Project title: The potential benefits of three modified plastic crop covers in Hardy Ornamental Nursery Stock production: initial investigations on a grower holding (Garden Centre Plants, Preston)

Project number: CP 19a

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Report: Final report

Project Co-ordinators: CP19 growers steering group

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Key words: spectral filter plastics, luminance THB, UV-transparent luminance, Solatrol, hardy ornamentals

The results and conclusions in this report are based on a series of crop scale observations, crop trials and more detailed field- and laboratory-based experiments. The conditions under which the studies were carried out and the results have been reported with detail and accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with the interpretation of the results especially if they are used as the basis for commercial product recommendations.

Authentication

I declare that this work was done under my supervision according to the procedures described herein and that this report represents a true and accurate record of the results obtained.

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Grower Summary

Headline

- Use of modified plastic crop covers confer a range of benefits to commercial nursery stock producers.

Background and expected deliverables

This pilot study was a collaboration between Lancaster University, Stockbridge Technology Centre and Garden Centre Plants (Preston). It was based largely on the knowledge of spectral filter plastics learned from HDC project CP 19, and aimed to take initial steps in transferring this knowledge into HONS crops. The key commercial end-points in HONS that might be delivered through the use of spectral filter plastics on permanently–clad structures were identified as:

a) growth regulation

b) improved pigmentation

c) pest and disease control

d) more 'hard' growth that copes better after transplantation into the field

Summary of project and main conclusions

The project was conducted between April and October 2005. In April, six existing tunnels at Garden Centre Plants (GCP) were clad with one of the following polythene products:

A. Luminance THB - a widely used diffusing plastic with no special spectral properties, which acted as the control

B. UV-transparent Luminance – a polythene with the same properties as Luminance THB, except that it transmits all the UV component of sunlight. Experience from CP 19 indicates that this produces more compact, tougher plants in many crops.

C. Solatrol – a polythene designed to regulate plant growth by increasing the ratio of red to far red light. Experience in CP 19 shows that Solatrol does deliver the expected growth control in many, but not all, crops.

Results

- The spectral filter Solatrol caused a statistically significant reduction in growth in *Acer palmatum* 'Orange Dream', *Imperata cylindrica* 'Red Baron' and *Lavatera × clementii* 'Barnsley'.
- In *Polygonum baldschuanicum*, extension growth was significantly reduced under the Solatrol film in measurements made in July, but the reverse effect was noted later in the season.
- In *Clematis* **'Carnaby',** extension growth was significantly increased under Solatrol.
- Other subjects showed no statistically significant response to Solatrol.
- Growth responses to the UV-transparent Luminance were unclear, and may have been affected by (i) temperature variation between tunnels and (ii) the fact that the project did not start until well in to the season. Assessment of this film would benefit from a more formal study under controlled experimental conditions.
- GCP staff also reported substantially reduced infection of honeysuckles (*Lonicera* spp) by powdery mildew, especially under Solatrol. This is commercially important since this disease is a significant problem on *Lonicera* at GCP. The use of Solatrol led to the reduction in the spray programme that was required for control. Disease levels were not formally quantified, but this response merits further research.

Conclusions

As a pilot study, this project gave some useful pointers for the further assessment of the use of spectral filters in HONS. Solatrol clearly delivered commercially useful growth regulation in many of the subjects studied, and appeared also to deliver some control of powdery mildew. Both these responses merit further investigations using a wider range of material. The value of UV-transparent film was less clear from this study, but may be more evident where 'hard' growth is required in early season or over-wintered crops, or where foliage colour is a key element of crop quality. This can only be confirmed through further study.

Financial benefits

Commercial assessments indicated that Solatrol could provide financial benefits to growers across a wider range of subjects than showed statistically significant growth responses. The main commercial benefit is as a non-chemical method of growth regulation, leading to reduced labour in trimming and tying-in. In addition, infection of honeysuckles (*Lonicera* spp) by powdery mildew, appears to be reduced under filters, especially under Solatrol.

Action points for growers

This was a pilot study and although commercially important benefits are indicated from the use of spectral filters for HONS, particularly through the use of Solatrol, verification of the results and economic analysis is required before firm recommendations can be made to growers.

Science section

Introduction

The background to this project is two-fold. Firstly, it builds on the success of HDC project CP19, which has been funded since 2003, with the overall aim of 'developing, evaluating and implementing technologies to exploit the benefits of modified plastic crop covers in UK horticulture'. CP19 has shown the value of the use of plastic cladding films that modify the light reaching the crop ("smart plastics") on "Spanish tunnels" (supplied by Haygrove Ltd) which (a) have open sides and ends and (b) which are only clad between March and November. The cultivation of crops under such plastic covered structures is now commonplace in many sectors of UK horticulture because of its potential to extend growing seasons, control harvests and improve the quality of produce.

While Haygrove structures, clad only during the main growing season, are commercially relevant to many crops, there are equally many other crops which require permanently and fully clad structures to provide tighter environmental control and all-year-round protection. One such sector is that of hardy ornamental nursery stock (HONS), which had been represented in year 1 of CP19 (see annual report for 2002-3) but subsequently dropped as the structures appeared to be of little commercial relevance for that sector. Nonetheless, the HONS sector is coming under increasing pressure from large retailers and consumers to improve product range and timing, enhance the quality of the product reaching the shelves and at the same time reduce point of sale costs. As a result a number of HONS growers are contemplating transferring production to relatively inexpensive plastic covered structures, whether as a replacement for permanent glass structures or for crops previously grown without protection. In addition, the results of CP19 suggested that there would be scope for improving HONS production through the appropriate use of "smart plastics" as claddings even where production was currently under plastic. In discussion with Mr Trevor Connah of Garden Centre plants, Preston (GCP), the key commercial end-points in HONS that might be delivered through the use of smart plastics on permanently–clad structures were identified as:

a) growth regulation,

b) improved pigmentation,

c) pest and disease control

d) more 'hard' growth that copes better after transplantation in to the field.

