Effect of UV Light on Foliar Potato Blight and Psyllid Yellows

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Dr Charles N Merfield

The BHU Future Farming Centre

Permanent Agriculture and Horticulture Science and Extension

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1. Summary

- Previous FFC field trials have found that mesh crop covers can significantly reduce the amount of main and/or early potato blight (*Phytophthora infestans* and *Alternaria solani*) but that under-mesh microclimate, both temperature and relative humidity (RH) did not appear to be the cause.
- It was hypothesised that the cause of the blight reduction could be a spectral filter effect, where the mesh is changing the light spectrum reaching the crop, particularly reducing ultraviolet (UV) light levels, which is inhibiting blight.
- A field trial was conducted in the 2015-2016 season to compare six different crop coverings with different spectral and UV transmission properties for their effect on blight. This included two meshes that had been used in previous years field trails, two meshes from Israel designed for use in protected cropping with contrasting UV transmission levels, and two polythene polytunnel sheets with high and near zero UV transmission but nearly identical visible light transmission, plus a null control.
- Due to the likelihood of polythene sheets killing the potato plants due to overheating if laid directly on the crop, as is done with mesh crop covers, large cloches were used and the sheets were laid onto the cloche hoops.
- The control plots had the lowest minimum, average and maximum temperatures and highest maximum RH, with minimum and average RH not being statistically significant. The temperatures of mesh treatments were higher than the control and lower than the polythene treatments, the latter also had the lowest maximum RH.
- Foliar blight was assessed using a visual key. There was a strong correlation (R^2 = 0.72) between the amount of UV light under the treatments and the amount of blight, with lower UV levels corresponding to lower blight.
- Due differences in foliar tomato potato psyllid (TPP) symptoms (psyllid yellows) appearing among the treatments as the trial progressed, psyllid yellows were also measured and a similarly strong correlation (R^2 = 0.68) was found between reduced UV levels and psyllid yellows.
- There appears to be a clear link between the amount of UV light and foliar symptoms of both blight and TPP. However, correlation is not causation, and the number of causal mechanisms for both are numerous, so, more controlled forms of research to demonstrate causality, especially for both blight species is essential.
- The relationship between yield and UV levels was unclear. There were still large and statistically significant increases in yield over the control from two best mesh treatments of 135% and 149%, which is consistent with previous and subsequent field trials and indicates the clear benefits of mesh crop covers for potato production.
- The polythene sheets, did not perform as well as mesh, and it is speculated that aspects of the microclimate under the cloches, beyond the temperature and humidity measured in this trial, may have had an effect.
- However, there was a clear relationship between UV light levels and tuber sizes with higher UV treatments having higher numbers of small tubers and lower UV treatments having a larger proportion of large tubers, which is consistent with previous and subsequent field trials.
- In conclusion, the original aim of finding a relationship between UV light levels and potato blight has been successful, with the added bonus of finding a relationship between UV light and psyllid yellows. However, the linkage between UV light levels and yield is unclear, and may be influenced by other factors such as cloche microclimate.
- Considering the importance of potatoes as a food crop, not only in the developed world, but particularly the developing world, this and other FFC research, shows the unparalleled potential of mesh crop covers to revolutionise potato production both for pest and disease control while achieving a large reduction in the use of, and reliance on, agrichemicals pest control.

2. Introduction

The BHU Future Farming Centre's first field experiment (Merfield, 2012) investigating the use of mesh crop covers for control of tomato potato psyllid (TPP, *Bactericera cockerelli*) produced the unexpected effect of also significantly reducing potato blight (*Phytophthora infestans* and/or *Alternaria solani*). It was initially hypothesised that the mesh was changing the under-sheet microclimate, e.g., temperature and/or relative humidity (RH) which was reducing disease symptoms. However, the second experiment (Merfield, 2013) found only small climatic differences between mesh and the uncovered control, which were considered insufficient to be the cause of the large differences in blight symptoms. A new hypothesis was proposed, that it was a 'spectral filter effect' whereby the mesh was changing the light spectrum reaching the crop, particularly by reducing ultraviolet (UV) light. A considerable amount of research has been conducted globally on the effects of spectral filters on both crop performance, and pest & disease levels, with dramatic results in some cases (West *et al.*, 2000; Anon., 2005; Paul *et al.*, 2005; Paul & Moore, 2006; Díaz & Fereres, 2007; Dáder *et al.*, 2015; Dáder *et al.*, 2017). A field experiment was therefore established to investigate the relationship between UV light and foliar blight, by using plastic coverings to change the light spectrum reaching a potato crop. As the trial progressed, it was observed that there was also a substantial difference in psyllid yellows between the treatments, so, an assessment of psyllid yellows was also made.

3. Methods

The overall aim was to compare a number of plastic covers, with contrasting UV transmission properties, to study their effect on foliar blight symptoms, to see if the reduction in blight seen in previous trials was due to a reduction in UV light under the mesh. Psyllid yellows, i.e., the foliar symptoms of TPP infestation, was also assessed.

3.1. Establishment

The trial was established in November 2015 at the Biological Husbandry Unit's, "Medium Input Block", Lincoln University, Canterbury, New Zealand, (43°39'00.18" S 172°27'24.64" E, w3w.co/samba.gliding.championship).

The site had been under pasture for the previous year. Soil type is Templeton silt loam, soil test results were: pH 6.3, Olsen phosphorus 17 mg/L, potassium 0.44 me/100g, calcium 8.8 me/100g, magnesium 1.00 me/100g, sodium 0.11 me/100g, available nitrogen (15cm Depth) 55 kg/ha, Organic Matter 3.8%.

The soil was surfaced worked to break up the pasture, then beds created and soil loosened with ridged tines between the tractor wheelings (1.65 m centers), rotovated (rotary hoed) between the wheelings, then second pass of ripping (to 40 cm depth) and rotovating to achieve a sufficiently fine and deep tilth.

Seed potatoes, Cv Red King (Edward), supplied by Morton Smith-Dawe Ltd., Christchurch, NZ, were then hand planted, in one line down the center of the beds on the 1st December 2015. Twelve tubers, were planted per bed, 37 cm apart, then a single ridge was formed over the top of the tubers, i.e., down the center of the bed, using a tractor mounted potato ridger. Nine days later (9th Dec) the ridges were pulled down with a spring tine cultivator and then ridged up again, to kill the weed flush.

From the 11th to 18th Dec cloches (Merfield, 1952) were installed. Cloches consisted of 12 mm diameter round steel bar bent into a hoop 0.75 m wide and 90 cm high (at the top of the hoop) above soil level (Figure 1). Approx. 30 cm of the ends of the steel bar were inserted in the soil. Cloches were orientated east-west so the long side was facing the midday sun to maximise the amount of UV exposure. Cloches were 5 m long from the first to last hoop.

On the week starting 11 January 2016 all cloches and surrounding soil were hand weeded and a pasture mix sown outside the cloches. Any haulm that grew out of the cloches was pushed back inside on a weekly basis.

Figure 1. Cloches at establishment on 18 December 2015.

3.2. Irrigation

Pressure compensated drip irrigation pipe was attached to the underside of the top of the cloche hoops, so that water would fall onto the potato foliage to wet it and increase RH. The irrigation pipe was 20 mm diameter with pressure compensated emitters every 20cm. The application rate was measured by collecting the water from all emitters down the entire 5 m length of three randomly chosen cloches, and then averaged. The time required to apply 32 mm rain equivalent for the ground area of the cloche was then calculated at 30 minutes, allowing the volume of water applied to be determined by duration. It was assumed that supply pressure was constant and that the pressure compensating drippers would equalise any variation in pressure that did occur.

Irrigation of 32 mm was applied at the following dates: 3 Feb, 10 Feb, 11 Feb, 12 Feb, 16 Feb, 17 Feb, 19 Feb, 22 Feb, 24 Feb, 26 Feb, 29 Feb, 2 March, 4 March, 7 March, 9 March, 11 March, 14 March, 16 March, 23 March, giving a total of 602 mm rainfall equivalent. Rainfall was not recorded as 2015-16 was a dry summer in Canterbury and the covers, especially the polythene sheets limited the amount of rainfall reaching the crop, and that volume was considered small compared with the amount of irrigation applied.

3.3. Cover materials / treatments

The experimental design was a randomised complete block with, six cover types / treatments, a null control with four reps.

The cover types / treatments are listed in Table 1. Two types of covers were used, woven mesh and polythene sheets. The mesh was both purpose designed field-crop mesh (Crop Sol) and glasshouse / polytunnel mesh (Cosio, Ginegar). Mesh was used as this was the material producing the blight reduction effects in previous trials, hence, why the two meshes from previous years were reused. Polythene sheets were used because these had more 'absolute' UV properties, particularly UV blocking, and, as there are no holes in sheets compared with mesh, all sunlight has to pass through the plastic, while with mesh, some light passes through the plastic threads and is therefore modified and some light goes through the holes and is unmodified. The two Ginegar meshes are sold on the basis of their UV blocking and transmission properties, but are otherwise considered the same. Likewise the Lumisol and Lumivar polythene sheets are sold as having the same general properties, with the exception of UV light transmission where one is UV blocking and the other transmitting. Having two pairs of covers (polythene sheet and Ginegar mesh) that are identical apart from their UV transmission was considered valuable in terms of a direct comparison of their results, without having confounding factors, e.g., hole sizes, visible light transmission, air transmission etc.

Table 1. Treatments / cover types. UVt = UV light transmitting, UVb = UV light blocking. Cosio and Crop Sol were not designed to have specific UV transmission properties so are un-classed. The Ginegar and polythene sheets were designed to have specific UV transmission properties and so are listed as such.

ID	Type	Source	Trade name	Measured hole size mm	Previously used
Control	N/a	N/a	N/a	N/a	N/a
Cosio	Mesh	Cosio Ltd. NZ www.cosio.co.nz	Biomesh 125 gsm	0.78 × 0.48	1st and 2nd years trials
Crop Sol	Mesh	Crop Solutions Ltd., UK www.cropsolutions.co.uk	0.6 mm insect net	0.57 × 0.43	2nd years trials
Ginegar UVt	Mesh	Ginegar Ltd, Israel www.ginegar.com	Transparent 50 mesh	0.89 × 0.24	New
Ginegar UVb	Mesh	As above	Optinet 50	0.92 × 0.23	New
Lumisol UVt	Polythene sheet	BPI Visqueen, Scotland bpivisqueen.com	Lumisol	N/a	New
Lumivar UVb	Polythene sheet	As above	Lumivar	N/a	New

Laying polythene sheet direction on the potato haulm was expected to result in very high, probably lethal, under-cover temperatures as the plastic sheets block all airflow unlike mesh. It was this concern that drove the decision to use cloches for all treatments, rather than laying covers direct on the crop as in previous trials, even though producing potatoes under cloches is a highly non-standard technique, and doing so considerably reduced the area / amount of potatoes from previous trials that had approx. 80 m^2 per plot.

Mesh hole sizes were directly measured. As the Cosio and Crop sol meshes were the actual sheets used in previous years trials, the hole size measurements from the previous reports has been used (Merfield, 2012, 2013). For the Ginegar mesh, two samples of mesh, for each mesh type, approx. 20 cm × 200 cm were taken prior to the mesh being used, and, for each piece, sixteen holes were measured using a microscope and averaged (Table 1).

