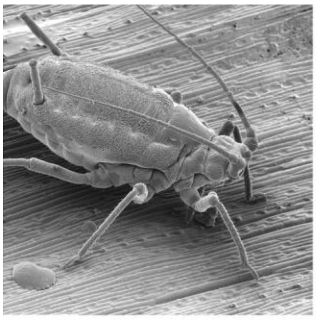
PFR SPTS No. 9350

Predicting the first occurrence of tomato potato psyllid in tomato and potato crops

Butler RC, Taylor N & Vereijssen J

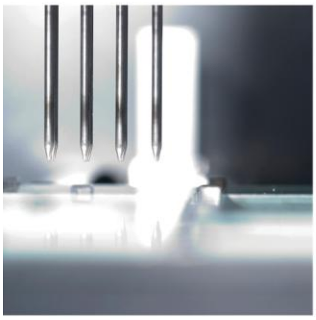
December 2013





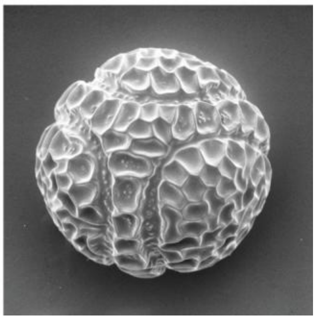










Confidential Report for:
Potatoes New Zealand Incorporated

CONFIDENTIALITY

This report contains valuable information in relation to the SFF11-058: Developing IPM Tools for Psyllid Management programme that is confidential to the business of Plant & Food Research and Potatoes New Zealand Incorporated. This report is provided solely for the purpose of advising on the progress of the SFF11-058: Developing IPM Tools for Psyllid Management programme, and the information it contains should be treated as “Confidential Information” in accordance with the Plant & Food Research Agreement with Potatoes New Zealand Incorporated].

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Executive summary

Predicting the first occurrence of tomato potato psyllid in tomato and potato crops

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Plant & Food Research: [1]Lincoln, [2]Hawke's Bay

December 2013

This research was conducted as part of milestone 11B in the third and final year of SFF11/058 'Developing IPM Tools for Psyllid Management'. The objective was to forecast the first arrival of tomato potato psyllid (TPP) in a crop, based on a refined version of Tran et al.'s (2012) degree day model. TPP is a major pest of solanaceous crops (e.g. potato, tomato, capsicum and tamarillo), primarily because it can vector the bacterium *Candidatus* Liberibacter solanacearum (Lso). The pathogen is responsible for Zebra Chip disease in potatoes, which becomes visible after frying the chip, which makes it a major concern for growers of processing potatoes. Effective management of TPP in these crops requires guidance on when to start spray programmes.

The analyses of TPP trapping data were conducted at PFR Lincoln in the period August to October 2013. Approximately weekly trapping data were collected from several sources, with 38 datasets available for potato, 133 for tomato and six for tamarillo. For each crop (location and year), the closest weather station listed on the MetWatch or NIWA CliFlo sites was identified. Hourly temperature data were downloaded, from 1 July at midnight to the following 14 January, at 2300 h. The July starting date was chosen as the proposed lowest density of TPP, and all crops had trapped at least 1 TPP by 14 January. Degree days (DD) were calculated from datasets of 24 temperatures per day.

The analysis showed that 980 DD were reached well before a significant rise in TPP numbers. If 980 DD had been used as an indicator for when to start a spray programme, then the majority of crops, both for Hawke's Bay and Pukekohe, would have been sprayed before the major rise in TPP. Before 980 DD had accumulated, most crops in both datasets had TPP catches of below 2 TPP/trap/day, and all were below 4 TPP/trap/day. The analysis also indicated that adult TPP were active before crop emergence.

Additional to the recommendations regarding data collection made previously (Dohmen-Vereijssen et al. 2013), there are still a few areas that need to be explored in order to develop a more refined 'prediction model': development of Lso-free versus Lso-positive TPP, development of TPP at temperatures lower than 8°C, the fluctuation in Lso incidence and titre within a year and between years, the role of non-crop solanaceous host plants in harbouring Lso, more data from unsprayed crops, and more data from a larger number of crops from the regions outside Hawke's Bay.

A sound understanding of the epidemiology of this pathosystem is essential. This requires extensive knowledge of the factors that drive it, as the dynamics of its four components (pathogen, host, vector, and environment) all need to be incorporated into a predictive model. TPP and Lso have been relatively recent additions to the pests and diseases present in New Zealand. After a few years of focusing on how to manage the insect vector and to decrease Zebra Chip disease incidence (caused by Lso), it now seems the biology and ecology of the insect and the pathogen are under-researched, and these factors are sometimes hindering progress. With further research and refinement, the 980 DD approach should supply another management strategy to control TPP and Lso early in the growing season.

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1 Introduction and Background

1.1 Managing insect vectors

Managing insect vectors, in this case insects that can transmit plant pathogenic bacteria, constitutes a challenging undertaking because of the complexity of the pathosystem, which includes the pathogen, the vector, the host plant and the environment. Effective management not only depends on diagnosis and knowledge of the pathogen, but also requires a thorough understanding of vector and pathogen biology, how vector and host plants interact, the epidemiological implications of the interaction, the underlying pathogen replication mechanisms and the environmental constraints of the vector, pathogen and host plant (e.g. Fry 1983; Weintraub 2012). Management often requires a multipronged approach in which several pathways (vector – plant host; pathogen – plant host) are interrupted (e.g. Hilje et al. 2001; Almeida et al. 2005; Jones et al. 2010). In some cases, diseases are suppressed efficiently when management efforts are directed at the vector, rather than, or in addition to, those aimed at the pathogen (Fry 1983). In this project, the use of accumulated degree days in tomato potato psyllid (TPP) management is explored as an additional approach to optimise vector management.

1.2 Using temperature and degree days in insect management

Insect growth is mostly affected by time and temperature. Because they are cold-blooded, their body temperature varies with the temperature of their surrounding environment. Insects require a certain amount of heat to develop from one stage in their life cycle to another (e.g. eggs to larvae to pupae to adults), but the amounts needed vary by insect species. Growth only occurs within a certain range of temperatures, the upper and lower developmental thresholds.

The amount of heat required by an organism to complete its development is known as physiological time. Physiological time is usually expressed in units called degree days, and these are the accumulation of heat units between the lower and upper threshold temperature for a 24-hour time period. One degree day results when the average temperature for a day is one degree over the minimum threshold. These values can be used in predicting insect activity and appearance of symptoms during the growing season. Degree days (DD) can be accumulated over a period of time and used to estimate growth and predict insect development. The accumulation of DD usually begins with either an arbitrary starting point such as a calendar date (for many insect pests 1 January or 1 March is used), or a biofix (the date to begin accumulating degree days, which varies with the species. Biofix dates are usually based on specific biological events such as planting dates, first trap catch, or first occurrence of a pest.).

Phenology models help to predict the timing of events in an organism's development using degree days. With integrated pest management (IPM), degree day accumulations are used to predict important events in the life of an insect pest (Wilson & Barnett 1983), including egg laying, egg hatch, scale crawler movement, appearance of insect pests or appearance of symptoms (e.g. Lindblad & Sigvald 1996; Murray 2008). These biological events are in turn used to schedule particular activities such as scouting and synchronizing insecticide sprays.

Degree day models are based on the assumption that the relationship between the rate of insect development and temperature above a certain base temperature is linear (Briere et al. 1999). In general, the cooler the temperature, the slower the rate of growth and development. However, higher temperatures, and therefore higher accumulated degree days, do not necessarily imply that pests will be more abundant.

Degree days have been and are used extensively to predict pest emergence, flight and so on. In some instances, a certain accumulated degree day total from first trap catch of a pest is used as a trigger to apply the first spray (e.g. Pitcairn et al. 1992).

1.3 Use of degree days in managing tomato potato psyllid

TPP is a major pest of solanaceous crops (e.g. potato, tomato, capsicum and tamarillo), primarily because it can vector the bacterium *Candidatus* Liberibacter solanacearum (Lso). The pathogen is responsible for Zebra Chip disease in potatoes, which becomes visible after frying the chip, making it a major concern for growers of processing potatoes. However, the pathogen also leads to reduced yields and larger numbers of smaller, unmarketable potatoes (Munyaneza et al. 2008).

Effective management of TPP in these crops requires guidance on when to start spray programmes. Currently, yellow sticky traps are placed in crops to monitor the arrival and build up of TPP numbers, but quite often a calendar spray programme is begun once TPP have been observed on the traps. A potential alternative start of the spray programme may be available, if the arrival of TPP can be predicted from weather data. Within this SFF programme, a field trial was conducted focusing on increasing periods between sprays and incorporating oils, as well as using degree day accumulation as the trigger for the first spray.

1.4 Objective

The objective for this milestone was to forecast the first arrival of TPP in a crop based on a refined version of Tran et al.’s (2012) DD model. The model was developed from data collected in a controlled temperature laboratory experiment, and had not been confirmed for field conditions. Thus, the model needed to be assessed, and this could be partly achieved through the analysis of existing monitoring datasets from sprayed crops, since sprays normally would not have been applied before the first arrival of TPP.

