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Mesh Crop Covers for Non-Chemical Potato Pest & Disease Control: Final results from the 2016-17 Field Trial of Mesh vs. Agrichemicals

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Table of contents

Table of figures

Table of tables

1. Summary

- A large-scale field trial, under commercial conditions, was conducted to compare three meshes with different hole sizes (0.3, 0.4 & 0.7 mm) with a 'full monty' fungicide & insecticide regime and a null control, on their effects on tomato potato psyllid (TPP, *Bactericera cockerelli*) aphids, and potato blight (*Phytophthora infestans* and *Alternaria solani*).
- Mesh practically eliminated TPP (total of 12 individuals across all three mesh treatments) compared with chemicals (total of 1,614) and the control (total of 1,250). From this result, added to previous years results, it is concluded that mesh is effectively a 100% means of controlling TPP on potatoes. There is also a very low chance of TPP developing 'resistance' to mesh, and so it can be considered a permanant and complete solution to the TPP problem, i.e., the TPP problem on potatoes has been solved if growers use mesh crop covers.
- As mesh prevents TPP even landing on the potato crop it is believed that it will also achieve close to 100% prevention of *Candidatus* Liberibacter solanacearum (CLSo) infection of potatoes. Due to insufficient funds, only 20 tubers from the control and 20 from the mesh 0.3 mm were tested with all control tubers infected and zero infection from mesh tubers.
- Yield was significantly increased by mesh, with a bulk yield of 94.53 t/ha for the best mesh compared with 84.47 t/ha for agrichemicals and 74.97 t/ha for the control, a 12% increase over chemicals and 26% increase over the control. Mesh marketable yield for tubers >60g was 86.5 t/ha, and 68.2 t /ha for >125g tubers, a 24% and 60% increase over agrichemicals. Average tuber weight and maximum tuber weight from mesh both increased 67% over agrichemicals. This yield increase considerably exceeds the industry target of 12% yield increase over ten years, providing more than double the target in a single year not a decade.
- The best two mesh yields also exceeded the modelled / theoretical maximum yield of 90 t/ha.
- Mesh is cheaper than agrichemicals which coupled with higher yields means that mesh increased the field gate returns by between $4,531 to $21,110 (27% to 75%) from a lower input - lower return to a higher input - higher return scenario. This considerably exceeds the industry target of a increase in returns of $1,500 over ten years, but achieving that increase in one year.
- Mesh also impacted microclimate with an increase in temperature, giving a 19% increase in growing degree days, as well as reducing relative humidity, at temperatures above 15°C and also considerably reducing wind damage to the haulm.
- As in previous trials, aphids got under the mesh and large populations started to build so were controlled by Chess. All other means by which the aphids could be getting under the mesh are now considered exhausted and it is hypothesised that winged adults are alighting on the mesh, producing nymphs which can then penetrate the mesh. Due to the very small holes that aphid nymphs can get through, coupled with mesh inevitably getting damaged / holed in real-world use, it is considered impossible to have an aphid proof mesh.
- Therefore, a biocontrol program, based on existing glasshouse practices, needs to be developed to control any aphids that get under the mesh, along with the residual TPP. This should then achieve as close to zero insect pests in potatoes as it is possible to attain.
- Due to low blight levels this year, this trial has produced little information on blight, apart from an indication that mesh and agrichemicals achieved similar control of blight which in turn had statistically lower levels than the control.
- A range of future research is considered vital to create a fully farm-ready mesh system for potatoes.
    - Solving the aphid problem with biocontrol, particularly for the seed industry.
    - Control of blight both early and late needs to be causally proven.
    - Direct growth / yield benefits of mesh need elucidating.
    - The ability of mesh to control all other potato pests needs to be established.

2. Introduction

This 2016-17 field trial builds on the previous work by the Future Farming Centre (FFC) and partner organisations on the use of mesh crop covers for the control of tomato potato psyllid (TPP) & blight while boosting crop yields (Merfield, 2012, 2013) available from www.bhu.org.nz/future-farming-centre/information/crop-management/crop-production/mesh-crop-covers-for-potato-blight-and-pest-control and two journal publications (Merfield *et al.*, 2014; Merfield *et al.*, 2015).

Previous trials and laboratory work had shown that 0.6 mm mesh is a total barrier and highly effective control for TPP, both as a physical barrier, and, it also appears that TPP is inhibited by reduced UV light levels, so even when TPP get under mesh their speed and growth under the mesh is considerably reduced from open field conditions.

2.1. UV light trial

The 2015-16 UV light trial (not yet published) showed a clear correlation between the level of UV light transmitted by different crop covers (mesh and polyethylene) and the level of foliar blight symptoms (Figure 1, left chart) indicating a possible cause. While this is a statistically strong correlation, it is not causation so the effect should still be considered as preliminary. A surprisingly similar result was found for foliar TPP symptoms (i.e., psyllid yellow) (Figure 1, right chart) which, on the bases that foliar symptoms are causally linked to TPP populations points to TPP being 'sensitive' to the UV light environment, though again this is a correlation with a proxy measure, so needs substantiation. This could also in theory be due to UV light directly effecting the CLSo within the plant, though this is considered a less likely scenario.

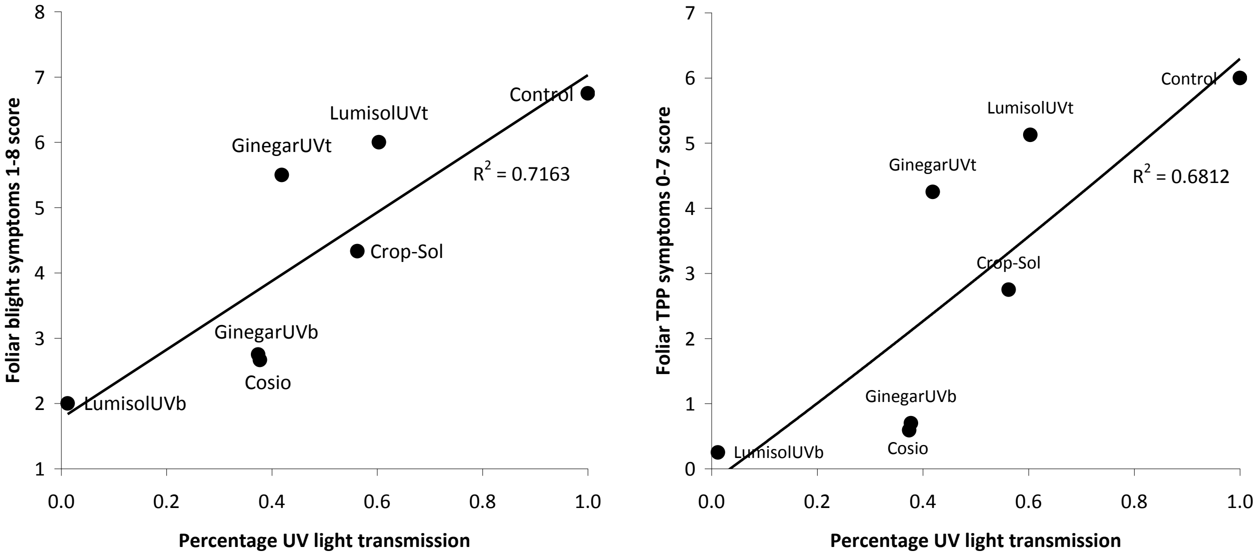

Figure 1. Relationship between the amount of UV light transmitted by the crop covers and foliar blight symptoms (left chart) and foliar TPP symptoms (psyllid yellows) (right chart).

2.2. 'Ultra fine mesh' test

Also in the 2015-16 season, a non-replicated 'test', using cv Moonlight, of a single piece of 'ultra fine mesh' with hole sizes of 0.15 x 0.35 (Ludvig Svensson ECONET 1535, www.ludvigsvensson.com/climatescreens/products/additional-products/insect-control/econet-1535) produced exceptional plant growth and yield with almost non-existent blight symptoms, despite condensation under the mesh for prolonged periods and poor crop husbandry (3rd year of organic cropping, no fertilisers, erratic irrigation) (Figures, 2, 3, & 4). In addition there was a very high proportion of exceptionally large tubers from under the mesh (Figure 5).


Figure 2. ECONET 1535 field test, showing accelerated potato growth under the mesh. Cv Moonlight.


Figure 3. ECONET 1535 mesh showing condensation under the mesh. Cv Moonlight.


Figure 4. Potato foliage from under the ECONET 1535 mesh left, uncovered right, at harvest. Cv Moonlight.


Figure 5. Comparative yield from ECONET 1535 left, compared with control right, note dominance of large tubers. Cv Moonlight.

Previous trials managed by FAR with Plant & Food Research (PFR) had also suggested that aphids, believed to be the peach-potato aphid (*Myzus persicae*), were getting under the mesh, potentially by penetrating the mesh.

2.3. Conclusions

Taken as a whole the research to date indicates that mesh can be:

- Highly effective at controlling TPP, especially if it is dug into the soil thus eliminating any entry for TPP around the mesh edges;
- That the UV blocking properties of mesh are probably the cause of the reduction in blight symptoms and also inhibition of TPP multiplication and spread under the mesh;
- Mesh may have a direct yield boosting effect and this is more pronounced the finer the mesh (smaller hole size).

This trial therefore aimed to build on these previous trials and fill in the gaps.

- Compare three different mesh hole sizes: 0.6, 0.3 and 0.15 mm;
- Compare mesh with a full agrichemical, blight and insect pest, management regime;
- Remove all green bridge effects as a source of aphid infestations.

3. Methods

3.1. Trial design

The trial location was the FAR field trial site at Lincoln University 43°38'15.89" S 172°28'17.43" E
www.google.co.nz/maps/@-43.6377885,172.4713695,182m/data=!3m1!1e3
http://w3w.co/cuts.shaky.rescuer

The trial is a randomised complete block field trial with 4 + 2 = 6 replicates: four replicates were used for all measurements except yield, which used the full six replicates to give increased statistical power.

Treatments were:
- Null control;
- Agrichemicals;
- Mesh 0.7 mm hole size;
- Mesh 0.4 mm hole size;
- Mesh 0.3 mm hole size.

Mesh was supplied free of charge by Crop Solutions Ltd. UK www.cropsolutions.co.uk. The original request for mesh hole sizes was 0.15, 0.3 and 0.6 mm, to match the 'ultra fine mesh' (0.15 mm) the smallest commercial hole size (0.3 mm) and the mesh used in previous research (0.6 mm). However, the supplied meshes, when measured, had larger hole sizes (as above) but due to time and cost limitations new sheets could not be supplied so the above mesh sizes were used. Mesh hole size was determined by measuring four randomly selected holes on four sheets for each mesh type under a microscope. The mesh supplied as 0.3 mm had oblong holes while the two other meshes had square holes. Measurements are summarised in Table 1.

Table 1. Measured hole sizes in the four mesh types according to manufactures size (labelled size). 0.3 mm labelled mesh had oblong holes so the short and long sides were measured.

Labelled size	Sheet average n=4				Combined measurements			Trial ID
	Sheet 1	Sheet 2	Sheet 3	Sheet 4	Mean	SD	SEM	
0.6	0.68	0.75	0.73	0.74	0.72	0.033	0.016	**0.7 mm**
0.3 short	0.37	0.40	0.38	0.39	0.38	0.013	0.007	**0.4 mm**
0.3 long	0.84	0.80	0.83	0.81	0.82	0.017	0.008	**0.4 mm**
0.2	0.33	0.33	0.34	0.30	0.33	0.018	0.009	**0.3 mm**

3.2. Site preparation including soil tests and fertilisers

The trial area was initially sprayed off with glyphosate, then the 1.65 m wide beds were marked out with a rotary hoe (rotovator) pass, that only cultivated the beds not the wheelings. Beds were then deep ripped using a set of ridged tines to a depth of at least 50 cm. Fertiliser was applied (Table 3) according to soil test taken 10 August (Table 2). The beds were then rotary hoed (rotovated) a second time to incorporate the fertilizers and produce a planting tilth.

Table 2. Soil test results.

Analysis	Level	Unit
pH	5.9	pH units
Olsen Phosphorus	20	mg/L
Potassium	0.64	me/100g
Calcium	10.9	me/100g
Magnesium	1.02	me/100g
Sodium	0.22	me/100g
CEC	18	me/100g
Total Base Saturation	69	%
Volume Weight	0.95	g/mL
Sulphate Sulphur	72	mg/kg
Boron	1.1	mg/kg

Table 3. Fertiliser types and application rates.

Fertiliser	Rate		Percent
Cropmaster diammonium phosphate (DAP)	300	kg /ha	24%
Potassium sulphate	200	kg /ha	16%
Potassium chloride	150	kg /ha	12%
Urea	100	kg /ha	8%
Kieserite (magnesium sulphate monohydrate)	150	kg /ha	12%
N-control 75 (slow release polymer coated urea)	350	kg /ha	28%
Borate 46 (15% elemental boron)	0.05	kg /ha	0.004%
Total	**1,250**	**kg /ha**	**100%**

3.3. Trial implementation

Plots were 9 × 9 meters to give real-world potato crop conditions. Plots were separated by approx. two meter buffers of pasture. Potatoes, cv Nadine, which is considered to have moderate blight resistance, were machine planted on 25-11-2016, ridged two days later, a further two days later 30 mm of irrigation was applied and eight days after that on the 9th Dec, the residual herbicides Sencor 500 + Batallion 2 L/ha were applied by tractor sprayer.

Mesh was laid on 13 & 14 Feb immediately prior to shoot emergence (Figure 6). Mesh was dug into the soil around the full periphery of each plot, and further residual herbicide was hand applied to the sheet edges, which eliminated all vegetation growing within a minimum of 20 cm from the outside edge of the sheet (Figure 7). Access under the mesh was by way of a one meter long, rain proof and therefore considered insect proof, zip sewn into the center of one edge of the mesh.

Figure 6. Field trial immediately post mesh laying, and pre-crop emergence.

Figure 7. Herbicide strip around edge of mesh.

3.4. Agrichemicals

Table 4. Agrichemical applications to field trial.

Agrichemicals applied to 'chemical' treatment					Agrichemicals applied to mesh	
Date	**Insecticide**	**Rate/ha**	**Fungicide**	**Rate/ha**	**Insecticide**	**Rate/ha**
6-Jan	Movento	560 mL	Nando	400 mL		
13 Jan	Movento	560 mL	Nando	400 mL		
20 Jan	Avid	600 mL	Bravo	1.6 litres		
			Mancozeb	2 kg		
27 Jan	Avid	600 mL	Bravo	1.6 litres		
3 Feb	Avid	600 mL	Copper Oxychloride	4 kg		
10 Feb	Sparta	500 mL	Reason	300 mL		
			Mancozeb	1 kg		
18 Feb	Sparta	500 mL	Reason	300 mL	Chess	200 g
			Mancozeb	1 kg		
23 Feb	Sparta	500 mL	Nando	400 mL	Chess	200 g
3 Mar	Sparta	500 mL	Nando	400 mL	Chess	200 g
8 Mar	Proteus	650 mL	Bravo	1.6 litres	Chess	200 g
			Mancozeb	2 kg		
17 Mar	Proteus	650 mL	Reason	300 mL	Chess	200 g
23 Mar	Proteus	650 mL	Copper Oxychloride	4 kg	Chess	200 g
8 Apr	Metafort	1.1 L	Copper Oxychloride	4 kg	Chess	200 g
15 Apr	Metafort	1.1 L	Copper Oxychloride	4 kg	Chess	200 g
21 Apr	Sparta	500 mL	Nando	400 mL		

An agrichemical regime, based on that used in the FAR field trials, was applied by tractor sprayer to the 'chemical' plots (Table 4). Effectively an insecticide and fungicide was applied weekly. The nozzles used were pairs of TeeJet Air induction XR Flat spray and XR extended range flat spray tips pointing forwards and backwards to maximise coverage and crop penetration as recommended by Nobel Adams (www.nobleadams.co.nz).