The Haygrove structures used in CP19 are fundamentally different from the permanent structures used by the HONS sector; the CP19 project cannot therefore properly address the needs of the HONS crop. However the results obtained, in combination with those from previous HDC funded work that assessed modified plastics for HONS crops (HNS108), provide clear pointers for what would be expected from plastics suited for HONS production. On that basis, the following plastics were selected for this pilot study.

i) **Luminance** (a diffusing film with no special spectral properties that reduces peak temperature during summer),

ii) **UV-transparent luminance** (which combines the benefits of diffusing films with the growth regulation and greater 'hardness' seen using UV-transparent film used in CP19). This is a novel combination of properties not included in CP19 (which has a UV-transparent clear film and a standard Luminance).

iii) **Solatrol** (a red: far red altering film that has produced good growth regulation in CP19).

Mr Connah agreed to host a small-scale study using these three plastics based at GCP using their current structures. The funding (approx £6,000) provided under this project (CP19a) allowed Lancaster University (LU) and Stockbridge Technology Centre (STC) to make additional inputs to the pilot trial, aimed largely at providing objective quantification of the growing environment and crop responses that would complement the commercial assessments of GCP staff.

Materials and Methods

Experimental layout

GCP dedicated six tunnels to the project, starting in spring 2005. The tunnels were standard commercial structures approximately 22m long by 6.4 m wide and standing 2.8m high at their highest point. Experimental design was limited by the existing layout, which formed a single row on a N-S axis. To minimise interference between tunnels, the two most southerly tunnels were clad with UV-transparent plastic, the two middle tunnels with Luminance, and the two most northerly tunnels with Solatrol. The tunnels were clad in April-May 2005, and plants introduced as soon after that as was consistent with the normal commercial practice at GCP.

Plant material

In developing the project, Trevor Connah of GCP had identified commercial end-points that might be delivered using spectral filters for a specific HONS crop, and this defined the range that were included in this project (Table 1). Commercially produced material of each species/cultivar was brought in to the tunnels according to the usual scheduling of that crop at GCP and all were managed according to the standard commercial procedures utilised on the holding, for example, when plants were pruned, staked or re-potted, the size of pot and growing medium used, and any treatment for pest and disease control. Experimental plants were divided equally between replicate tunnels and were laid-out in blocks along both sides of the central pathway in each tunnel.

Detailed measurements

The funding of the project allowed some initial detailed quantification of growth responses under the plastics using the labour of summer students. The limits on this were recognised at the proposal stage. Data are mostly focussed on rather simple non-destructive measurements made at intervals through the latter part of the season (July-September). In addition, having the project based on a commercial nursery had the benefit of providing direct industrial relevance, but with the disadvantage that possible measurements were partly limited by the commercial practices applied to the plants. The data that were obtained (Table 1) was determined through what was feasible in the context of commercial production with the available labour. Overall, detailed measurements were focussed on extension growth in all subjects. Where total plant height or stem length could not be measured easily, as was the case with many of the regularly tied climbers, individual internodes were tagged and measured instead. Due to the normal commercial management of the more vigorous crops, such as *Polygonum baldschuanicum*, some internodes tagged early in the project were pruned out. In these cases, measurements were made on successive sets of tagged internodes.

A minimum of ten plants per tunnel were measured, and for some subjects up to 40 per tunnel (Table 1). Initial analyses indicated that differences between the two tunnels of each plastic were rarely significant and so, with a few exceptions, data analysis was based on pooled data for both tunnels of each plastic. These data were subject to one-way ANOVA with SPSS. Note that data were recorded by summer students after initial training by NDP, but data analysis and interpretation was handled solely by NDP.

Table 1: Species/cultivars examined in trials with list of measurements taken.

Plant	Desired end-point	Measurements taken
Acer palmatum **'Orange Dream'**	Maintenance of growth combined with good colour (reduced scorching).	Maximum plant height to the tip of the longest shoot
Acer palmatum dissectum atropurpureum	Maintenance of growth combined with good red foliage colour.	Maximum plant height to the tip of the longest shoot
Hedera **'Gold Child'**	Maintenance of growth at high temperature	Length of longest shoot
Hydrangea petiolaris	Maintenance of growth at high temperature	Length of second internode from the apex of the dominant shoot.
Imperata cylindrica **'Red Baron'**	Improved root growth, foliage colour	Maximum plant height to the tip of the longest leaf
Jasminum officinale **'Fiona Sunrise'**	General improvement on ease of production	Length of longest shoot
Lavatera × clementii **'Barnsley'**	Growth regulation / reduced stretching	Length of second internode from the apex of the dominant shoot.
Lonicera henryii	Growth regulation / reduced stretching Reduced powdery mildew and *Botrytis*	Length of second internode from the apex of the dominant shoot.
Lonicera pericylmenum **'Belgica'**		
Lonicera pericylmenum **'Serotina'**		
Lonicera x brownii '**Dropmore Scarlet'**		
Parthenocissus tricuspidata **'Veitchii'**	Improved growth in 1st year, esp. roots	No detailed measurements made.
Polygonum baldschuanicum	Growth regulation / reduced stretching	Length of second internode from the apex of the dominant shoot.

Clematis Hybrids liners **'Carnaby'** **'Clair de Lune'** **'Dr Rupple'**	Sustain growth (bulking-up) while limiting stretching. Improved flower colour in **'Clair de Lune'**	Length of second internode from the apex of the dominant shoot.

Results and Discussion

The effects of the plastics on the growing environment.

The initial laboratory scans of the plastics supplied and installed at GCP confirmed that standard Luminance, UV-transparent Luminance (UV-T) film and solatrol all had the spectral properties that had been anticipated (Figure 1). This was confirmed by spectral measurements made in the tunnels (Figure 2). Thus, the UV-T film provided a spectrum (300-800nm) within the tunnel close to that of the field sunlight, while Luminance removed most of the UV-B and much of the UV-A. Solatrol not only increased R:FR by selective absorbance of FR, it was also highly UV-opaque.