The null control setup was identical to the cloches except for having no cover, i.e., the metal hoops and irrigation were installed the same as for the cloches.

To determine the light transmission, at both visible and UV wavelengths, a spectral analysis of the materials was conducted. Two methods were used: Spectral properties of the polythene sheets Lumisol and Lumivar were confirmed by replicated transmission measurements of UV and visible wavelengths under clear sky, middle-of-day, ambient solar conditions during New Zealand summertime, using a double-scanning monochromatic spectroradiometer (OL756, Gooch and Housego, FL, USA) (Figure 2). Spectral properties of mesh materials were confirmed via transmission analysis using bench-top spectrophotometric sampling (Libra S60, Biochrom Ltd, UK) (Figure 2) and (Table 2).

Due to the similarities of the Cosio and Ginegar UVb mesh in the above spectral analysis, but, significantly different results, a second measurement of the two sheets was undertaken at the time of report writing to confirm the first measurements. This was done using a bench-top Shimadzu UV-1800 UV/Vis spectrophotometer. A baseline correction was first performed with the chamber empty, then a scan from 1100 to 190nm was carried out for each sample. The results, confirmed the first spectral analysis, in that the spectra were very similar within the variability of the mesh samples used and different equipment. Data not presented.

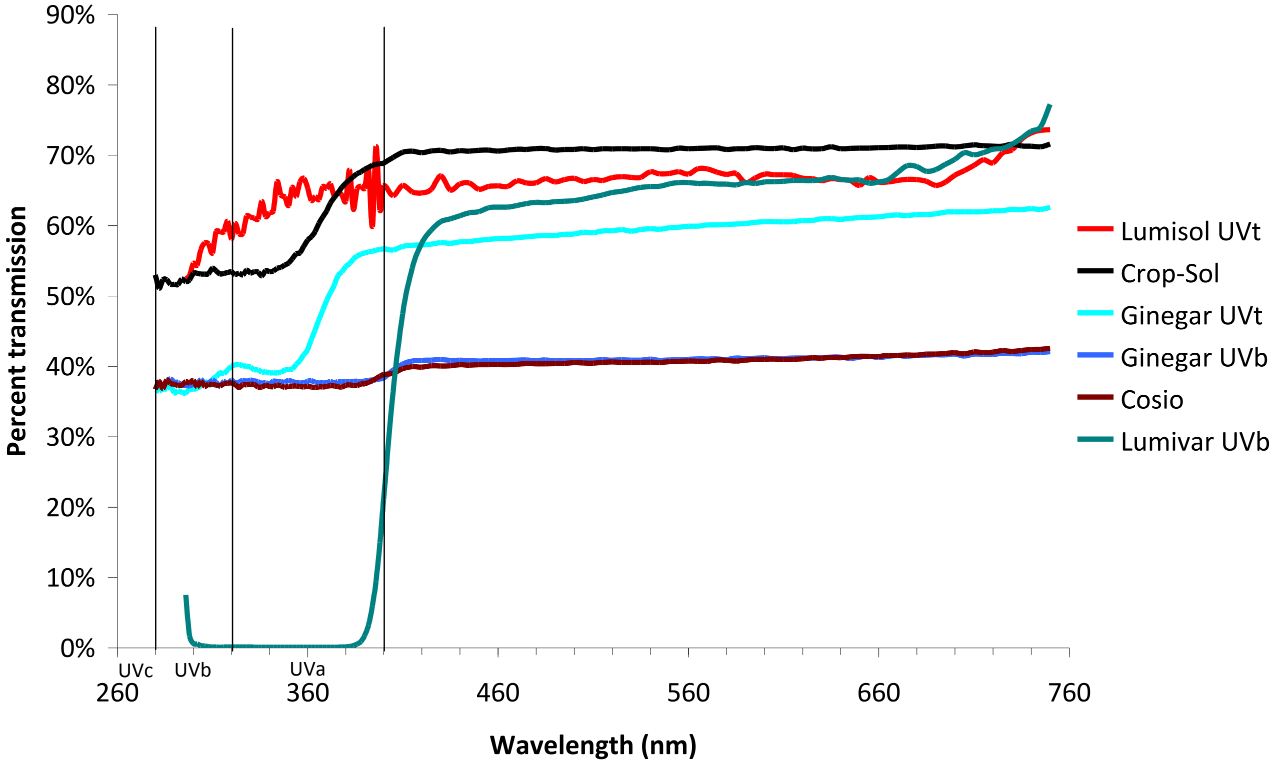

Figure 2. Percentage light transmission of the six different covers / treatments. UVt = UV transmitting and UVb = UV blocking. Cosio and Crop Sol are mesh crop covers so do not make UV transmission claims. Ginegar are meshes designed to have UVt and UVb properties. Lumisol and Lumivar are polythene sheets designed to have UVt and UVb properties.

Table 2. Percentage UV light transmission (UVa and UVb combined) for the six treatments compared with the control.

Treatment	Control	Lumisol UVt	Crop-Sol	Ginegar UVt	Ginegar UVb	Cosio	Lumivar UVb
UV-transmission	100%	60%	56%	42%	38%	37%	1%

The cover materials were laid over the hoops. The long edge of the covers were wrapped around and fastened to 2.5 × 5 cm wooden battens, and the ends of the covers were gathered up and tied to an anchor stake in the soil. The wooden battens were in turn attached to the hoops with cable ties, which allowed the battens to be slid up and down for access. There was an approximate 5 to 15 cm gap between the soil and the bottom of the covers to allow for air flow. Generally the sheet on the side facing the sun (North, in the southern hemisphere) was kept lower and the shady / south side was higher to minimise direct light entry, particularly UV light, into the cloches (Figure 1).

3.4. Temperature and relative humidity measurements

Digitech QP-6013 data loggers were placed in every cloche on a data station. These 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 from sun, irritation and rain. Data loggers were initially attached with hook and loop fastener, but, the adhesive failed on some, so they were then more securely attached with letter clips. Data from loggers that fell down was discarded from the point of the last download.

3.5. Foliar blight and psyllid yellow assessments

Foliar blight was assessed using the Cruickshank et al., (1982) illustrated assessment key, but, with the score reversed, so that a score of 1 corresponded to <10% blight and 8 > 90% blight (Figure 3).

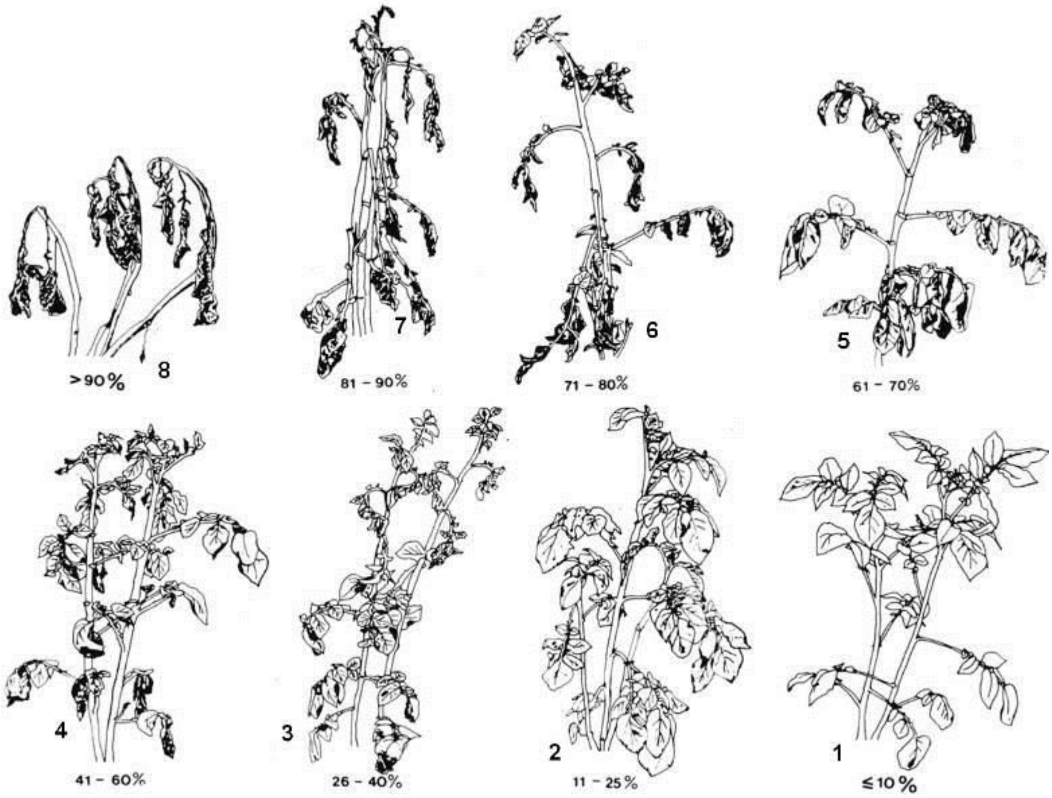

Figure 3. Cruickshank et al., (1982) illustrated assessment key for foliage late blight of potatoes, with reversed scale.

The assessment procedure was to open the north side of each cloche, then in the middle, in the same location each time, plants were compared with the visual keys in the field to give a score. Potatoes leaves that had naturally senesced / died, especially towards the end of the trial were differentiated from blight infected leaf tissue and were ignored in estimating the score. Photos were taken of every plot at all assessment dates.

Foliar blight was assessed on 11 Jan, 25 Jan, 10 Feb, 24 Feb, 16 Mar, 23 Mar, 6 Apr. Sampling did not start until the 11 Jan as there were very few blight symptoms until that date.

Levels of psyllid yellows was determined with an assessment key based on the approach of Cruickshank et al., (1982), but using photographed potato leaves from the trial in place of drawings, and supplemented with a written key. The written key is:

1. Normal leaf, green with flat leaflets.
2. Leaf normal green, slight folding of some leaflets margins.
3. General slight loss of leaf colour, some leaflets' margins folding.
4. General slight yellowing of leaf, most leaflets' margins folding.
5. General yellowing of leaf, most leaflets cupped.
6. Patchy mottled chlorosis, all leaflets cupped.
7. Leaves have interveinal chlorosis with main veins darker green, extensive leaflet cupping.
8. Leaves almost completely chlorotic with small areas of light green on main veins, extensive leaflet cupping.

The photographic assessment key is shown in (Figure 4).