In addition, due to the outbreak of aphids in the mesh treatments, Chess was applied eight times to the mesh plots from the 18th February again using the tractor mounted sprayer (Table 4).

On the 24 Apr the burn-down herbicide Reglone was applied at 4.0 L to the chemical plots to destroy the haulm to prevent further damage from TPP feeding. The control and the mesh plots were not sprayed, to maintain the null foliar chemical application to the control plots and the haulm under the mesh had naturally senesced at this date so spraying off was not required.

3.5. Water management

Irrigation was applied by a travelling boom irrigator. Rainfall was measured with an on-site, rain gauge.

3.6. Data stations and pest and disease sampling

Each plot, in the first four replicates, had a data station positioned in the center of the plot, and under the mesh in the mesh plots. The data station consisted of a one meter long wooden stake, which was pushed into the soil with square piece of white painted plywood, 12 mm thick and 15 × 15 cm square, attached horizontally to the top of the stake, to provide protection for the data logger and vaseline slide from sun and rain, and to allow the mesh to slide over the data station.

Data stations carried a data logger which recorded temperature and RH every hour, a yellow sticky trap for TPP and aphids (and other insects) and a vaseline coated slide for trapping blight (*Phytophthora infestans* and *Alternaria solani*) spores. Yellow sticky and slide traps were put out for one week, every other week, i.e., one week on, one week off. Sticky trap and spore slides were read blind, with the whole trap / slide read for insects and spores respectively. It was realised after the second sampling date that staff could be vectors for aphids and TPP between the mesh treatments, e.g., a staff member enters a control plot, where aphids and/or TPP attached to their clothing, then moves to a mesh plot where the insects are dislodged. To reduce the possibility of such cross-contamination, staff first entered all the 0.3 mm mesh, then the 0.4 and 0.7 mm mesh, then the chemical and finally the control plots.

On seven dates, approximately two weeks apart, five whole leaves, from approximately the middle of the plant, were collected from each plot and the number of TPP and aphids on the leaves were counted.

On the same dates visual assessment of foliar TPP and blight symptoms were made against a visual key (Cruickshank *et al.*, 1982) for blight and the TPP psyllid yellows key developed for the 2015-16 UV light trial.

From the 10th Jan to 14 Feb, on four occasions, the length of four haulm stems was measured.

Figure 8. Trial on 18th April 2017 shortly prior to harvest.

3.7. Harvest

Total trial duration was 150 days. Research harvest lasted from the 26 April to 25 May 2017, i.e., starting shortly after Reglone burn down of the chemical plots. For each plot, four, 3 m lengths of row, containing 10 plants (total of 12 m, 40 plants per plot), were hand dug from all six reps and all tubers, down to approx. 1 cm dia. were collected. No tubers were dug from the first meter from the plot edge to avoid edge effects.

The total weight of tubers from each plot was recorded, then a representative sub-sample of 50 tubers per plot was collected by individually shaking the tubers out of the storage bags and taking every 20th tuber. Each of the 50 tubers in the sub-sample was cleaned, then, individually weighed to give a frequency distribution, and then the marketable yield of tubers >60g and >125g were calculated from the combined weight of the 50 tuber sample and the combined weights of the >60g and >125g tubers.

The 50 tuber sample was also used to determine the specific gravity (SG). Only market grade tubers, >60 g were used. Tubers were first weighed on scales, to 1 g accuracy, in a bucket with holes in the bottom and then the bucket was immersed in a container of water, placed on the same scales, without the bucket touching the container (the bucket was suspended in the container) again to 1 g accuracy. SG was calculated as weight in air / weight of water. As the SG was only used to compare among treatments, rather than an absolute determination of SG, water and potato temperature corrections were not used.

Ten tubers per plot of marketable grade >60 g were sub-sampled from the 50 tuber sub-sample and put into storage in a cool dark room for 50 days to test for sprouting. Due to the unexpected result of more sprouts on the mesh tubers at the day 50 count, tubers were then transferred to a controlled temperature (CT) room, (min 15°C max 25°C) in their paper sample bags and placed directly under (20 cm to top potato) four fluorescent lights (mix warm and day light tubes) for 25 days and sprouts >1mm long, and large sprouts >5 mm long, were counted.

Twenty tubers from control plots and 20 tubers from mesh 0.3 mm plots were tested for *Candidatus* Liberibacter solanacearum.

All results were analysed by ANOVA on untransformed data and separated by LSD at 5%. On all charts where error bars are presented the bar is the LSD. Where letters are used to signify statistical significance, columns with the same letters are statistically the same, columns with different letters are statistically different.

4. Results and discussion

4.1. Climate data

4.1.1. Water

A total of 255 ml of irrigation, in nine individual applications of ~25 mm was applied approx. fortnightly depending on rainfall. The total precipitation from the on-site rain gauge was 279.5 ml, giving a total of 534.5 ml of water applied, equating to 3.6 mm of water on average per day. The crop was therefore well watered and did not suffer from water stress at any time.

4.1.2. Temperature

Mesh caused an increase in temperature from the control through to 0.3 mm mesh, a 1°C increase for minimum temperature, a 1.6°C increase for average and a 6.3°C increase for maximum temperature, with the increase in temperature increasing with decreasing mesh hole size (Figure 12).

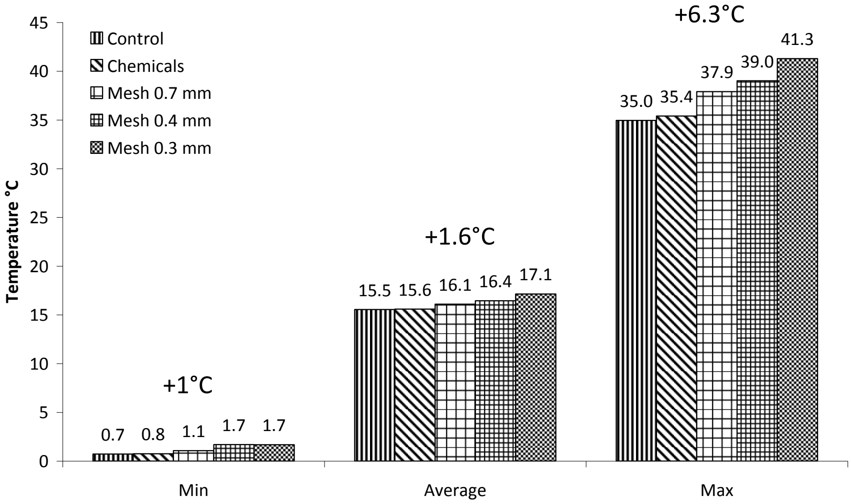

Figure 9. Minimum, average and maximum temperature for the treatments and increase from lowest to highest values.

While the temperature differences are relatively small, they add up to a considerable increase in growing degree days. Based on the formula $(((T_{max}+T_{min})/2)-4.4)$ with 4.4°C as the base temperature there are an extra 338 GDD for the mesh 0.3 mm treatment compared with the control which is a 19% increase from the control to the mesh 0.3 mm (Figures 10 & 11).

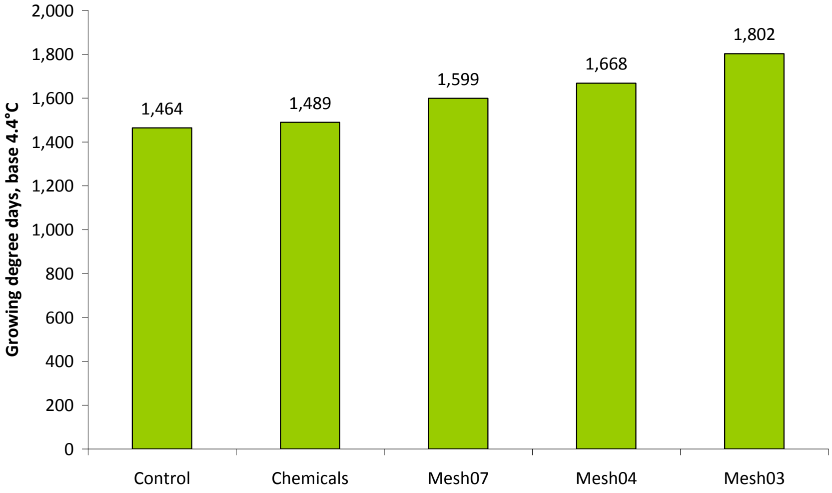

Figure 10. Total growing degree days for the five treatments, a 19% increase from the control to mesh 0.3 mm.

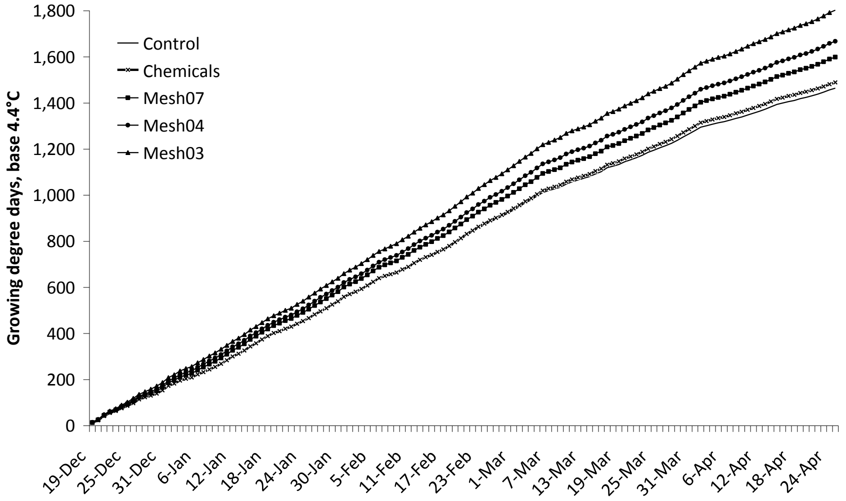

Figure 11. Cumulative growing degree days for the five treatments.

4.1.3. Relative humidity

The opposite trend was seen for relative humidity with mesh causing a reduction in RH with the smaller mesh having the greatest reduction (Figure 12). For minimum RH there was a four percentage point reduction in RH between the control and 0.3 mm mesh and for average RH a 2.3 percentage point drop. Maximum RH was the same for all treatments at 100%. The loggers did not read exactly 100% due to data logger variation / calibration issues, which while not ideal, as the variation was 0.7% this is not considered to be a critical problem.

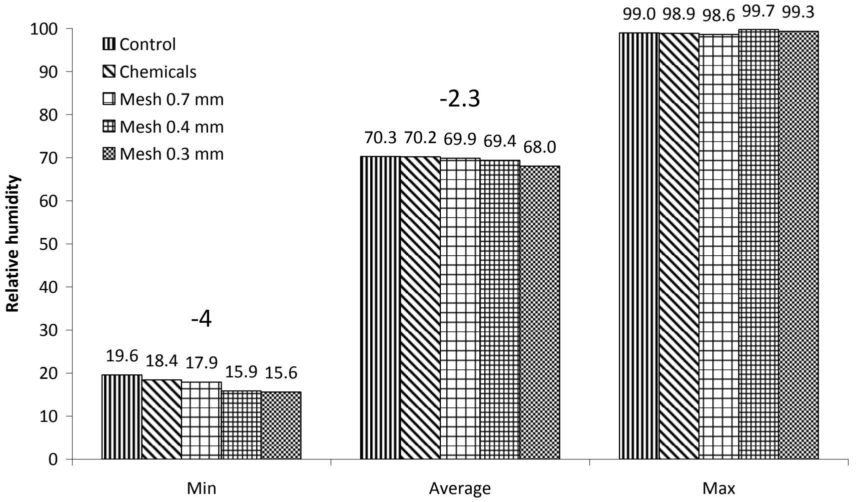

Figure 12. Minimum, average and maximum relative humidity, and number of percentage points decrease from highest to lowest RH / control to 0.3 mm mesh.

4.1.4. Microclimate effects of mesh

The data clearly show that mesh has an noticeable effect on under-mesh microclimate both for temperature and RH. This is considered a likely cause, at least in part, of the increase in haulm growth rate and length (section 4.2.1) and overall yield increases (section 4.2.2).

4.1.4.1. Relative humidity

The reduction in RH under mesh, though small on average, was unexpected considering the mesh is likely to be acting as a partial barrier to air exchange with the atmosphere, and there are both soil and potato leaves loosing water under the mesh. That the RH was lower under the finer meshes was counter-intuitive. Also, the condensation observed on the 'ultra fine mesh' test from the 2015-16 season (Figure 3) was taken to indicate very high humidity under the mesh. However, a reanalysis of the second field trial in 2012-13 also shows that mesh also decreased RH (Table 5) indicating a similar effect in that experiment.

Table 5. Minimum and average RH from the second mesh field trial in 2012-13.

Treatment	Minimum RH	Average RH
Control	20.9	80.7
Cosio mesh	16.9	80.1
CropSolutions mesh	17.9	78.3

Further analysis of RH data was therefore undertaken: the average RH of all the control and chemical plots (i.e., an average of the individual averages for the control and chemical replicates) was calculated for each sampling event (hourly) to produce an average RH for all the uncovered treatments at each sampling event. Then for each mesh treatment, the RH at each sampling event was subtracted from the RH for the uncovered treatments at the same sampling time, which gives the difference in the RH between the uncovered and each mesh treatment for each hour for the whole length of the trial, with a positive number showing lower RH under the mesh and a negative number a higher RH under mesh. The three mesh treatments were then averaged together to produce the mean of the covered treatments. The RH difference between covered and uncovered treatments was then grouped by the hours in the day to produce Figure 13. This shows a clear diurnal pattern, with the mesh having a higher RH than the uncovered treatments during the night (negative number on the chart) and lower RH during the day (positive numbers on the chart). Undertaking the same retrospective analysis of the second 2012-13 field trail data shows the same pattern of significantly lower RH under the mesh during the day and slightly higher RH at night (data not presented).

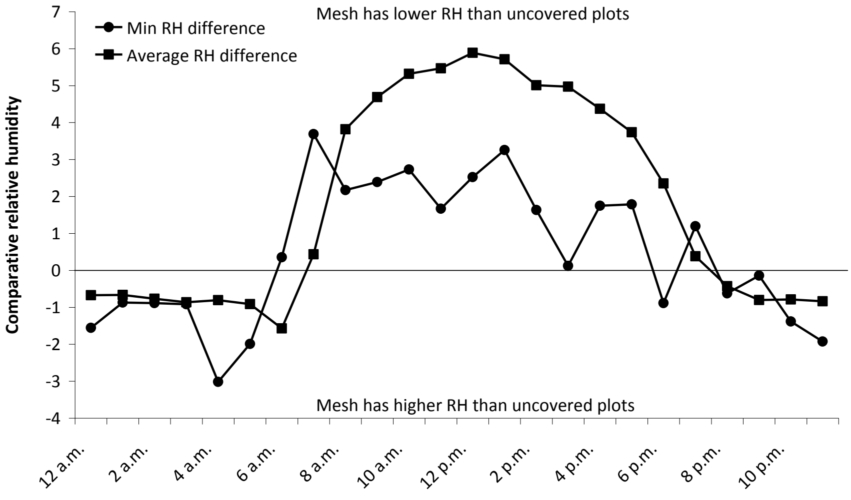

Figure 13. The average of the average & minimum RH of the mesh covered treatments, subtracted from (difference between) the average of the average & minimum RH of uncovered treatments (control and chemical), grouped by hours in the day, over the entire length of the trial.

Time of day is a proxy for temperature. The analysis was therefore redone using temperature rather than time of day as the basis for the comparison. In addition, as the difference in minimum RH was less consistent (a spiky line on the chart) than average RH, and minimum RH is considered a less useful measure, minimum RH was therefore dropped from the analysis.