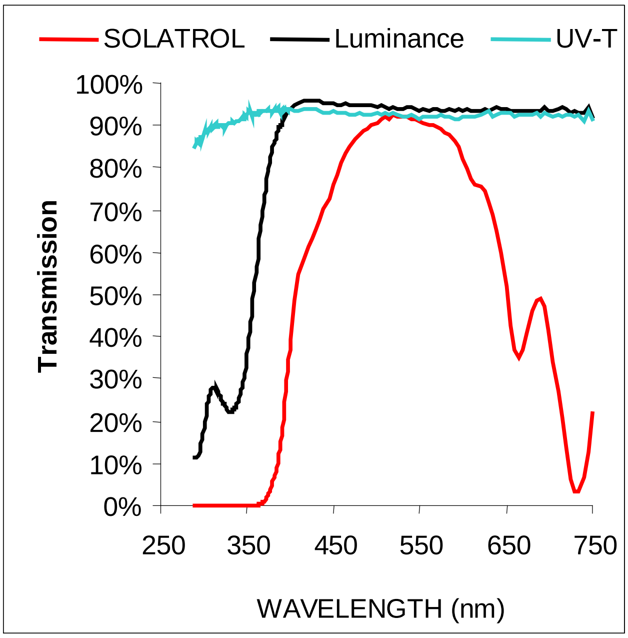


Figure 1

Spectral transmission data for the three plastics determined in the laboratory using a 75W Xenon arc lamp (LOT Oriel, Leatherhead, UK) and 10 cm integrating sphere, and a double scanning spectroradiometer (Macam Photometrics, Livingston, UK).

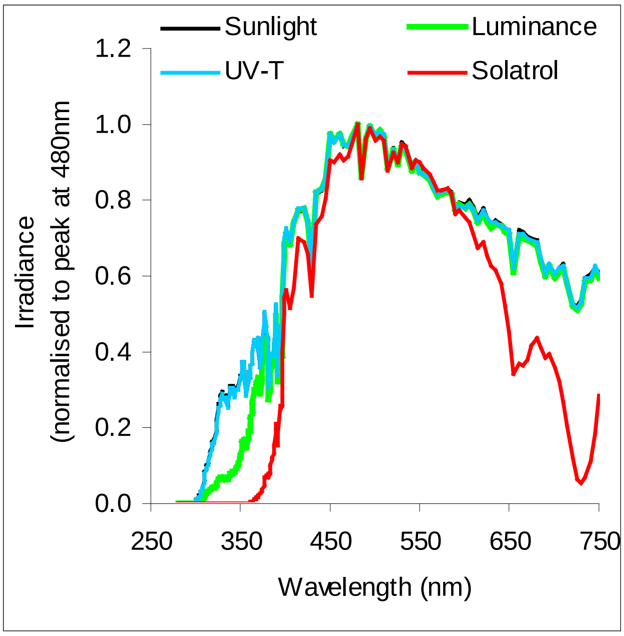


Figure 2

Spectral irradiances within the polytunnels at GCP. Spectral irradiances in the tunnels and of field sunlight were measured on a sunny day in late August using a double monochromator spectoradiometer (S9910-PC Macam Photometrics, Livingston, UK). To correct for variation in solar input due to cloud etc., all data were normalised to the peak irradiance (480nm). Data for the plastic are means of measurements made across the two replicate tunnels.

The Tiny tag humidity data was excessively variable and inconsistent across all tunnels, perhaps because the sensors were sometimes wetted when the crop was watered, followed by variable periods until the unit was dry enough to provide reliable data. Overall, all that can be said from the RH data is that there is no evidence of any gross difference between tunnels.

There were no apparent problems with the temperature data. There were no major differences in mean daily temperatures between plastics (Figure 3) but closer examination reveals patterns that need to be considered when interpreting crop responses. Mean daily temperature (Figure 3) show periods when the UV-T treatment was a little warmer than the other plastics. This is not apparent in daily minimum temperature (Figure 4), but is more obvious in daily maximum temperatures (Figure 5).

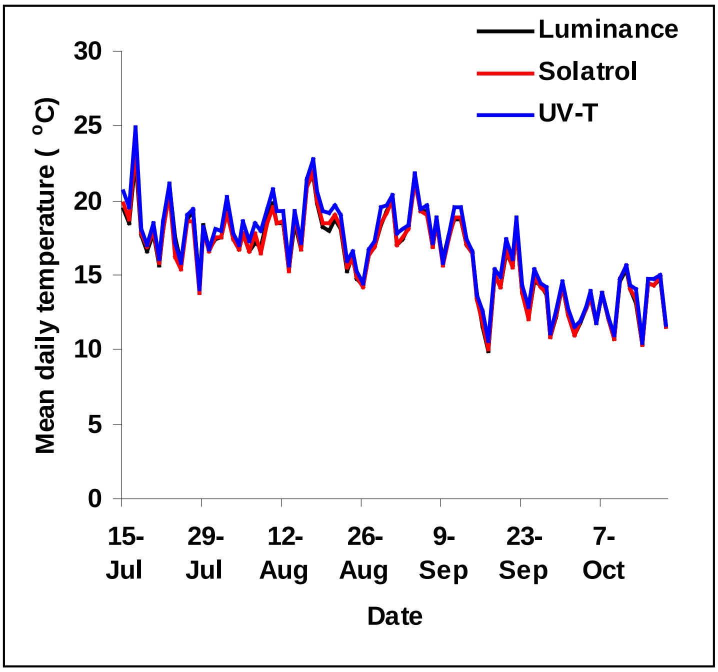


Figure 3.

Mean daily air temperature under the three plastics over the entire study. Data for each plastic is the mean from the two replicate houses. Means for individual tunnels are based on data logged at 15 minute intervals, with each logged datum being the mean of measurements made at 1 minute intervals throughout the day.

