laciniatum*, plants are similar in appearance and growth habit, and are sometimes confused. It is unclear if the two plants are two distinct species (Wikipedia, 2011). Flower and stem colour morphologically distinguishes the two ‘species’; *S. laciniatum* has “deep blue-purple flowers and purple stems whilst *S. aviculare* has green stems and lavender coloured flowers” (*ibid*.). Based on the morphological characteristics above it is likely that the plants sampled for this research are *S. laciniatum* rather than *S. aviculare*, although many do not see the distinction and class the two as poroporo or *S. aviculare*. There are also two varieties of poroporo; *Solanum aviculare* var. *albiflorum* and *Solanum aviculare* var. *latifolium.* All four of the aforementioned plants bear edible berries which are poisonous when unripe, as are the uncooked leaves.

5.4.1 Growth Habit

Poroporo is a fast growing soft wooded shrub reaching 3-4m in height (Biotechlearn, 2009; Te Mara Reo, 2009;); native to New Zealand, it is found throughout the North Island and top of the South Island. Poroporo can also be found in “Australia and the Kermadec, Three King and Chatham Islands” (Sampson, 1985). The leaves are dark green and lobed when immature, changing to sickle shaped when the plants have matured. The plants are commonly found in disturbed habitats and ruderal sites. The hermaphroditic flowers are white, mauve or dark purple. Poroporo flower all year round followed by fruiting. The berries are green changing to yellow and then dark orange when ripe. The berries are suitable for consumption when they start splitting. Birds such as wax-eyes (*Zosterops latralis*) and kereru (New Zealand wood pigeon, *Hemiphaga novaeseelandiae*) eat the flesh and distribute the small black seeds. Young poroporo plants are frost intolerant.

5.4.2 Uses

Traditionally poroporo had many purposes as a food supplement, natural contraceptive and to treat skin disorders. Māori planted poroporo around Pa sites (Te Mara Reo, 2009) where it was used as a food supplement; the ripe berries were classed as kai tamariki or children’s food (Roskruge, 2007). Settlers would also make jam from the ripe berries (Te Mara Reo, 2009). The juice of the leaves was commonly used to treat skin disorders such as “insect bites, ulcers, bruises, sores, eczema and dandruff” (Go native, 2009). Poroporo was also used to treat arthritis (Te Mara Reo, 2009). The juice of the leaf was also used as a natural contraceptive by Māori (Birch, 1993). It has been found that poroporo contains solasdine which is a base material for the production of steroid contraceptives (Wikipedia, 2011). This discovery led to the commercial cultivation of poroporo in Taranaki in 1976-83 (Te Ara, 2011), the extract containing solasdine was sent to Eastern Europe where it was manufactured into a “modern oral contraceptive” (Te Mara Reo, 2009). Unseasonable frosts (*ibid*.) and high plant nutrient demand saw cultivation cease here in New Zealand which led to the production of synthetic alternatives which were inevitably cheaper to produce. Poroporo is no longer commercially cultivated in New Zealand and is now considered a major agricultural weed.

5.4.3 TPP and poroporo

Poroporo is recognised as a common weed host of the TPP in New Zealand and growers of solanaceous crops are recommended to minimize the presence of the plant in and around their farms (Potatoes New Zealand, 2009). Belonging to the solanaceae plant family, it is possible TPP may complete their lifecycle on the plant although there is no documentation supporting this relationship. Poroporo produces green foliage all year round and may therefore serve as a host for the insect year round and a potential source of ongoing liberibacter infection.

5.5 Chapter summary

Three traditional Māori food sources are susceptible to TPP; taewa (Solanaceae, *Solanum tuberosum* ssp. *andigena* and ssp. *tuberosum*), kūmara (Convolvulaceae, *Ipomoea batatas*) and poroporo (Solanaceae, *Solanum aviculare*). Kūmara and taewa are key cultivated crops and traditionally major foods within the Māori diet whereas poroporo is an uncultivated crop with many uses including; flavouring in hangi, a natural contraceptive and the ripe berries eaten by children or processed as a jam. Taewa is particularly susceptible to TPP and ZC; damage effects have been widespread affecting taewa growers throughout New Zealand. The major issue facing taewa is seed vigour.

Information relating to the suitability and capacity of poroporo and kūmara as host plants of TPP is virtually non-existent; this study is aimed at assessing these relationships and determining host suitability.

Chapter Six

Zebra Chip Disease Complex

6.1 Zebra Chip (ZC)

TPP vectors *Candidatus* Liberibacter solanacearum (syn. psyllaurous) (liberibacter or Zebra Chip), the causal agent associated with Zebra chip and psyllid yellows disease. The disease is referred to as a 'disease complex' as more than one causal agent may be associated in producing disease symptoms (Wen *et al*. 2010). The causal agent is acquired through feeding on infected plants and carried on the stylet or transferred transovarially; not all psyllids carry the disease agent.