2 Data

2.1 Tomato potato psyllid development model

Before DD can be calculated and accumulated, the development of TPP at different temperatures needs to be estimated. In New Zealand, Tran et al. (2012) estimated from laboratory studies that the time from egg oviposition to adult emergence was 358 degree days for temperatures above a lower threshold of 7.1°C. Therefore, their model involves TPP development and does not predict the first appearance of TPP in a season, or adult flight patterns. Their work suggested, however, that egg and nymph development in field conditions could be predicted, and thus the arrival of adult TPP in a crop could be predicted as being a small time later. Prediction from such a model would require that TPP were either dormant or at very low numbers at one point during the year, with egg laying activity (or development of eggs) essentially negligible until the temperature was above a certain lower development threshold. However, we know this is not in the case for TPP. Tran et al. (2012) estimated the lower development threshold for eggs at 7.9°C on potato and 7.2°C on tomato. In addition, the model developed by Tran et al. (2012) assumes that temperature is the major driver of TPP development and activity (flights, movement); if other factors (such as wind, landscape features, other host plants) have a substantial effect on either TPP development or activity, then this model based on temperature alone may well not have very high prediction accuracy.

2.2 Trapping data

Approximately weekly trapping data were collected from several sources, with 38 datasets available for potato, 133 for tomato and six for tamarillo (Table 1). Although trapping was nominally weekly, the numbers of days traps that were left in the field ranged from 2 to 29 days (mean=7.4). In addition, the number of traps per crop varied from one to 12 (mean 3.6), with the number of traps varying between weeks for some crops. Crops with more than five traps in a crop were all Wattie's tomato crops. For all datasets, the numbers of TPP for each sticky trap in each trapping period were recorded.

Table 1: Summary of numbers of tomato potato psyllid datasets available, by crop, year and dataset.

Crop	Set Name	Regions	2009	2010	2011	2012	Total
Potato	Allenby	HB	0	2	0	0	2
	Sticky1	Various	0	0	16	0	16
	Sticky2	Various	0	0	0	4	4
	PRS*	SAuckland	3	4	5	4	16
	Total		3	6	22	15	45
Tamarillo	Sticky1	Northland	0	0	6	0	6
	Total		0	0	6	0	6
Tomato	Sticky1	HB	0	0	1	0	1
	Sticky2	HB	0	0	0	1	1
	Wattie's	HB	39	38	22	32	131
	Total		39	38	23	33	133

*PRS: Pukekohe Research Station: 'crops' are identified by location and whether there was a potato crop in the field or just volunteer potatoes. Trapping was almost continual in adjacent locations over the 4 years. HB = Hawke's Bay.

Most effort was put in collating, sorting and checking these data. Partly, this was because the data from the various datasets were formatted very differently or the datasets contained many errors (e.g. date formatting, incorrect year, no uniformity in data entry between weeks), making analysis impossible.

Within each region, the first trapping dates varied considerably (Table 2). Thus, the amount of information about TPP populations in crops was inconsistent across the dates, and in particular, there was perhaps less information about TPP numbers prior to the main population increase than may be required for reliable modelling. For the Northland tamarillo data, the total catch across the season was two or fewer TPP, so these data were not explored further. All these inconsistencies, whether they occurred in the field or while entering the data, confirm the findings of the scoping exercise of existing monitoring data in year two of this SFF programme (Dohmen-Vereijssen et al. 2013).

Table 2: Range of dates on which tomato potato psyllid traps were first put into crops (excludes Pukekohe PRS dataset).

Region	Season	First Trapping Dates
Northland	2011-12	11Sep - 25Sep
South Auckland/Waikato	2011-12	8Nov - 16Jan
	2012-13	28Nov - 14Feb
Hawke’s Bay	2009-10	28Oct - 21Dec
	2010-11	16Nov - 16Dec
	2011-12	13Oct - 2Apr
	2012-13	18Oct - 13Feb
Manawatu	2011-12	14Nov - 3Feb
Canterbury	2011-12	7Nov - 22Nov
Southland	2011-12	18Nov - 18Nov

For the majority of datasets, neither planting nor emergence dates were available. However, other than for the Pukekohe PRS traps, trapping did not begin until after planting, for either potatoes or tomatoes. Thus, apart from at PRS, there was no information on TPP numbers in a field before the planting of a crop there.

For nine of the 29 non-PRS potato crops, planting or emergence dates were available (Table 3). Of these, emergence data were available for seven, and of these seven, traps were placed into four of the crops after emergence, with three prior to emergence. Two of these three crops (both Allenby) had very high trap catches for the first set of traps.

Table 3: Summary of tomato potato psyllid (TPP) datasets for which planting or emergence data were available (potato crops only). Numbers trapped are for those TPP caught at the first week traps were put out.

Season	Crop	Planting	1st Trap into Crop	Emergence	Trapped
2010/11	Allenby	29/11/10	9/12/10	22/12/10	44
	West Rd	25/11/10	9/12/10	13/12/10	69
2011/12	Hawke’s Bay B	25/10/11	15/11/11	12/11/11	1
	Manawatu A	27/10/11	7/11/11	28/11/11	0
	Mid Canterbury B	25/10/11	9/11/11	-	1
	South Auckland B	10/08/11	1/11/11	-	0
	South Auckland C	11/12/11	9/01/12	28/12/11	7
	Southland A	26/10/11	11/11/11	7/11/11	0
2012/13	Hawke’s Bay A	4/9/12	10/10/12	3/10/12	0

2.3 Weather data

For each crop (location and year), the closest weather station listed on the MetWatch (www.hortplus.metwatch.co.nz) or NIWA CliFlo (cliflo.niwa.co.nz) sites was identified. For each of the growing seasons, hourly temperature data (Mean dry bulb, or Min and Max dry bulb, from which the mean was calculated) were downloaded, from 1 July at midnight to the following 14 January, at 2300 h. The July starting date was chosen as the proposed lowest density of TPP, and all crops had trapped at least 1 TPP by 14 January.

In several weather datasets, temperatures were missing on some dates for some hours. In a few datasets, there were long runs of missing data. Gaps of less than 24 hours were filled by linear interpolation.
Gaps of longer than 24 hours were filled by using the mean temperatures for each hour of datasets from other weather stations within the same region.

3 Methods of analysis

3.1 Degree days

Degree days (DD) is the sum of temperatures above a threshold θ, and below an upper threshold, from a given starting date (d=0) until an event of interest (d=D_e). In most New Zealand situations, the upper threshold can be ignored. Ignoring the upper threshold, DD is generally calculated using an estimated mean daily temperature T_d, where T_d might be estimated as the mean of the minimum and maximum daily temperatures, or by using a more complex method, such as the sine method (see Lindblad & Sigvald 1996for more references). DD is then calculated as follows:

$$DD = \sum_{d=0}^{D_e} (T_d - \theta) \times (T_d > \theta)$$

Here, $(T_d > \theta)$ is 1 if T_d is larger than θ, and 0 if T_d is less than or equal to θ.

For the present study, hourly mean temperatures T_h were available, allowing DD to be calculated from datasets of 24 temperatures per day instead of from estimated daily means. The calculation used was therefore:

$$DD = \left(\sum_{h=0}^{H_e} (T_h - \theta) \times (T_h > \theta) \right) \Big/ 24$$

where H_e is the number of hours to the event of interest, and the sum is divided by 24 to convert from degree-hours into degree days.

Two similar studies in the literature have been identified. In the first (Lindblad & Sigvald 1996), a degree day model was developed to predict the first occurrence of frit flies in oat crops. In the second (Bostanian et al. 2006), a model was developed to predict leafhopper cumulative abundance in vineyards at 5, 50, and 95% of the maximum population. In the frit fly paper (Lindblad & Sigvald 1996), the model was developed from data collected within a single region, for three or four crops within each of four seasons. In each year, the date on which five insects per trap per day had been caught was recorded per crop (traps were generally replaced daily). The median dates to a catch of five insects for each year were used for modelling, and degree days calculated for this median. The % coefficient of variation (%Cv=100*standard deviation/mean) between degree days for the four yearly medians was used to identify the ‘best’ combination of starting date (three were assessed) and lower threshold (six were assessed): the combination chosen was that with the smallest %Cv. The model was validated using data obtained for different regions. That paper describes a situation that is very close to the data explored here.

In the second paper for leafhoppers (Bostanian et al. 2006), the numbers of degree days until various percentages of the final population had appeared were identified by minimising the mean-square error between the predicted time and the actual time. This is a rather different situation from the one explored here. For the data described in this current report, a mean square-error for a particular threshold and start date can be calculated as the standard deviation (sd) of the calculated DD over crops, either for DD until the first non-zero trap, or DD until the first trapping with >0.5 TPP per trap per day. However, as the threshold is increased from the minimum observed temperature to the maximum, the sd will necessarily decrease to zero. This thus makes this second approach inappropriate for the current study.