More detailed assessment of the higher temperatures in the UV-T treatment showed (i) that this only occurred during the warmest part of the day on warm sunny days and (ii) that the elevated temperature occurred only in one of the two UV-T tunnels. This is exemplified by the diurnal temperature plots for 10th August (Figure 6), when temperatures in Tunnel 11 during early afternoon where up to 5°C higher than the average of the other tunnels. By contrast, there was no consistent difference between the other UV-T tunnel (tunnel 9) and the remaining structures. It is probably pertinent that (i) T11 is the southernmost tunnel and (ii) was the only tunnel to not to have a neighbouring tunnel on its south side. Thus, we conclude that the warmer temperature under UV-T was not a result of any difference between the plastics, but simply a function of the position of T11. The layout of the experiment was determined by the positions of the existing tunnels at GCP, and it was recognised at the outset that this was a factor in experimental design. Although unavoidable, the temperature difference is an unfortunate feature of the study and necessitated some careful interpretation of plant growth data (see Figures 4 to 6).

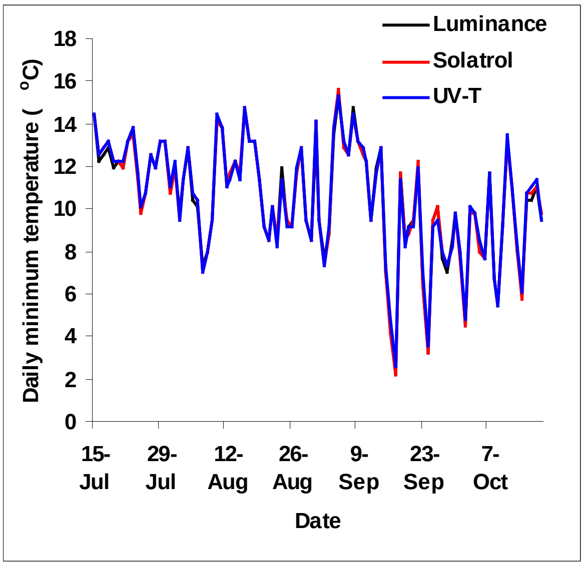


Figure 4.

Daily minimum air temperature under the three plastics over the entire study. Data for each plastic is the mean from the two replicate houses. Daily minima for individual tunnels are based on daily minimum of temperature data logged at 15 minute intervals, with each logged datum being the mean of measurements made at 1 minute intervals throughout the day.

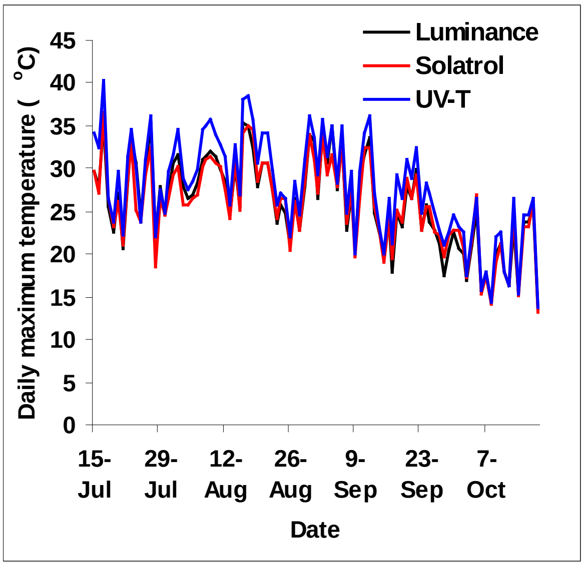


Figure 5.

Daily maximum air temperature under the three plastics over the entire study. Data for each plastic is the mean from the two replicate houses. Daily maxima for individual tunnels are based on daily maximum of temperature data logged at 15 minute intervals, with each logged datum being the mean of measurements made at 1 minute intervals throughout the day. .

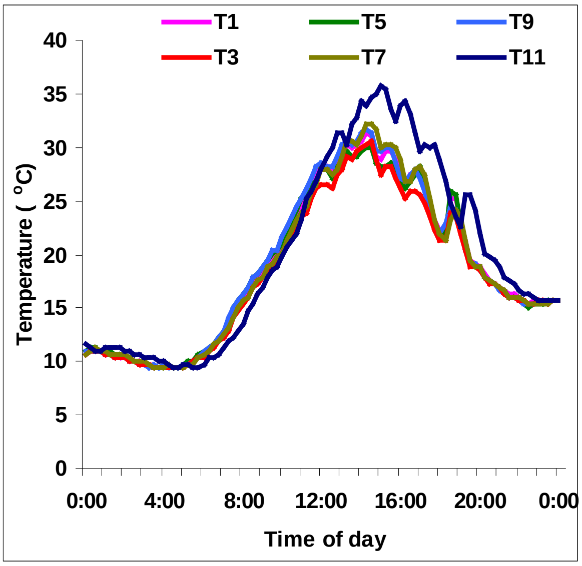


Figure 6.

The duirnal course of air temperature under the six tunnels on 9th August 2005, which was chosen as being representative of the warmer days of the experiment. The data logged at 15 minute intervals, with each logged datum being the mean of measurements made at 1 minute intervals throughout the day. Note the higher afternoon temperature in T11, the southernmost tunnel and one of the UV-T clad structures.

Commercial assessments of crop grown under the different plastics

All plants were subject to the usual commercial assessment carried out by GCP staff on all their stock. The following summarises the main points identified by GCP as being commercially significant.