Further, due to the requested mesh sizes (0.15, 0.3 and 0.6 mm) not being supplied the single piece of 'ultra fine mesh' from the previous years test (section 2.2, hole size 0.15 × 0.35, mm) was installed in the same field about 100 meters from the main trial, with Nadine again as the cultivar. Due to the residual herbicides being over applied due to manual application, potato emergence and growth was uneven so mostly no data was collected as it was considered unreliable. However, a data logger was put under the mesh allowing the RH and temperature under the 'ultra fine mesh' to also be analysed.

The four mesh sizes were then individually compared with the average of the uncovered plots for each measurement point (hourly) and then grouped by temperature instead of time of day (Figure 14). The same as the diurnal variation, the RH was higher under the mesh at cold temperatures, but RH was lower at temperatures above approx. 15°C up to the mid thirties, when the difference collapsed, due to uncovered plots not reaching the same maximum temperatures under the mesh (mesh was up to 6.3°C hotter than uncovered plots) so the calculations became meaningless.

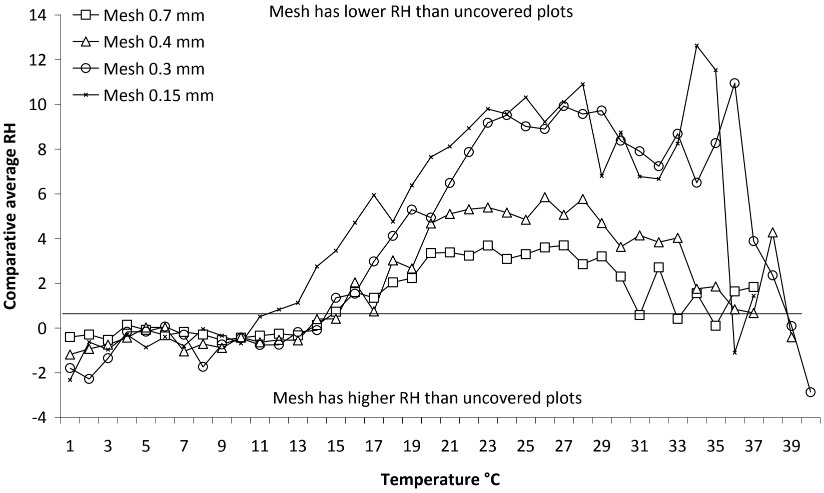

Figure 14. The average RH of the four mesh covered treatments, subtracted from (difference between) the average RH of uncovered treatments (control and chemical) grouped by temperatures from 1 to 40°C, over the entire length of the trial.

There are two key observations.

1. The finer the mesh, the larger the reduction in RH. While the difference between the 0.3 and 0.15 mm mesh was not as large as the 0.7 and 0.4 mm mesh, the 0.15 mm mesh achieved a positive RH difference at a lower temperature (~11°C) than the other three meshes (~15°C). Though due to there being only once piece of 0.15 mm mesh with poor potato growth this should be treated cautiously.
2. The size of the reduction in RH in the mid twenties Celsius is up to 10 percentage points lower. This is considered a very significant difference in RH from a crop production perspective particularly from a blight infection perspective.

The exact cause of this difference has not been established from the trial results, but, Ton Habraken from Ludvig Svensson BV, the Netherlands that specialise in glasshouse climate screens and who donated the ECONET 1535 aka 'ultra fine mesh' stated that this would be due to the higher temperatures under the mesh which change the amount of water vapour the air can hold and therefore changes the **relative** humidity. See hnt.letsgrow.com/psychro for a psychrometry / hygrometry diagram showing the relationship between temperature, vapour content and RH. Temperature is therefore considered to be the likely main reason why RH is lower under the mesh above 15°C, however, there could still be other causes, and also effects that are competing against higher temperatures to increase RH, such as increased transpiration in the warmer conditions.

Effect of decrease under-mesh RH on fungal diseases

Both early and late blight infection is determined by RH and leaf wetness, although once infected RH has a more limited effect on disease growth within the leaves.

The Smith Period is the temperature and RH conditions required for *P. infestans* / late blight infection and is defined as at least two consecutive days where minimum temperature is 10 °C or above and on each day at least 11 hours when the relative humidity is greater than 90%. This means that the increased RH under mesh at temperatures below 10°C is immaterial for *P. infestans* infection, while at higher temperatures, the lower RH is potentially increasingly important, especially as the speed / rate of fungal growth and infection increases with increasing temperatures (up to the organisms optimum temperature).

A. solani needs surface water on the leaves to be able to infect the plant, and, infection is often associated with existing leaf damage, e.g., from wind. The minimum temperature for infection is around 4°C, much lower than for *P. infestans*, but, infection rate and amount at this limit will be slow and small. Optimum growth occurs from the mid to high twenties Celsius. Lower RH under mesh at higher temperatures may well therefore be reducing leaf wetness though this is not a forgone conclusion. Direct measurements of leaf wetness against RH and mesh covering are required to fully determine this effect.

There is therefore potential that mesh may be reducing blight not only via reduced UV light levels (see section 2.1) but also reduced RH at temperatures above 15°C.

However, potato leaves touching the meshes, particularly the 'ultra fine mesh', were wet for considerable periods due to the condensation on the mesh (Figure 15). The above data and arguments about reduced RH therefore do not apply to these leaves. However, visual observations of these leaves (Figure 15) show that they have neither higher nor lower levels of blight than leaves not touching the mesh. Therefore UV and potentially other factors, may be inhibiting blight on these leaves. It is therefore considered that there may be more to the blight reduction effect than has been understood to date.

Figure 15. Potato leaves touching the underside of 'ultra fine mesh' (left) and therefore constantly wet due to condensation but with very low blight symptoms (right).

4.1.4.2. Wind abatement

From visual observations both of damage to leaves and movement of the haulm in windy conditions it is clear that mesh also provides considerable wind protection, although it is acknowledged that no physical recording of under vs. above mesh wind speed or haulm movement has been taken. Figure 16 shows the difference on the 4 April between the foliage of the chemical and mesh 0.3 mm treatment, with the chemical treatment having considerably more foliar damage which has subsequently been infected by a range of foliar diseases, most of which are **not** main or early blight, as well as there being some TPP yellows, while the potatoes under the mesh have still mostly intact healthy leaves with the exception of the top most leaves which have suffered some abrasion against the mesh.

Figure 16. Potato haulm on 4th April 2017, chemical treatment left photo, mesh 0.3 mm right photo.

It is not just physical damage from wind and the subsequent loss of photosynthetic area, but, even relatively mild shaking of plants has been shown to produce significant yield losses (Biddington, 1986). Canterbury has a relatively windy climate, particularly the Nor'wester and southerlies that can reach gale strength and have been know to destroy the haulm of entire crops. But the research on plant shaking shows that even gentle wind and resulting foliage movement can reduce yield, so even winds of 10 kph could be having a yield impact. Mesh may therefore be directly increasing yield by reducing haulm movement, even, in light winds, and providing significant haulm and yield protection in strong winds.

It may not just therefore be increased temperature and reduced RH that is causing the increased growth and yield of mesh grown potatoes, but, also protection from wind. Mesh may well therefore be directly creating a significantly improved overall microclimate (temperature, RH and wind) for the crop which together is directly causing yield increases, even in the absence of pests & diseases. The indications are that finer mesh (smaller holes) had a more pronounced effect, potentially down to the 'ultra fine mesh' with hole sizes of 0.15 x 0.35 mm. If correct this indicates that regardless of their effects on pest and diseases, that finer meshes will give the best yield, though, the higher cost of finer meshes needs to be economically balanced against increase marketable yield.

On top of this mesh is acting as a kind of 'insurance policy' in that in some years, wind storms can completely defoliate crops thus destroying them. Mesh therefore has the potential to prevent such losses, and therefore, when longer term economic comparisons are made, the prevention of complete crop loss should be factored into the overall cost of mesh vs. agrichemicals.

4.2. Crop performance

4.2.1. Haulm length

The haulm under the mesh grew faster and longer than the chemical treatment and controls Figure 17. All four measurement dates were analysed separately with each being highly significant ($p<0.001$).

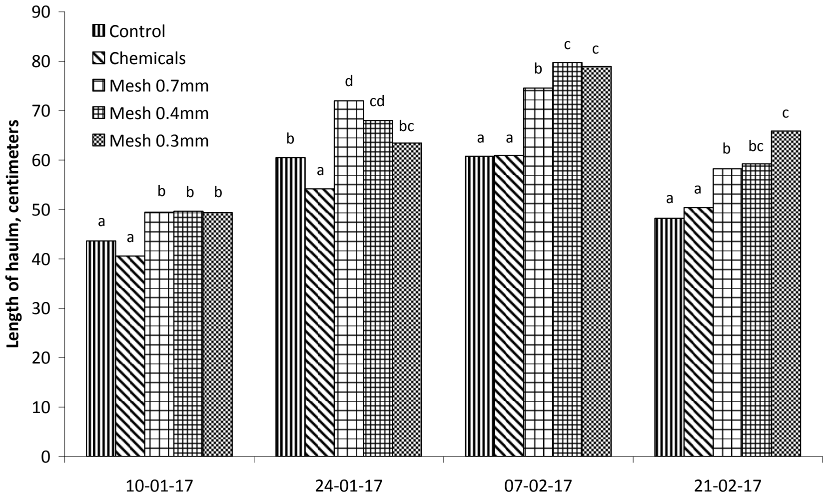

Figure 17. Potato haulm length at four dates, p<0.001, LSDs 35.24, 49.21, 30.69 and 69.40 for each date in chronological order. For each date, columns with the same letter are not statistically different.

In all previous trials it was visually observed that the haulm grew faster under mesh than the controls, but, this experiment was the first time that haulm growth was objectively measured. The results clearly substantiate the previous visual observations and show a both statistically and biologically significant increase in growth. As crop growth is driven by photosynthesis, increasing the amount of leaf area should increase crop performance including yield. However, haulm length is not necessarily directly linked to increased leaf / photosynthetic area, it may be that the internode length is increasing without increasing the number and/or size of the leaves. This result therefore has to be taken as indicative rather than causal, and if this effect is considered important, future research will need to focus on more detailed, and therefore time consuming, measures of photosynthetic area, and/or measures of haulm dry weight.

4.2.2. Yield

4.2.2.1. Bulk yield

There was a significant difference in bulk yield (p=0.012) but the chemical and controls were not significantly different and the chemical and all mesh treatments were also not significantly different from each other (Figure 18).

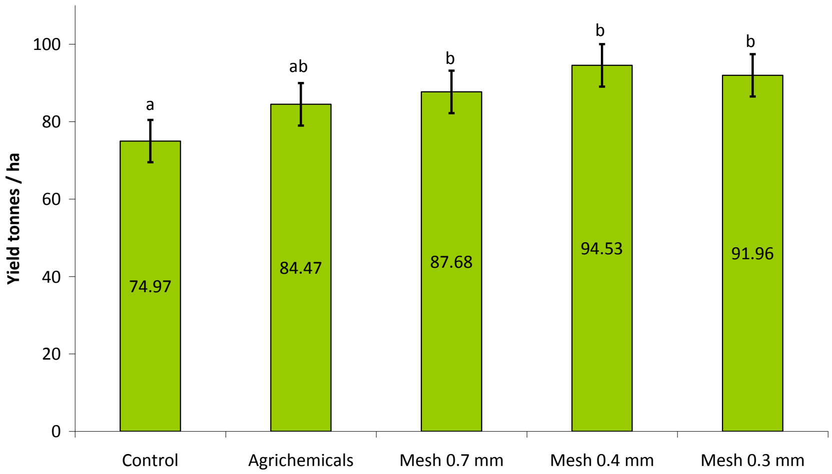

Figure 18. Bulk yield from the five treatments, p=0.012, LSD=10.96. Error bars = LSD. Columns with the same letter are not statistically different. Mesh 0.4 mm had a 12% increaser over agrichemicals and a 26% increase over the control.

It is noted that the LSD at 10.96 t/ha is just 0.9 t/ha larger that the 10.06 t/ha yield difference between chemicals at 84.47 t/ha and the best yielding mesh at 94.53 t/ha. Rigorously, this should be considered to mean the results are the same, but, as the all the subsequent yield measurements show highly significant differences (p<0.001) between all the mesh treatments and the agrichemical & control treatments, it is considered that the statistics were not powerful enough to detect a real difference, despite the considerable statistical power from the six replicates (which is a high number for a field trial) and the large within plot harvest (total of 12 m / 40 plants per plot). As the 10 tonne/ha yield difference between agrichemicals and the best mesh is agronomically and economically significant this indicates that even more replicates and/or larger in-plot samples will be required to capture such yield differences in future trials.

The maximum yield of 94.5 t/ha for mesh 0.4 mm exceeds by 5 to 8 tonnes/ha the maximum theoretical yield of 87-90 t/ha for Canterbury from the Potato Yield Gap Project (Sinton, 2013). It is noted that the model is of “potential yield” while farmers are reporting “paddock yield” which will exclude smaller tubers ‘rejected’ by the harvesters due to being undersize, and also “paid yield” which excludes tubers < 67 mm in length. As the ‘bulk yield’ from this trial included all tubers down to ~1 cm diameter, the bulk yield results are therefore considered comparable to the modelled ‘potential yield’. The fact that the two best mesh yields exceeded the theoretical maximum yield is another indication that mesh is directly boosting yield.

The 84.5 t/ha yield of the agrichemical treatment (and similar yield for the 0.7 mm mesh) is also a very good yield, and close to the modelled maximum.

The control treatment was close to 10 t/ha less than agrichemicals, which shows that the agrichemicals had a positive effect though again the lack of statistical difference is frustrating, especially considering marketable yield was clearly different.

The best yielding mesh (0.4 mm) therefore had a 12% yield increase over agrichemicals and a 26% increase over the control.

4.2.2.2. Sub-sample yields

In comparison, the combined weight of the 50 tuber sub-sample was highly significantly different (p<0.001) between the control and agrichemicals and all the mesh treatments (Figures 19 & 20). This high level of significance (p<0.001) was the same for all further measurements of the 50 tuber sample except specific gravity. The difference between this measure of yield and the ‘field yield’ is due to the control and agrichemicals having a larger proportion of smaller tubers / mesh having a greater number of larger tubers (Figure 25).

Figure 19. The sub-sample of 50 tubers from all five treatments from replicate one. Ruler is 30 cm long.

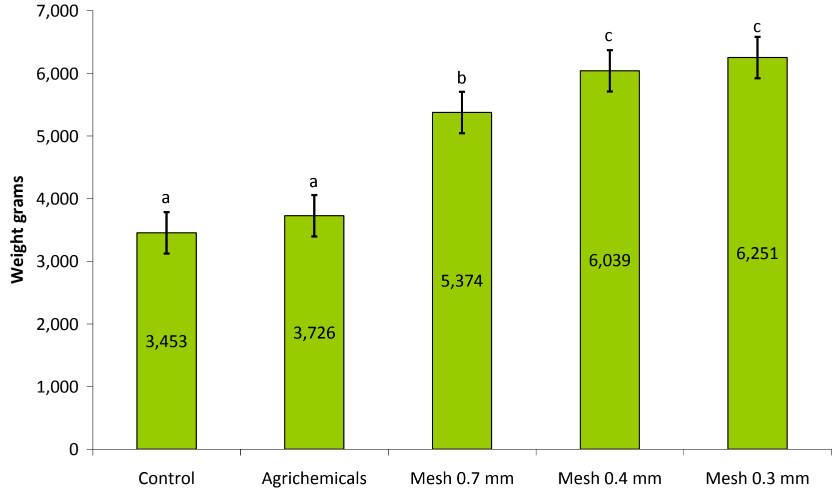

Figure 20. Combined weight of the 50 tuber sub-sample, LSD = 660.3, p<0.001. Error bars = LSD. Columns with the same letter are not statistically different. Mesh 0.3 mm has a 68% increase on agrichemicals and 81% increase over the control.