ZC foliage symptoms include; plant stunting, scorching, purpling or reddening at the leaf margins and plant death in severe infections (Horticulture New Zealand, 2008²). Typically infected tubers exhibit zebra-like striped discolouration, hence the name ZC. The discolouration is caused by "necrosis of the medullary ray tissue" (Wen *et al.* 2010). Early tuber infections result in high tuber set and small tuber size, whilst late infections result in ZC pigmentation. ZC is a lethal condition in potatoes (*ibid.*).

PY infected plants exhibit chlorotic leaves, leaf curl, plant stunting and slight tuber discolouration (*ibid*). PY is rarely lethal and infected plants may "recover and return to a healthy condition" (Wen *et al*. 2010:1102)

TPP are also suspected vectors of *Candidatus* Phytoplasma australiense (phytoplasma) although this has not yet been confirmed in New Zealand, insofar it is clear that TPP acquire phytoplasma but are not yet implicated in the transmission of the disease (Berry, 2010). Phytoplasma causes leaf and tuber symptoms similar to liberibacter (Potatoes New Zealand, 2009²). ZC and PY are discussed at length in Chapter five of this thesis.

Zebra Chip (ZC, Liberibacter, Zebra complex, Zebra disease complex) disease symptoms were first reported in the early 1990s in Mexican potatoes (Crosslin *et al*. 2010) and formally identified in 1994 (Secor *et al*. 2006). In 2000, symptoms were again reported in potatoes in Texas and in 2008 in California; New Zealand greenhouse tomato and pepper crops were symptomatic of ZC the same year. Potatoes will be the focus of the following discussion due to their relevance to this project. ZC symptoms have also been seen in tomato and capsicums. Similar leaf symptoms are seen in both species including "chlorotic or pale green leaves, leaf cupping, shortened internodes and flower abortion" (Weir, 2008). Tomato fruit may be deformed and development uneven (MAF Biosecurity New Zealand, 2009).

ZC is referred to as a disease complex due to the association of more than one pathogen with the disease (Wen *et al.* 2009). Two recently discovered alpha proteobacteria from the *Candidatus* Liberibacter genus have been identified as the causal agents of ZC and psyllid yellows disease (PY); *Ca.* Liberibacter solanacearum (Wen *et al.* 2009; Liefting *et al*. 2009) and *Ca.* L. psyllaurous (Hansen *et al*. 2008; EPPO, 2010), respectively. ZC (and PY) is closely related to Huanglongbing disease (HLB, syn. Yellow Dragon disease, citrus vein phloem degeneration, citrus greening disease, yellow shoot disease, leaf mottle yellows, and citrus dieback) which affects citrus trees. Three *Candidatus* Liberibacter species are known causal agents of this disease *Ca*. L. asiaticus, *Ca*. L. africanus and *Ca*. L. americanus

6.2 Causal agent identification

Identifying the causal agent and vector of ZC disease has proved difficult and only recently in 2009 *Ca*. L. solanacearum was discovered by MAF Biosecurity New Zealand (MAFBNZ) (Liefting *et al*. 2009; Lin *et al*. 2009); MAFBNZ also identified TPP as the possible vector (Liefting *et al*. 2009).

Initially phytoplasma were the suspected causal agents (Munyaneza *et al*. 2005; Crosslin *et al*. 2009) of the plant damage seen in affected solanaceous plants particularly due to their similarity to Potato Purple Top disease (PPT) infected plants. PPT is caused by a number of phytoplasma (Munyaneza *et al*. 2005; Crosslin *et al*. 2009; Secor *et al*. 2009) and vectored by leafhoppers. Tests for phytoplasma were negative in both the infected plants and suspected insect vectors (Crosslin *et al*. 2010). Numerous tests followed for common viruses and diseases of cucumbers, tomatoes and potatoes; all were negative (Crosslin *et al*. 2009; Liefting *et al*. 2009). This then led to the assumption that ZC may be caused by a bacterium-like organism (BLO) (Secor *et al*. 2009) which is a "phloem limited proteobacteria vectored by plant sap feeding insects" (Secor *et al*. 2009: 575). Diseases caused by BLOs include yellow vine of cucurbit and citrus greening (huanglongbing). Liefting *et al.* (2009) identified *Ca*. L. solanacearum using PCR (Polymerase Chain Reaction) primers used to detect citrus greening disease (*Ca*. L. asiaticus); this causal agent has insofar been associated with ZC in tomatoes, capsicum, tamarillo (*Solanum betaceum*) and the cape gooseberry (*Physalis peruviana*) (Secor *et al*. 2009). Hansen *et al*. (2008) reported the association of *Ca.* L. psyllaurous with PY disease in tomatoes and potatoes in New Zealand and potatoes in North America" (Secor *et al*. 2009; Brown *et al*. 2010; Nelson *et al*. 2010).