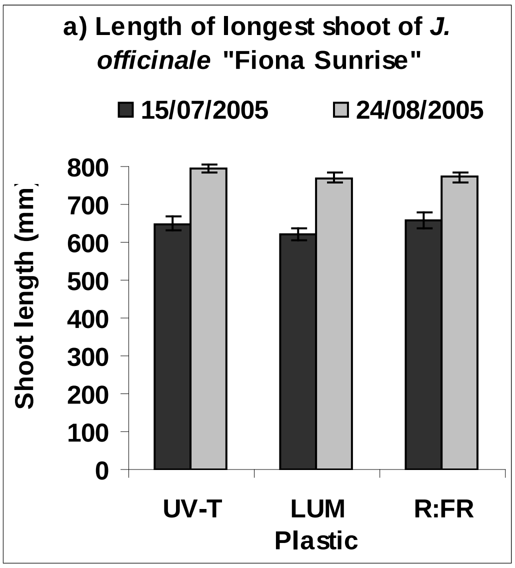
- The plants produced under the tunnels were of consistently high quality across all subjects. There was no evidence that production under the plastics reduced commercial quality in any species/cultivar.
- The desired control in vigorous subjects like the *Lonicera* spp, *Polygonum baldschuanicum* and *Lavatera* × *clementii* **'Barnsley'** was achieved under Solatrol. This was reflected in these subjects being easier to manage under this plastic and the view of the staff at GCP was that this would reduce the labour involved in training and cutting-back under full production conditions.
- There was a consistently low level of powdery mildew infection in all experimental tunnels compared with the main commercial crops on these species on the holding. This surprised GCP staff as the nature of the tunnels had been expected to cause increased powdery mildew due to lower ventilation and greater humidity than the main commercial growing areas. As the season progressed, significant mildew did occur is all experimental tunnels but the commercial assessment was that infection remained notably lower under solatrol than any other plastic used in the trial. The reduced mildew severity under the experimental plastics led to a reduced and delayed need to use fungicides for this disease.
- There were no notable effects of any of the plastics on foliage colour, either the red pigmentation in *Acer palmatum dissectum atropurpureum*, or the pale foliage of *Jasminum officinale* **'Fiona Sunrise'**, *Hedera* **'Gold Child'**, or *Acer palmatum* **'Orange Dream'.** Scorching in *Acer palmatum* **'Orange Dream'** seemed unaffected by the plastic used.

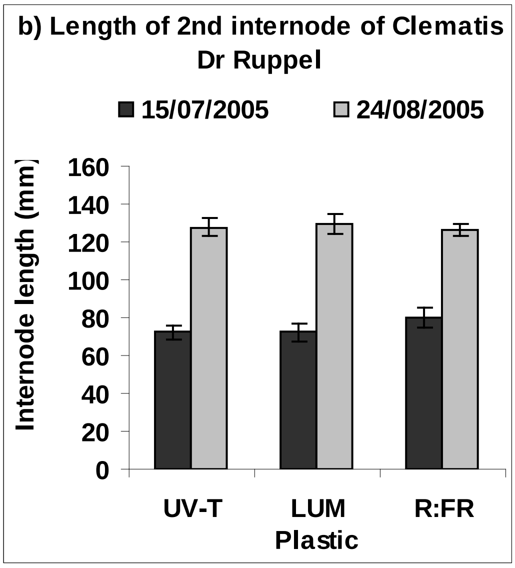
Quantification of plant responses to the different plastics

The twelve subjects on which detailed measurements of growth were made can be divided in to three groups on the basis of their responses.

Group 1: no significant difference between plastics in any of the growth measurements

This group consisted of three species, *Jasminum officinale* **'Fiona Sunrise'** (Figure 7a), Clematis **'Dr Rupple'** (Figure 7b) and *Hydrangea petiolaris* (Figure 7c) There was no indication that the lack of significant response in these plants was due to greater variability than in the other species, and on that basis, it seems that these plants are genuinely unresponsive to the changes in light environment that the plastics produce.





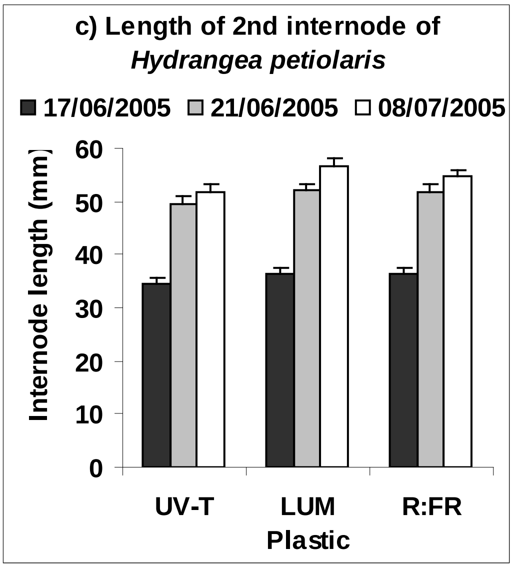


Figure 7.

The effects of cultivation under smart plastics on (a) total shoot length in *Jasminum officinale* **'Fiona Sunrise'** (n ≥ 40), (b) internode length in Clematis **'Dr Rupple'** (n ≥ 20), and (c) *Hydrangea petiolaris*. Data are means ± SEM. In all cases the replicate plants were divided across two tunnels per plastic, but data have been pooled. There were no significant differences between plastics

Group 2: growth consistently increased under UV-T compared with the other two plastics

In this second group of four species (*Acer palmatum* dissectum atropurpureum, *Hedera* **'Gold Child',** *Lonicera x brownii* **'Dropmore Scarlet'** and *Lonicera pericylmenum*

'Serotina',) there was increased growth under UV-T compared with the other two plastics, but no difference between Luminance and Solatrol (Figure 8). In some cases the difference occurred only earlier in the season (*Acer*), but in others it was consistent throughout the season. This response is initially surprising since UV-T is normally expected to reduce vegetative growth, as has been shown in several crops in CP19 (see annual reports). This unexpected result could be interpreted as being due to at least three causes:-

1. The exclusion of ambient solar UV directly inhibits growth. UV stimulation of growth is rare, but not unknown [6, 23]. While this mechanism can not be excluded, it is unlikely.

2. The exclusion of ambient solar UV allows an increase in pest or disease, or their effects, which results in growth stimulation when the crop is exposed to the full solar spectrum under the UV-T film. The suppression of pest and disease by solar UV widely reported in the literature ([8, 17, 20, 26]) is consistent with this hypothesis, but equally there are reports that UV can increase damage ([4, 5, 12, 16]). Experienced production staff at GCP certainly perceived that there was less disease pressure in the experimental tunnels, especially with respect to powdery mildew of *Lonicera* spp. (*Podosphaera clandestine*), but it was not clear that this was specific to UV-T (see above). No systematic monitoring of either pest or disease attack was possible in the present pilot study, but this is an area that appears to merit further study (also see below).