4.2.2.3. Average and maximum tuber weights

The average tuber weight was highly significant (p<0.001) with a near doubling in weight between the control and 0.3 mm mesh (Figure 21).

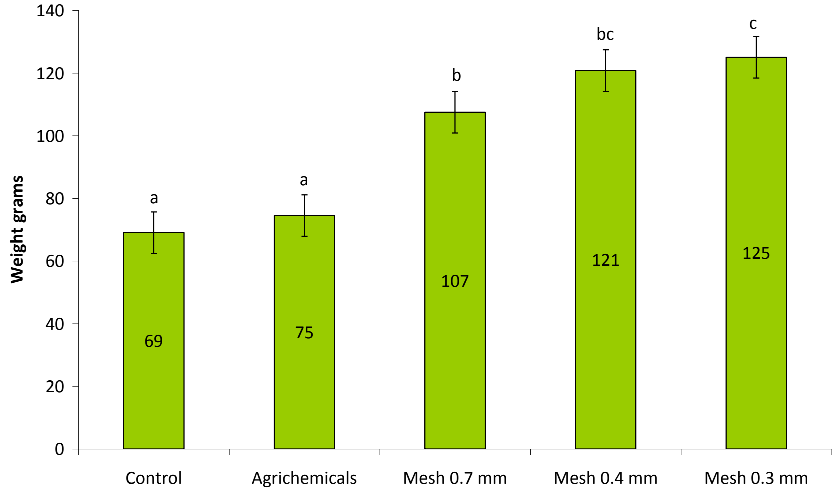

Figure 21. Average tuber weight, LSD=13.24, p<0.001. Error bars = LSD. Columns with the same letter are not statistically different. Mesh 0.3 mm had a 67% increase over agrichemicals and a 81% increase over the control.

Likewise, maximum tuber weight was highly significant and increased from the control, then agrichemicals, followed by mesh by decreasing hole size (Figure 22).

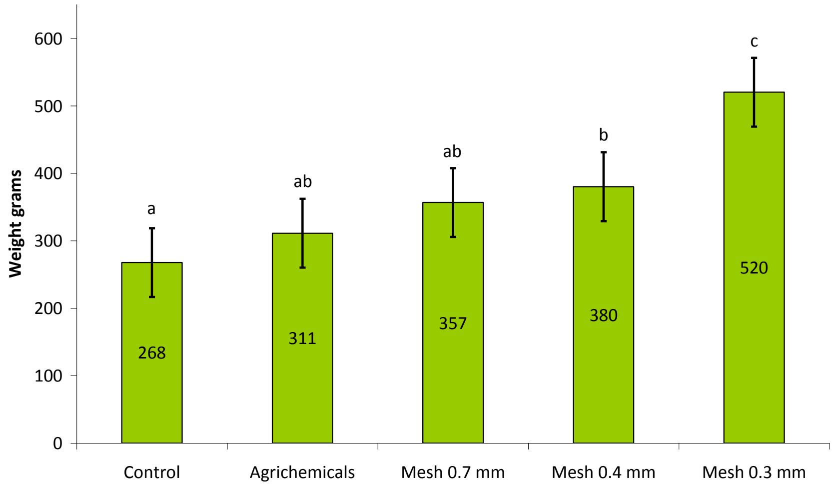

Figure 22. Maximum tuber weight, LSD=102.0, p<0.001. Error bars = LSD. Columns with the same letter are not statistically different. Mesh 0.3 mm had a 67% increase over agrichemicals and 94% increase over the control.

4.2.2.4. Marketable yield

Marketable grade yield was analysed for tubers >60g as used in Wright et al., (2017) and >125g as used in previous mesh studies. Yield was significantly higher (p<0.001) for all mesh treatments than control and agrichemicals for both the >60g (Figure 23) and >125g (Figure 24) tuber weights.

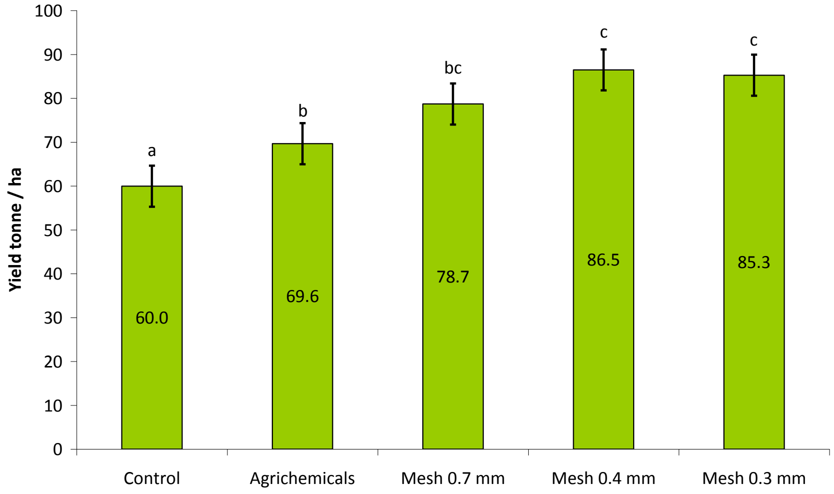

Figure 23. Yield of marketable tubers >60g, LSD=9.37, p<0.001. Error bars = LSD. Columns with the same letter are not statistically different. Mesh 0.4 mm had a 24% increase over agrichemicals and a 44% increase over the control.

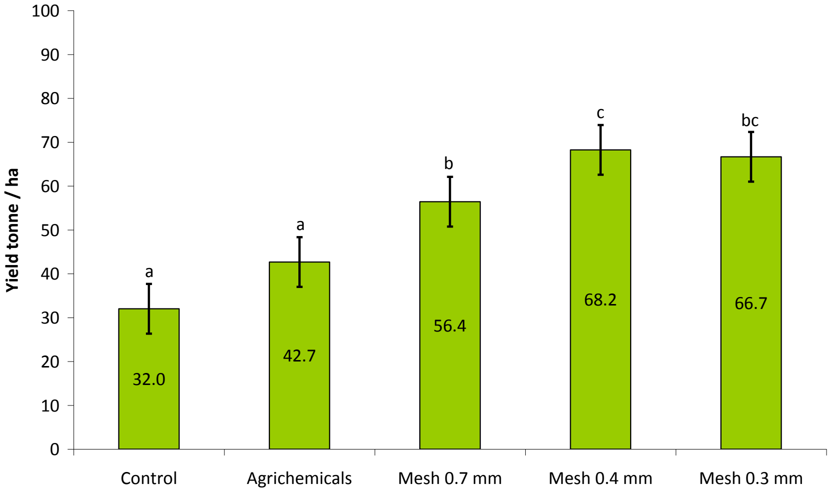

Figure 24. Yield of marketable tubers >125g, LSD=11.33, p<0.001. Error bars = LSD. Columns with the same letter are not statistically different. Mesh 0.4 mm had a 60% increase over agrichemicals and a 113% increase over the control.

The higher marketable yield from mesh vs. control and agrichemical treatments is due to the greater proportion of larger tubers from the mesh treatments as shown by the size distribution / frequency (Figure 25).

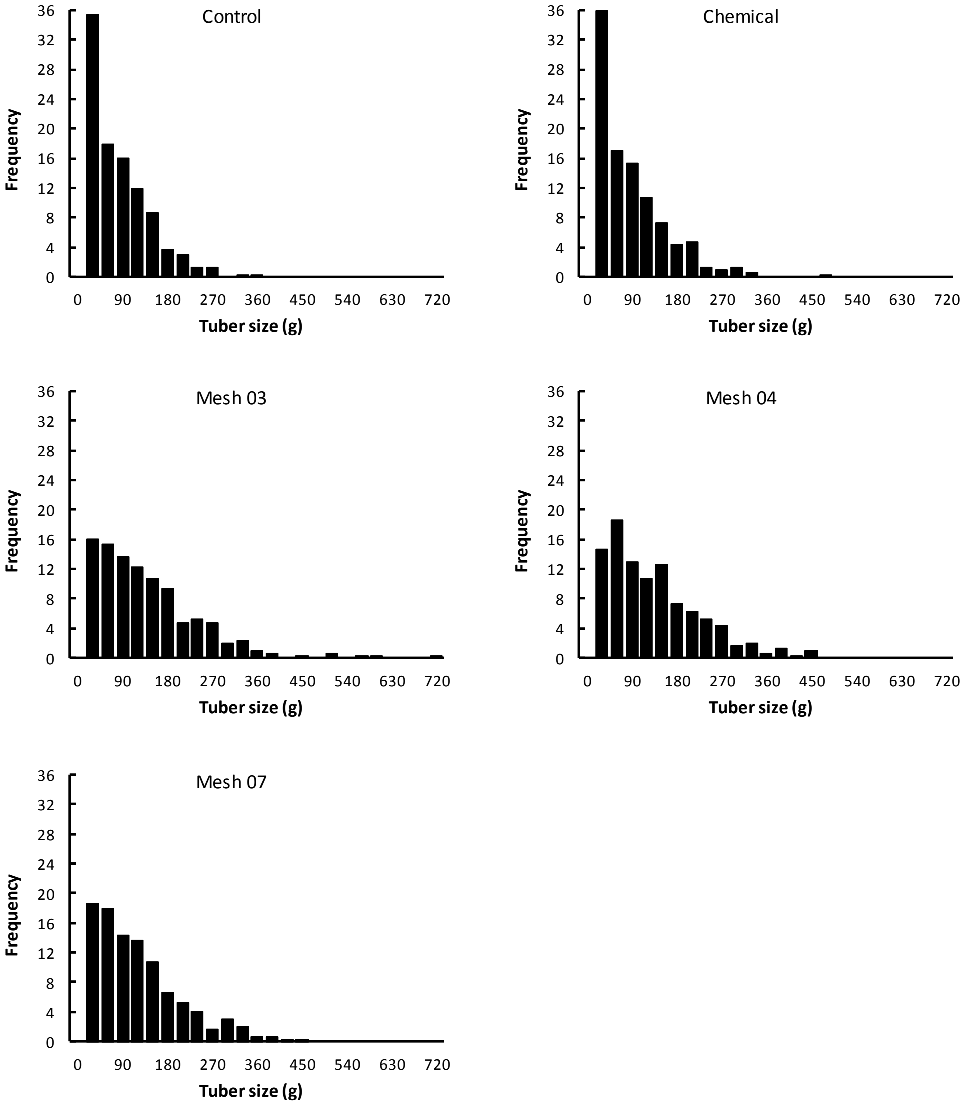

Figure 25. Tuber size distribution / frequency.

Yield discussion

The combined weight of the 50 tuber sub-sample, along with average & maximum tuber weight and the size distribution / frequency all illustrate the same effect of mesh increasing tuber size / reducing the number of small tubers. This is consistent with previous trials where mesh resulted in larger tubers which in turn resulted in statistically / agronomically and economically significant yield increases. Measuring maximum tuber size has the risk of a single large potato skewing the results if the sample size is small, but, as the frequency charts in Figure 25 shows the overall number of larger tubers does increase with decreasing mesh size showing that this is not a spurious result.

This tuber size increase is what drives the considerable increase in marketable yield, with a 24% increase in the best mesh yield compared with agrichemicals for tubers >60 g and a 60% increase for tubers >125 g. The marketable yield of 86.5 t/ha for mesh 0.4 mm for tubers >60 g is itself close to the modelled maximum yield and considerably larger than the farmers ‘paddock yields’ of 50-60 t/ha reported in Sinton (2013), which are more comparable with the 70 t/ha yield for the agrichemical treatment.

The very high yields achieved under mesh were also achieved despite the outbreak of aphids under the mesh (see section 4.4). Aphids affect potatoes directly by removing sap, so draining the plant of nutrients and energy, and also by injecting viruses which stunt the plants. However, there were no visual signs of virus damage in the mesh crops - images were taken fortnightly from all plots as references - so it appears that viruses were not introduced - discussed further in the aphids section (4.4). With the high numbers of aphids on the potatoes prior to spaying with Chess it is not unreasonable to believe they could of had a direct negative impact on yield, so, had they been controlled from the start of the trial, it is possible that mesh yields could of been even higher.

The Potato Industry Strategy Targets includes the aim of increasing profit by $150 per annum, which equates to a 12% yield increase over ten years. This result indicates that the industry could achieve more than double its ten year target, in only one year, by changing to mesh.

4.2.2.5. Specific gravity

Specific gravity (SG) was not significant overall at the p=0.05 level with a p value of 0.070, however, there were significant differences in the individual treatment SGs (Figure 26) with SG increasing with decreasing mesh size, i.e., the same trend of finer mesh producing better results overall.

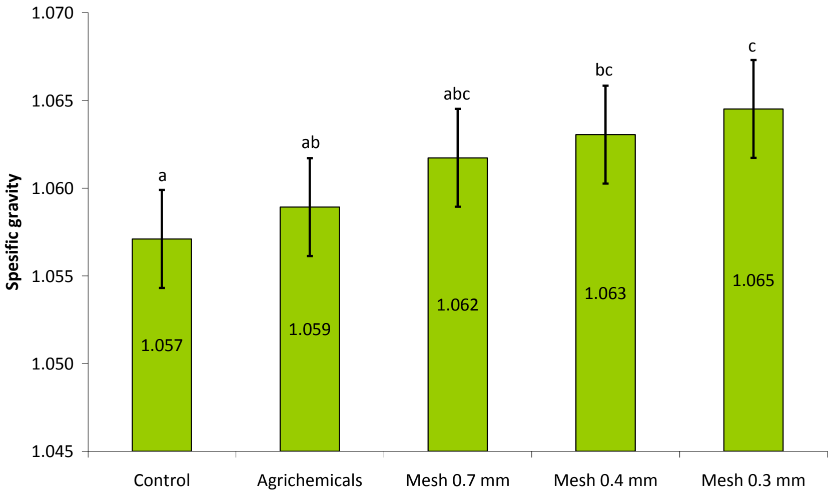

Figure 26. Specific gravity, p=0.07 LSD=0.00558. Error bars = LSD. Columns with the same letter are not statistically different. Mesh 0.3 mm had a 0.57% increase over agrichemicals and a 0.76% increase over the control.

4.3. TPP

The effect of mesh on TPP control is completely unambiguous. Across the whole duration of the trial a total of just 12 individual TPP were caught under all mesh treatments combined, from both leaf counts (five leaves, counted fortnightly) and sticky traps (out for 7 days, every other week), while for the control there were 1,250 TPP and 1,614 TPP for the chemical treatment. The averages (n=4) of these total are presented in (Figure 27).

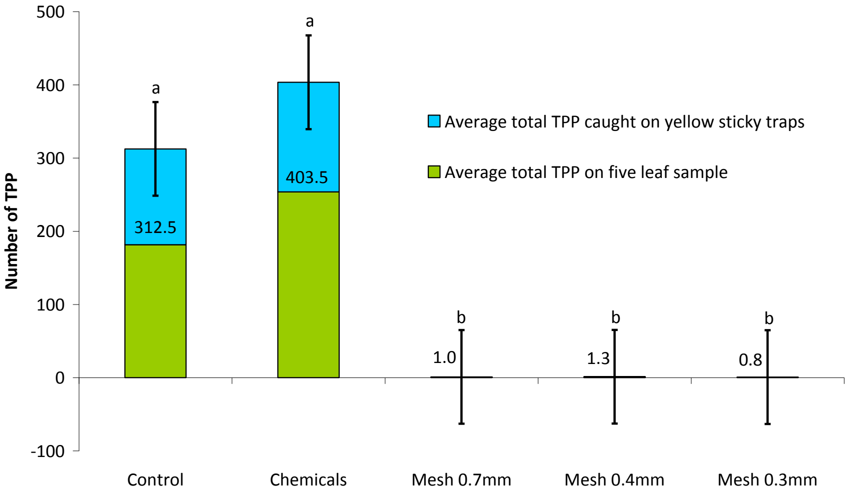

Figure 27. Average of the total TPP caught across the whole duration of the trial, on yellow sticky traps and from counts on five leaves, sampled once a fortnight, LSD=128.0, p<0.001. Error bars = LSD. Columns with the same letter are not statistically different. Mesh 0.3 mm had a 50,338% reduction compared with agrichemicals, and 38,963% reduction compared with the control.