DNA sequencing shows that *Ca*. L. solanacearum and *Ca*. L psyllaurous are very similar and only a few minor differences have been detected between the two implying that there is more than one variant of the bacterium (Secor *et al.* 2006; Liefting *et al.* 2008²; Crosslin *et al.* 2010). The closely related causal agents are now considered to be synonymous; the classification *Ca.* L. solanacearum syn. psyllaurous (Hansen *et al*. 2008) or *Ca.* L solanacearum (syn. *Ca.* L. psyllaurous) (Munyaneza, 2010; Nelson *et al*. 2010: EPPO, 2010; Brown *et al*. 2010; Yang *et al*. 2010). It is "now accepted that *Ca*. L. solanacearum bacterium is the causal agent of ZC associated with potatoes" (Liefting *et al*. 2008; Abad *et al.* 2009; Crosslin and Bester 2009; Lin *et al.* 2009; Munyaneza *et al.* 2009; Secor *et al.* 2009; Rehman *et al.* 2010; Nelson *et al.* 2010).

6.3 Acquisition and Transmission

ZC (*Ca*. L. solanacearum syn. psyllaurous) is acquired by TPP through feeding on infected plants (Brown *et al*. 2010) or transferred transovarially (horizontally) (Hansen *et al*. 2008) maternally throughout the generations. ZC is carried in the stylet and vectored vertically (plant to plant) to susceptible hosts by TPP (*ibid*.). During feeding the stylet penetrates the epidermal and subcutaneous tissues into the phloem;

after a period of approximately one hour solidary, compounds are secreted and feeding begins (Munyaneza, 2010; Trumble, 2010). ZC is transmitted to susceptible host plants in these secretions. Dr Munyaneza (2010), a research entomologist based in Washington, showed that in potatoes, TPP needed to feed for a period of at least one hour on a ZC infected host plant to acquire the disease. He also found that ZC infected TPP transmit the disease to healthy host plants after approximately two hours of feeding (*ibid*.).

6.4 Disease Symptoms in Potatoes

6.4.1 Foliar symptoms

In potatoes foliar symptoms produced by ZC, PY and PPT (potato purple top disease) are similar, these include; stunting, chlorosis, twisted stems, swollen nodes, aerial tubers, vascular discolouration and leaf scorching and wilting (see Figures 6.1a and 6.1b) (Cranshaw 1994; Cranshaw, 2001; Secor *et al*. 2009; Wen *et al*. 2009; Nachappa, 2011).

Figure 6.1a) Leaf purpling (left) and chlorosis (right) caused by ZC

(Source: Crosslin *et al*. 2010)

Figure 6.1b) Severe leaf scorching caused by ZC in potatoes

(Source: Crosslin *et al*. 2010)

6.4.2 Tuber symptoms

ZC, PY and PPT affect the "transport of assimilates in the phloem vessels" (Secor *et al*. 2009: 574). PY and PPT only cause slight vascular degeneration which results in mild discolouration, whilst ZC induces tuber necrosis (premature cell or tissue death); this factor characterises ZC. ZC infected tubers exhibit "browning of the vascular ring and medullary rays throughout the entire length of the tuber" (Wen *et al.* 2009:1102) whereas discolouration caused by PPT only occurs at the stem end of the tuber (Secor *et al*. 2009: 574). This accounts for the difference in severity between diseases. ZC tuber discolouration occurs in a striped pattern and is thought to be caused by "the conversion of tuber starches to sugars" (Horticulture New Zealand, 2008²) and necrosis (cell death) which become more pronounced when the tubers are fried"(Munyaneza *et al*. 2007). For this reason ZC infected tubers are commercially unacceptable for the process market. In terms of edibility the tubers pose no health risk to the consumer but may have an 'off taste' (Wikipedia, 2011) or sweet flavour (Roskruge, pers. comms. 2010).

ZC infection early in crop development (juvenile plants) results in the development of numerous small fruits or tubers whilst late infections (mature plants) cause the zebra chip symptoms. It is thought that small tubers result from the “diversion of sugars away from the establishing tubers to be used elsewhere in the plant to maintain above ground plant growth” (Fletcher, pers. comms. 2009). PY is also associated with “misshapen tubers and roughened periderm” (Secor *et al*. 2009: 574).