To use the approach of the Lindblad & Sigvald (1996) paper described above, a set of data over several seasons from within one region is required. Only the Wattie's tomato dataset contained several crops in a single region for each of several seasons. However, trapping for those crops was only weekly, starting after the crop was planted, and sometimes there was no trapping within a week (for example, around Christmas). Therefore, this dataset was also not suitable to use with the approach of Lindblad & Sigvald (1996).

Some further formal data explorations were carried out using the dates of all crops until first occurrence of TPP, or until more than 0.5 TPP/trap/day (details not presented). However, none of this work resulted in a reliable indicator for the start of the major influx of TPP. The majority of the analysis presented here therefore consists of data summaries and graphical exploration. TPP numbers are in general presented as TPP/trap/day, which were calculated as:

$$\text{TPP/Trap/day}=\left(\text{Total TPP caught/No.Traps}\right)\text{/days traps were in the crop}$$

In many cases, graphs are drawn with x-axis as days since 1 July. Table 4 gives the number of days for the first of each of the following six months.

Table 4: Number of days from 1 July (all seasons) to the 1st of each successive month.

Date	1 Aug	1 Sept	1 Oct	1 Nov	1 Dec	1 Jan	1 Feb
Days from 1 July	32	63	93	124	154	185	216

All data manipulation, summary, graphing and analysis was carried out using GenStat (GenStat Committee 2013).

4 Results and Discussion

4.1 Pukekohe Research Station trapping data from potato crops

The majority of the potato trapping data from Pukekohe was collected from locations within the Pukekohe Research Station (PRS), with some data also from three locations that were reasonably close to PRS. This dataset includes almost continuous trapping values from mid August 2009 to mid March 2013 (Figure 1). In addition, trapping was done before potato crops (or experimental trials) were sown at the location, when there were only volunteer potato plants around.

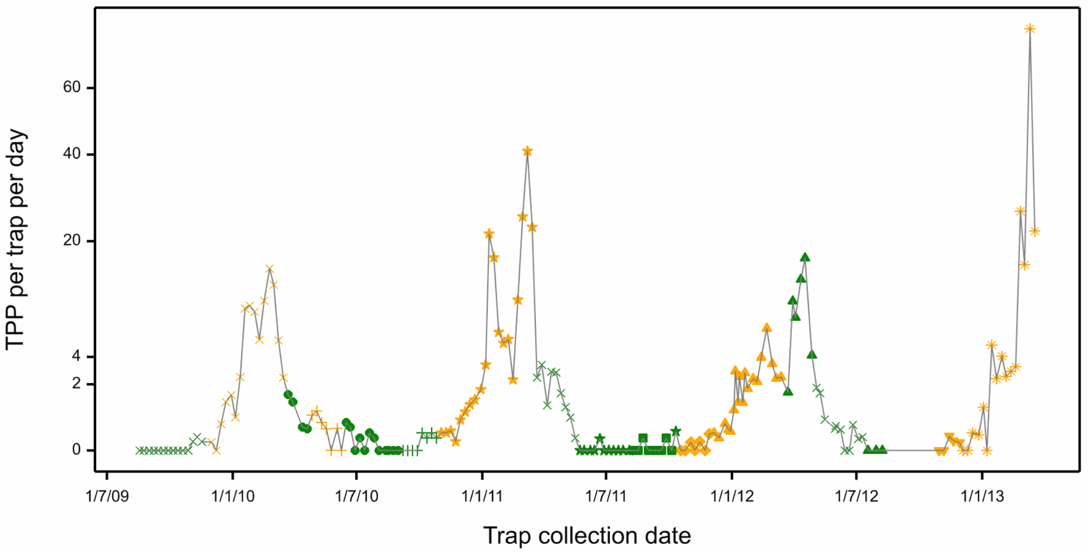

Figure 1: Trapping results for tomato potato psyllid (TPP) in potato crops at Pukekohe Research Station over several years. TPP counts are per trap and corrected for the number of days the trap was out in the field. Note that the Y-axis is square-root spaced, so smaller counts are easier to see. Symbols indicate nine different trapping locations. Colours indicate whether there was a crop/potato trial at the location (Orange: crop; Green no crop/just volunteer potatoes).

In each season, trap catches were low between about the middle of June and the end of October. After October, there was a steep rise in numbers, either immediately or by the end of December. The pattern was unaffected by the presence of the crop, in that there was no obvious step change in TPP numbers at the times when crops were planted/harvested.

For the three years where the entire potato growing season was covered, there were two peaks in numbers, with the first peak 7-10 weeks after the start of the rise in population, and a second peak 4-8 weeks after that. This suggests that two generations of TPP occur during the growing season.

Figure 2 shows the same trapping data, but plotted against days from 1 July, with catches shown until 14 January. This allows a comparison between seasons of the timing of the increase in TPP numbers, and also allows a better assessment of the rate of ‘background’ catch during the winter. The background catch was generally below 0.5 TPP/trap/day, and the rapid increase occurred after trapping numbers rose above 2-4 TPP/trap/day.

For all four seasons, the rise in numbers occurred after 150 days from 1 July (that is, the end of November or later, refer to Table 4). The rise in TPP numbers was earliest and largest for the 2010-11 season, which was an intermediate year for Pukekohe in terms of temperature (the warmest growing season since 2006 being 2007-08; (Vereijssen et al. 2013b). The timing of the rise was similar for the other three seasons, at c. 170 to 190 days after 1 July.

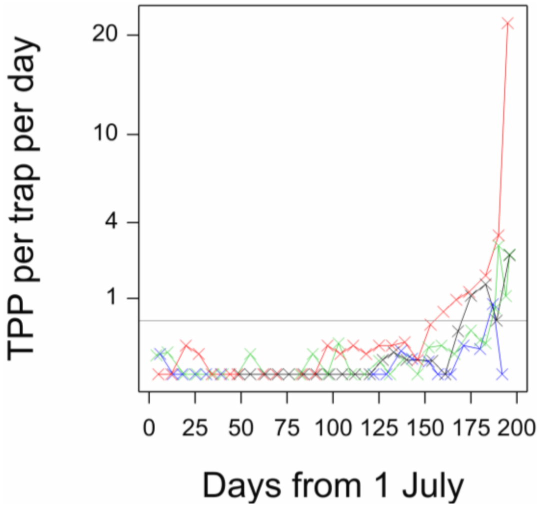

Figure 2: Tomato potato psyllid (TPP) trap catches for each season (to 14 January) plotted against the number of days since 1 July. Black: 2009-10; Red: 2010-11; Green: 2011-12; Blue: 2012-13. Grey line is at 0.5 TPP/trap/day. Note the Y-axis is square-root scaled, to enable detail in the smaller catches to be seen more easily.

The differences in timing of the rise in TPP numbers are probably related to weather, and temperature in particular. Figure 3 summarizes the temperatures for the whole study period. The observed TPP rise occurred after temperatures increased above a daily mean of about 12.5°C. The general temperature trend was very similar for the four seasons studied, with differences in mean trend between years for any day generally of 2°C or less. The overall mean temperatures for the four seasons were all between 13.3 and 14.6°C.Thus, any temperature influence on TPP development and arrival in a crop would be quite subtle, and the effect largely similar for the four seasons. In addition, with just a single set of traps, we had no information about variation between crops within the region in terms of the arrival of TPP. It is unlikely that exactly the same pattern of catches would be observed, even for crops that were located quite close to each other. Therefore, any model built using just these PRS data is unlikely to be robust.

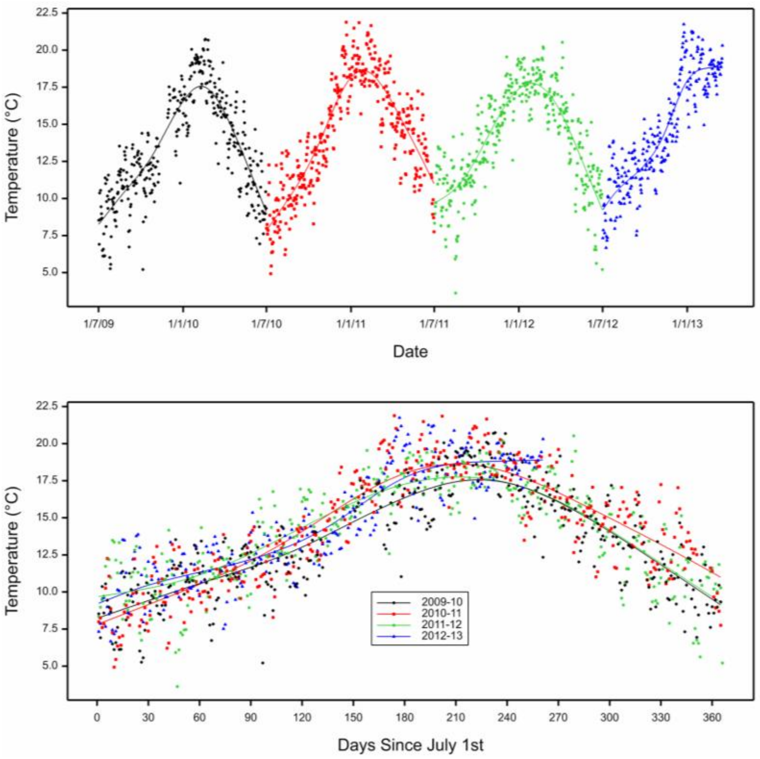

Figure 3: Mean daily temperatures for the study period for Pukekohe Research Station, plotted against date (top) or days since 1 July (bottom). Lines are smoothed trends (cubic smoothing splines).