The 2016-17 season was considered to be poor for TPP, with TPP not being detected in traps across a number of trials and crops until after Christmas (Jessica Dohmen-Vereijssen, Plant & Food Research, pers. comm.). This is reflected in the low numbers of TPP caught in traps and found on leaves until the middle of February (Figures 28 & 29).

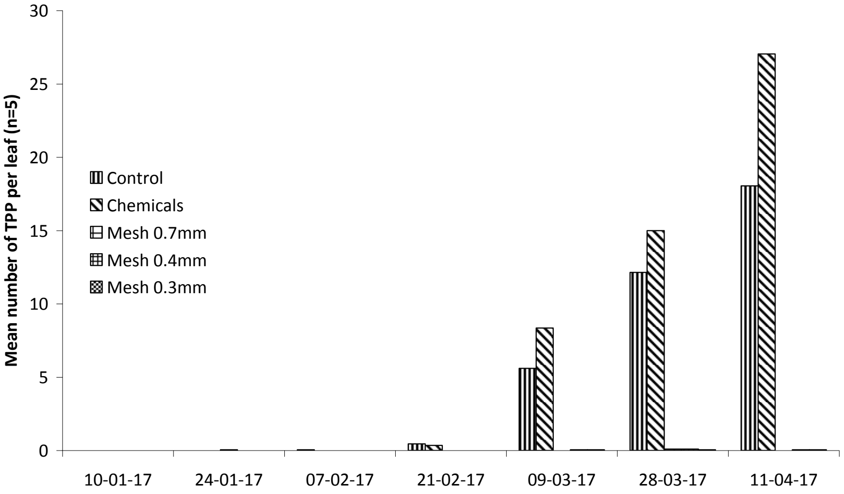

Figure 28. Mean number of TPP (adults and juveniles) per leaf (from five leaves) over seven sampling dates.

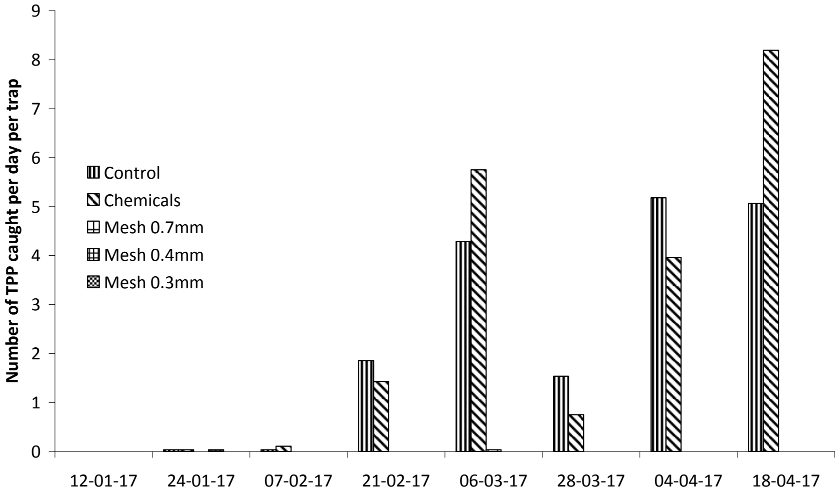

Figure 29. Mean TPP caught per day, per yellow sticky trap, stationed for seven days, over eight sampling dates.

With hindsight, the visual TPP symptom scores are considered unreliable, due to two different people taking the scores and the key being based on the cultivar 'Red King' not Nadine. Visual inspection of the multi-cultivar planting, for a seed inspector training workshop, in the same field approx. 100 m away from the trial, showed TPP symptoms varying considerably among cultivars (Figure 30) even though there were only two ridges of each cultivar, the planting was continuous, so different cultivars were physically close to each other so the opportunity for them to be infested by TPP was considered to be the same. If visual keys are used they should therefore be done for each cultivar. In addition plants under mesh were scored as having symptoms by one assessor yet analysis of actual TPP counts from leaf samples and yellow traps showed nearly zero TPP, such that symptoms should not be seen.

Figure 30. Variation in TPP foliar symptoms between two cultivars (unknown) in seed inspector training block.

4.3.1. TPP discussion

The almost complete elimination of TPP from the mesh treatments is not only unambiguous but in line with previous research. Laboratory work clearly showed 0.6 mm mesh is a 100% effective barrier to adult TPP. The initial field trial which consisted of 10 m squares of mesh laid on a contiguous crop of potatoes (i.e., a complete green bridge around the mesh edge) still found statistically and biologically significantly lower numbers of TPP in the centre of the mesh than outside. The second field trial without a green bridge but with mesh anchored in place with metal stakes (i.e., not dug in) so there were gaps around the sheet edges (i.e., not fully sealed) found a dramatic reduction in TPP under mesh even though it was physically easy for TPP get under the sheets from the open edges. The UV trial found a strong correlation between reduced UV light levels and TPP foliar symptoms (psyllid yellows). This trial, with the mesh dug into the ground, and therefore hermetically sealed practically eliminated TPP.

Perhaps the more interesting question is why there were any TPP found under the mesh at all. TPP could of been introduced on staff entering under the mesh and moving between plots and transferring TPP, even with the precaution of starting with the finest mesh plots and finishing with the controls. TPP may also have entered via damage to the mesh or via eggs laid on mesh and the hatchling juveniles then penetrating the mesh.

Clearly this requires more research and it is important for the long-term sustainability of using mesh for TPP control that the entry mechanism is determined, but, based on the cumulative research it can be concluded that mesh crop covers are a complete means of controlling TPP on potato crops. At the same time, the proposed solution to the aphid problem could also include biocontrol agents that also kill TPP, thus ensuring that any TPP that do get through mesh are eliminated.

4.3.1.1. Impact of very low TPP on Candidatus *Liberibacter solanacearum*

The near 100% control TPP is critically important due to it carrying Candidatus *Liberibacter solanacearum* (CLSo), which is what is causing the yield and quality loss in potatoes, rather than TPP itself. Agrichemicals can only control TPP by killing TPP that are already on the crop. However, as transmission of CLSo happens within minutes to hours of a TPP feeding, then, even daily agrichemical applications will be unable to prevent CLSo transmission, even with systemic insecticides, as these take time to kill insects after alighting and feeding. Research by Plant & Food Research this season has also indicated that psyllid yellows are **not** caused by TPP directly, rather they are entirely due to CLSo (Jessica Dohmen-Vereijssen, Plant & Food Research, pers. comm.). Therefore the key to limiting damage from TPP and CLSo is to prevent TPP reaching the crop in the first place, which only mesh can achieve.

Due to insufficient funds, full testing of the tubers for CLSo was not possible. Unfortunately Nadine, the cultivar used in this trial, is unsuited for the fry test (Andy Pitman, Plant & Food, pers. comm.) so that could not be used. However, AsureQuality undertook a visual assessment, backed up by PCR tests of 20 tubers each from of the control and mesh 0.3 mm plots. All control tubers exhibited internal discoloration associated with CLSo and PCR tests on a sub-sample of tubers found high levels of CLSo while the bulked tissue sample from the 20 mesh potatoes found zero CLSo. As this is a non-replicated sample the results must be treated with caution, but, if the same result was found in replicated tests, mesh could also be considered a complete solution for preventing CLSo infection.

4.3.1.2. Evolved resistance to mesh

As mesh does not kill TPP, as agrichemicals do, it is considered that it does not create the same evolutionary selection pressure for resistance that agrichemicals are clearly shown to do. In terms of the long-term sustainability / effectiveness of the two management approaches, it is clear that resistance to agrichemicals is a well established issue and one that has to be constantly and actively managed through rotation of chemicals, but even then, resistance is likely to occur. In comparison there is very limited selection pressure created by mesh, as TPP simply move on to find another host plant. It is therefore considered that mesh will remain an effective control for TTP for the imaginable future, especially when paired with introduced biocontrol agents under the mesh (section 7.1.2).

4.3.1.3. Impact of Chess on TPP

One problem potentially confounding the result is the use of Chess to control the aphids under the mesh (see section 4.4), in that Chess also kills TPP (John Thompson, Bioforce, pers. comm.). It could therefore be argued that the Chess was responsible for the low TPP numbers under mesh. It could also be argued that to keep the experimental design consistent that Chess should of also been applied to the chemical treatments in addition to the existing spray program. The use of Chess was therefore a necessary evil, in that it created the above confounding factors, but, had it not been used then the aphids could of killed the potatoes under the mesh rendering the trial meaningless. It was therefore considered the only effective option considering the size of the aphid populations, as alternatives, such as biocontrol agents, would of been required in such large numbers that sufficient supply was unavailable. If Chess had been sprayed on the agrichemical treatments on top of the existing spray program, then it would have changed that treatment from industry best practice / full spray program into something else, so, then comparisons with that would also have been jeopardised in terms of being relevant to growers. Finally, while it is likely the Chess did reduce TPP numbers under the mesh, it was clear from TPP counts before the start of the Chess spray program that there were very few TPP for Chess to control, and, if insecticides as a whole were so effective at TPP control, then the chemical treatments should of seen the same very low TPP counts, which they clearly did not. However, this matter can clearly not be decided by debate, and, future research using pre-planned biocontrol for under-mesh aphid control will be required to confirm the matter.

4.3.1.4. Agrichemicals vs. the null control and biocontrols

The high numbers of TPP on the agrichemical treatments is somewhat concerning. Statistically the number of TPP on the control and chemicals were the same, but, the difference is close to the LSD indicating that spraying may not be achieving better control than no sprays. The agrichemical regime is considered robust. The spraying nozzles are considered a good quality setup, and it would require changing to an air assisted sprayer to improve penetration, so, it is not believed that insufficient effort was put into the agrichemical treatments to achieve success. The number of aphids on the agrichemical plots (see section 4.4) was also similar to the number of aphids on the control but the difference was very small compared with the LSD so, they the are considered statistically and biologically the same. This begs the question as to why chemicals did not achieve lower TPP numbers under the agrichemicals compared with the control, rather than higher numbers.

It is considered possible that the chemicals could be killing TPP (and aphid) biocontrol agents, but failing to kill sufficient TPP, as TPP are difficult to kill due to being well protected on the underside of the foliage and the juveniles are immobile and shield-like. The effect of the mesh on aphids is therefore the reversal of this situation: once aphids are under the mesh, the mesh excludes their biocontrol agents / natural predators (the exception being lacewings see section 4.5) meaning their populations explode, becoming many times in excess of the unsprayed control. The most obvious reason that the unsprayed control does not have the same aphid populations as under the mesh, is that biocontrol agents are controlling them. This is also not the only example of pesticides increasing pest numbers, with many reports in the scientific literature of this phenomenon.

Leaving aside mesh, it may be that agrichemicals are not the most effective means of controlling TPP in potatoes, due to chemicals killing more biocontrol agents than TPP, and that an ecological approach / IPM (integrated pest management) approach, such as the Greening Waipara program (https://bioprotection.org.nz/research/programme/greening-waipara), that has achieved complete control of leafroller caterpillars in vineyards, could be developed to control TPP, aphids, and others pests in potato crops, thereby dramatically reducing the number of agrichemicals required, and returning the industry to the IPM systems used before the arrival of TPP. The introduction of *Tamarixia triozae* for TPP control, as a parasitoid, would almost certainly benefit from the provision of floral resources to improve its longevity and fecundity, while the continued use of insecticides is highly likely to kill *Tamarixia* and prevent it from controlling TPP in potato crops.

4.3.2. Conclusions

Mesh crop covers can therefore be considered a permanant solution for the complete control of TPP on potatoes. In short the problem of TPP on potatoes has been solved. Following on from this it appears that mesh also provides complete control of CLSo on potatoes, so that problem can also be considered solved.

There is therefore believed to be considerable potential for using mesh to control TPP on other field crops such as tomatoes, especially as domestic gardeners are reporting that mesh grown tomatoes are some of the best crops they have produced getgrowing.realviewdigital.com/?iid=151565#folio=11 www.bhu.org.nz/future-farming-centre/ffc/information/misc/nz-gardener-2015-psyllid-and-mesh.pdf.

4.4. Aphids

The situation with aphids was a complete reversal of that for TPP, with an outbreak of aphids occurring under all mesh sheets, but particularly the 0.7 mm, with the lowest aphid numbers in the control and chemical treatments (Figure 31) though it is noted these are not statistically different, but they are considered biologically significant.

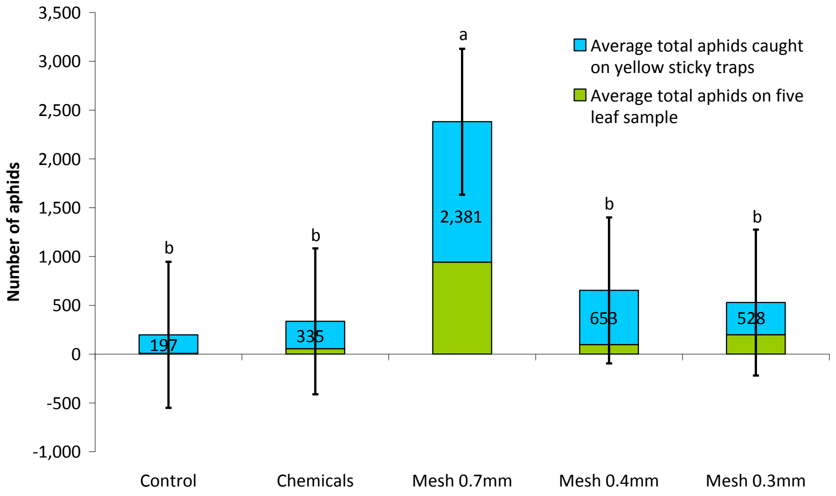

Figure 31. Average total of aphids caught across the whole duration of the trial, on yellow sticky traps and from counts on five leaves, sampled once a fortnight, from the first four replicates, LSD=1495.9, p=0.046. Error bars = LSD. Columns with the same letter are not statistically different. Mesh 0.7 mm has an increase in aphid numbers of 611% compared with the chemicals and 1,109% compared with the control.

To avoid the aphids killing the potatoes and rendering the experiment meaningless, aphids in the mesh treatments were controlled with Chess from 15th February onwards (Figures 32 & 33).

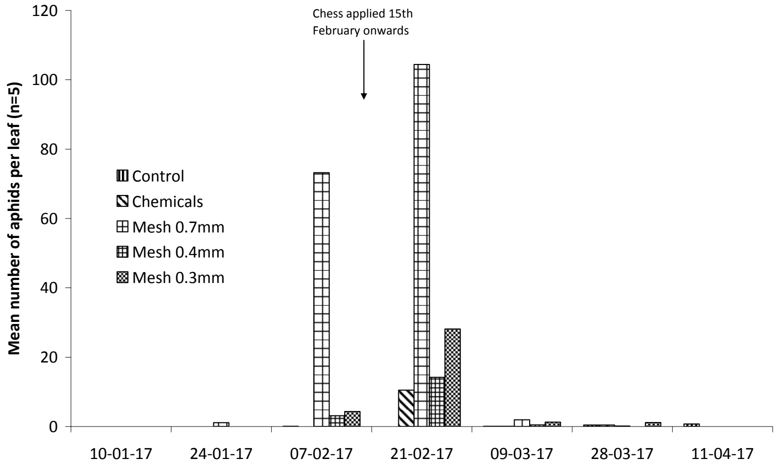

Figure 32. Mean number of aphids (all life stages) per leaf (from five leaves) over seven sampling dates.