Figure 6.1c) ZC potato tuber symptoms

(Source: American Vegetable Grower, 2009)

6.4.3 Potato seed tuber quality

Henne *et al.* (2010) showed that approximately 60-80% ZC infected tubers were barren; the remainder may sprout dependent on individual seed tuber infection and cultivar. Low seed tuber and shoot vigour was also noted. Delayed emergence and plant death after a few weeks of growing is common (*ibid*.; Potatoes New Zealand, 2010). Plants produced from infected seed produce shallower and less extensive root systems than healthy plants and few produce inflorescences (Henne *et al.* 2010). It is unlikely that these plants serve as a primary source of ZC inoculum for the spread of ZC as many die before TPP arrive or are sheltered by surrounding healthy plants (*ibid.*).There are concerns that infected potato seed tubers may end up in ZC free areas due to the lack of seed certification protocols in relation to ZC, although this may not be an issue in areas where TPP does not occur (*ibid*.). In some instances tuber malformation and small size affect the suitability of tubers for use as seed.

6.5 Traditional impact

Three host plants are assessed in this research. Taewa are the most vulnerable to TPP attack and disease transmission. Very little is known about the relationship between TPP and kūmara and poroporo; this thesis is the first which assess these relationships in depth. Kūmara is deemed as a ‘poor host’ of TPP and although feeding damage is still concerning. It is also unclear if kūmara are susceptible to ZC. Poroporo, as a solanaceous plant, is vulnerable to TPP attack and furthermore may be susceptible to ZC infection and more importantly, harbour the disease throughout the year.

Taewa exhibit damage and disease symptoms as in conventional potato varieties. TPP and ZC have caused problems in taewa crops across the North Island in Palmerston North, Bulls, Hawkes Bay and Gisborne amongst others. Taewa are a major host of TPP and the key issues facing the crop are reduced yield and declining seed tuber quality due to Liberibacter, especially regarding some of the rarer or relic varieties. Tubers harvested from plants with early ZC infection are too small or misshapen and therefore are generally unsuitable for use as seed for the following season. Overall, ZC threatens the perpetuation of some taewa varieties particularly the rarer varieties (e.g. Tutaekuri) (Roskruge, pers. comms. 2010).

6.6 Economic impact

ZC causes “severe economic losses in all classes of potatoes” (Secor *et al*. 2009: 574), and the effects of the disease are evident at all levels of the potato production industry both on and off-farm. In terms of farming activities; job losses, increased production costs (i.e. pesticides, pest monitoring and consultancy services), reduced sales and yield prices can be expected as a result of ZC infection (Centre for North American Studies; 2006). The effects of any reduction in farming activities may in turn affect off-farm activities such as marketing, transportation and trading.

In Texas, where local potato production was estimated at US$84.2 million in 2008, it was estimated that ZC would “affect 35-40% of local potato acreage from yield losses or reduced prices” (*ibid*.). This equates to the loss of approximately 3055ha and US$33.4 million annually. Losses on some individual farms have exceeded US$2 million (*ibid.*). Potatoes New Zealand (PNZ) (2010) has reported that since the arrival of TPP, the pest has cost the potato industry alone approximately NZ$60 million and it is expected this figure will continue to rise. PNZ has also estimated that local growers face an extra NZ$700 per hectare in costs to manage TPP (*ibid.*). In 2009, Mr Terry Olsen, Potatoes New Zealand Chairman, tentatively reported that New Zealand growers saw 10-20% reductions in their yields due to TPP infestation (Galloway, 2009) and the threat has yet to be resolved.

In New Zealand ZC infected tubers which are rejected by the process industry are sold onto the fresh market, sometimes at a reduced price. In the USA these tubers are considered "unsuitable for both fresh market sales and processing into food products (crisps and fries)" (Secor *et al*. 2009: 574). In severe cases ZC may affect up to 80% of a growers yield in a single season (*ibid.*). Entire fields have been abandoned due to severe infection at this level (Ewing, 2008).

6.7 Chapter summary

ZC is a major issue for growers of solanaceous plants where both crop yield and quality may be affected. ZC is referred to as a disease complex due to the association of more than one pathogen with the disease (Wen *et al.* 2009). MAF Biosecurity New Zealand played a major role in identifying TPP in New Zealand as the vector of ZC. In relation to the three hosts assessed in this study taewa is the species of most concern as it is clear the crop is highly susceptible to both TPP and ZC. The most pressing issue concerning the crop is low seed tuber vigour especially in the face of declining seed stocks nationwide. It is not yet known if poroporo and kūmara are susceptible to ZC.

Chapter Seven

Discussion

7.1 Open environment monitoring

7.1.1 Comparison of sites: Bulls vs. Massey

TPP were present in lower numbers for a longer period of time at the Massey Hill site. At the Bulls site TPP were no longer present at week four of July whereas at the Massey Hill site TPP were present until week four of August. This may be due to the nature of the two monitoring sites; the Bulls site was an open site consisting of a number of individual poroporo plants occurring naturally along the Parewahawaha Marae garden fence line. The Massey Hill site was more sheltered, this site is currently under restoration by the Palmerston North City Council involving eradication of invasive weeds and planting of native trees, shrubs and other plant life. The individual sampling units were surrounded by other plants; some of these units were difficult to access due to the surrounding plants. This may have lessened the effect of environmental factors such as wind, rain and temperature. The Bulls site was notably more susceptible to frost damage. Throughout the monitoring period the Massey Hill plants appeared to be healthier than those at Bulls. No browning and wilting was recorded on the mature poroporo stands; those that died of frost damage were immature plants susceptible to frost.