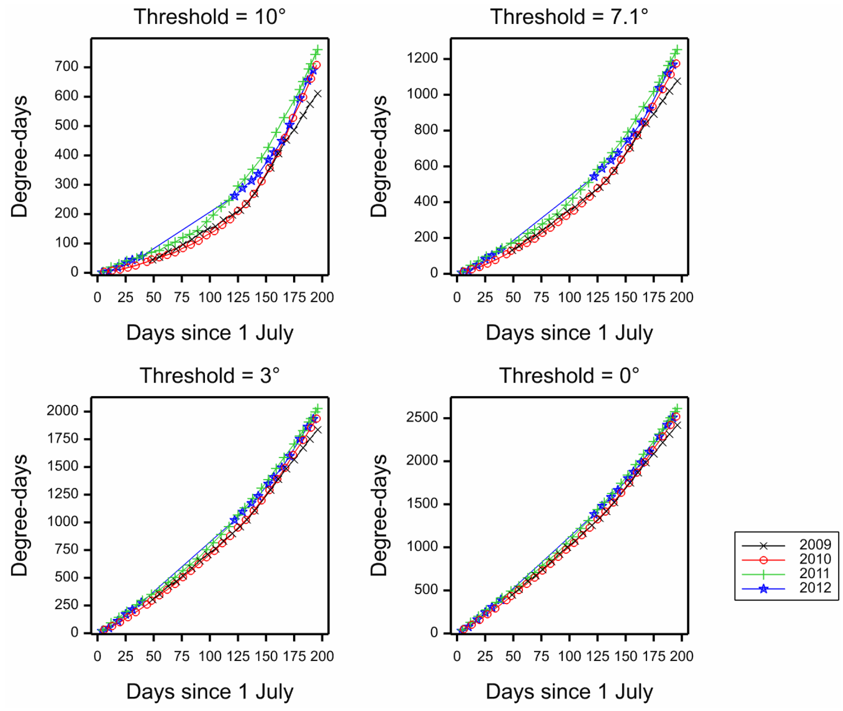

Figure 4: Accumulated degree days from 1 July for four seasons at Pukekohe Research Station, for four temperature thresholds, for dates when tomato potato psyllid traps were collected.

The differences between the seasons can be explored in slightly more detail by looking at DD (Figure 4). The greatest (visual) difference between the different planting seasons can be seen for the thresholds of 10 or 7.1°C. Thus, if temperature were the major driver of the differences between seasons, either of these thresholds would be most useful for predicting the different dates when the rise in TPP numbers was likely to occur. This is explored directly in Figure 5, where the data from Figure 3 are plotted against degree days, calculated using two starting dates and four different thresholds (θ). The starting dates were chosen as (a) 1 July, proposed by various PFR scientists working with TPP, although quite often winter (1 January or 1 March in the Northern Hemisphere) is used as a starting date (Pruess 1983); and (b) 1 October, as this is before planting/emergence for most crops. The thresholds chosen were 10°C (as this is below the temperature where the TPP numbers appeared to rise rapidly), 7.1°C (as used in the model of Tran et al. 2012), 3°C (~half of 7.1°C), and 0°C (the possible lowest threshold for TPP development).

The patterns for the eight combinations were extremely similar and closely followed those for the trap data plotted against days (Figure 2): there was no combination of start date and threshold for which the trap catch from the four seasons rose at very similar DD accumulations. The rise in trap numbers for the 2010-11 season always preceded that for 2009-10, which preceded that for the other two seasons, which in turn rose at reasonably similar DD accumulations.

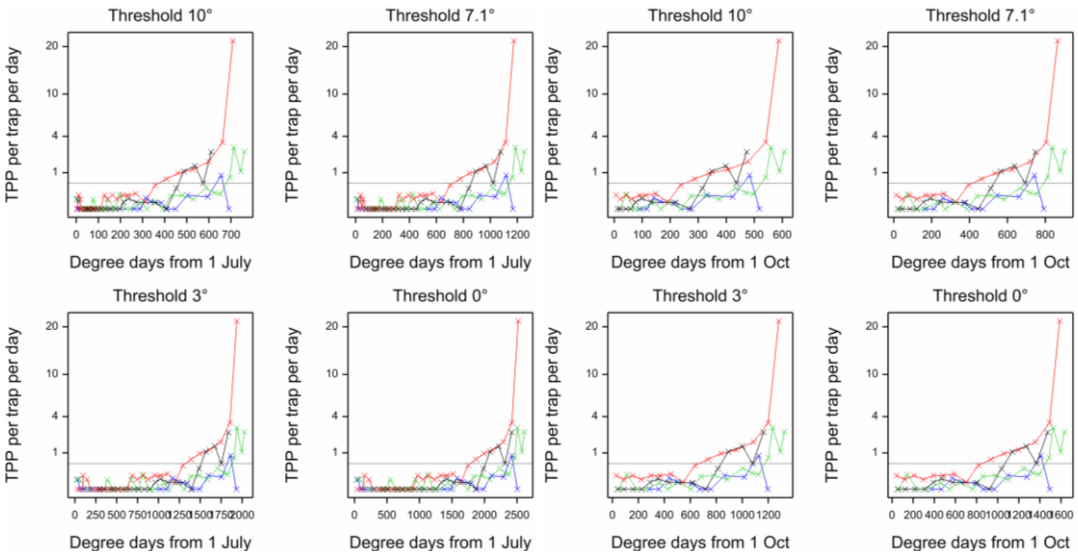

Figure 5: Accumulated degree days from 1 July (left) or 1 October (right), to 14 January, with temperature thresholds for tomato potato psyllid (TPP) of 10, 7.1 (Tran et al. 2012), 3 and 0°C at Pukekohe Research Station. Note that since the lowest hourly temperature was 0.4°C, a threshold of 0°C means that DD is the sum of the observed temperatures. The grey horizontal line is at 0.5 TPP/trap/day.

Pukekohe has relatively mild over-winter temperatures compared with regions further south, so it is possible that in the cooler regions, TPP become less active over winter. In these cases, it would be expected that there would be an obvious time when TPP begin to be active, since trap catches would change clearly from none caught to some caught. So far, continuous trapping in a single location over many months/years has not been carried out other than at the Pukekohe Research Station, so background TPP numbers and seasonal patterns are harder to explore for the other regions.

4.2 Hawke’s Bay trapping data from tomato crops

Trapping for TPP began in each crop shortly after planting the seedlings. However, initial trapping varied considerably between crops (Figure 6), and the earliest date on which traps were set up was earlier in 2009 and 2011 than in 2010 and 2012.

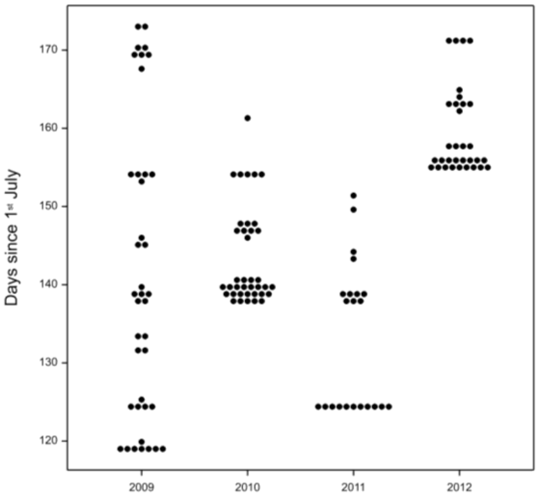

Figure 6: Dot-histogram of days since 1 July that tomato potato psyllid traps were first collected, for four seasons, with one dot for each of the Wattie's tomato crops in Hawke's Bay.

This very variable start date for trapping may mean difficulty in identifying a good predictor (in terms of DD) for when TPP numbers begin to increase sharply. However, as an initial examination, the method of Lindblad & Sigvald (1996) was used with DD to both 0.5 and 4 TPP/trap/day (thresholds as identified from the PRS data). The median dates to catches of 4 TPP/trap/day varied from 7 to 25 January, and for 0.5 TPP/trap/day from 9 December to 7 January. Two starting dates, 1 July and 1 October, and four thresholds (10, 7.1, 3, 0°C) were examined, as used with the PRS data above. For this method to be effective, the temperatures across the region would need to be similar. When mean daily temperatures between the weather stations closest to the individual crops where trapping data were available in each season were compared, the mean daily temperatures were indeed very similar (Figure 7). This indicates also that any differences in catches between crops at any given trapping date will be driven by factors other than temperature.