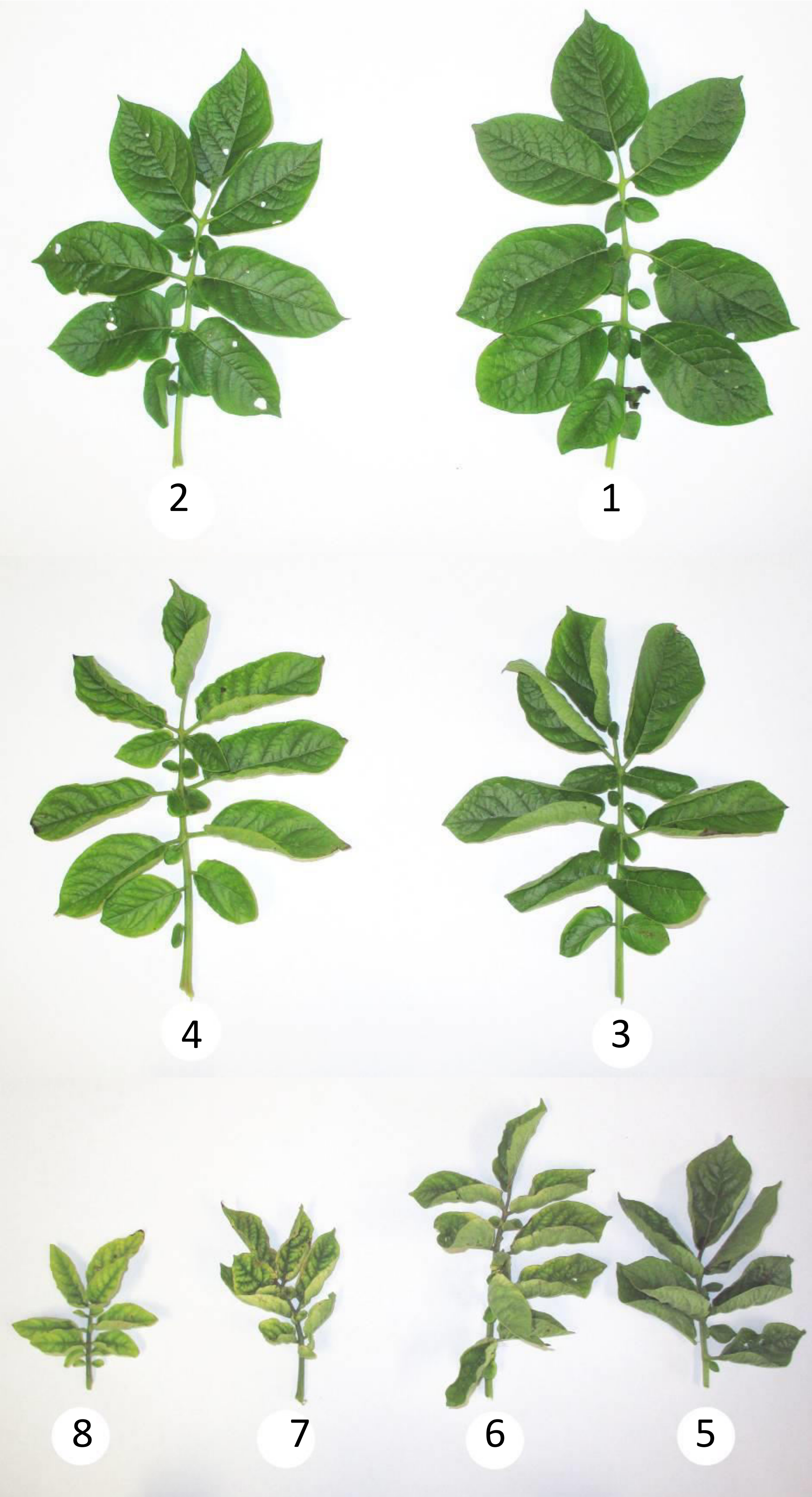

Figure 4. Psyllid yellows, photographic, assessment key, using Red King (Edward) cultivar, created using potato leaves from the trial.

Psyllid yellows were assessed on 23 Mar and 6 Apr, as the decision to assess yellows was only made as the trial progressed. They were made at the same time as assessing blight.

3.6. Harvest - yield and specific gravity

The trial was hand harvested on 13 April 2016, with all tubers down to 1 cm diameter retained. The number of plants per plot surviving until harvest were counted. The tubers were then hand washed. Then the total weight of tubers per plot was taken, then, each tuber was individually weighed, to give an average and maximum tuber weight, and the average number of tubers per plant.

Per plant yield was used due to the variation in the number of emerged plants and the small number of tubers that were planted (12). It is acknowledged that where plants were missing the neighbouring plants may have benefited from the reduced competition and therefore yielded more as a result. However, with the spacing used and the small size of the haulm on cv. Red King, it has been assumed this effect is minimal and has therefore been ignored.

Specific gravity was measured by weighing approx. 5 kg of tubers on scales, to 1 g accuracy, in a bucket with holes in the bottom. 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.

3.7. Storage trial

In previous trials, tubers from treatments with high levels of TPP infestation / psyllid yellows, sprouted sooner and had more sprouts than treatments with low numbers of TPP. While TPP populations were not directly counted in this study, visual assessments of psyllid yellows were made.

The ten tubers from each plot were placed in a paper bag, which was then placed at ground level in a cool and dark, store room. Four data loggers were placed among the bags to measure temperature and RH. The storage trial started on 12 May 2016, the first assessment was undertaken on 1 Jul, 50 days later, and then again on 20 Aug, 100 days since storage started. At each sampling date the number of sprouts that were greater than 1 mm long were counted on the ten tubers from each plot and an average taken was then used in the statistical analysis.

3.8. Statistical analysis

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. Potato emergence

Despite careful hand planting, the number of emerged plants was highly variable, with a range from six to twelve plants (twelve tubers were planted) with overall mean of 10 plants. An ANOVA analysis of the emerged numbers had a p value of 0.844 (Table 3), so, despite the variability the number of tubers per treatment was considered sufficiently similar to not jeopardise the results.

Table 3. The mean number of emerged plants, from twelve planted tubers, for each treatment, p = 0.844, LSD = 2.460.

Control	Cosio	Crop-Sol	Ginegar UVt	Ginegar UVb	Lumisol UVt	Lumivar UVb
10.00	10.50	9.50	9.50	10.75	10.50	10.75

That up to 50% of tubers per plot did not emerge was unexpected, but, it is consistent with reports from potato growers that they also experience significant crop emergence failures, which are put down to the effect of TPP and CLso on seed tuber production, as these kinds of failures are said to be rare, prior to the arrival of TPP.

4.2. Temperature and RH

4.2.1. Results

The different coverings had a small effect on temperature and relative humidity (RH) (Figures 5 & 6).

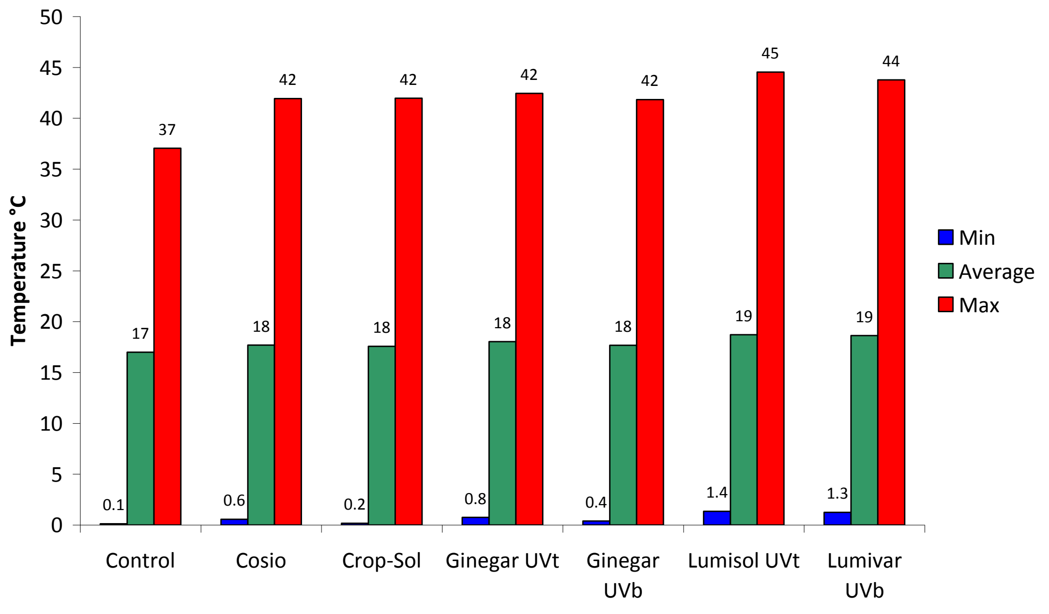

Figure 5. Minimum, average and maximum temperatures for the seven treatments.

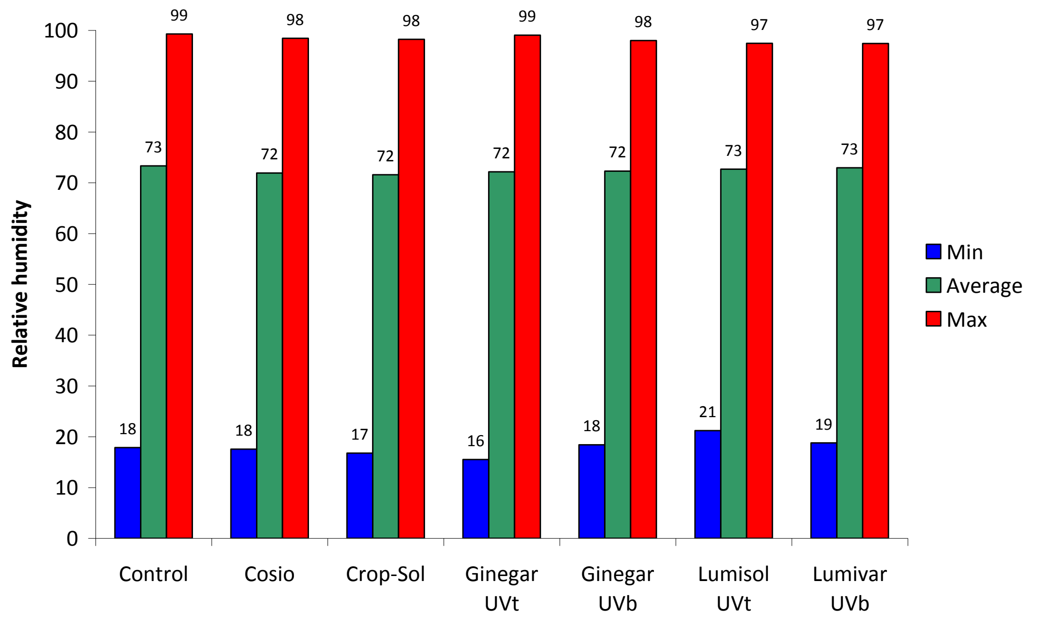

Figure 6. Minimum, average and maximum relative humidity for the seven treatments

Statistical analysis of temperature and RH found that all temperature differences were statistically significant (minimum temperature, p=0.013, LSD=0.970, average temperature, p<0.001, LSD=0.968, maximum temperature, p<0.01, LSD=2.332) while only maximum RH was statistically significant (minimum RH, p=0.311, LSD=5.407, average RH, p=0.156, LSD=1.763, maximum RH, p<0.001, LSD 1.042).

4.2.2. Discussion

The uncovered control was colder across all temperature measurements, which is to be expected, even, with the ventilation gaps along the bottom edges of the cloches. The four mesh treatments were very similar, with the two polythene covers the warmest, again across all three measurements. This is again expected as mesh has a higher level of air permeability than polythene so it should have greater air exchange and therefore lower temperatures. While the difference of two to three degrees between mesh and the polythene may not appear to be large from an agronomic perspective, as noted in the 2016-17 field trial (Merfield, 2017), (the results of which were published before this report), these add up to a considerable increase in growing degree days and therefore a significant acceleration and increase in crop growth.