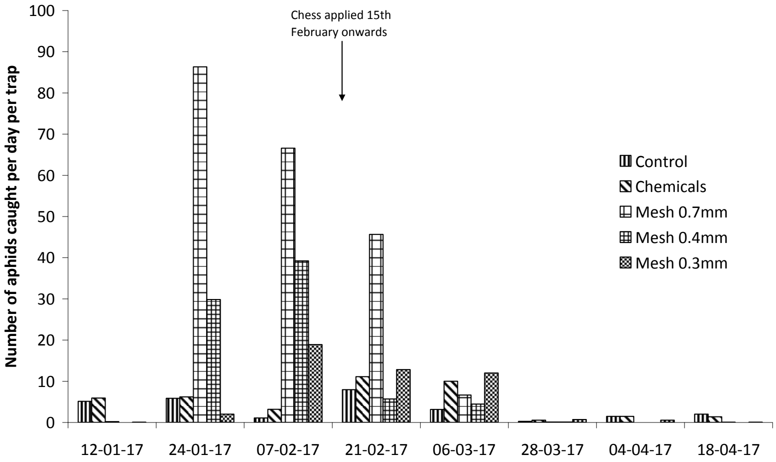

Figure 33. Mean aphids caught per day, per sticky trap, stationed for seven days, over eight sampling dates.

The potential for staff to cross-contaminate mesh plots with both TPP and aphids was realised early on in the trial (section 3.6) with precautions then undertaken. However, it still could not be ruled out that staff had not introduced aphids under the mesh via their clothing. It was therefore decided to check the number of aphids on the last two replicates which had not been opened / entered at all. Therefore, on the 18 February 2017 a sample of ten leaves was taken from all plots in the last two reps (5 & 6) and the number of aphids counted. All the mesh plots in these last two reps had aphids in them with very few in the control and chemical treatments (Table 6).

Table 6. Average number of aphids per leaf from the last two replicates (5&6) based on ten leaf sample on 18 Feb 2017.

	Average aphids per leaf n=10		
Treatment	**Rep 5**	**Rep 6**	**Average**
Control	0.4	0.0	0.2
Chemicals	0.0	0.0	0.0
Mesh 0.7 mm	261.3	183.6	222.5
Mesh 0.4 mm	71.6	19.9	45.8
Mesh 0.3 mm	87.3	545.9	316.6

The 0.3 mm mesh from rep 6 had particularly high levels of aphids, which was an anomaly compared with the other mesh 0.3 mm and 0.4 mm plots. As all mesh plots had aphids in them, it is considered that aphids just happened to penetrate this particular plot and/or in larger numbers resulting in the high numbers at the sampling date. This indicates that while on average the larger mesh sizes will have more aphids, it is possible for fine mesh to also have high aphid numbers.

4.4.1. Aphid discussion

There is considerably irony that mesh crop covers, a general purpose insect barrier, which are such a highly effective and permanant solution to TPP on potatoes, and a wide range of other insect pests on an equally wide range of other crops, are creating aphid outbreaks. There are now also reports of aphids becoming a problem on turnips and swedes being grown under mesh in the UK (John Sarup, SPUD Agronomy & Consultancy Ltd., UK, pers. comm.).

How the aphids are getting under the mesh has yet to be unambiguously established (i.e., directly observed), but, a number of possibilities have been eliminated. In the initial FAR trials of mesh alongside agrichemicals it was originally thought that due to potato haulm laying against the mesh this was allowing aphid nymphs to walk off uncovered potato haulm and through the mesh to the covered haulm. However, subsequent FAR trials eliminated this green bridge and in this experiment there was no vegetation growing next to the mesh due to the use of residual herbicides, and there were large (>2 m) inter-plot alleyways without potatoes, but, aphids still got under the mesh in both FAR and this trial so the green bridge hypothesis cannot be the cause of aphid ingress in these situations.

In addition, as all the mesh plots in the last two replicates (5 & 6) that were never entered by staff, and all (i.e., every mesh plot) had aphids in them, including some with very high levels, therefore, cross contamination by staff cannot be the sole cause.

It is therefore hypothesised that winged / adult aphids (believed to be *Myzus persicae*) are landing on the mesh (either randomly or though a sensory cue), then detecting the potatoes under the mesh, resulting in them remaining on the mesh rather than taking flight again to look for other food sources, and while they are resident on the mesh, they produce nymphs (aphids produce live young by asexual reproduction) which are so small they can penetrate the mesh. Once the nymphs have penetrated the mesh, the mesh excludes their natural enemies, such as parasitoids, ladybirds, hoverflies etc., so the aphids are able to grow and multiply without predation.

Current research at Lincoln University has shown that only the absolutely finest mesh available, which has a hole size of 0.15 × 0.15 mm (smaller than 'ultra fine mesh' at 0.15 × 0.35 mm) is aphid proof. Also mesh is not required to touch the potato leaves for aphid nymphs to penetrate it, although penetration rates appear to be higher where leaves are touching (Howard London & Shola Olaniyan, Lincoln University, pers. comm.).

However, while the above research indicates it is possible to decrease the mesh hole size to the point that aphids are unable to penetrate, 1) the cost of mesh increases with decreasing hole size, and 2) in the real world of farming, mesh will inevitably become damaged with rips and holes and spreading of the threads providing access points for aphids. Even in this trial with mesh laid and dug in entirely by hand, holes were created in the mesh (Figure 34), possibly by a stone from grass mowing.

Figure 34. Hole ripped in 0.3 mm mesh in field trial - possibly by a stone from grass mowing.

It is therefore concluded that it will be impossible to make mesh covers completely proof against aphids in real-world field use, particularly *M. persicae* which is very small (Figure 35). In addition laboratory experiments indicate that aphids have a very intensive searching behaviour which means they are likely to locate damaged areas of mesh to find their way in. Alternative control methods will therefore be required. Suggestions for how to solve this are addressed in 'Future Research' section 7, but, briefly, the concept is to treat the mesh as a protected growing environment, such as a glasshouse, and introduce aphid (and TPP) predators under the mesh and support them / maximise their efficacy, by providing floral resources (nectar and pollen) and/or banker plants to host non-potato pest, prey.

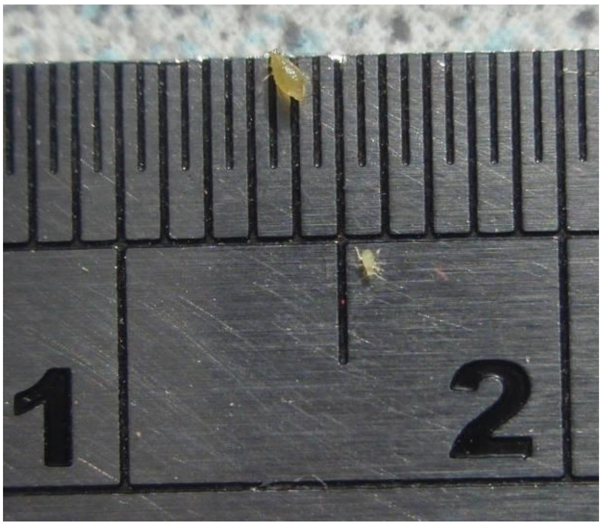

Figure 35. Adult and juvenile *Myzus persicae*.

4.5. Lacewings

It was not planned to monitor lacewings, as it was expected that there should be very few other insects under the mesh treatments. Fortunately, the Plant & Food Research staff reading the yellow sticky traps were particularly diligent and also annotated the aphid and TPP counts for each trap with any other noteworthy insects they identified. For the traps dated 28 March very large numbers of adult lacewings were caught on all traps under mesh (Figure 36), with numbers declining over the next two trap dates of 4 and 18th April.

Figure 36. Lacewings on yellow sticky trap from underneath mesh.

The 'outbreak' of lacewings under all of the mesh treatment plots was another completely unexpected result. As for the aphids it is unclear how they got under the mesh, as the adults, which are the only mobile life stage, are over a centimetre long (Figure 36), and therefore far too large to get through mesh, especially smaller sizes such as 0.4 and 0.3 mm. In addition it was not just a few lacewings, but, large populations that occurred in every mesh plot.

The current hypothesis for how they got in, is similar to that for aphids. The adult lacewings are believed to be landing on the mesh, they can then detect the aphids underneath, they are then laying eggs, which are very small (Figure 37) on the mesh, which then hatch and the newly hatched larvae are able to penetrate the mesh.

Figure 37. Lacewing eggs, source http://istockpho.to/2rSGvvi.

It is then believed that several generations of lacewings would have cycled under the mesh, and as the adults cannot escape once they are inside, this would of caused the populations to build to high levels.

There are a number of outcomes of this result. First, it believed to only be the second example of an insect penetrating mesh en-mass, the first being the aphids penetrating mesh in this and previous FAR trials of mesh on potatoes. While lacewings are a beneficial insect, and therefore not causing crop damage, it is somewhat disconcerting that this has occurred twice, as it indicates other pests may be able to circumvent mesh by the same 'technique'. Second, the lacewing populations built up during the period Chess was being applied (Chess from 15th Feb, maximum lacewings last week in March) indicating that Chess has low toxicity for lacewings. Although the aphid populations were declining due to the Chess sprays, it shows that at least one biological control agent can thrive underneath mesh, boosting the idea of controlling aphids, and any residual TPP, using introduced biocontrol agents.

4.6. Blight

Remarkably there were no *P. infestans* spores found at all across the eight sampling dates (same dates as yellow sticky traps). *A. solani* spores were only detected on the last two sampling dates (Figure 38).

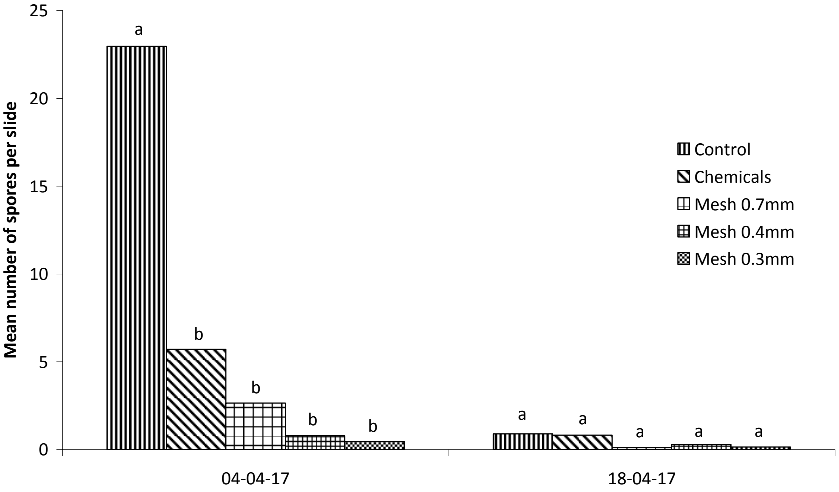

Figure 38. Mean number of *A. solani* spores caught on vaseline coated slides on two dates. 04-04-17 LSD=7.24, p<0.001, 18-10-17 LSD=0.787, p=0.132 (not significant). Columns with the same letter are not statistically different.

On reflection, like TPP visual scores, visual blight scores were also considered less reliable, due to two different people taking the scores. However, as blight symptoms are much more consistent among cultivars (Cruickshank *et al.*, 1982), unlike foliar TPP symptoms, and with the limited number of spores trapped, it is considered that the data has some value. The peak in visual symptoms on 04-04-17 in the control treatment matches up with the peak in spores on the same date for spores caught on vaseline slides (Figure 39) indicating a level of reliability in the visual scores.

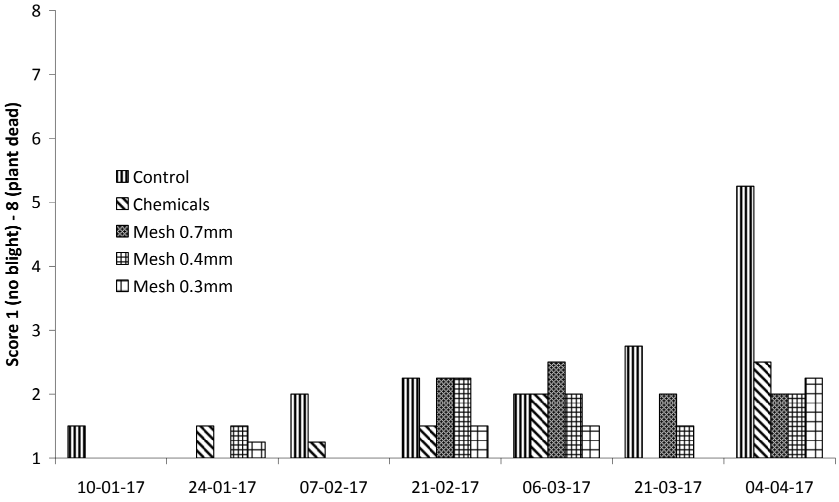

Figure 39. Visual blight scores over seven dates.

Averaging all of the blight scores across all dates indicates no statistical or biological difference among the chemicals and the mesh treatments, but with the control just significantly higher (Figure 40).

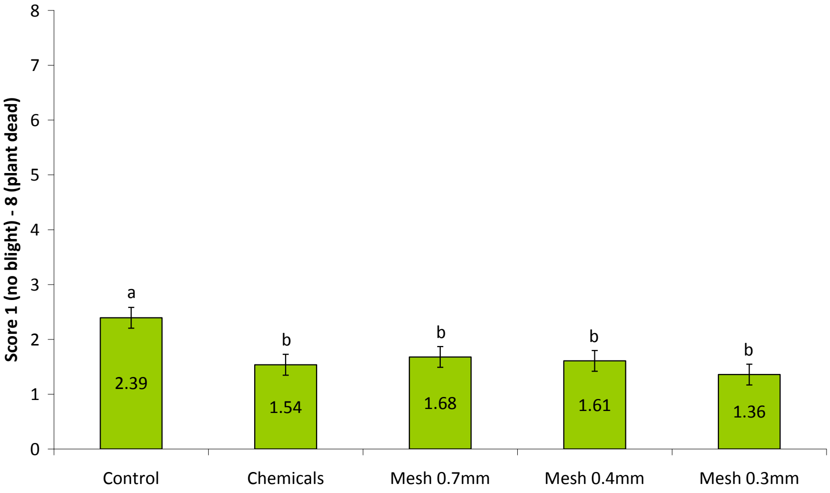

Figure 40. Total combined mean visual blight symptom scores, LSD=0.3792, p<0.001. Error bars = LSD. Columns with the same letter are not statistically different.

As 2016-17 was a very poor year for blight, coupled with the fact blight on the plants was only determined by visual observations, rather than laboratory diagnostics which give a definitive identification, means these results are limited. On the one date were there was a significant amount of *A. solani* spores, there were clearly many more in the control, than agrichemical and mesh treatments, an indication that both the fungicides and mesh were having an effect. If the main effect of mesh on blight control is via reducing UV light (section 2.1), then much more manipulative / controlled experiments will be required to demonstrate causality than measuring blight in field trials. This is discussed in detail in section 7.2.

4.7. Sprouting in storage

A random sub-sample of ten, >60g tubers (market grade) from the 50 tuber sample were placed in a cool dark room for 50 days to test for sprouting. In previous trials ((Merfield, 2013) and unpublished data from the UV trial) tubers from treatments with higher levels of TPP and/or psyllid yellow, produced more sprouts and sprouted more quickly than those from the mesh and lower UV treatments. However, after 50 days storage, in this trial there were significantly more (p=0.008) sprouts on the tubers from the mesh treatments than the control and agrichemical plots (Figure 41), which was unexpected. The cultivars in all three trials are different, with Moonlight used in the second years trial (Merfield, 2013), Red King in the UV trial and Nadine in this trial. Growers have been reporting that they have been experiencing crop emergence failures, which they have been attributing to TPP/ CLSo affected seed. It was therefore considered that the Nadine tubers in this trial could therefore be exhibiting a reduction in sprouting rather than an enhancement of sprouting, as seen in earlier trials with Moonlight and Red King. Therefore instead of returning the tubers to cool storage, they were transferred to a controlled temperature room (CT room, min 15°C max 25°C) under fluorescent lights for 25 days and then all sprouts >1 mm long were counted (Figure 41).