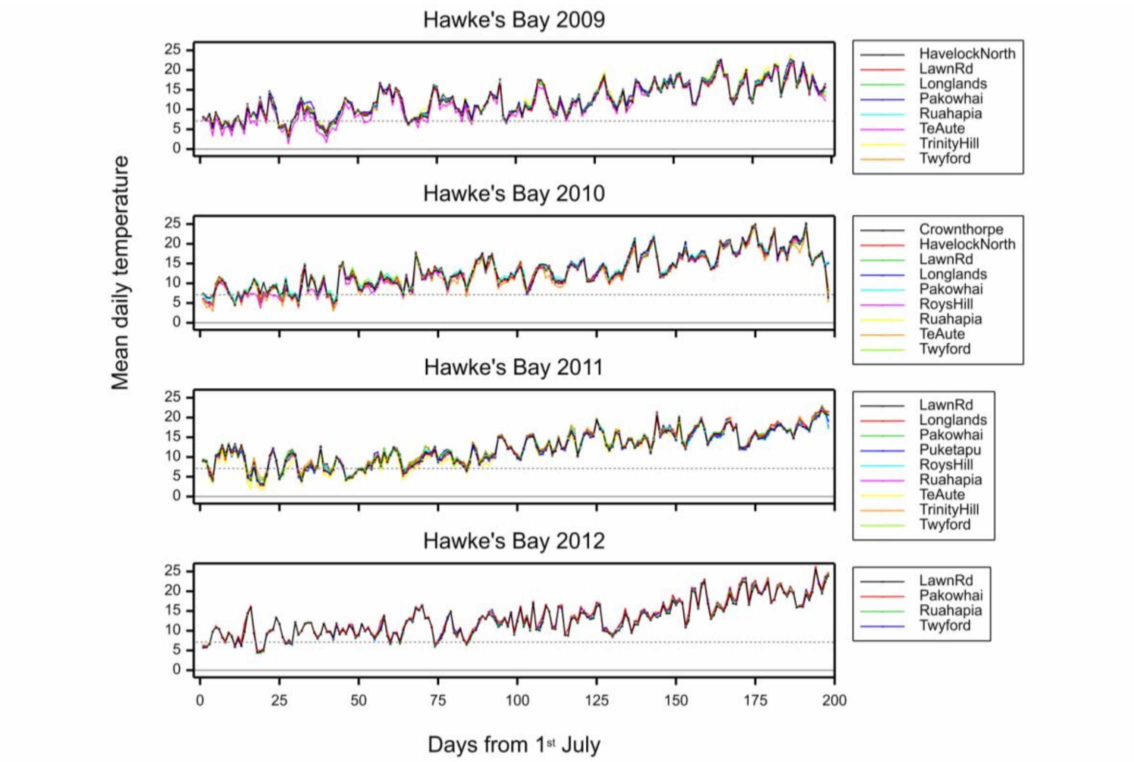

Figure 7: Mean daily temperature for each weather station for each season in Hawke's Bay. Grey solid line is at 0°C and grey dotted line at 7.1°C.

Since the weather data within a season were very similar for stations across the region, the temperature data from the Lawn Rd station were used for the analysis (Figure 8). For both trapping numbers, the 'best' combination of start date and temperature threshold from those examined was 0°C. From this, the predicted DD accumulations above 0°C from 1 July to 0.5 and 4 TPP/trap/day were 2130 and 2520 respectively. However, a lower %Cv may have been obtained for a threshold below 0°C (the lowest observed hourly mean temperature for Hawke's Bay as measured at Lawn Rd for the period of trapping shown here was -3.1°C).

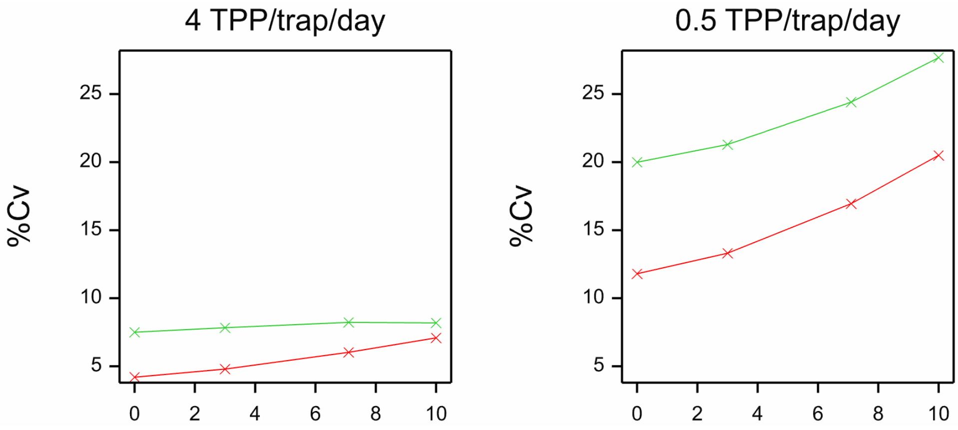

Figure 8: Percent coefficient of variation (%Cv) (to quantify the variation in the measurements) for degree day (DD) calculations using four different temperature thresholds (θ, x-axis) and two starting dates (1 July: red line, 1 October: green line), for the median date until either 0.5 or 4 tomato potato psyllid (TPP)/trap/day was reached within each season (after Lindblad & Sigvald (1996)).

Because the PRS data suggested that such a simple approach might not produce reliable results, a more detailed look at the Wattie's data was warranted. Figure 9 shows the trapping data for all the Wattie's tomato crops, for all four seasons: the average trap catch started low and rose rapidly, similarly to the PRS data. However, even when the average trap catch was high, there were still crops for which the catch was quite low or even zero, and there was a large variation at any date in catch between crops. This may be in part because some crops had been sprayed. The rapid rise started at approximately the start of January, but for some crops, there were larger numbers (2-4 TPP/trap/day) before this date.

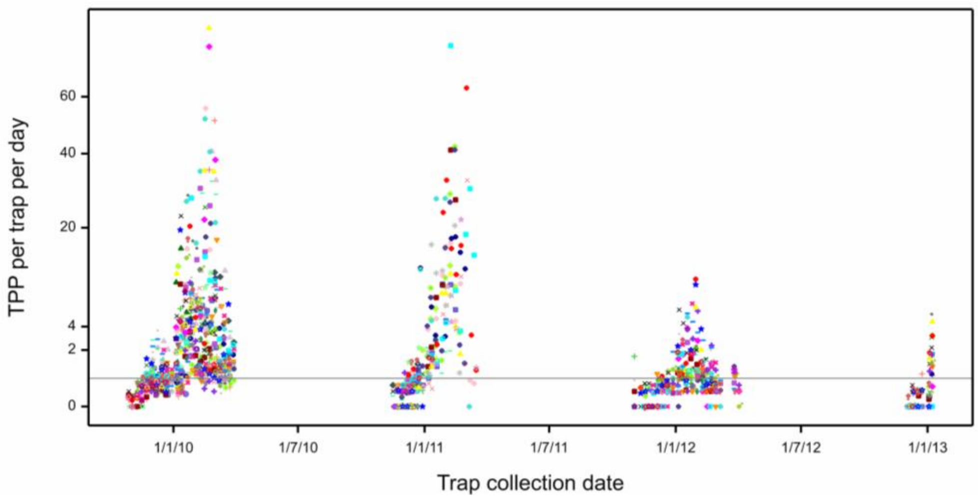

Figure 9: Tomato potato psyllid (TPP) in tomato crops for Hawke's Bay (Wattie's). TPP counts are per trap and corrected for the number of days for which the trap was out in the field. Note that the Y-axis is square-root spaced, so smaller counts are easier to see. Symbols/ colours indicate different trapping locations within a season. Grey line is at 0.5 TPP/trap/day.

As for the PRS data, if temperature were the major driver of the rise in TPP numbers, it would be expected that differences between seasons in the timing of this rise would be reflected in DD. DD data for the same four thresholds (θ) and two starting dates as above are shown in Figure 10 for the Lawn Rd temperature data.

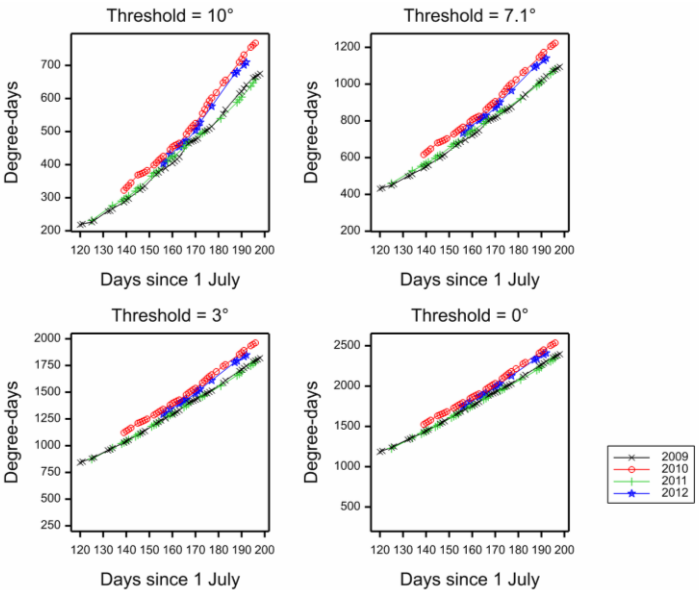

Figure 10: Accumulated degree days for four seasons at Hawke's Bay (Lawn Rd temperature data), for four lower development thresholds of tomato potato psyllid.