As the above report also discusses the effect that increased temperature reduces RH, contrary to expectations, which is evidenced here by the statistically significantly lower maximum RH for the mesh and plastic compared to the control. However, as cloches are not a normal growing environment for potatoes, no detailed analysis of the difference in RH at each degree Celsius has been undertaken, as was done for the 2016-17 field trial (Merfield, 2017) because it is very uncommon to use cloches for potato production so the information is considered to be of limited value.

The key point is that while temperature and RH did vary, and behaved in a consistent fashion with other trials, the differences are not considered large in terms of their effect on blight or TPP, and are therefore not considered to be key drivers in the levels of blight and TPP found across the treatments, though it is possible that the lower RH associated with higher temperature may play a partial role.

4.3. Foliar blight

4.3.1. Results

Foliar blight was not observed until 10 Feb, 71 days after planting (Figure 7). This is typical of blight development, with low levels early on the crop, and levels increasing as the crop ages and wetter / more humid, autumn weather arrives. In the trial, blight progressively increased as the crop aged, with differences between the treatments increasing as the trial progressed (Figure 7).

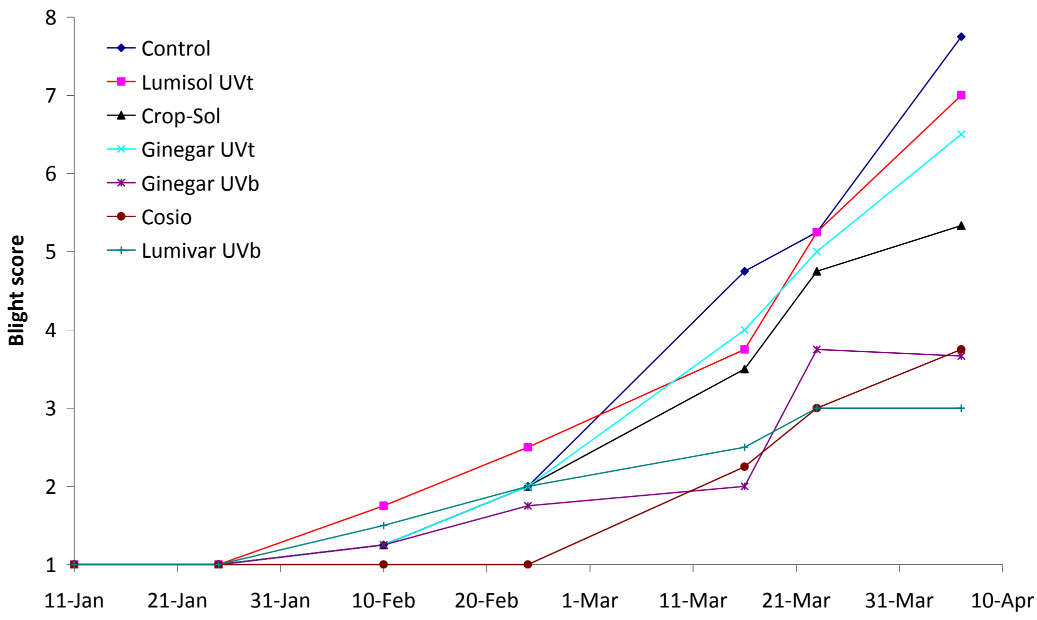

Figure 7. Progressive increase in foliar blight scores over the trial duration, 1 = <10% blight, 8 = >90% blight.

The amount of blight on the last measurement date on April 6th, was correlated with the amount of UV light, A and B bands combined, transmitted by the covers compared with the control (Figure 8).

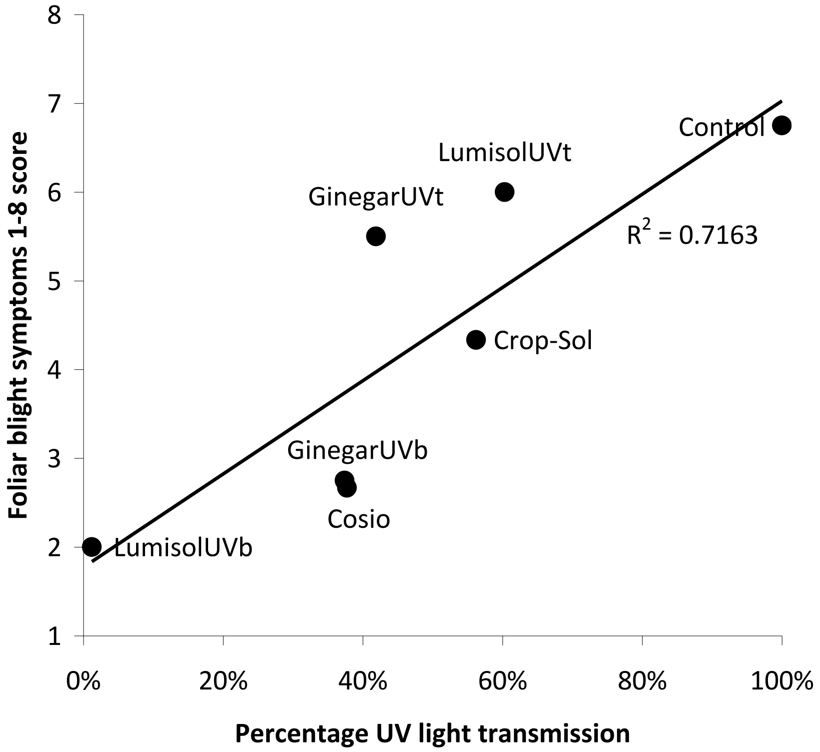

Figure 8. Correlation between the amount of UV light transmitted by each treatment relative to the control, with mean foliar blight scores on 6 April (1 = <10% blight, 8 = >90% blight).

When UVa and UV b were analysed separately the results were almost identical, so only the combined results are presented. The correlation (Figure 8) shows a strong relationship between the levels of UV light and blight score with lower levels of UV light produces lower blight scores. Figure 9 shows photos of foliage from the treatments the 16 March, the last date before some treatments started senescing, i.e., green foliage was present in all treatments.

Control

Crop Solutions | Cosio

Ginegar UVb | Ginegar UVt

Lumisol UVb | Lumisol UVt

Figure 9. Potato foliage showing blight and psyllid yellow symptoms of the seven treatments on 16 March 2016, 116 days after planting.

The difference in blight levels between the two Lumisol and two Ginegar treatments, which differ only in UV transmission is particularly striking (Figure 9).

Visual disease assessments are inherently subjective and their reliability has been questioned by multiple authors (Parker *et al.*, 1995; Bock *et al.*, 2010). The spectral analysis of the treatments that was undertaken revealed that the Cosio and Ginegar UVb had exactly the same spectrum (Figure 2). Subsequent enquiries to the manufacturers found that they used the same thread material, so were effectively the same. This information was not known at the time the visual assessments were undertaken so were in effect a blind assessment of the visual assessments. That the scores of the two treatments were similar (Figures 7 & 8) it is considered good evidence that the scoring was unbiased.

4.3.2. Discussion

A good level of blight developed over the duration of the trial which allowed a fair comparison of the different treatments. The results show a strong and clear correlation between foliar blight symptoms and amount of UV light. This is considered to be good evidence for the hypothesis that there is a link between UV light levels and blight. However, correlation is not causation: The plants were infected by naturally occurring blight, not from known disease isolates from laboratory cultures. In addition, potato blight is two diseases, early blight (*Alternaria solani*) and late or main blight (*Phytophthora infestans*), and due to the funding limits of this trial it was not possible to formally identify which species of blight, and/or other foliar fungal pathogens were present. Post-hoc visual inspection of the photos by a potato blight expert concluded that it was more likely, but not definitively, to be *A. solani* than *P. infestans* (David Shaw, Sarvari Research Trust, pers. comm. 2017). Due to these limitations, this result can only be considered indicative not conclusive. However, the strong correlation indicates that UV light is affecting disease levels and therefore further investigation is essential.

The use of spectral filters and the effect of UV light on plant diseases, and also direct effects on crops is well know (West *et al.*, 2000; Raviv & Antignus, 2004; Anon., 2005; Paul *et al.*, 2005). *Alternaria* fungi are also known not to sporulate in Petri dish cultures unless they are exposed to UVa light (Merfield, 2006). Little is know about the behaviour of *P. infestans* to UV light levels as no research has been found studying the topic, though the effect of high UV light levels on sporangia survival has been researched (Kessel & Förch, 2006). Existing research therefore supports the hypothesis that UV light levels can affect blight, particularly *A. solani*, and therefore research to clearly demonstrate a causal effect for both blight species is considered imperative.

4.4. Psyllid yellows

4.4.1. Results

As the trial was originally focused on the effect of UV light on blight, the measurement of the effects of the treatments on psyllid yellows, was only made after it was incidentally observed that there were large differences in psyllid yellows appearing among the treatments. This meant that the measurements were made on only two occasions, the results of which are listed in Table 4.

Table 4. Psyllid yellows scores for the two samples dates. Treatments are in order of decreasing UV light transmission. Values in the same row with the same letter are not statistically different.

	Control	Lumisol UVt	Crop-Sol	Ginegar UVt	Ginegar UVb	Cosio	Lumivar UVb	p value	LSD
23-Mar	8.0 a	6.8 ab	4.8 c	5.5 bc	2.3 d	3.0 d	2.3 d	<0.001	1.526
6-Apr	8.0 a	7.5 a	5.3 b	7.0 a	3.3 c	2.3 d	2.3 cd	<0.001	1.040

The same as for blight, the psyllid yellow scores on the last measurement date of the 6^{th} April were correlated with the amount of UV light transmitted through the treatments (Figure 10).

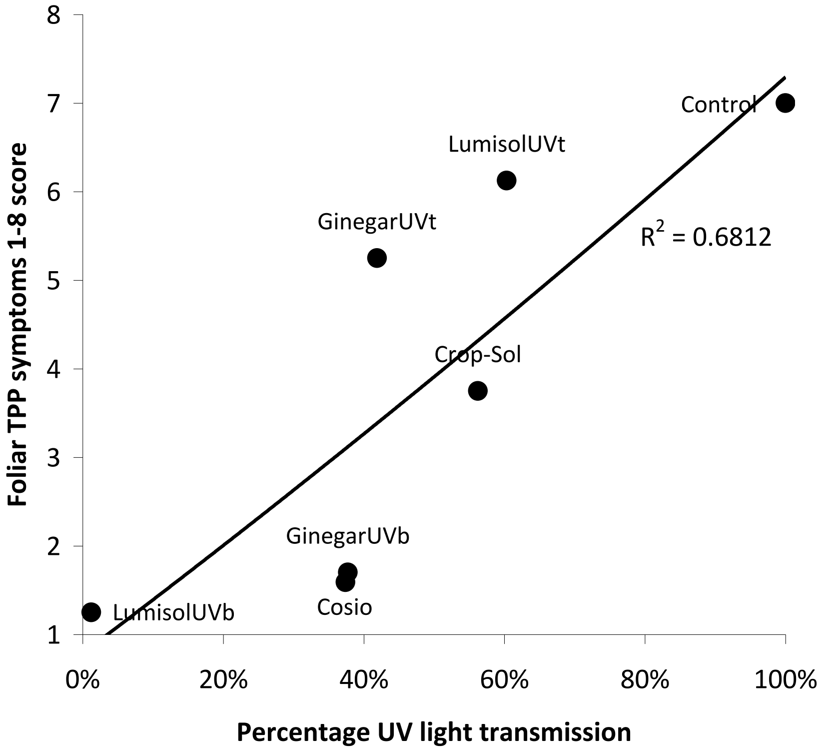

Figure 10. Correlation between the amount of UV light transmitted by each treatment relative to the control, with mean psyllid yellow scores, on 6 April (1 = no psyllid yellows, 8 = highest level of yellows).