3. The air temperatures recorded under the UV-T plastic was slightly but consistently higher than with the other plastics, which we attribute to a temperature gradient across the six tunnels (see above). As a result, we are not able to exclude the possibility that the response observed in these species was a function of temperature rather than any response to spectral modification. However, with the exception of *H. helix* **'Gold Child'**, there were no significant differences in growth between T11 and T9, and limiting UV-T data to that from T9 did not alter the statistical comparison between plastics. Thus, a direct effect of temperature rather than spectrum seems most likely for *H. helix helix* **'Gold Child'** where growth was significantly greater in the warmer UV-T tunnel (T11) than the other (T9), and statistical analysis in which UV-T data was limited to T9 showed no significant difference from the other plastics.

Based on this pilot study it is not possible to say more than that there may have been specific responses to UV-T in these species, but that this requires further confirmation. In particular, the possible role of changes in pest or disease attack in growth responses would require careful experimental design and quantification of disease that could only be achieved through a purpose-designed experimental system free from the constraints existing on a commercial holding.

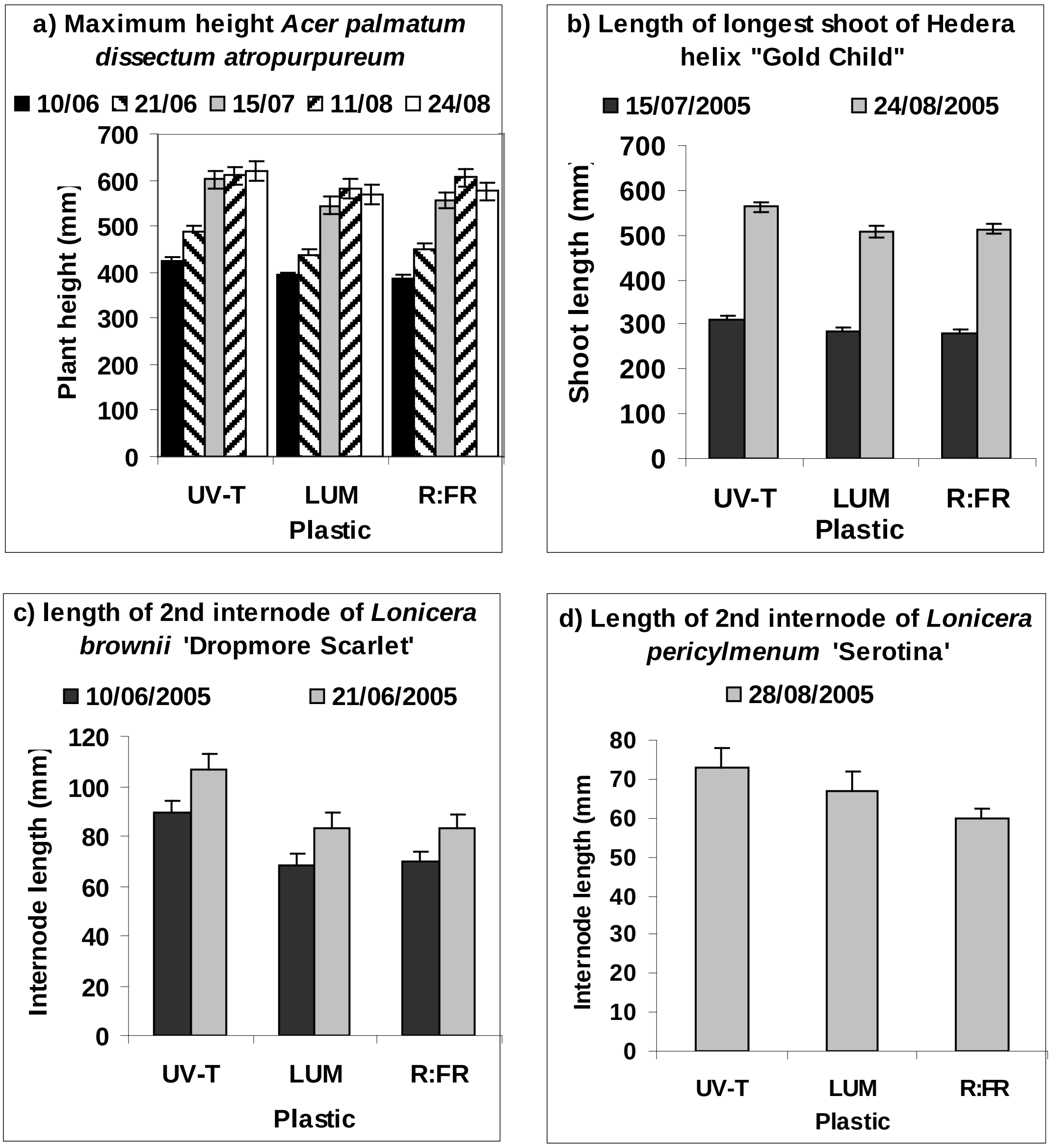
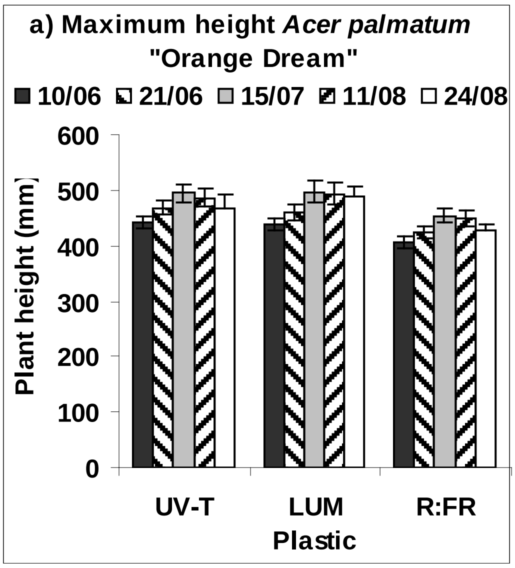