As at PRS, the greatest (visual) difference between the seasons was for 10 and 7.1°C. However, the DD patterns did not vary as much between seasons for this region as for Pukekohe.

4.3 Combining Pukekohe and Hawke's Bay trapping and DD data

The TPP trapping data for PRS plotted against DD from 1 July with a threshold of 7.1°C are shown in Figure 11, (repeating part of Figure 5). Data for the Hawke's Bay tomato crops are summarized in Figure 12. For both, the rise in TPP numbers is between c. 950 and 1100 DD. If 980 DD (marked in both figures) had been used as an indicator for when to start a spray programme, then the majority of crops, both for Hawke's Bay and PRS, would have been sprayed before the major rise in TPP. For the Hawke's Bay crops, 980 DD corresponded to 22 December to 5 January, and for Pukekohe, 17 December to 1 January. For Hawke's Bay, several crops did not have a rise in TPP until after this DD, but there were no crops before this date that had a significant rise in TPP numbers. Prior to 980 DD, most crops in both datasets had TPP catches of below 2 TPP/trap/day, and all were below 4 TPP/trap per day. This suggested decision point to initiate a spray programme (980 DD) is somewhat earlier than indicated by the results of the Lindblad & Sigvald (1996) analysis of the Hawke's Bay data, probably because that method uses the median date until a particular trapping threshold is reached. However, for good crop protection, it is desirable to identify a date or DD prior to when the majority of crops experience large increases in TPP numbers. In this sense, this ad hoc approach of simply looking at the data is likely to be more effective than using a more formal modelling approach.

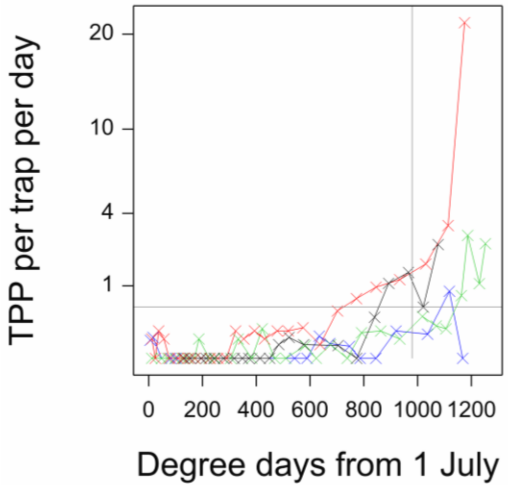

Figure 11: Tomato potato psyllid (TPP)/trap/day for Pukekohe Research Station data against cumulative degrees days above 7.1°C, from 1 July, for 2009 (Black), 2010 (Red), 2011 (Green) and 2012 (Blue). Horizontal grey line is at 0.5 TPP/trap/day. Vertical grey line is at 980 degree days.

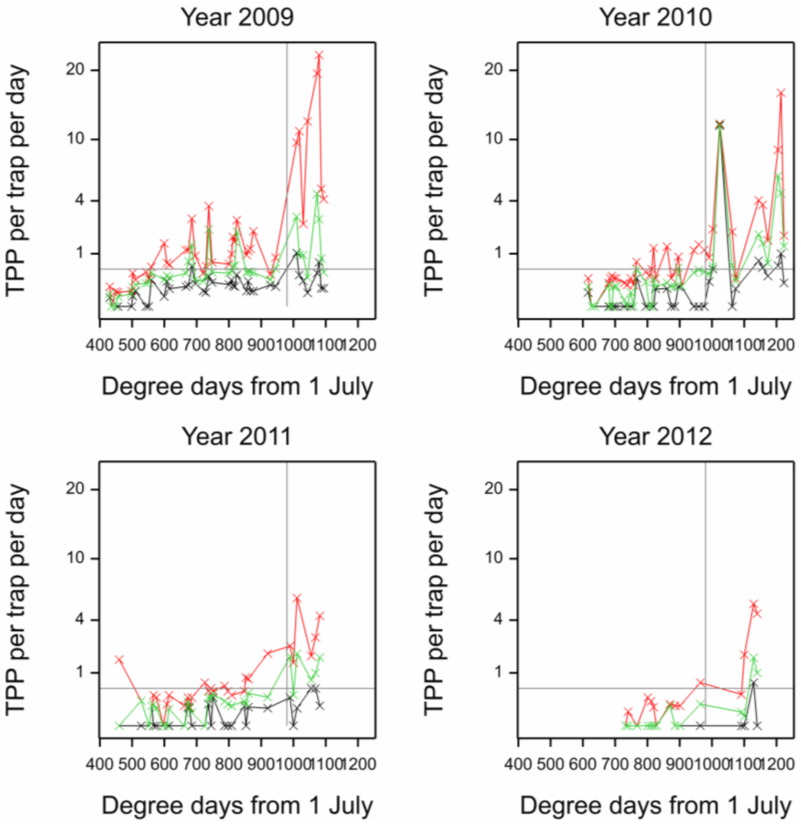

Figure 12: Minimum (black), median (green) and maximum (red) tomato potato psyllid (TPP)/trap/day for Hawke's Bay tomato data, against cumulative degrees days above 7.1°C, from 1 July, for four seasons. Horizontal grey line is at 0.5 TPP/trap/day. Vertical grey line is at 980 degree days.

4.4 Potato crops at locations other than Pukekohe Research Station

Figure 13 shows the data for the potato crops not so far discussed. As with the Hawke's Bay tomato data, the three North Island regions also experienced an obvious rise in TPP numbers reasonably soon after trapping began. However, there were fewer TPP caught for the South Island potato crops, and it is difficult therefore to determine whether the same pattern occurred there.

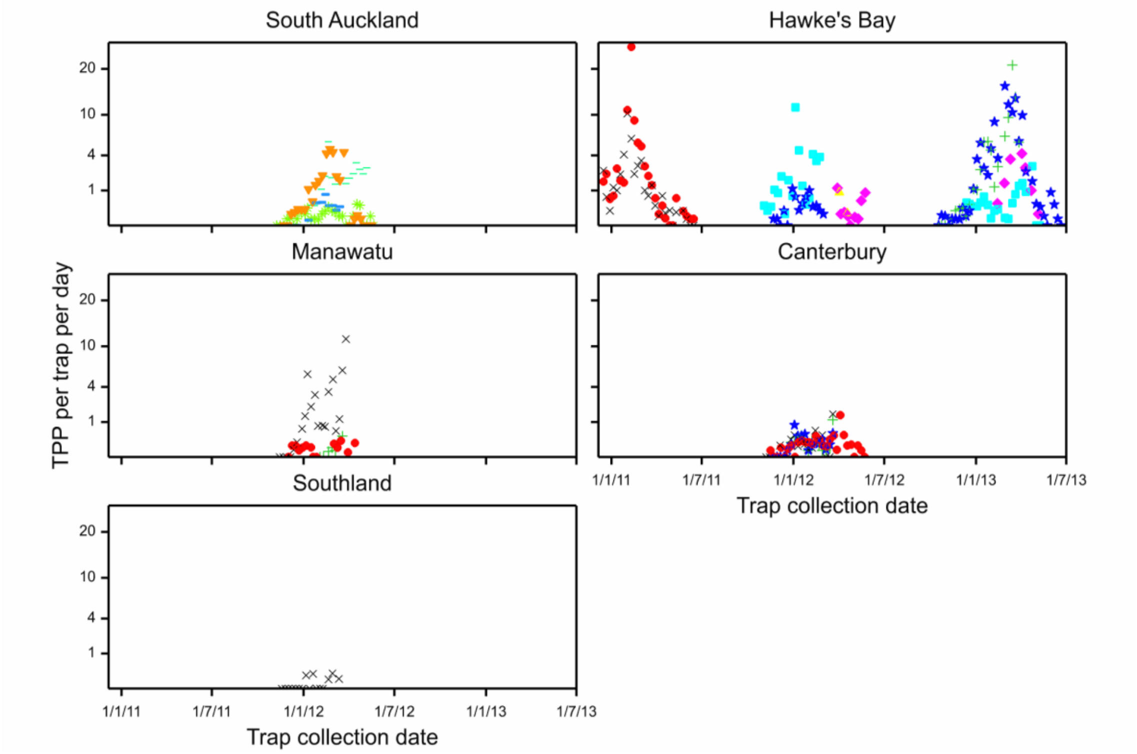

Figure 13: Tomato potato psyllid (TPP) trapping data for potato crops in locations other than Pukekohe Research Station. TPP counts are per trap, and corrected for the number of days the trap was out in the field. Note that the Y-axis is square-root spaced, so smaller counts are easier to see. Symbols/colours indicate different trapping locations.