The Massey Hill site saw an influx of TPP (eggs and adults) again in January 2011. This influx was not seen at the Bulls site as the plants were no longer viable due to being sprayed by the marae manager. The natural enemy population were noted at the Bulls site in September, earlier than the Massey Hill site which was not populated by natural enemies until October. The number of natural enemies peaked at 18 at Bulls and only six at Massey Hill.

The overall results indicate that poroporo is not a significant or important overwintering host of the TPP in the context of this study. Poroporo may be thought of however as an alternative food source for the insect when the primary host species (tomato, potato, capsicum etc.) are no longer present, or as a refuge crop. If poroporo was in fact an overwintering host of the TPP, psyllid would have been detected on these plants throughout the winter and spring months. The fact that over this period (winter and spring) no TPP were detected at both sites indicates that the population either died out or migrated from the site. In North America it has been noted that TPP migrate north towards the northern states from the overwintering and breeding grounds in California, Arizona, Northern Mexico and Southern New Mexico (Munyaneza *et al.* 2009) in response to wind currents and high temperatures. Migration has yet to be identified in New Zealand.

In this study poroporo was not found to be a naturally occurring important overwintering host of TPP. This point requires further investigation especially in regards to poroporo occurring in different regions of New Zealand. Differing results may be found when comparing poroporo stands further north of the Manawatu – Rangitikei district where temperatures may be conducive to TPP overwintering. Further research into the nature of poroporo stands (age, height, and width, environment (open or closed/sheltered) may also reveal different relationships between insect and host.

7.1.2 Poroporo as an overwintering host of TPP

It is clear that naturally occurring poroporo in the context of this research is not a significant overwintering or bridging host of the TPP, rather it is an alternative host of the insect in the absence of the primary solanaceous summer annuals (potatoes, tomatoes, capsicum etc.). The fact that there was a break in the TPP population at both the Bulls and Massey Hill sites shows that poroporo is not a bridging or overwintering host of TPP. This is further supported by the fact that TPP were again present at the Massey Hill site December 2010 and January 2011.

7.2 Closed environment monitoring

It is clear that kūmara is a ‘poor’ host of the TPP; this is supported by the fact that egg incubation period was significantly longer and survivorship (egg and nymph) significantly lower on kūmara in comparison to taewa and poroporo. Survivorship of both eggs and nymphs was very low at 2.6 ± 0.56 and 1.6 ± 0.34 respectively (Table 7), in light of this it would seem unlikely that population outbreaks would occur on the host. The major issue with kūmara is that it may play host to TPP in times of high infestation on primary host plants providing alternative refuge, ensuring the longevity of the pest.

As expected poroporo seems to be a ‘good’ host of the TPP, many of the parameters measured in this study were similar for taewa and poroporo. Female fecundity and survivorship (egg and nymph) were significantly higher on taewa in comparison to poroporo.

The total development period (Incubation period + Nymph development) was similar on taewa and poroporo at 20.4 ± 0.3a and 22.6 ± 0.5a days respectively (Table 6). This parameter was significantly longer on kūmara at 30.3 ± 3.49b days.

Total development period relationship = Taewa> Poroporo> Kūmara

The results showed that TPP lifecycle (total development + pre oviposition period, Table 6) was shortest on taewa (27.5 ± 0.56b days, $LSD_{0.05}$= 7.583, df= 2, 27, P= 0.013), followed by poroporo (total lifecycle = 30 ± 0.89b days) and finally kūmara (total lifecycle = 39 ± 4.4a days).

Total lifecycle relationship = Taewa> Poroporo> Kūmara

Shorter development and total lifecycle periods may be conducive to faster population growth which may then contribute to excessive population outbreaks.

7.3 Contained leaf samples

Based on the results for the contained leaf samples taewa is the most suitable host of TPP. The oviposition period and adult longevity (both male and female) were similar on taewa and poroporo; female fecundity was significantly higher on taewa and the pre mating period significantly shorter on the host in comparison to poroporo. The results indicate that kūmara is the poorest host of the TPP with significantly; shorter oviposition period and longevity (male and female), lower fecundity and longer pre mating period. The overall trend obtained from these results is as follows;

Taewa> Poroporo> Kūmara.