4.4.2. Discussion

The similarity between the blight and psyllid yellows correlations (Figures 8 & 10) is considered remarkable. While all the same arguments as for blight, regarding this result being a correlation not causation, apply, the data indicates that there is a clear interaction between UV light levels and psyllid yellows. However, the potential causes are more complex than for blight as there are two organisms, TPP and CLso, interacting to produce the yellows.

It is well established that many insects respond to UV wavelength of light (Barghini & Souza de Medeiros, 2012) and therefore it is possible that TPP require UV for some purpose, e.g., navigation, orientation, plant detection, mate finding, etc., and therefore reduced UV light may impede these behaviours resulting in reduced numbers of TPP on the potatoes under lower UV levels, with a consequent reduction in psyllid yellows.

However, research by Plant & Food Research in 2016-17 showed that, contrary to previous beliefs psyllid yellows are not directly caused by psyllids feeding, but, rather it is entirely caused by Candidatus *Liberibacter solanacearum* (CLso), as TPP that do not carry CLso ('cold' psyllids) do not cause any plant symptoms, only 'hot' psyllids with CLso can cause yellows (Jessica Dohmen-Vereijssen, Plant & Food Research, 2017, pers. comm.). Psyllid yellows is therefore a misnomer, rather it should be CLso yellows, as it is CLso not TPP that causes the leaf deformation and chlorosis. However as 'psyllid yellows' is the normal term, this report uses that, rather than 'CLso yellows'.

Therefore, as it is not TPP that causes psyllid yellows, rather it is only CLso, there is not necessarily a direct link between TPP populations on a plant and the amount and severity of psyllid yellows, as the level of yellows depends on the number of hot psyllids and how early in the plant's life that it was infected, and therefore the amount of time that CLso has to multiply within the potato plant.

There are also other possible causal mechanisms: For example, the altered UV spectrum could be having a direct effect on the CLso (i.e., rather than TPP), for example, reducing infection rates, reducing the spread of the bacteria through the plant etc., (Jessica Dohmen-Vereijssen, Plant & Food Research, 2017, pers. comm.). However, as CLso travels through the plant's vascular system, which will experience lower levels of light, as it has to travel through the outer layers of the plant to reach the phloem, this hypothesis is considered the less likely, but not impossible. It may also be a combination of UV affecting both TPP and CLso. It is also possible that reduced UV levels causes changes in the potato plant's ability to host or 'fight' CLso infections.

This finding helps explain data and observations from previous trials. In the first years trial, (Merfield, 2012) there were less TPP in the centre of the 10 x 10 m mesh squares than the control, despite there being continuous potato foliage (a green bridge) from the control to the mesh plots, such that it should of been easy for psyllids to travel from the control, through the potato foliage and under the mesh. It therefore appeared that while the mesh was not acting as a physical barrier in this situation, some other aspect of the mesh was inhibiting the population of under-mesh TPP. In the second years trials (Merfield, 2013), where the green bridge effect was eliminated, but the sheets were not dug in i.e., 'hermetically sealed', three sheets were infested by aphids which reached exceptionally high populations within a two week period, before 'crashing' due to large numbers of beneficial insects and entomopathic fungi controlling them. In comparison one sheet had a TPP infestation in a corner, however, it spread only a meter into the plot over a period of a month. It therefore appeared that while the aphids were unaffected by being under the mesh, as evidenced by the large and rapid population expansion, in comparison, TPP were inhibited in some way as the infestation remained small and localised. In addition TPP were trapped at low levels under the mesh treatments, showing they were present, but, their populations were highly suppressed compared with the uncovered control.

It therefore appears a reasonable hypothesis that the reduced UV levels under the mesh, and the treatments in this trial, are somehow, inhibiting TPP from entering under mesh crop covers, and/or, they are inhibiting the normal, including reproductive, behaviour of TPP once under the mesh. The potential mechanisms for this, are, however, considerable, and include not only direct effects on TPP, but, also indirect effects, such as altering the potato plants, e.g., the volatiles they produce, which may then alter TPP behaviour. Therefore a considerable amount of research is required to first causally confirm this effect and to elucidate the possible causal mechanisms.

4.5. Yield

4.5.1. Results

4.5.1.1. Total yield per plant

Due to the small number of potatoes per plot, and because the number of emerged plants varied, the, total yield was calculated on a per-plant basis in grams (Figure 11) rather than yield per plot. This has been converted into a tonne / ha yield (Table 5) however, this involves a very large multiplication factor, so small differences in the grams per plant value, e.g., ± 1 tuber produces a large difference in the tonnage figure, so, they should be taken as indicative of the yield rather than absolute.

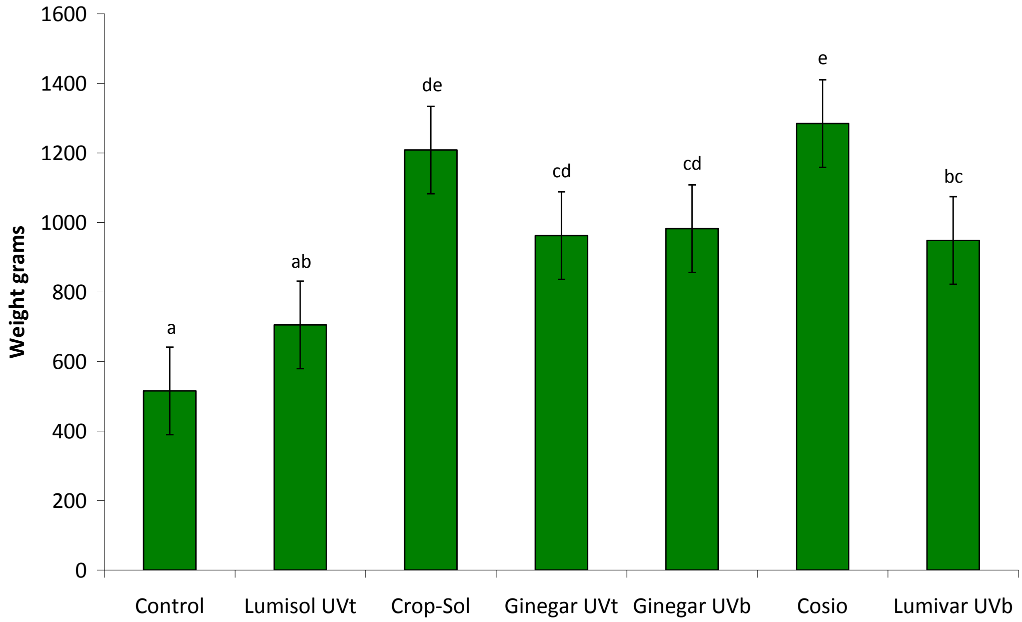

Figure 11. Total yield per plant, p<0.001, LSD=251.8. Error bars = LSD. Columns with the same letter are not statistically different. Treatments are in order of decreasing UV light transmission.

Table 5. Yield per plant (g) converted into tonnes / ha

Control	Lumisol UVt	Crop-Sol	Ginegar UVt	Ginegar UVb	Cosio	Lumivar UVb
15.0	20.5	35.1	28.0	28.6	37.4	27.6

A comparison of each treatment's yield against all the other treatments shows that some considerable yield gains were achieved, with the Cosio treatment achieving a 149% increase over the control (Table 6).

Table 6. Comparison of the percentage yield increase / decrease of every treatment against all other treatments.

	Control	Lumisol UVt	Crop-Sol	Ginegar UVt	Ginegar UVb	Cosio	Lumivar UVb
Control	0%	37%	135%	87%	91%	149%	84%
Lumisol UVt	-27%	0%	71%	36%	39%	82%	34%
Crop-Sol	-57%	-42%	0%	-20%	-19%	6%	-22%
Ginegar UVt	-46%	-27%	26%	0%	2%	33%	-1%
Ginegar UVb	-48%	-28%	23%	-2%	0%	31%	-3%
Cosio	-60%	-45%	-6%	-25%	-24%	0%	-26%
Lumivar UVb	-46%	-26%	27%	1%	4%	35%	0%

Total yield includes tubers down to marble size, so, consists of both marketable and unmarketable (undersized tubers). Taking 100g as marketable size (a mid-point between 60 and 125g tuber sizes that have been used in other mesh trials) a re-analysis of the yield per plant was not significant (p=0.103), due to the smaller number of tubers, especially for the higher UV treatments. However, some individual treatments did differ from each other (Figure 12).

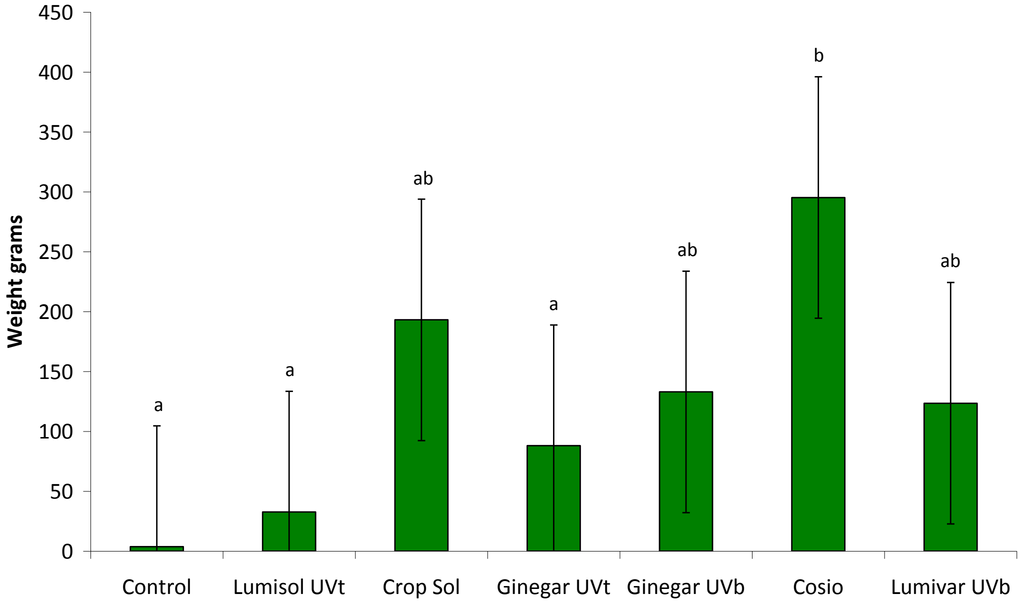

Figure 12. Yield per plant for marketable tubers >100g, p<0.103, LSD=201.6. Error bars = LSD. Columns with the same letter are not statistically different. Treatments are in order of decreasing UV light transmission.