The weather associated with regions other than Pukekohe and Hawke's Bay is shown in Figure 14. As for the other regions, where there were data from more than one weather station (Canterbury), the temperature profiles were extremely similar for the stations. Thus, if temperature were the primary driver of TPP numbers, it would be expected that the changes in trapping would be quite similar for all crops within a region within a season.

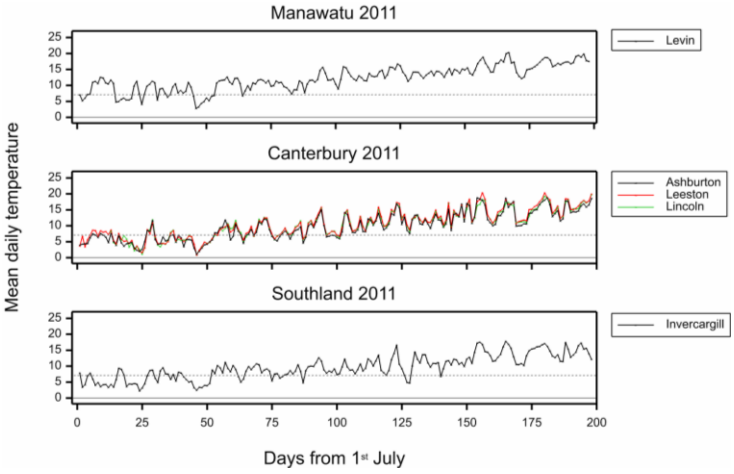

Figure 14: Mean daily temperature for each weather station for each season in regions other than Hawke's Bay and Pukekohe. Grey solid line is at 0°C, and grey dotted line at 7.1°C.

Figure 15 shows the TPP catches plotted against days since 1 July to 14 January. More than half the crops did not show a substantial rise in TPP numbers, including half those both in Hawke’s Bay and in South Auckland (Pukekohe, sites not at PRS). Figure 13 suggests that there was a rise in TPP for crops in these regions, but that it occurred later than in mid January.

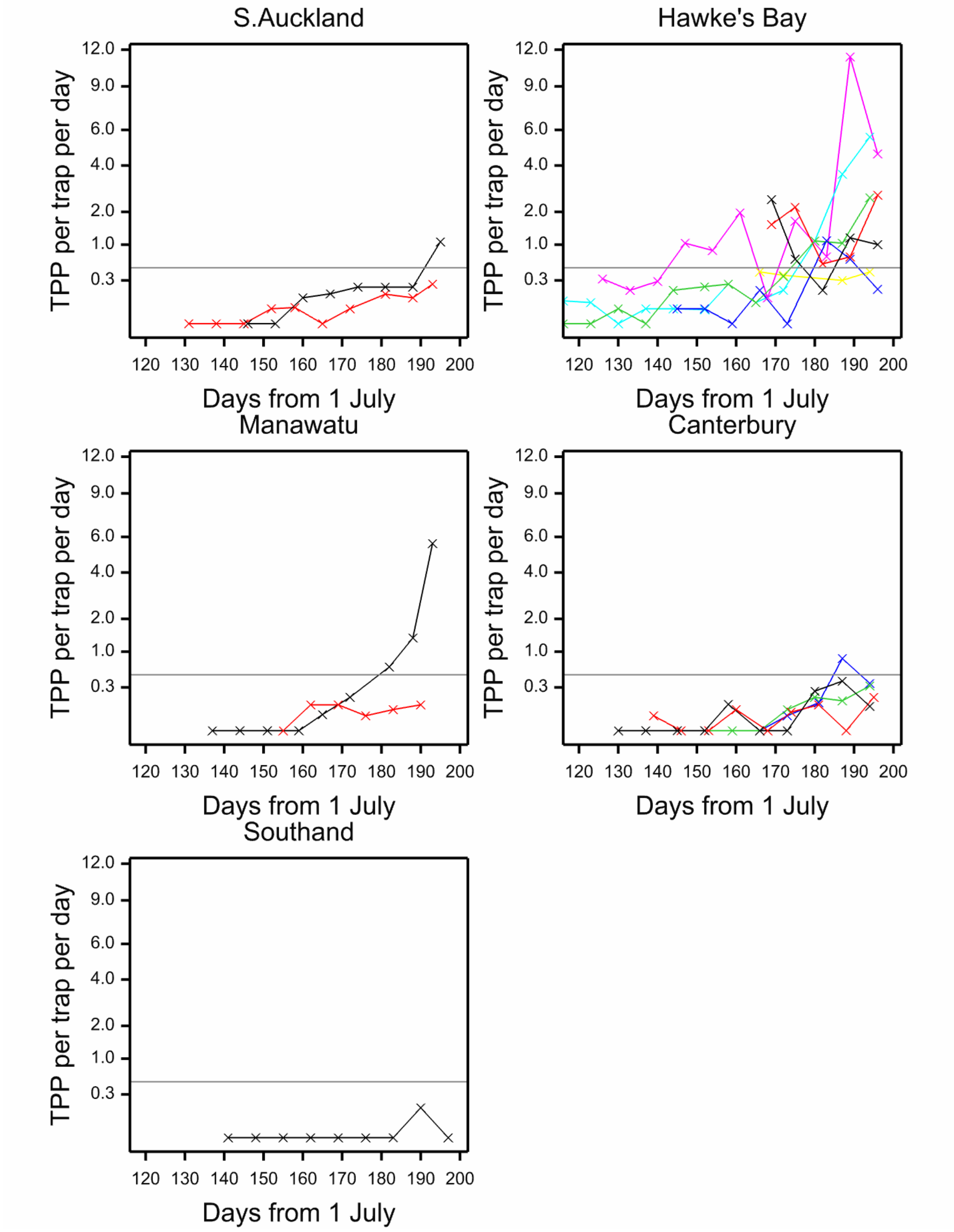

Figure 15: Tomato potato psyllid (TPP) trap catches in potato crops for each season (to 14 January) plotted against the number of days since 1 July for locations other than Pukekohe Research Station. Colours indicate individual crops. Grey line is at 0.5 TPP/trap/day. Note the Y-axis is square-root scaled, to enable detail in the smaller catches to be seen more easily.

Figure 16 shows the same data plotted against DD from 1 July (threshold of 7.1°C), including a line indicating 980 DD. For the two South Auckland crops, 980 DD occurred well before the rise in TPP numbers, but at an appropriate time to indicate the start of a rise for the Hawke's Bay and Manawatu crops (and possibly those in the Waikato). Psyllid numbers in Canterbury and Southland did not rise above 4 TPP/trap/day, indicating that spraying was probably not required for crops in these regions in those years. This will need to be reassessed with current data, as we have observed higher than normal TPP numbers in 2012-13 in Canterbury.