7.4 Overwintering, host suitability and importance

Poroporo was not found to be a significant overwintering host of TPP in this study, rather an alternative food source in the absence of summer annual solanaceous host species. TPP did not overwinter in the two strata assessed in this study.

In terms of host suitability taewa and poroporo are the preferred hosts out of the three host species assessed in this study. Poroporo was the intermediary host. Survival and fecundity were significantly lower on kūmara than taewa and poroporo and development time was longer. This indicates that kūmara was the least suitable host of the TPP of the three plants assessed in this study.

Chapter Eight

Conclusion

It is clear that from this study poroporo is not an important or significant overwintering host of the TPP; rather it can be viewed as an alternative or refuge host species. TPP were detected at the monitoring sites long after annual summer solanaceous crops were no longer present. If TPP did overwinter on poroporo the insect would have been seen throughout the entirety of the monitoring period, instead TPP were seen to decline in numbers over the winter months (June through to August); no TPP were detected after August. This indicates that poroporo is not a significant overwintering host of the TPP in the context of this study.

It is noted that in their home range TPP migrate North from their overwintering and breeding areas in California, Arizona, Northern Mexico and Southern New Mexico (Munyaneza *et al*. 2009) returning to the summer feeding grounds in the Northern states. Migration has not yet been assessed in New Zealand and it remains unknown as to where, when, or even if, migration occurs here. This study looked at poroporo as a specific host species important to Māori and potentially susceptible to TPP all year round due to its growth habit thereby providing an alternative source of food in the absence of favoured host plants. This study has proven that this is not so in the areas monitored. It is theoretically possible that TPP may remain on poroporo during winter in the warmer regions of New Zealand where both the insect and host species occur, although this is an assumption and more research would need to be undertaken to prove this.

The results obtained in this study indicate that taewa is a more suitable host of the TPP than poroporo and kūmara. In the same vein poroporo is more suitable than kūmara. This was expected as the preference for solanaceous plants has been well supported.

In terms of host suitability it seems taewa and poroporo are the most suitable hosts for TPP, this is confirmed in the fact that many of the parameters measured in this research were similar between the two hosts. The suitability of taewa as the ‘best’ host of the TPP in this study is supported by the fact that the egg incubation was significantly higher on the host in comparison to kūmara and survivorship (both egg and nymph) was significantly higher on taewa in comparison to the other two hosts. Total development and lifecycle calculations were similar on taewa and poroporo but significantly shorter on taewa in comparison to kūmara. This coupled with increased reproductive potential (significantly shorter pre mating period and higher fecundity) makes taewa more suitable for the TPP in terms of survival and population growth. Shorter development time, high reproductive potential and higher survivorship (egg and nymph) on taewa in comparison to poroporo and kūmara shows that as a host of the TPP, taewa is a more suitable host plant than the other two species assessed in this study. Compared with the other two hosts assessed in this study taewa would be more susceptible to high TPP infestation and subject to excessive population outbreaks.

Poroporo is the intermediate host out of the three host species assessed in this study. The results show that TPP development was longer on poroporo than taewa. Egg and nymph survivorship was significantly lower on poroporo than taewa but significantly higher than kūmara. Egg incubation period was also significantly shorter on poroporo compared to kūmara. Reproductive potential was significantly lower on poroporo than taewa; only female fecundity differed significantly from kūmara. Adult longevity (male and female) and oviposition period were significantly longer on kūmara than poroporo. These parameters show that poroporo is a secondary host of the TPP in comparison to taewa and kūmara.

Longer development period coupled with significantly lower survival and female fecundity indicates that kūmara was the least suitable host of the TPP in this study. Although it was confirmed that TPP are capable of completing their lifecycle on the host. This study supports the claim that kūmara is a ‘poor’ host of the TPP.

The relationship seen in this study between host species and suitability as a host plant for the TPP can be pictorially represented as; Taewa> Poroporo> Kūmara.

This study has revealed and confirmed that TPP are capable of completing their lifecycle on each of the three hosts assessed in this study. Growers need to be vigilant with each host and employ suitable management strategies to reduce the potential effects of TPP and ZC.

Due to the significance of taewa in the annual lifecycle of the TPP in New Zealand, management strategies should be employed before planting and throughout the entirety of the cropping season. Volunteer potatoes growing out of season should be removed and disposed of appropriately to minimise the risk of such plants posing as bridging hosts of the TPP and ZC. Due to the recognition of poroporo as an 'intermediate' host of the TPP it too may be subject to removal or chemical spraying especially during the summer cropping season. Although no damage symptoms have been recorded or quantified on kūmara as a host of the TPP it is suggested that growers monitor their crops and manage TPP populations if they eventuate; reducing the risk of further population growth.

This study indicates that poroporo is not a significant overwintering host of the TPP in the Manawatu/Rangitikei region; rather it is an alternative host or refuge for the TPP in the absence of primary solanaceous host plants. The association between TPP, taewa, kūmara and poroporo was confirmed and it was shown that TPP are capable of completing their lifecycle on each of the three hosts.