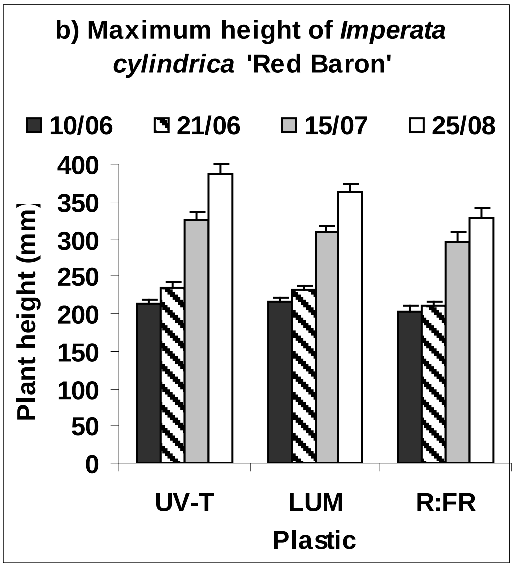
Figure 8. The effects of cultivation under smart plastics on (a) maximum plant height in *Acer palmatum dissectum atropurpureum* (b) length of the longest shoot in *Hedera helix* **'Gold Child'** (n ≥ 40), (c) internode length in *Lonicera x brownii* '**Dropmore Scarlet'** and (d) internode length in *Lonicera pericylmenum* **'Serotina'**. Data are means ± SEM. In all cases the replicate plants were divided across two tunnels per plastic, but data have been pooled. In this group, growth tended to significantly greater in the UV-T tunnels compared to the other plastics, although this may not be a simple function of altered light spectrum (see text for details).

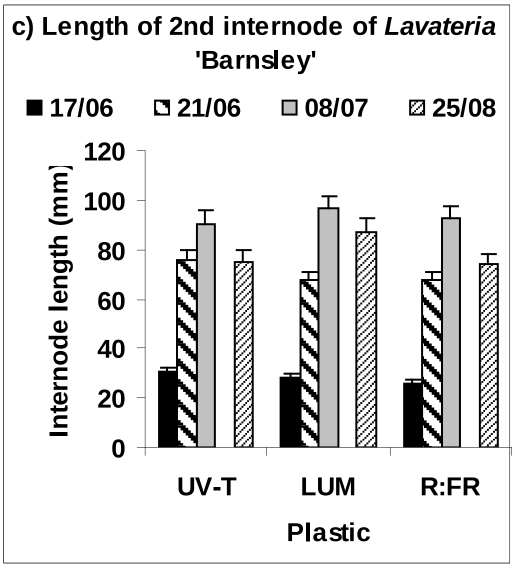
Group 3: growth consistently reduced under solatrol compared with the other two plastics

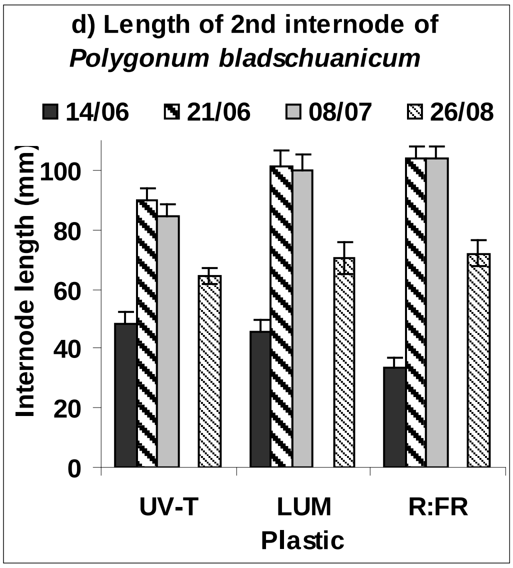
This group of five subjects (*Acer palmatum* **'Orange Dream'**, *Clematis* **'Carnaby'**, *Imperata cylindrica* **'Red Baron'**, *Lavatera × clementii* **'Barnsley'**, *and Polygonum baldschuanicum*). All five showed significant responses to solatrol, the red:far red modifying plastic, more or less consistently over the season (Figure 9). Note that, given the temperature difference between T11 and T9, these two UV-T tunnels were formally compared for this group of species, but in no case was there a statistically significant difference in growth. Thus, we are confident that the differences between solatrol and the other plastics for these species are a true function of spectral differences.

In the case of *Acer palmatum* **'Orange Dream'** (Figure 9a) total plant height was consistently reduced by 8-10% in solatrol compared with the other treatments and this was significant ($p<0.05$) at all measurement dates except 11th August when the significance was marginal ($0.05<p<0.10$). In *Imperata cylindrica* **'Red Baron'** (Figure 9b) the effect of solatrol was not significant at the first measurement but thereafter plant height was reduced by 8-13% (consistently significant at $p<0.05$). The growth reduction in *Lavatera × clementii* **'Barnsley'** (Figure 9c) under solatrol were more variable, both in terms of the magnitude of reductions, which varied between 2 and 12% at different harvests, and their significant ($p<0.05$ only at the first and last measurements). During the experiment this plant was inherently quite variable, both before and after cutting back in early August, and this perhaps limited the power of the experiment to prove significant differences, although the trend for growth reduction under solatrol was consistent across all measurements. This contrasted with the results obtained with *Polygonum baldschuanicum* (Figure 9d). At the first measurement (14th June) internode length was substantially (approx 30%) and highly significantly reduced under solatrol ($p<0.01$). However, after the first harvest plant under solatrol grew strongly. At the second harvest there was no significant differences between plastics while at the third measurement plants under solatrol had significantly ($p<0.05$) longer internodes than those under the other plastics (approx 12%). In regrowth-shoots produced after cutting back in early August there was no significant difference between plastics. In *Clematis* **'Carnaby'** (Figure 9e) there was no significant effect of plastics at the first measurement, but at the second (21st June) internode length was significantly greater (16%, $p<0.01$) than under the other two plastics.