4.5.1.2. Average tuber weights

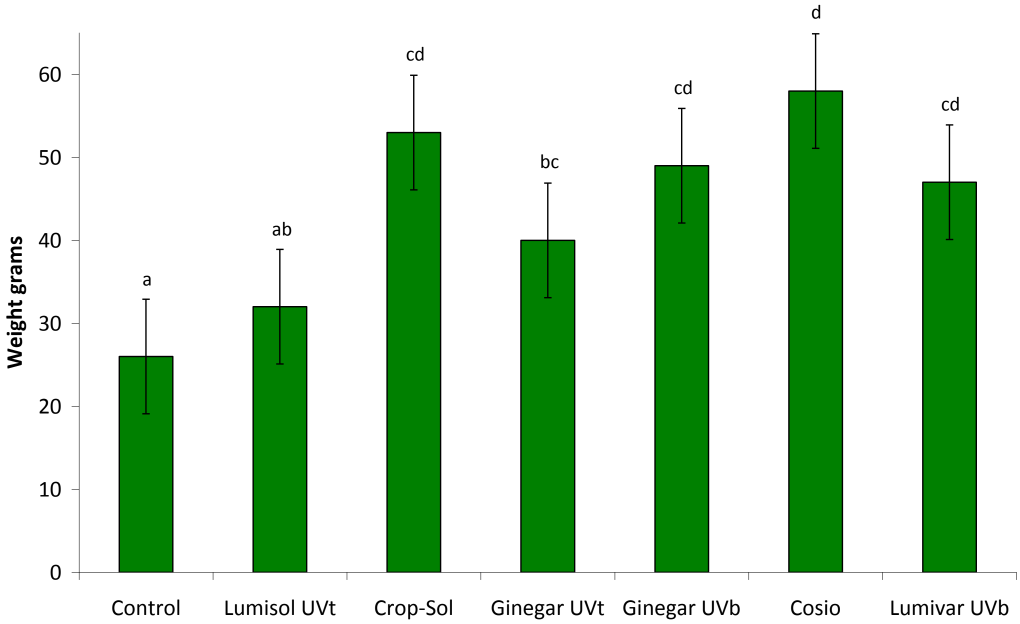

Figure 13. Average tuber weight p<0.001, LSD=13.81. Error bars = LSD. Columns with the same letter are not statistically different. Treatments are in order of decreasing UV light transmission.

Average tuber weight (Figure 13) is considered to be less affected by the small number of plants / sample size than yield, as there were a mean number of 220 tubers per plot, which is considered a good sample size.

4.5.1.3. Maximum tuber weight

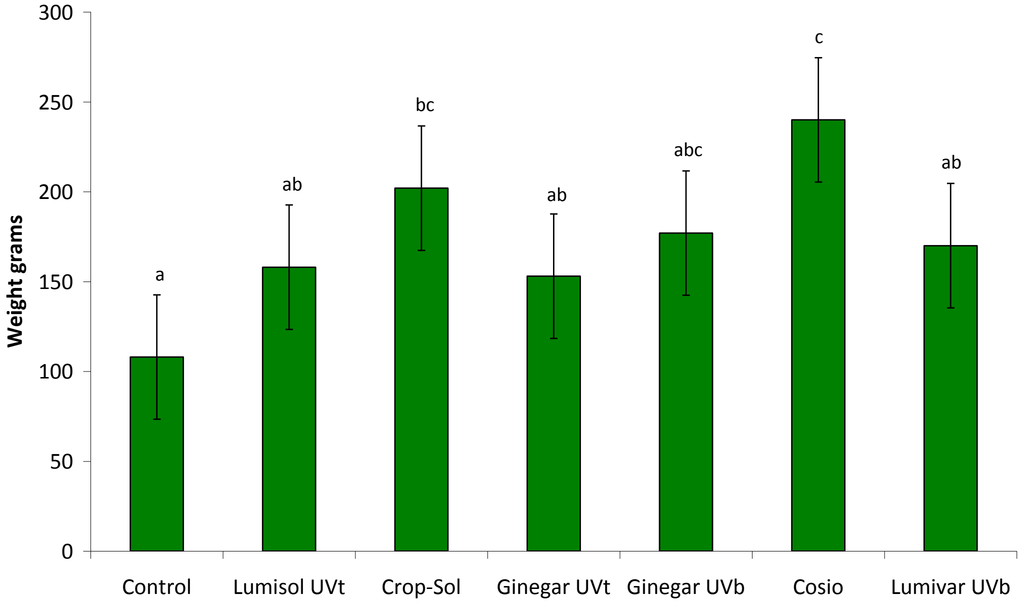

Figure 14. Maximum tuber weight p=0.027, LSD=69.23. Error bars = LSD. Columns with the same letter are not statistically different. Treatments are in order of decreasing UV light transmission.

Maximum tuber weight (Figure 14) has the potential to be distorted by single 'rogue' outsized potatoes, so the frequency distributions (Figure 15) are a more useful measure, however, the treatments with the largest tubers also had the highest yields and average sizes, indicating that outliers are not a significant issue.

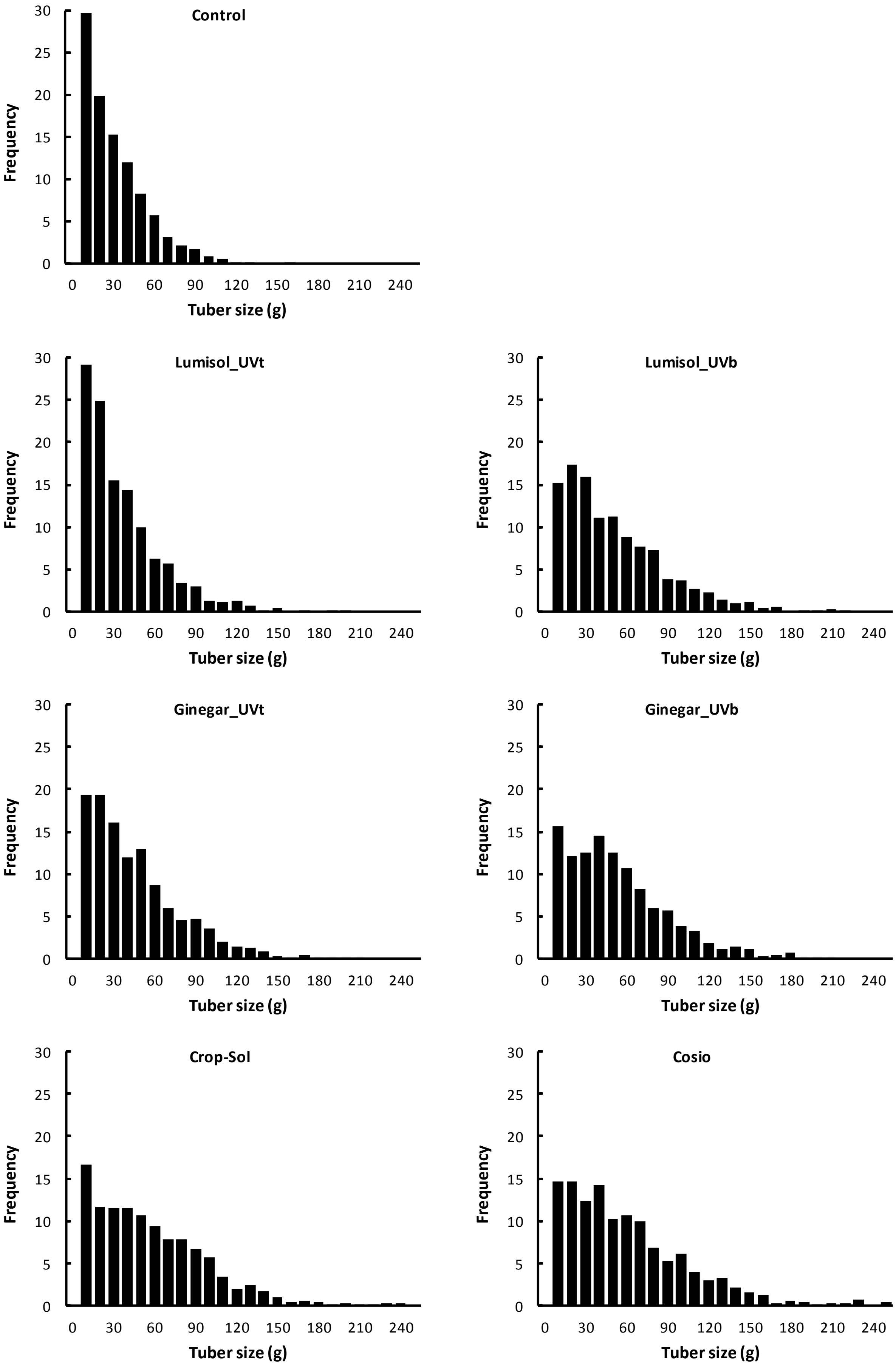

Figure 15. Size class distribution of tubers. Frequency is the percentage in that size class based all the tubers collected from all plants harvested in four replicate plots for each treatment.

The tuber size distribution (Figure 15) shows a greater number of smaller tubers for the control and UV transmitting treatments.

4.5.1.4. Average number of tubers per plant

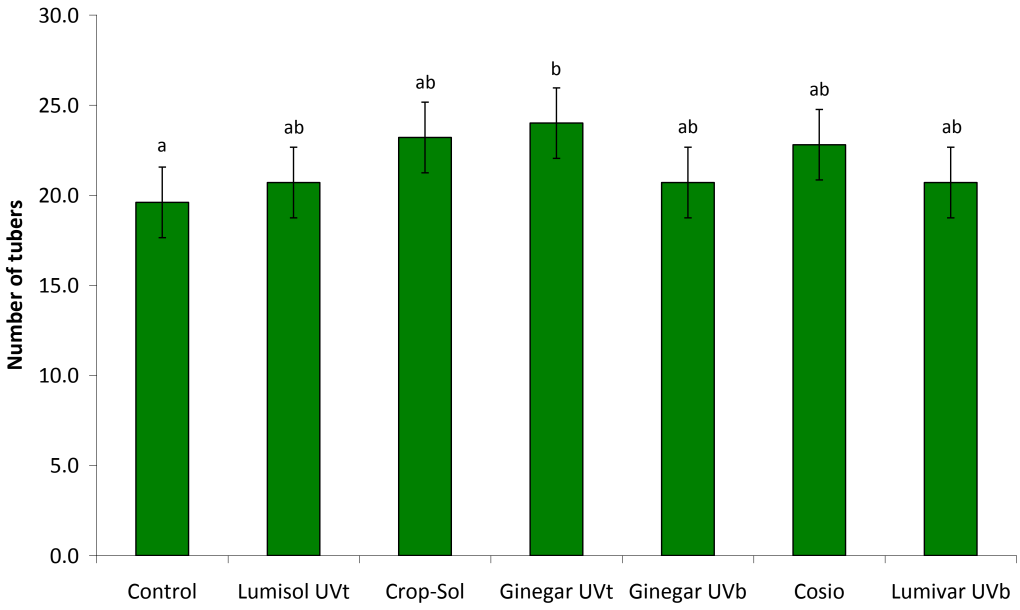

Figure 16. Average number of tubers per plant. p=0.178, LSD=3.916. Error bars = LSD. Columns with the same letter are not statistically different. Treatments are in order of decreasing UV light transmission.