8.1 Recommendations and future research topics

- Assess the overwintering potential of poroporo on a wider (national) scale in different areas of New Zealand in an attempt to provide a well investigated and comprehensive conclusion.
- For this study to be comparable to other studies; controlled environmental conditions would have been favourable. Repeating this study under controlled conditions at an average of 26-27° C, 12:12 hour day/night regime and controlled relative humidity would have yielded more verifiable and comparable results.
- Further investigation into the relationship (or non-relationship) between poroporo, kūmara and ZC disease would widen the scope of researchers and provide traditional Māori growers with important information regarding their crops.
- Investigate the role of solanaceous weed species and volunteer potatoes as hosts of the TPP in the natural environment.

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Appendices

Appendix I – Tomato/Potato Psyllid Fact Sheet prepared for the 'Spud in a Bucket' initiative

Tomato/Potato Psyllid

Kutu-peke ā riwai

The Tomato/Potato (TP) Psyllid (*Bactericera cockerelli*) is a new pest in New Zealand which attacks tomato, potato, capsicum and tamarillo crops.

The adult TP Psyllid is similar in appearance to the cicada but is only 2-3mm in length with transparent wings with two white stripes across their abdomen. The nymphs (immature stage) are light green and fringed with short white hairs and are usually found on the underside of the leaves. Eggs are found at the leaf margins, raised by a short stalk.

The nymphs and adults feed by piercing leaf tissues and suck sugars from the sap. The TP Psyllid is a vector of the bacterial disease Liberibacter (*Candidatus liberibacter*) commonly known as Zebra chip. Liberibacter causes tuber pigmentation and yield losses which can be as high as 80% in severe cases. Liberibacter infected plants may appear stunted, yellow to brown in colour and the leaves may roll and turn pink at leaf margins.

If you think this pest is present in your crops see the following websites for management options:

http://www.hortnz.co.nz/communications/pdfs/PsyllidFactsheet.pdf
http://www.freshvegetables.co.nz/user_files/PDF/Psyllid_Growers_Guide_Nov_08.pdf
http://www.bioforce.net.nz/pests/tomato-potato_psyllid.html
http://www.biosecurity.govt.nz/pests/potato-tomato-psyllid

Eggs

Nymphs

Adult Psyllid

Appendix II – Insect Identification Sheet

Natural Enemy ID sheet

Adult brown lacewing (*Micromanus tasmaniae*) (Photo source: HortNet, 2006²)

Lacewing larvae (*Micromanus tasmaniae*) (Photo source: HortNet, 2006²)

Adult hoverfly (*Melanostoma fasciatum*) (Photo source: Landcare Research, 2010)

Hoverfly larvae (*Melanostoma fasciatum*) (Photo source: Landcare Research, 2010)

Adult 11 spotted ladybird beetle (*Coccinella undecimpunctata*) (Hortnet, 2006)

11 spotted ladybird beetle larvae (*Coccinella undecimpunctata*) (Hortnet, 2006)

Appendix III – List of Chemicals used to control TPP and their availability in New Zealand

Chemical Group	Active Ingredient	Chemical Trade Name	Mode of Action	Available in New Zealand
1A (Carbamates)	Carbyryl	Carbaryl 50, Sevin Flo	Contact and Ingestion	YES
1A	Methomyl	Lannate L	Contact and Ingestion	YES
1A	Oxamyl	Vydate L	Contact Ingestion Plant systemic	YES
1A	Pirimicarb	Pirimax 500 Pirimor 50 Pirimisect Prohive TM , Aphisex WG, Piritek	Contact Fumigant Trans laminar	YES
1B (Organophosphates)	Acephate	Lancer 750 DF, Orthene WSG	Plant translocated, contact and systemic, stomach poison	YES
1B	Azinphos methyl	Cotnion 200		YES
1B	Diazinon	Dew 500 Diazinon 800/W Diazonyl 60 EC	Contact, Ingestion, Respiratory	YES
1B	Dimethoate	Dimezyl 40 EC, Perfekthion S	Contact or ingestion, Plant systemic	YES
1B	Malathion	Maldison	Contact Ingestion	?
1B	Methamidophos	Metafort 60 SL Monitor Tamaron	Contact Ingestion, Plant systemic	YES
1B	Phorate	Crop care phorate 20G, Disect, Nufarm phorate, Thimet 20G	Plant systemic, contact and fumigant	YES
1B	Pirimiphos methyl	Actellic SG	Contact Ingestion Fumigant	YES
3A (Synthetic pyrethroid)	Alpha-cypermethrin	Bestseller 100EC Cypher Dominex 100 Fastac	Contact Ingestion	YES
3A	Esfenvalorate	Sumi-alfa	Contact or ingestion,	YES
3A	Deltamethrin	Ballistic, Decis Forte Deltaphar 25 EC Cislin Insectigone	Contact Ingestion	YES
3A	Lambda-cyalothrin	Karate-Zeon	Contact Ingestion	YES
3A	Taufluvalinate	Mavrik	Contact Ingestion	? (Mavrik WDG, Mavrik Aqua Flo)
4A	Imidacloripid	Confidor	Contact Ingestion, Plant systemic	YES
4A	Thiacloprid	Calypso	Contact Ingestion, Plant systemic	YES
4A	Thiamethoxam	Actara, Cruiser	Contact Ingestion Plant systemic	YES