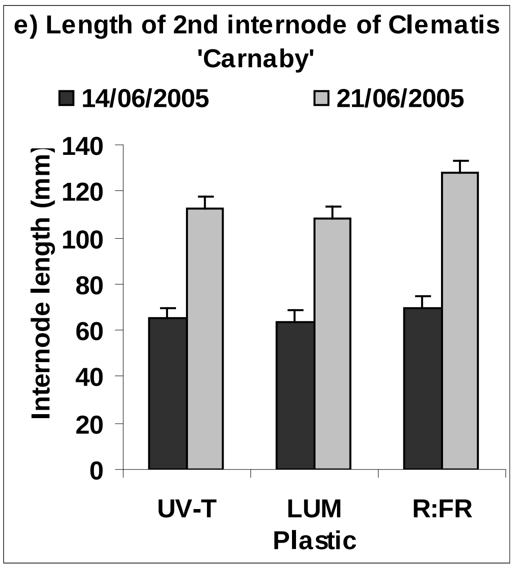


Figure 9. The effects of cultivation under smart plastics on (a) maximum plant height in *Acer palmatum* **'Orange Dream'** (b) maximum plant height in *Imperata cylindrica* **'Red Baron'** (n ≥ 40), (c) internode length in *Lavatera × clementii* **'Barnsley'**, (d) internode length in *Polygonum baldschuanicum and (e)*) internode length in *Clematis* **'Carnaby'**. Data are means + SEM. In all cases the replicate plants were divided across two tunnels per plastic, but data have been pooled. In this group, growth tended to significantly affected by production under solatrol compared to the other plastics (see

Conclusions

1) Conducting this pilot trial on a commercial holding had many benefits, above all the input of GCP staff in making commercial assessments of the crops that identified changes that were not apparent in the formal growth measurements. On the other hand, the constraints on experimental layout and design did limit the interpretation of some of the responses. The greater temperature observed in tunnel 11, one of the UV-T tunnels, was a particular issue. This problem did not substantially reduce the information that the project delivered, but does highlight the limits on work on commercial holdings. Ideally, such studies should run along-side work conducted in a more formal research environment. It is certainly the case that some of the specific responses noted here require detailed follow-up (see below), but that seems an entirely appropriate outcome for a pilot study of this type.

2) One of the major commercial objectives of HONS production under spectrally-modified plastics was growth regulation of vigorous, fast growing subjects. Solatrol delivered this growth regulation in many but not all subjects (see point 3 below). It was of note that the commercial assessments of crop growth and management attributed greater value to the effect of solatrol than was apparent in the formal quantification of extension growth. This is an interesting observation in the sense that direct measurement of stem or internode length did not "capture" the commercial quality of the crop. Clearly, the formal measurements that were possible in this pilot study were quite limited but, even so, the project makes clear the value of combining scientific and commercial assessments in obtaining the maximum information on a crop response, as has also been apparent in CP19.

3) The growth regulation obtained under solatrol is expected since this plastic is specifically designed to reduce extension growth. However, the data obtained here shows that solatrol can not be expected to deliver the same degree of growth regulation across all HONS crops and cultivars. The range of responses to solatrol is consistent with the results obtained under CP19 (see annual reports), and elsewhere using films that increase R:FR ratio [1, 3, 10, 11, 13, 15, 18, 19, 22, 24, 25]. The degree of growth reduction under R:FR increasing films reported in the literature for "responsive species" is approximately 5-25%, and the reductions observed in this project were typically within this range. The lack of significant response to increased

R:FR in many of the species studied here is consistent with a lack of response to solatrol-type films that seems to occur in at least some genotypes of a range of species [1, 13, 24]. A significant increase in growth under solatrol was seen here with *Clematis* **'Carnaby'** and *Polygonum baldschuanicum* late in the growing season (Figure 9d,e). In CP19 we have also seen subjects where extension growth is increased under solatrol, and this has also been reported occasionally in the literature [24]. We have interpreted this responses as the product of (a) no response to increased R:FR and (b) growth stimulation due to the exclusion of UV radiation under solatrol, which is by far the most UV-opaque of the plastics in this trial. The rarity of this response in the existing literature may be due to the frequent use of R:FR increasing films within glasshouses or growth rooms, which are inherently UV-deficient, rather than as the sole cladding (as here, in CP19). Commercially, solatrol can not provide a "one stop" solution for the growth regulation of all HONS subjects, but the results obtained here suggest that it can contribute usefully to the more efficient management of many subjects. Interestingly, there is evidence that increasing R:FR can be used with chemical growth regulators to gain additive effects [22]. Overall, the results of this pilot study have been sufficient to persuade GCP to look to use solatrol as a cover on some of their main production areas.

4) The reduction in powdery mildew under solatrol, as assessed by the GCP staff, was not expected, but was seen as commercially important. Clearly, this pilot study was not able to formally quantify in detail changes in powdery mildew, and based solely on the data obtained here some caution is required before this response is assigned to spectral changes. However, there is one published report that increased R:FR can reduce powdery mildew [21], and an increasing recognition in the fundamental plant biology literature that there are interactions between the R:FR-mediated "shade response" and defence against pest and disease attack [2, 7, 9, 14]. Overall, the possible effect of spectral modification on powdery mildew appears to be a commercially important effect that merits more detailed research in the context of a formally designed project conducted under more controlled conditions with scope for more intensive measurements.

5) In terms of future research, both growth regulation and disease control under spectral filters do appear to be commercially useful for HONS crops. These responses need confirmation over multiple seasons and with a wider range of crops, and the disease effect in particular requires far more detailed experimental design and

measurement than was possible in this pilot study. GCP will continue with the use of the tunnels and plastics used in this project, and have agreed that the scientific staff involved here may continue to assess the material on an *ad hoc* basis. In parallel with this, formal research and development in to the responses identified here will be best advanced through the inclusion of HONS in any collaborative work between Lancaster and STC that develops from CP19.

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