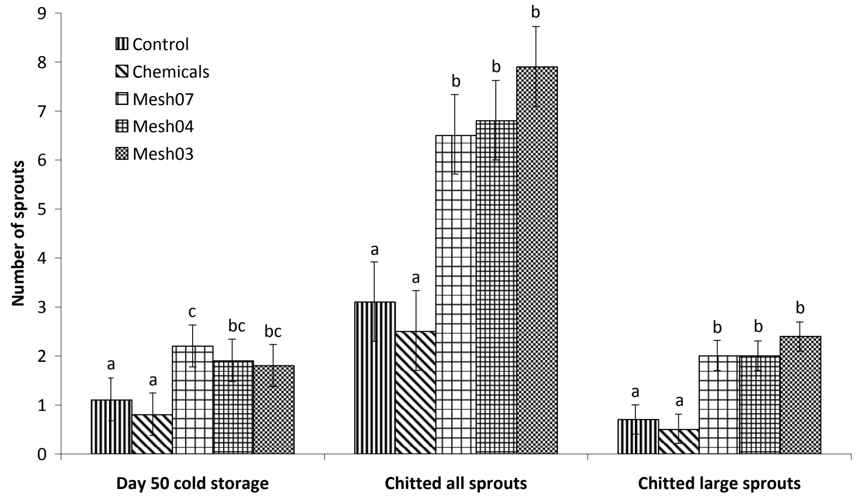

Figure 41. Number of tuber sprouts >1 mm after storage in the cool & dark for 50 days LSD=0.774, p=0.008. Number of sprouts >1 mm after a subsequent 25 d chitting in the warm & light LSD=1.682, p<0.001. Error bars = LSD. Number of sprouts >5 mm after a subsequent 25 d chitting in the warm & light LSD=0.6041, p>0.001. Columns within each group, with the same letter, are not statistically different.

This also produced the result of significantly (p<0.001) more sprouts on the mesh tubers than control and chemicals. It was observed during counting that the sprouts fell into two main types, 1) where the eye had broken dormancy but only produced a small, white coloured, ~1 mm sprout that did not appear to be growing any further, as there were often a handful of these on any given tuber and most tubers had them, and, 2) a sprout that was clearly growing, i.e., was >5 mm long, had turned green, had swollen, was producing side shoots, etc. It was believed that the small white sprouts were 'dormant', in that while the eye had sprouted, the sprouts' growth was inhibited, presumably by apical dominance from the larger sprouts. The number of large sprouts was then counted (Figure 41). This showed the same pattern as for total sprouts, but, at much lower numbers, which were again statistically significant (p<0.001). It was also observed that some tubers had small sprouts that had died, i.e., become dry and flaky / disintegrated instead of soft and pliable. Typically where a tuber had dead sprouts all the sprouts had died. A note was made of which plots had tubers exhibiting dead sprouts, and it was found that it was only the chemical and control plots that had dead sprouts and **all** chemical and control plots had them. None were found from any mesh plot.

It is therefore concluded that in this trial, with Nadine as the cultivar, TPP / CLSo had inhibited sprouting, contrary to the results in previous trials. All the results taken together are indicating that the effect of TPP / CLSo on tuber storage may well be influenced by cultivar. However, as these are separate trials, grown in different seasons, under different treatments, this suggestion is only tentative and if this is a issue of importance to the industry it needs to be tested by growing a range of cultivars in the same trial, with two treatments, one allowing TPP / CLSo infestation / infection (i.e., either agrichemicals or a null control), and the second stopping infection / infestation (i.e., using mesh), and then comparing their storage behaviours both among cultivars and between + and - CLSo treatments. This difference is also interesting when compared to the seed industry inspectors training plots in the same field where different cultivars exhibited noticeably different levels of psyllid yellows despite being in right next to each other (Figure 30).

In the early years after TPPs arrival there was discussion that there may be cultivar differences to TPP / CLSo and Moonlight was believed to be more 'susceptible' (John Anderson (2013), Plant & Food Research, pers. comm.), however, in more recent years this belief has waned. These trials, and the visual observations of the seed industry inspectors training plots, are indicating that the initial belief may be in fact correct.

5. General discussion

5.1. Overview of trial

Overall the trial is a considerable success. The mesh treatments have produced exceptional yields, demonstrated almost complete control of TPP, achieved foliar blight symptoms at the same levels as chemicals and indicated that mesh increases crop growth and yield independent of pest and disease control. At the same time the ability for aphids to penetrate the mesh is frustrating, but, it is now clear that aphids must be penetrating the mesh, not going around the edges.

It is considered that the crop husbandry was as close to ideal as it is possible to get. The land has been under organic management for 16 years, with large applications of compost in the last decade, meaning that soil health / quality and organic matter was very high and provided a strong foundation for the full rate fertiliser application. The land has not had potatoes on it since at least 1993 (23 years) and probably much longer than that, so potato soil borne diseases would be as low as possible. Soil compaction was eliminated in the beds down to 50 cm, deeper than most of the potato root system would be expected to reach. Soil moisture levels were well maintained with frequent irrigation and rain, and fertilisers were applied at optimum levels. It was also a poor year for blight and also TPP.

This is the first mesh trial where the industry standard agrichemical regime was compared with mesh, so this is the first time an economic comparison can be made.

5.2. Economics

A simple comparative gross margin of the returns from using mesh vs. agrichemicals has been calculated (Table 7). Seed & Field Services Ltd. provided costs for agrichemicals, mesh and field gate prices. Real-world costs of agrichemicals range from $1,500 to $2,000/ha with application costs of $18/ha with between 12 and 15 sprays per crop. The purchase price of mesh ranges from $8,500 to $10,000/ha (depending on exchange rate), which, spread over the expected 10 year life of mesh (growers in Europe typically get more than ten years out of a sheet) gives an annual cost of $850 to $1,000/ha/yr. To which needs to be added the cost of laying and removal of $160/ha. Yield figures are taken from this trial using marketable yields for >60 g and >125 g tubers to give a field gate yield. Field gate prices range widely: the fresh market five year average is $250 - $650/t but the current top price is $850. Processing prices are consistently $300-$425/t. From this information, three scenarios, a low, mid and high for both costs and income have been created (i.e., lower costs are paired with lower returns, and vice versa, high costs and high returns are paired). Only the costs of pest and disease control are including in the gross margin as these are the only variables in this analysis. Other costs, e.g., tillage, planting, weed management, harvest are considered to be the same for all so have not been included.

Table 7. Gross margin comparing the costs and returns of agrichemicals vs. mesh. Common costs, e.g., cultivation, herbicides, planting, harvest, are not included.

Agrichemicals

Range	Low	Mid	High
Chemical cost	$1,500	$1,750	$2,000
Application cost	$18	$18	$18
Number of applications	12	13	15
Total cost	$1,716	$1,984	$2,270
Yield t/ha >60g tubers	69.6	69.6	69.6
Yield t/ha >125g tubers	42.7	42.7	42.7
Field gate price	$250	$400	$800
Return on >60g tubers	$17,400	$27,840	$55,680
Return on >125g tubers	$10,675	$17,080	$34,160
Gross margin on >60g tubers	$15,684	$25,856	$53,410
Gross margin on >125g tubers	$8,959	$15,096	$31,890

Mesh

Range	Low	Mid	High
Purchase price	$8,500	$9,000	$10,000
Purchase price spread over 10 years	$850	$900	$1,000
Laying/ removal	$160	$160	$160
Biocontrol costs (guestimate)	$400	$400	$400
Total cost	$1,410	$1,460	$1,560
Yield t/ha >60g tubers	86.5	86.5	86.5
Yield t/ha >125g tubers	68.2	68.2	68.2
Field gate price	$250	$400	$800
Return on >60g tubers	$21,625	$34,600	$69,200
Return on >125g tubers	$17,050	$27,280	$54,560
Gross margin on >60g tubers	$20,215	$33,140	$67,640
Gross margin on >125g tubers	$15,640	$25,820	$53,000
Increased returns from mesh			
>60g tubers	$4,531	$7,284	$14,230
>125g tubers	$6,681	$10,724	$21,110
Percentage increase in returns from mesh			
>60g tubers	29%	28%	27%
>125g tubers	75%	71%	66%

The economic benefits of mesh are therefore very clear. Mesh is cheaper to use than agrichemicals and produces higher yields, and therefore creates a substantial increase in gross margin. In addition the gross margin is conservative for mesh, in that typical mesh lifespan by large growers in Europe is typically 12 not 10 years, and mesh grown / agrichemical free potatoes, with larger tuber sizes could also achieve higher prices, which would make mesh even more profitable than the above example shows.

The Potato Industry Strategy Targets has, as its first target, to "Increase profit from productivity by $150 per annum. ... [This] Equates to a 12% yield increase and $1,500 per ha over ten years." Changing the crop management system from an agrichemical to a mesh system could achieve significantly more than the industries target in one year not ten. Based on this research marketable yields would increase between 24% to 60% (>60g to >125g tubers), i.e., at a minimum double the target 12% yield increase over ten years, but achieved in one season not a decade. Also the dollar value increase in returns from mesh ranged from $4,531 to $21,110, which at a minimum is over three times the $1,500 per ha return over ten years, again achievable in one year. These exceptional results, far exceeding industry targets, can be achieved using an existing technology already widely used on tens of thousands of farms across Europe, that can also dramatically reduce agrichemical use, plus have a multitude of other benefits. It is therefore increasingly clear if the potato industry wishes to dramatically improve its profits, and license to operate through reduced agrichemical use, mesh crop covers are the technology the industry has to change to.

While this appears an unambiguous reason to immediately change to mesh, there are still open research questions, particularly on how to control aphids and if the control of blight applies to both *Phytophthora infestans* and *Alternaria solani* and if the effect is reliable. No one should therefore bet the farm on mesh just yet. It is recommended that growers start trialling small areas of mesh themselves, to start understanding how to use it, how it effects crop management and what impact it has on their crops. Once the problems are addressed then it will be safe for the whole of the NZ potato industry to change to mesh crop covers.

6. Conclusions

This trial has pulled together a number of threads from previous experiments and continued the run of unexpected results from research on mesh crop covers on potatoes.

The original impetus for the research - controlling TPP on potatoes without agrichemicals - is now considered to be unambiguously demonstrated, with levels of efficacy far greater than agrichemicals at significantly lower costs. The key reason to control TPP is to prevent CLSo infection, and the best way to prevent CLSo is to stop TPP reaching the crop, rather than trying to kill TPP after it has fed. Mesh should therefore give the best control of CLSo of any technique, and, the limited, non replicated CLSo testing of mesh 0.3 mm and control treatment tubers indicates this is the likely outcome.

The two finest mesh treatments exceeded the theoretical maximum yield for potatoes and considerably out-yielded agrichemicals, indicating that mesh not only is very effective at TPP control, but, is also directly increasing yield, probably via increased temperature, but also likely due to protection from wind / movement RH effects and potentially other factors. To test this requires potatoes to be grown uncovered without TPP, which requires the experiment to be conducted in a country free of TPP. This has just been done in the UK and initial results from on-farm tests had 30% yields increases with a considerable increase in tuber size / number of large tubers (Ian Campbell, CropSolutions Ltd. UK).

Yield is not profit, but the comparative gross margin unambiguously shows that mesh is significantly more profitable than agrichemicals, even when excluding potentially higher prices for mesh grown /

agrichemical free potatoes. As the experience in the UK indicates, mesh may even pay for itself just off enhanced yield, even, if agrichemical programs had to be maintained.

The bigger goal of controlling blight is still very much a live issue, particularly as blight is two very different pathogen species, and conclusive experiments have yet to be undertaken to show if blocking UV light controls both species. In addition there may be other under-sheet climatic factors, such as lower RH during typical daytime temperatures, that may also be influencing blight levels. Even if mesh is shown not to effectively control both blight species, as for other crops grown under mesh, fungicides can still be applied through mesh, so mesh can still control insect pests while blight is controlled with fungicides.

That aphids are penetrating the mesh is therefore exceptionally frustrating, but, it is considered that a non-chemical solution is entirely feasible as biocontrol of aphids and other pests in protected environments is well understood. The biocontrol agents can then also 'mop up' any TPP and other pests that penetrate the mesh. To create a robust, reliable and economical protocol is however, a substantial piece of research. But, once completed it will be a permanant solution.

If mesh can also be shown to be effective an reliable means of controlling both early and late blight, as well as all other potato insect pests, then mesh with BCAs has the potential to be a complete control for all potato pests and the major foliar fungal disease, thereby eliminating the need for foliar agrichemicals on potatoes, i.e., creating 'spray free' potato crops.

This trial has therefore confirmed and extended the results of previous work on mesh and shown for the first time the clear benefits of mesh over agrichemical control of TPP. The results also achieve yield and profit increases, in a single season, far in excess of industry strategic targets with a ten year time horizon. If the potato industry wishes to dramatically increase profit, reduce its environmental impact and increase its sustainability, potatoes in future are clearly going to be grown under mesh crop covers.

7. Future research

The main areas for future research of mesh on potatoes are aphids, blight, direct yield benefits, control of other pests, followed by TPP & CLSo. Beyond potatoes the potential of mesh for controlling TPP and other pests on field tomatoes and other solanaceae crops, such as tamarillos, needs investigating, and, the potential for manipulating UV light as a means of controlling TPP in protected cropping is also considered to have significant potential.

7.1. Aphids

A number of prongs of attack are required to address the aphid problem. These are both to understand how and why aphids are circumventing mesh and to find solutions.

A key potential benefit of mesh is to fully eliminate aphids from potato seed production crop, especially early stage multiplication, for virus control. However, the current field trial demonstrates that 0.3 mm and above mesh is not aphid proof. The previous trial on 'ultra fine mesh' (UFM) with 0.15 x 0.35 mm hole size did not have aphids penetrate the mesh, but this year, the same piece of mesh did get aphids underneath, although as staff were entering under the mesh this is not clear if it is due to cross-contamination or penetration, including thought damaged to the mesh.

Laboratory experiments trying to determine minimum mesh size have indicated that a very small number of nymphs can penetrate 0.15 × 0.35 mm mesh but none penetrated 0.15 × 0.15 mm mesh, but, these are far removed from field conditions. In addition observations of adult aphids on mesh with a potato leaves underneath have **not** found any of them feeding on potato leaves through the mesh (Howard London, Shola Olaniyan, Lincoln University, pers. comm.). In comparison, the issue of newly born nymphs penetrating the mesh is less of an issue for virus transmission as viruses are not passed from the mother aphid to her offspring, rather aphids only pick up viruses from feeding on infected plants (Simon Hodge, Future Farming Centre; Steve Wratten, Lincoln University, Stewart Gray, USDA; pers. comm.). Therefore unfed nymphs penetrating the mesh do not carry viruses and cannot transmit them. They can, however, clearly cause significant harm through the large numbers that can build up though feeding on the crop. Also if plants under the mesh already carry virus, then, the 'clean' nymphs could pick that virus up and spread it around.

As it appears to be impossible to make mesh completely aphid proof, due to the inevitable damage to mesh in field situations, the use of smaller sized mesh, on the face of it, appears to be of little benefit. However, from these results it appears that aphids are penetrating the courser mesh quicker and/or in larger numbers than the finer meshes. Therefore meshes that can minimise aphid ingress are considered to have additional value. There is also the potential yield and blight control benefits of finer mesh (section 7.3) which adds to the potential value of finer mesh.