5	Spinetoram		Contact Ingestion	?
5	Spinosad	Success Naturalyte	Contact Ingestion	YES
6A	Abamectin	Abamax Apostle Avid Verdex	Contact Ingestion	YES
9A	Pymetrozine	Chess WG	Feeding inhibitor	YES
15	Novaluron	Rimon	Chitin Inhibitor	NO
17A Thiadiazine	Buprofezin	Mortar Ovation 50WDG Pilan Applaud 40 SC Buprimax	Insect growth regulator	YES
21A	Fenpyroximate	Fenamite	Contact	YES
21	Spiromesifen	Oberon	Inhibits development and fecundity. Ovicidal	YES
23	Spirotetramat	Movento	Inhibition of lipid production	YES
28	Chlorantraniliprole	Coragen	Nerve & muscle action	NO
Organic Compound	Azadirachtin	Neem	Insect growth regulator, antifeedant, Yes	YES
Mineral oil	Mineral oil	Sunspray	contact, intefere with metabolic processes	YES

(Source: Young, 2010)

Appendix IV – Glossary of Māori terms

Māori Term	Translation
Aotearoa	New Zealand
Aute	paper mulberry, *Broussonetia papyrifera* - formerly cultivated to make cloth, but now no longer found in Aotearoa/New Zealand
Hapū	kinship group, clan, tribe, subtribe - section of a large kinship group
Hāngi	earth oven - earth oven to cook food with steam and heat from heated stones.
Hawaiiki	Māori ancestral home, from where Māori originated
Kai tamariki	Children's food
Iwi	extended kinship group, tribe, nation, people, nationality, race - often refers to a large group of people descended from a common ancestor
Kaitiaki	trustee, minder, guard, custodian, guardian, keeper
Kaitiakitanga	guardianship, trustee, the act of guardianship
Kaupapa	topic, policy, matter for discussion, plan, scheme, proposal, agenda, subject, programme, theme
Kōkihi	New Zealand spinach
Koanga	Koanga meaning spring or planting time
Kūmara	sweetpotato, *Ipomoea batatas*
Mana	prestige, authority, control, power, influence, status, spiritual power, charisma - *mana* is a supernatural force in a person, place or object
Māori	Māori, indigenous New Zealander, indigenous person of Aotearoa/New Zealand
Marae	courtyard - the open area in front of the *wharenui*, where formal greetings and discussions take place. Often also used to include the complex of buildings around the *marae*
Mauri	life principle, special nature, a material symbol of a life principle, source of emotions
Ngāti Awa	Eastern Bay of Plenty tribe
Ngāti Porou	North Island East Coast tribe
Noa	be free from the extensions of *tapu*, ordinary, unrestricted
Parareka	potato (Eastern dialect), *Solanum tuberosum* - a general term for potato but also refers to a specific oval-shaped cultivar with pink-and-yellow mottled skin and white floury flesh
Poroporo	poroporo, *Solanum aviculare* and *Solanum laciniatum* - native shrubs to 3 m tall with dark, soft, lance-shaped or lobed, alternating leaves. Flowers are white to blue-purple and the fruit yellow to orange. Most common along the edges of forest and in scrub. The fruit is poisonous until fully ripe

Taewa	Māori potato, *Solanum tuberosum*
Tahuri Whenua	Literally - to turn the land or turn to the land: National Māori Vegetable Growers Collective (Website: http://tahuriwhenua.org.nz/)
Tapu	be sacred, prohibited, restricted, set apart, forbidden, under *atua* protection
Te Whanau a Apanui	Eastern Bay of Plenty tribe
Tikanga	correct procedure, custom, habit, lore, method, manner, rule, way, code, meaning, plan, practice, convention
Tī Kouka	cabbage tree, *Cordyline australis* - a palm-like tree with strong, long, narrow leaves; the young inner leaves are eaten both raw and cooked
Tuhoe	Inland Eastern Bay of Plenty tribe
Ure	penis
Whakapapa	genealogy, genealogical table, lineage, descent

(Translations taken from Māori dictionary, 2011)