Unlike other yield measures, the number of tubers per plant (Figure 16) was statistically not significant and biologically very similar with a range of 19.6 to 24.0 tubers.

4.5.1.5. Specific gravity

There was no significant difference in the specific gravity among treatments (p=0.327) (Figure 17) although the Cosio treatment alone was just different from the control and Lumisol UVt treatments.

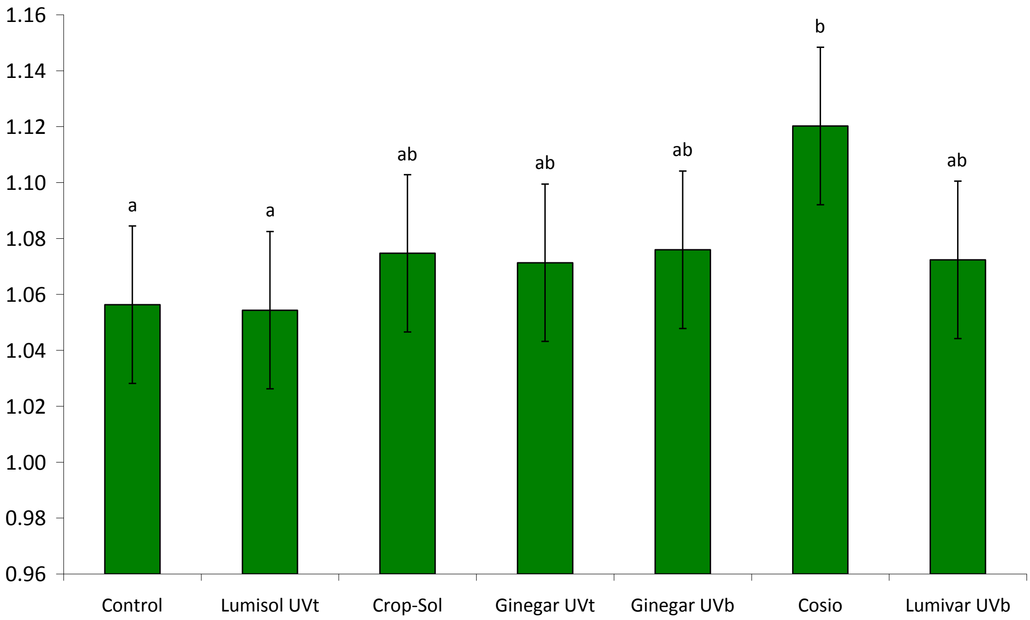

Figure 17. Tuber specific gravity. p=0.327, LSD=0.05631. Error bars = LSD. Columns with the same letter are not statistically different. Treatments are in order of decreasing UV light transmission.

4.5.2. Discussion

Interpreting the yield results is somewhat complex due to no obvious trends relating to UV light levels, unlike blight and psyllid yellows.

Overall the yield is relatively modest by commercial standards compared with a typical Canterbury farm yield of approx. 60 t/ha and a modelled maximum of 90 t/ha (Sinton, 2013). However, Red King is an older and lower yielding cultivar, plus the crop was grown under certified organic regulations, so no nitrogen fertilizer was used, so the yield is still respectable, particularly for the best yield of 37 t/ha, and shows that the crop growth was comparable with commercial cropping, despite the non-standard, cloche system.

While the overall yields are low, the variation in yields is considerable. The control is the lowest yielding, which is consistent with previous trial work (Merfield, 2012, 2013) where mesh treatments significantly out yielded the uncovered controls. Crop Sol and Cosio were the highest yielding more than doubling yields over the control (Figure 11, Table 6). Marketable yield shows the same pattern, but, with the reduced number of tubers statistical variation increases such that the results should be treated with caution. With that in mind the fact that the lower UV treatments Ginegar UVb and Lumivar did not produce a larger proportion of marketable grade tubers is puzzling.

4.5.2.1. UV light

There is no obvious effect of UV light levels on yield. The pattern of results for total yield (Figure 11), average tuber weight (Figure 13) and maximum tuber weight (Figure 14) are similar, indicating a good level of consistency among the results, and the significance levels were high, showing that the treatments did have clear effects. Correlations were undertaken between UV levels and the yield results, as was done for blight a psyllid yellows, but, no clear relationships were found, with R^2 values ranging from 0.39 to 0.55 (data not presented). This result is surprising as it was expected that the higher levels of blight and psyllid yellows would of resulted in the same pattern for yield. This indicates that the link between blight & psyllid yellows and yield may be weaker than was assumed, and therefore other factors, e.g., cloche microclimate, other impacts of altered light spectrum, etc., may also be having a direct effect on yield that partially overrides the effects of blight and TPP.

4.5.2.2. Polythene sheet treatments

Broadly the two polythene sheets (Lumisol and Lumivar) underperformed the mesh treatments, though in some cases they were statistically the same and biologically similar. It was a concern that polythene sheets would get too hot if they were placed directly on the crop, as is done with mesh crop covers, that resulted in the use of cloches for this trial, with the aim of preventing excessive heat build up under the impermeable polythene sheets. Even with the use of cloches temperatures under the polythene treatments were higher, though only by a few degrees. It is noted that small temperature increases can convert to a significant number of extra growing degree days, and in other trials (Merfield, 2013, 2017) this increase has been linked with accelerated growth rates and increased yields, but only if soil moisture levels are maintained (Bohl & Johnson, 2010). In the case of the polythene, higher temperatures did not result in higher yield. Irrigation was frequent and plentiful, so, it is not believed that the crop was lacking in water at any stage. However, the polythene did block the small amount of rain that did fall, and even with the irrigation falling on the potato foliage, it was observed that the soil surface in the polythene cloches was considerably dryer than other treatments. Further, mesh being permeable it is considered to have greater air exchange than polythene, especially as the only ventilation is under the bottom edge, so potentially air, especially in hot conditions with low wind speeds, may have become ‘trapped’ in the polythene cloches compared with the mesh ones, that can ventilate across their entire surface area. This could of had a number of effects, for example, CO_2 levels could of become depleted in the polythene cloches leading to reduced photosynthesis. Finally it was observed that the potato plants under the polythene sheets simply looks less vigorous and healthy than those under the mesh (Figure 9). Overall it is therefore concluded that there may be a number of environmental factors, beyond those measured here, that may have been negatively impacting the potatoes under the polythene treatments.

Comparing the two polythene sheets, the UV blocking sheet had statistically and biological larger yields and average size, but no impact on maximum tuber weight, which was unexpected. As the only difference between the two polythene treatments is their UV transmissivity, this indicates that there could be multiple benefits from blocking UV light, both indirect, from reduced blight and psyllid yellows, and potentially direct, e.g., reduced UV light increasing yield as shown in Anon., (2005).

4.5.2.3. Mesh treatments

The mesh treatments generally performed better than the polythene, with the exception of the Ginegar UVt mesh which performed similarly to polythene.

As the spectral analysis found that the Cosio and Ginegar UVb sheets were identical in terms of their light spectra (Figure 2), that they produced statistically and biologically significantly different yields is perplexing. There is a slight difference in the hole size between the sheets, with Cosio 0.78 × 0.48 mm = 0.37 mm^2 vs. Ginegar UVb 0.92 × 0.23 mm = 0.21 mm^2. Microscopic measurements of the threads in both sheets found them to be the same diameter (0.25 mm). This means Cosio mesh had a higher level of permeability as it had larger holes, although this is not reflected in the amount of light transmission from the spectrum analysis, which cannot be explained. It is therefore considered surprising, but not impossible, that the hole size difference alone could account for the difference in the crop performance between the two sheets. However, in the 2016-17 trials (Merfield, 2017) the smaller the mesh hole size the better the crop performance, including yield. So, if these results were consistent with the 2016-17 results the Ginegar mesh with smaller holes should of performed better. This difference therefore cannot currently be explained.

Further, the paired treatments, of Lumisol & Lumivar polythene and Ginegar UVt & UVb mesh were originally considered identical except for their UV transmission. While this is true of the polythene, where their visible light spectra are closely matched, this is not true of the Ginegar meshes where the UVb mesh is between 15 to 20 percentage points lower in it visible light transmission than the UVt mesh. However, in previous trials (Merfield, 2013), the Cosio and Crop-Sol mesh produced identical results despite a 30 percentage point difference in visible light transmission. It is therefore unclear if the difference in visible light transmission between the two Ginegar meshes could be affecting the result or not.

For total yield, Cosio was the best performer, followed by Crop-sol and Ginegar UVb which were statistically the same, with Ginegar UVt being only slightly lower than Ginegar UVb, but sufficient to make it statistically different from Crop-Sol. In the second years trial (Merfield, 2012) Crop-Sol and Cosio gave identical yields, so, there is no clear reason for the difference in this trial, except to note the difference while statistically significant, is only 2.2 t/ha which agronomically is small, especially compared to the variation in yield among all treatments.

Statistically all the mesh treatments except Ginegar UVt produced the same average tuber weight, maximum tuber weight and number of tubers per plant, and biologically the differences were also small and not significant.

The size frequency distribution, showed that the control, and the higher UV transmission treatments had a larger proportion of smaller tubers and fewer larger tubers, while the lower UV treatments and the Cosio and Crop-Sol meshes had the opposite effect with fewer smaller and more larger tubers. This is the one yield result where there appears to be a correlation between UV light levels and the results. In previous trials, small tubers have been associated with higher TPP populations and/or higher levels of psyllid yellows, which have been assumed to be related to higher levels of CLso which have then affected tuber development. It therefore appears reasonable that lower levels of UV light correlating with lower psyllid yellows, would then correlated with larger tubers.

The biological and statistical differences in the specific gravity measurement were small, though the cause of the slightly larger specific gravity for the Cosio treatment is unclear, again, considering it and the Ginegar UVb meshes are very similar.

As in previous trials (Merfield, 2013, 2017), there are substantial (more than double) the yield between the worse (control) and best (Cosio and Crop-Sol) treatments. However, the expected correlation of yield with UV light levels, assumed to be driven by lower blight and psyllid yellows under the lower UV level treatments, has not materialised, except in the size frequency distributions. The causes of this are unclear: it could be related to the use of cloches; the smaller plot sizes, although a number of the results were statistically significant, even highly significant; it could be due to the inherent variability of agronomic science; or there are other factors, beyond those measured in this trial having an effect on yield. With these multiple variables and unknowns a strong statement therefore cannot be made about the cause of yield variation, especially between the mesh and polythene treatments. Hopefully, like the unexplained observations from previous trials that this experiment helped explain, future research will shed further light on these yield results.

4.6. Storage / sprouting

4.6.1. Results

There was a significant difference (p=0.007) in the number of sprouts at 50 days after harvest, although this difference became just non-significant at 100 days (p=0.059) (Figure 18).