It is therefore considered vital, especially for seed production, that the:

- The method and rate of penetration of different meshes by aphids in the field is established;
- Establish a biocontrol protocol to control any aphids that do penetrate mesh.

7.1.1. Determining how aphids penetrate mesh and if they search for ingress points

The method by which aphids are penetrating the mesh needs to be established. The current hypothesis that winged adults are alighting on the mesh and producing nymphs which then penetrate the mesh needs testing. This will require behavioural studies in real-world conditions to confirm the laboratory studies. For example, small pieces of mesh e.g., 1 x 1 meter with potatoes underneath are video recorded to observe if winged adults do alight and produce nymphs.

It also needs to be determined if the winged adults alighting on the mesh, and/or the nymphs they produce, are actively seeking a way through the mesh, and are therefore finding damage-holes in the mesh to gain entry. Observations from laboratory tests of mesh have found that even small gaps where mesh has been glued to the testing apparatus, or, where mesh threads have been damaged / spread, will result in aphid nymphs penetrating such samples. It appears that aphids are very active in seeking ways though the mesh, unlike TPP adults which would often fail to penetrate mesh even when they were easily capable of doing so. The 0.15 × 0.35 mesh holes are also visibly smaller than the aphid nymphs and it appears they are able to push / squeeze themselves though gaps smaller than their size as they are quite soft.

7.1.2. Introduced biocontrol agents

As mesh can never be made completely aphid proof due to inevitable wear and tear and other factors, a means of controlling aphids that do penetrate the mesh is essential, and ideally one that avoids agrichemical solutions so that the potato industry can return to integrate pest management (IPM). The control of aphids through commercially available biological control agents (BCAs) is well established, particularly in protected cropping such as glasshouses. As mesh covered crops are a form of protected cropping, using BCAs is an obvious solution and the extensive established knowledge gives a considerable head start on finding a solution. At the same time, there is no prior research looking at using BCAs in mesh covered crops of any kind, so there is also a significant level of novelty, that needs to be researched to find a robust solution.

7.1.2.1. Specialist vs. generalist biocontrol agents

BCAs can be roughly divided into two types: specialists and generalists. Specialists are those that only feed on one or a very small number of pray species, parasitic wasps (parasitoids) being a good example. Generalists will prey on a wide range of species, with ladybirds, being a classic example. There are a number of pros and cons of each BCA type.

Specialists tend to have better abilities to locate prey, as they need to find their prey species among many other pests, and/or when their prey occurs at low densities. This means they are more likely to find aphids when their numbers are low. However, parasitoids generally only attack fully, or near fully grown prey, as immature prey individuals are too small for the parasitoid to develop inside them, so smaller aphids will be left alone, which may or may not be problematic. Specialists also are unable to make use of and therefore control other pests such as TPP. They may also have limited ability to make use of alternative food sources such as floral resources although some species are dependent on nectar and pollen.

Generalists mostly have the opposite attributes of specialists: their ability to locate aphids, especially when they are at low populations or mixed among other prey (which may be more attractive) is less. They mostly eat any prey life stage, i.e., small aphids, and they may also eat other pests, such as TPP and will consume all juvenile stages and also eggs. In some species the adults may need additional resources, though, there is potential for these to also reduce their feeding on pest species.

There are therefore pros and cons to both specialists and generalists and it is quite possible that the best approach may be to use more than one BCA and to mix a specialist and a generalist. This does not mean that the cost need increase when using two or more BCAs as fewer individuals of each species will be required.

7.1.2.2. Preventative vs. curative use of BCAs

There are two main approaches to using BCAs in protected cropping. Preventative, where the BCA is introduced before the pest is seen, typically on a calendar or prescriptive basis, or, curative, where the crop is monitored for the pest and when its presence is identified, BCA's are only then introduced, typically at high rates to overwhelm the pest.

For mesh covered potato crops, monitoring for aphids is likely to be sufficiently time consuming, and the likelihood of aphids penetrating the mesh, sufficiently high, that a preventative approach is probably required, although this should be verified as part of the research.

7.1.2.3. Floral resources and banker plants

It is assumed that the total number and rate of aphids penetrating mesh are quite small (although this needs to be verified), if so they will not provide sufficient food or hosts to sustain the introduced BCAs. It is therefore considered likely that the BCA's will benefit from additional food sources and hosts to keep them alive. Such resources have also been shown to dramatically boost the efficacy of BCAs, often at low cost, e.g., the Greening Waipara program (https://bioprotection.org.nz/research/programme/greening-waipara).

There are two main approaches to BCA resource prevision: flowers and banker plants.

The use of flowers to boost biocontrol is widely known, often going under the name of 'companion planting' in gardening circles. However, much of these traditional recommendations are mostly lore not science, and, considerable research has been undertaken to clearly identify which plant species provides the right nectar and pollen for any given BCA and that fits into a given production system.

Banker plants are those that host alternative prey of the BCA. In terms of aphids on potatoes, another plant, e.g., cereals, that hosts cereal aphid species that cannot live on potatoes (many aphids can only feed on only a narrow range of plant species) is grown among the potato crop, the BCA then feeds on or parasitizes the aphids on the cereals so maintaining its population, so when potato aphids do penetrate the mesh, there are plenty of BCAs present to control them.

7.1.2.4. Biocontrol agent conclusions

While controlling aphids in protected cropping through introduced biocontrol agents is a mature science and protected cropping industry best practice, finding the best BCA(s) and resource plants to control aphids on potatoes under mesh and creating a reliable, robust and cost effective combination will require a reasonable amount of research. However, once this research has been done, the same as other programs like Greening Waipara, potato growers will have a permanant solution, that will ensure the absolute minimum number of aphids, TPP and other potato pests.

7.1.3. Natural biocontrol agents

Some organic growers are already managing aphids under mesh by not sealing the mesh all the way round, but, leaving part of the sheets open, e.g., at the ends, which allows BCA's that are naturally present in the field, to be able to enter the mesh and control the aphids. While simple and cheap, this approach needs to be researched to determine how effective it is. Monitoring of actual farm crops is considered to be the best approach as commercial mesh sheets can be as large as 40 x 200m which cannot be replicated in research plots because sheet size will effect aphid and BCA movement. This research needs to determine the extent of aphid and BCA penetration under the mesh, if the approach is consistently reliable, and, also if the aphids are vectoring viruses before they are controlled by the BCAs.

7.2. Blight management

To date, all measurements of the effect of mesh on blight are visual foliar symptom assessments. While the reduction in blight symptoms has been highly consistent both in trials and on-farm with some dramatically lower blight symptoms under mesh, there are two blight species, early blight *Alternaria solani* and late blight *Phytophthora infestans* which are biologically very different, early blight being a true fungi and late blight an oomycete. Most of the research and growers using mesh are on the east coast where blight levels, particularly *P. infestans*, are lower due to lower rainfall and relative humidity. It is therefore completely unknown if mesh is controlling both blight species or only one. In addition, foliar blight looks similar to a range of other potato foliar diseases, e.g., Rhizoctonia, and it is clear from this trial, that foliage can have a wide range of foliar diseases yet hardly any blight at all.

Research to date therefore has 'only' achieved a correlation between UV light levels and foliage symptoms that look like blight, and while a the correlations have been strong and results consistent, correlations are not the same as demonstrating a causal connection. Considering blight can inflict massive crop losses it is considered essential that cause and effect are shown for how mesh is reducing blight. This will require potatoes to be grown in isolation from airborne fungal spores, then deliberately inoculated with individual blight spp and grown under plus and minus UV conditions, or a gradient of UV levels, and then the resulting foliar infections tested to confirm their identification. This work was attempted this season using growth chambers and artificial UV lights, but met multiple problems, which have been solved for the design of future experiments.

7.3. Yield / growth enhancement from mesh

The results of this trial, particularly mesh yielding above the theoretical maximum, along with the 2015-16 'ultra fine mesh' test and the enhanced growth seen in other trials, particularly in the UK which is free of TPP, indicates that there is a direct positive benefit on potato growth and yield from mesh, in the absence of pests & disease. This is believed to be due to multiple factors including, an increase in temperature / growing degree days, reduced UV levels and wind protection. The reduced relative humidity may also be having an effect, both positive and negative. It also appears that finer mesh is achieving a greater yield increase. It is considered possible that the yield from this trial could even be exceeded and yields of over 100 t/ha are possible, based on the fact that there were still a number of small tubers from mesh treatments in this trial, indicating unfulfilled yield potential.

It is considered important to better understand which of these factors is increasing yield and the relative amounts so that positive factors can be enhanced, while negative ones, reduced.

7.4. Impact on seed crops

7.4.1. Carry over effect of TPP / CLSo on seed crops

One of the industry's concerns is that due to the difficulty of controlling TPP, seed crops are still being infested by TPP at low levels and transmitting CLSo, which is then having an impact on the subsequent food crops, as evidenced by poor emergence, plant deaths, and reduced yields.

It was hoped to undertake a cross over cross over trial next season, i.e., tubers from this years chemical treatment will be planted in two treatments, chemicals and mesh, and likewise tubers from this years mesh 0.3mm treatment will be planted under chemical and mesh treatments. If the yields under the two mesh treatments differ and likewise the yields under the two chemical treatments differ, this, would demonstrate that there is a carry over impact from the seed tubers. This would of required CLSo testing of planting tubers. However, funding has not been provided to carry this research out.

As discussed in section 4.7 there appears to be variation in how different cultivars respond to CLSo infection, especially in storage with contrary results coming from the different research trials in this project. Therefore undertaking a cultivar comparison trial with two treatments of + and - TPP/CLSo could be particularly informative. The tubers from that trial could then also be used in a cross-over trial which would make those results even more informative due to the multiple cultivars.

7.4.2. Viruses

Clearly one issue for the mesh treatments is the larger numbers of aphids that infested them and therefore the potential for them to transmit viruses. However, as section 7.1 noted, if it is new born aphids that are penetrating the mesh, they should be free of viruses, so, the mesh treatments should prevent the introduction of viruses from outside the crop.

One of the emerging routes of virus transmission is sap vectored viruses spread from wind damaged plants and machinery, especially spraying machinery use to control aphids to control virus - i.e., current virus control by spraying aphids is producing a Catch 22 situation in that it reduces one infection path but increases another. Mesh should minimise the potential for sap spread viruses as wind speed and haulm movement and thus damage is dramatically reduced under mesh, and tractor tramlines are outside the mesh sheets so there would be no machinery driving through the crop. This should be a particular boon in early generations.

Plus the other benefits of mesh, such as increased yield, would also be valuable. With the inherent risk adverse nature of seed crop production, especially early generation, there is potential to combine current spray regimes with mesh, as sprays go through mesh, to allow early testing of mesh, by the seed industry by giving them confidence that they have done everything to ensure the lowest possible aphid and TPP populations.

Mesh therefore has the potential to also revolutionise the seed potato industry, by allowing the production of effectively CLSo and virus free potato seed.

7.5. Other potato pests

Mesh is expected to be effective against all other potato insect pests, e.g., potato tuber moth, green potato bug, potato leafhopper, and overseas, the likes of Colorado beetle. However, this should be positively confirmed and tested for unexpected results and consequences, because, as with aphids, unexpected results do occur. If successful, this would solve a number of difficult potato pest problems globally.

Mesh could also be a ready and waiting solution to the 'next TPP' i.e., the next pest to defeat NZ's biosecurity, such as Brown marmorated stink bug (*Halyomorpha halys*). Part of the issue with the arrival of TPP is that there were not the right insecticides approved and available in NZ when TPP arrived, plus when they became available spray programs still had to be worked out which took several years, during which TPP control was limited. If the same scenario occurs with the next introduced pest then the industry could be looking at several years of yield losses and increased costs. In comparison, growers already using mesh on potatoes would probably have to make no changes to their production systems at all and can carry on as normal.

7.6. TPP & UV light and other crops

The spectral filter experiment (section 2.1) 'only' established a correlation between foliar TPP symptoms and UV levels. While this effect is somewhat incidental for potato production, as mesh is such an effective means of TPP control, this finding could have significant implications for production of solanaceae crops grown under protection, e.g., tomatoes, peppers etc. For example a UV blocking plastic on polytunnels could control TPP populations, or UV light could be a TPP attractant to trap / kill them, e.g., as per commercial UV fly traps for food premises. Domestic gardeners growing tomatoes under mesh are reporting exceptional results (http://getgrowing.realviewdigital.com/?iid=151565#folio=11 http://www.bhu.org.nz/future-farming-centre/ffc/information/crop-management/production/mesh-potatoes/2015-10--nz-gardener-2015-psyllid-and-mesh.pdf), even better than pre TPP, and research on tomato production under UV blocking covers has also found positive results (Díaz & Fereres, 2007).

Fundamental studies of TPP's response to UV light therefore needs to be established and then this used to guide how this can be used for TPP management in protected cropping. It is considered that mesh could produce the same kinds of benefits on field tomatoes as it has done on potatoes, and, therefore field trials on field tomatoes would be exceptionally valuable.

7.7. Biocontrol of potato pests through ecosystem enhancement

The exceptional effectiveness of mesh for TPP control plus its apparent yield boosting effects, potential control of blight and lower cost indicate that moving to mesh for potato production is the future for the industry. However, for producers looking for an alternatives to mesh, e.g., for early season potatoes when TPP populations are lower, there could be considerable value in developing, a system of ecosystem enhancements, such as floral resources and banker plants, to enhance natural biological control agents to control all potato pests. This and previous trials have indicated that there is considerable predation of aphids by biocontrol agents due to the low numbers on the unsprayed control treatments and high numbers that develop in the absence of BCAs under mesh, even in the middle of commercial potato crops sprayed with insecticides. There is therefore considered to be significant potential to control potato pests by ecosystem enhancement as alternative to insecticides when mesh is not used. Considering the lower numbers of TPP in this trial on the control than the agrichemical plots, it is not inconceivable that ecosystem enhancement / an IPM program could be more effective than agrichemicals for TPP management.

Having effective biological control of aphids and other insect pests would be particularly important if *Tamarixia triozae* proves highly effective at TPP control and brings the nationwide populations down to low levels / below economic thresholds such that mesh or chemicals are no longer required for TPP control. However, the success rate for this kind of classical biological control is only 10%, so, this outcome is unlikely.

Where *Tamarixia* does not 'eliminate' TPP from New Zealand, it may still be able to provide valuable control of TPP within potato crops. However, if growers are using insecticides, it is highly likely this will kill off any *Tamarixia*, as parasitoids are generally highly susceptible to insecticides, so they wont get any biological control benefits. Therefore if the most is to be gained from *Tamarixia* it is likely that the industry needs to return to an IPM system which will be boosted by ecosystem enhancements.

Even if mesh were no longer required for TPP due to *Tamarixia* 'eliminating' it, it may be economically viable to use mesh just for yield enhancement and 'insurance' against wind damage.

7.8. Research conclusions

While some very significant 'wins' have been achieved by using mesh crop covers on potatoes, there are still some significant issues to be resolved before growers can 'bet the farm' on mesh as a technology. None of the issues are considered insurmountable, indeed, most have considerable prior research and best practice from other industries as a foundation. If the required research is completed at sufficient pace there is potential for mesh to be fully farm ready within a few years. In the interim, it is recommended that growers start testing mesh in their farm systems to get their heads around what is involved. At the same time, the pressure on agrichemicals from pest and consumer resistance is only expected to increase, and mesh therefore represents a significant opportunity on many other crops to provide more effective pest control than chemicals while potentially also boosting yield, quality and profit. It is now common for horticultural enterprises in Europe to use mesh. If New Zealand horticulture wants to produce higher value products that achieve premium prices, then using and undertaking research into mesh, is going to be a key part of that future.

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