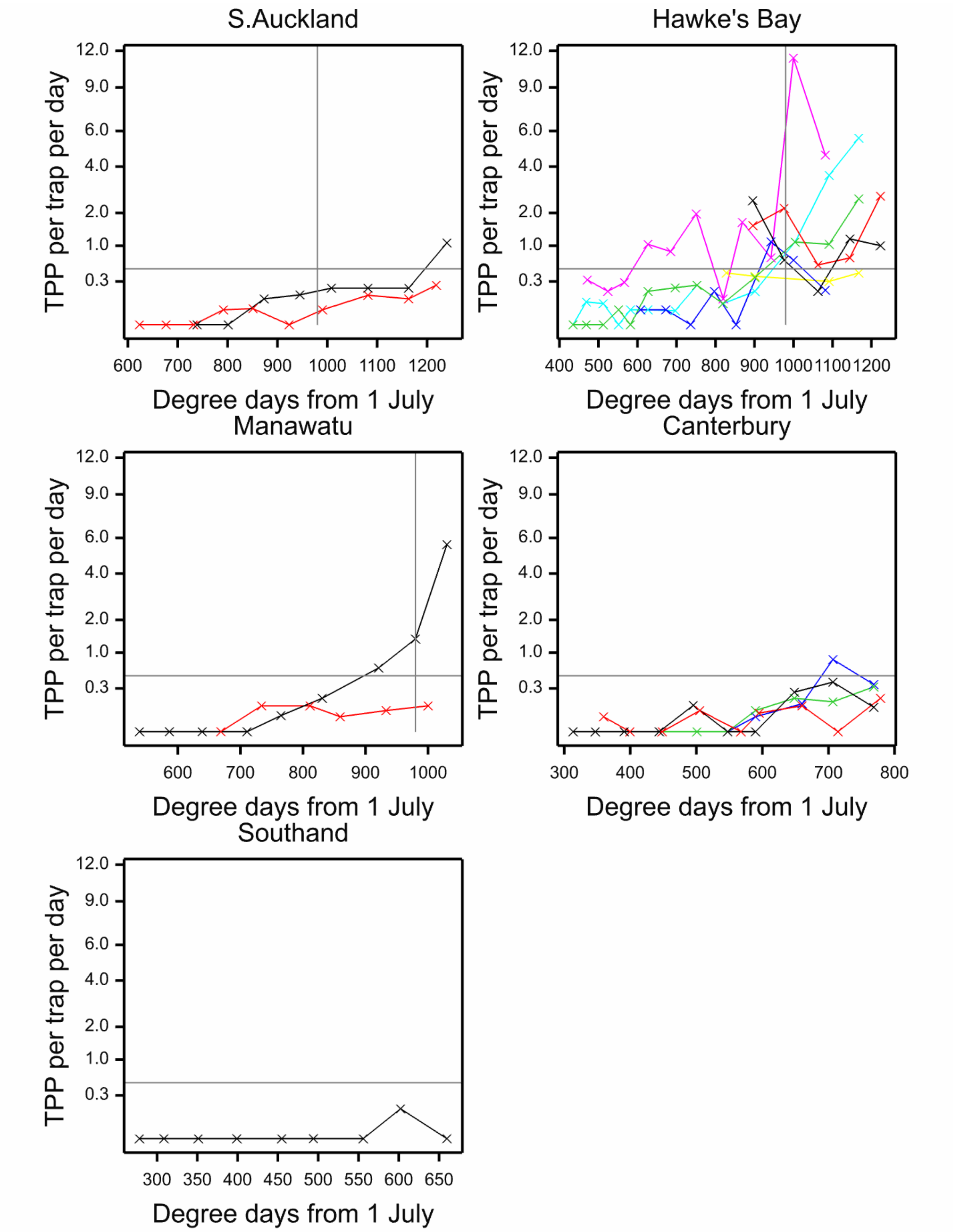

Figure 16: Tomato potato psyllid trap (TPP) catches for potato crops for each season (to 14 January) plotted against the degree days from 1 July for locations other than Pukekohe Research Station with at threshold of 7.1°C. Colours indicate individual crops. Grey line is at 0.5 TPP/trap/day. Vertical grey line is at 980 degree days. Note the Y-axis is square-root scaled, to enable detail in the smaller catches to be seen more easily.

5 Discussion of practical application

The data exploration presented here suggests that, for degree days calculated from 1 July with a threshold of 7.1°C, c. 980 DD provides a useful indication for North Island crops of when TPP numbers are about to increase rapidly. However, this threshold was less useful for South Island crops, principally because the large increase in TPP numbers was not observed in these regions in the years included in the analysis. However, we observed higher numbers than previously in the 2012-13 season, and the 2013-14 season has had a very warm start that will probably lead to higher numbers earlier in the growing season.

The associated 0.5 TPP/day/trap (3.5 TPP per week) at 980 DD corresponds well with results from work carried out by Walker et al. (2012), who concluded for early crops in Pukekohe that "from these 3 years of trials ... low trap catches (<3 TPP adults per trap [per week]) may indicate that invading populations are below an economic threshold up until about mid-December, or in crops close to harvest in December."

Given the patterns observed in Figure 5, it is probable that an equally useful indicator could have been derived from DD based on a later date or a different threshold; the starting date of 1 July has primarily been chosen based on the experience of scientists, and the 7.1°C threshold because that was used in the model of Tran et al. (2012). These are based on experience and, in case of the threshold, an estimate resulting from small laboratory studies, which may not represent the environment in the field (Bergant & Trdan 2006). The development time for the different life stages of Lso-free TPP and the egg-to-adult total degree days were estimated under constant temperatures and optimal conditions in the laboratory (Tran et al. 2012). Under field conditions, temperatures are not constant, and also the generation time of TPP will probably be variable because of host quality, microclimatic effects and genetic variation, which has already been shown by Yang et al. (2013). It is not known if there are genetically different TPP populations in New Zealand and this will be the focus of the research planned in the 'Growing Potato Exports' MBIE programme.

Estimated lower development thresholds vary for each of the TPP life stages, for each crop, and between TPP populations. Tran et al. (2012) estimated a lower development threshold of 7.1°C for total development (egg oviposition to adult) on potato. This is very similar to the temperature estimated by Marin-Jarillo et al. (1995), which was 7.0°C, but recent research on TPP populations in Texas, USA, estimated a lower development threshold of 5.85°C (Lewis et al. 2013). Tran et al. (2012) estimated the lower development thresholds for egg and nymph development at 7.9 and 4.2°C respectively. However, recent research estimated the lower development threshold for nymphs (Texas populations) at -2°C (OM Lewis and GJ Michels, pers. comm.). This is more consistent with field observations in New Zealand and the northern states in the USA, where recently emerged TPP adults have been observed in winter (J. Vereijssen, unpubl. data; Horton et al. 2013). The cold-hardiness of the different life stages has also been confirmed in other studies and observations (e.g. Pletsch 1947; Henne et al. 2010; Whipple et al. 2012), which indicates a probable lower development threshold than that estimated by Tran et al. (2012).

The analyses described here also indicate that rather than using degree days as a predictor of increases in TPP, adult TPP will be caught on sticky traps in a crop when the temperature is consistently above 12.5°C. This observation needs to be explored further using trapping data from trials where temperature is also monitored.

The data exploration did not result in a prediction of the time of first arrival of psyllids in a crop. TPP trap data were unaffected by the presence of a crop and that there were always some TPP around before the crop emerged. This confirms that TPP is present year-round in New Zealand, even in areas below the frost line (Taylor & Berry 2011; Vereijssen et al. 2013a; Vereijssen & Scott 2013). In periods when the crops are not in the field, TPP can be found in large numbers on other solanaceous plants like African boxthorn (*Lycium ferrocissimum*), poroporo (*Solanum aviculare* and *S. laciniatum*) (Taylor & Berry 2011; Vereijssen et al. 2013a; Vereijssen & Scott 2013), and other surviving solanaceous weeds (Taylor & Berry 2011), as well as volunteer potatoes (A. Pitman, pers. comm.). A preliminary study in 2012-13 in Motukarara (Canterbury) showed that while large numbers of all TPP life stages were found on African boxthorn in the period 29 June 2012 - 17 January 2013, hardly any TPP were found in the potato crop. After a few adults had been observed in the crop, aggregated populations of all life stages of TPP could be found in the crop a couple of weeks later. In general, psyllids are not regarded as strong flyers (A. Yen, pers. comm.) and TPP have been found to move in the prevailing wind direction (Cameron et al. 2013), TPP also respond to colour (Taylor et al. ; Henne et al. 2010) and seem to be attracted to Lso-infected plants before they move to non-infected plants (Davis et al. 2012). These factors may influence the movement of TPP in the environment and thus the colonisation of a crop. The spatio-temporal dynamics of TPP in relation to the non-crop and crop host plants throughout the year is researched in a Plant Biosecurity Cooperative Research Centre project.

Additional to the recommendations regarding data collection made previously (Dohmen-Vereijssen et al. 2013), there are other areas that need to be explored to develop a more refined ‘prediction model’. Firstly, Tran et al.’s (2012) work was conducted on Lso-free TPP. It is known that Lso has an impact on TPP (Nachappa et al. 2012), so their study should be repeated with Lso-positive TPP. Secondly, the development of TPP at temperatures lower than 8°C, which is the lowest temperature tested by Tran et al. (2012), should be explored for New Zealand TPP populations. Thirdly, the incidence of Lso in natural TPP populations is not known. Is there an annual difference in incidence and titre and what does this mean in practice? How many Lso-positive TPP could you have in a crop before it is rejected, and for how long? From trials conducted in 2012-13 in Lincoln, we know that Lso-free TPP also affect potato yields (A. Pitman, pers. comm.). The SFF field trials in Pukekohe and Lincoln should shed some light on this and the questions will also in part be explored in the current “Growing Potato Exports” MBIE programme. Also, what is the role of non-crop solanaceous host plants in harbouring Lso? These plants could be a source of Lso, which means Lso-positive TPP are readily available when the crop emerges. Finally, the usefulness of 980 DD as an indicator for the start of a spray programme should be re-assessed, using more data from unsprayed crops. It would be particularly useful to have data from a larger number of crops from the regions outside Hawke’s Bay and also to have continuous trapping (as at PRS) for regions other than Pukekohe. It would also be useful to have data that enables the exploration of factors other than temperature that may influence TPP numbers, for example diet (host plant) of the insect, prevailing wind direction, landscape characteristics, and the presence of non-crop host plants for both TPP and Lso.

According to Jones et al. (2010), obtaining a sound understanding of the epidemiology of the pathosystem selected is essential. This requires extensive knowledge of the factors that drive it, as the dynamics of its four components (pathogen, host, vector, and environment) all need to be incorporated into a predictive model. TPP and Lso have been relatively recent additions to the pests and diseases present in New Zealand. After a few years of focusing on how to manage the insect vector and to decrease Zebra Chip disease incidence (caused by Lso), it now seems the biology and ecology of the insect and the pathogen are under-researched, and these factors are sometimes hindering progress. Experience in New Zealand regarding management of TPP and resulting Zebra Chip disease incidence indicated that best results were obtained when insects were controlled when still low in numbers. The results of the analysis conducted in this study showed that if 980 DD had been used as an indicator for when to start a spray programme, then the majority of crops, both for Hawke’s Bay and Pukekohe, would have been sprayed before the major rise in TPP. With further research and refinement, the 980 DD approach should supply another management strategy to control TPP and Lso early in the growing season.

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