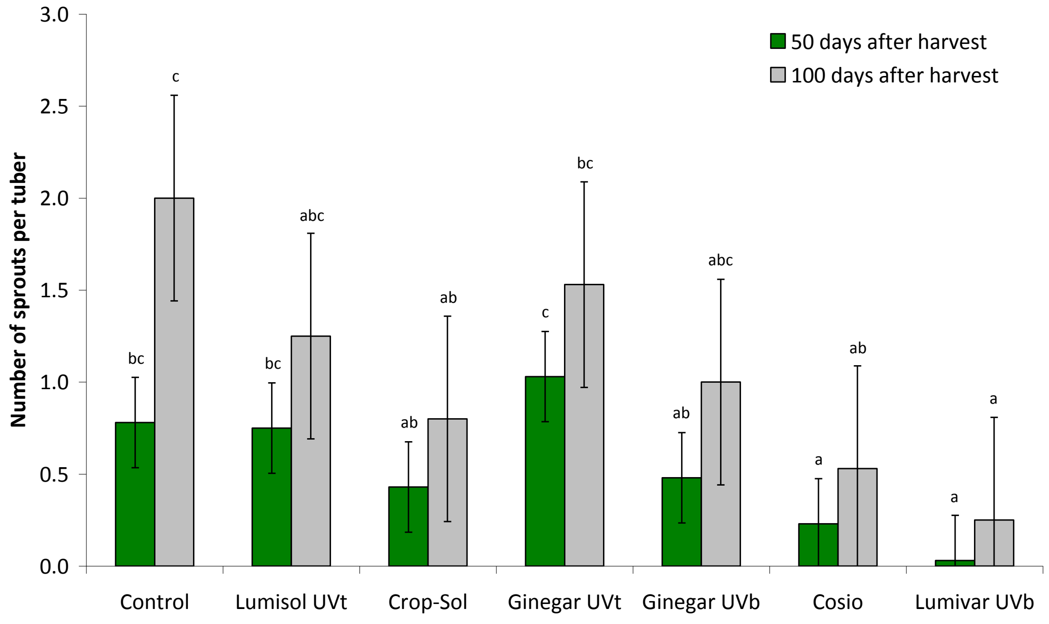

Figure 18. Number of sprouts per tuber after 50 and 100 days in storage after harvest. 50 days p=0.007, LSD=0.4910. 100 days p=0.59, LSD=1.117. Error bars = LSD. Columns within the same measurement duration (50 vs. 100 days) with the same letter are not statistically different. Treatments are in order of decreasing UV light transmission.

Figure 18 appears to show a trend for lower sprout numbers with lower UV levels. Correlating treatments' UV transmission rates against sprout numbers for the two sampling dates does show a correlation (Figure 19).

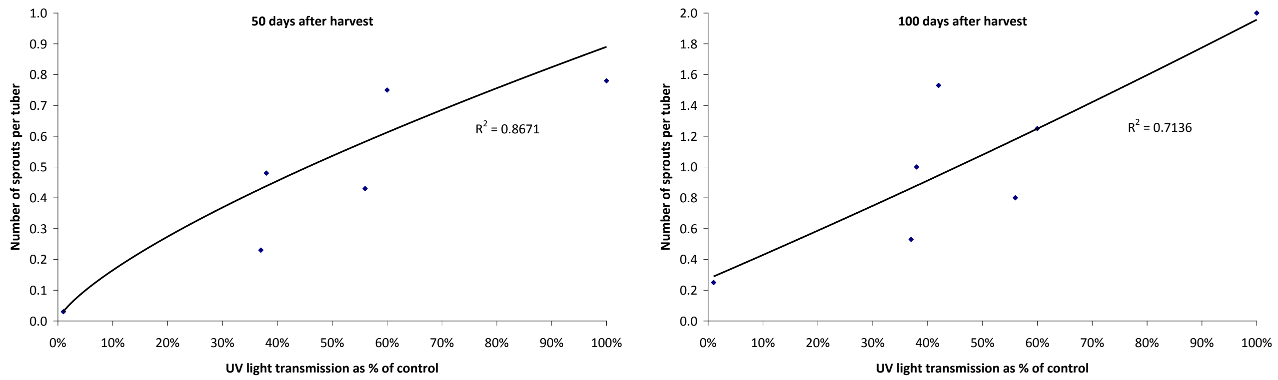

Figure 19. Correlation between the amount of UV light transmitted by each treatment relative to the control, with the number of sprouts per tuber at 50 and 100 days after harvest.

The temperature and RH for the storage period are shown in Figure 21.

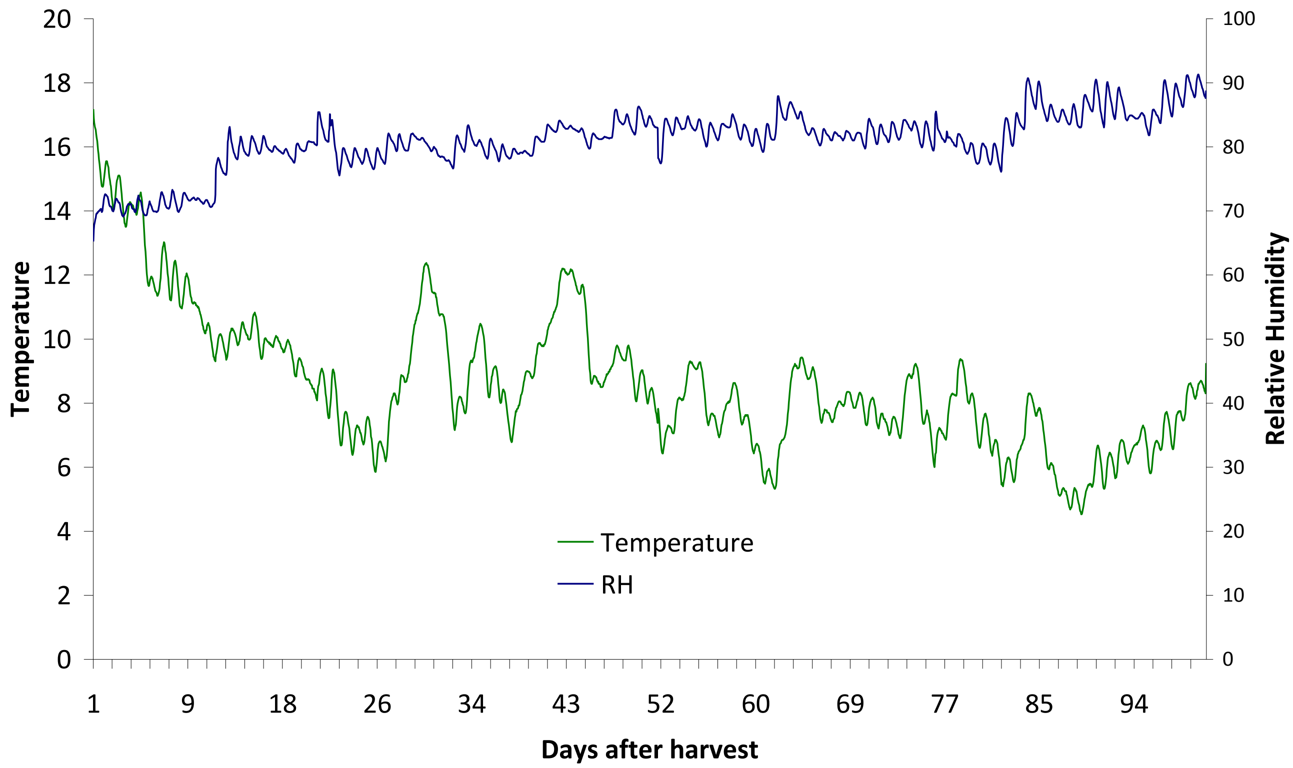

Figure 20. Temperature and relative humidity averaged from four data loggers stored with potato tubers in storage room.

The minimum, average and maximum temperatures and RH are given in Table 7.

Table 7. The minimum, average and maximum temperatures and RH for the 100 days the tubers were in storage.

	Minimum	Average	Maximum
Temperature °C	4.5	8.6	17.2
Relative humidity %	65	81	91

4.6.2. Discussion

There is a much stronger relationship between the sprouting data and UV transmission levels than the yield data. From previous trials (Merfield, 2013, 2017) it was believed that the numbers of sprouts was linked to TPP populations / psyllid yellows levels, as it is assumed that there is a relationship between TPP populations in the field and CLso infection levels in the crop and it is CLso levels that are believed to be the cause of increased sprouting. Further, the work by Plant & Food (section 4.4.2, page 19) that showed that it is only CLso, not TPP, that causes psyllid yellows. Psyllid yellows can therefore be considered a clear indication that the plant has been infected with CLso, and the level of infection is indicated by the severity of the yellowing. It would therefore further be expected that the greater the level of psyllid yellows, the more storage will be affected.

A direct comparison with psyllid yellow score and sprouting data at 50 days also shows a correlation, if somewhat weaker than for UV light levels (Figure 21)

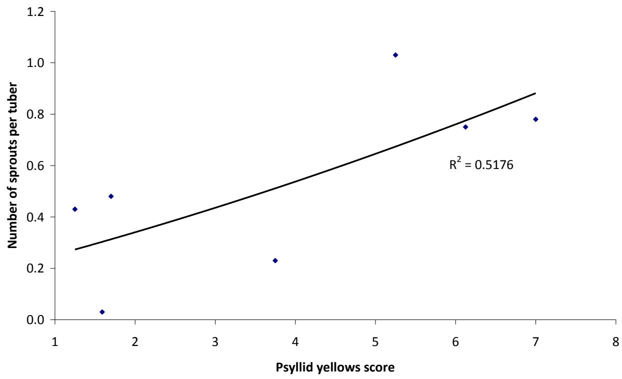

Figure 21. Correlation between psyllid yellow scores at the final measurement date with the number of sprouts per tuber at 50 days after harvest.

This result is in agreement with the first two trials where mesh treatments had less sprouting than the controls, and so appears to be related to TPP populations / CLso infection levels.

5. General discussion

Overall the results are considered to fall into two camps: The foliar blight, psyllid yellows and sprouting data are all related to the level of UV light transmission by the different treatments. However, those effects have only partly carried over into the yield data which is more ambiguous in terms of the impact of reduced UV light. However, the direct effects of UV light levels on blight and psyllid yellows are very striking and are considered to be a strong indication that there is a real effect, and therefore, it needs to be confirmed with causal studies, especially separating out early and main blight to confirm if the effect applies to both or just one of them.

Considering that potatoes are the forth most important food crop globally, and the developing world now produces more potatoes than the developed world[1], combined with blight being the most important fungal pathogen of potatoes with both species developing resistance to fungicides, it is considered vital that non-chemical means of blight management are developed and proven. Therefore the potential of a simple, sustainable, reliable and already widely used technology in the form of mesh crop covers to be able to control blight through physical means, along with all potato insect pests, is considered to be profound, and therefore it is essential that the research to clearly determine if the effect is real and effective on both blight species is essential. In addition the 2016-17 trials (Merfield, 2017) showed direct benefits of mesh resulting in very substantial yield increases compared with agrichemical control of fungal and insect pests of 12 to 60% which mean that mesh crop covers have the potential to be the future of potato production globally.

[1] https://www.potatopro.com/world/potato-statistics

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