Project Title:	**Glasshouses: Evaluation of an infra-red filter material as an internal screen and its effects on the internal environment.**
Project number:	PC 169
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Report:	Final Report, April 2000
Key workers:	**HRI**

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Date commenced:	May 1999
Date completed:	November 1999
Keywords:	Spectral filters, infra-red, glasshouse environment, summer heatloads, plant quality, chrysanthemum, Luminance THB.

The results and conclusions in this report are based a series of experiments conducted over a one year period. 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.

CONTENTS

PRACTICAL SECTION FOR GROWERS

Background and objectives

Luminance THB is a polyethylene film incorporating a chromophore designed to selectively reduce the transmission of the infra-red component of solar radiation. Previous studies have indicated that it can transmit 75% of Photosynthetically Active Radiation (PAR), but only about 45% of infra-red radiation (700 - 2000 nm), which contributes to the heating of the greenhouse environment. PAR is the component of light energy that is used by plants. The material is being actively marketed as a greenhouse cladding material, particularly in southern areas of Europe, where there is a need to reduce the summer heat load in greenhouses. Studies have indicated that when used in this way, Luminance THB reduces the heat load in the greenhouse by between 10 and 20%. If these results prove accurate, summer cropping of heat-sensitive crops in Luminance-clad structures could increase markedly in southern production areas and increase the competition faced by UK producers.

The question arises, does Luminance THB have the potential to benefit summer glasshouse production in the UK where product quality can be affected by excess heat? In this case Luminance THB would be used as an internal glasshouse shade screen since the vast bulk of high-input protected cropping in the UK is in glasshouse structures. Conventional shade screen materials (such as ULS 15F) would be expected to give a greater reduction in total Infra-Red radiation than Luminance THB, but this would be at the cost of a much greater reduction in PAR.

To date, Luminance THB has not been used as an internal shade screen in glasshouses and this project aims to test the effect of Luminance THB in summer on the growing environment below the screen.

Objectives

1. To determine the physical effects of utilising Luminance THB as an internal shade screen on the growing **environment** below the screen and also on the aerial environment above the screen.

2. To determine the effect of the internal screen on **ventilation rates** in order to optimise the potential benefits of using infra-red spectral filters as internal shade screens within glasshouses.

3. To determine the effects of using Luminance THB as an internal shade on a **growing crop** of year-round chrysanthemums.

If successful the project has the scope to improve the glasshouse environment for both the growing crop and the workers. If the vents can be kept closed longer, (due to a reduced heatload within the glasshouse), CO_2 enrichment could be used more cost effectively during the summer.

The experiment was conducted in identical size compartments, with and without an internal Luminance THB screen. These are referred to as un-screened and screened hereafter for clarity. Each compartment had two vents with a maximum opening angle of 80°, and the vent angle fixed to achieve comparable venting characteristics to those in commercial houses using recommendations from SRI. Environmental set-points in the house were controlled by a Priva computer, taking measurements from a aspirated screen located in the middle of each house, just above crop height (and therefore below the Luminance THB screen). The target level for carbon dioxide enrichment was to maintain ambient levels of 350 ppm during the day. The temperature heating set points were 18°C night and 19°C day with venting at 23°C. Night-length control was achieved by black plastic sheeting, supported over each bed during the blackout period. The Luminance screen was fitted at a height of 2.83 m from the ground, with an automatic screen movement system integrated to the Priva control computer, programmed to be moved over the crop when external light levels exceeded 400 Wm^{-2} for more than 15 minutes. Conversely, the screen was removed when light levels decreased below 400 W m^{-2} for more than 15 minutes, to prevent patchy cloud conditions moving the screen prematurely.

The dimensions of each compartment were, 6.7 m x12.0 m, with height to gutter 3.25 m and height to the ridge 4.7 m, so that the ground area was 80.4 m^2 and the internal volume 320 m^3. The volume below the screen was 228 m^3. Environmental conditions were monitored by the Priva computer and an array of independent sensors located in both compartments measuring, air temperature, leaf temperature, light levels and carbon dioxide concentrations. Ventilation rates were assessed at intervals using a tracer gas technique, full details of which are given in the main report.

A crop of AYR spray chrysanthemums (*Dendranthema grandiflora* cv Dark Splendid Reagan & White Reagan) was established in both trial houses on 21st June 1999 (week 25). Cuttings (approximately 8cm in height) were supplied rooted into peat blocks (5 x 5 x 3 cm in size). The growing substrate was a sand hydroponic system based on previous MAFF funded work (HH 1344), with three beds per compartment. An automatic feeding unit supplied hourly feeds from 06.00 hours to 19.00 hours, each for a duration of 2 minutes (during long days), increasing to 4 minutes during short days, when plants had increased in size.

Cuttings were planted on to the beds on 21st June 1999, at a planting density of 65 plants per m^{-2}. Each of the beds was divided into two equal areas (north and south) and planted either with a purple (Dark Splendid Reagan) or white (White Reagan) cuttings.

After planting, long days were given until the average height was 30cm, (achieved on 30 June) after which short days were applied. The commencement of an interruption was timed on the basis of light integral from commencing short days as described previously (Langton, 1992). Plants were harvested when they reached a commercially marketable stage, this was defined as when the maximum number of flowers were open, but before pollen was shed in the outer row of disc petals of the uppermost flower.

Assessments were made on two occasions, at the end of long days and at final harvest and included, plant height, leaf number, fresh/dry weight and leaf area.

Summary of results

- The Luminance THB screen reduced the light transmission by approximately 20% when averaged over the duration of the chrysanthemum crop.

- The screen significantly reduced ventilation rates, which increased with windspeed, from 25% in calm conditions to 48% for a windspeed of 4 m/s. The effect of this was to increase the average temperature by 0.7°C beneath the Luminance THB screen compared to an unscreened house. On a hot sunny day, the temperature differential excess was 2°C averaged from noon to early evening. The maximum difference recorded was 3.3°C.

- Leaf temperatures were affected less by the screen than air temperature. Under high irradiance conditions, leaf temperatures under the luminance screen were 2°C lower than air temperature, whereas the difference without the screen was about 1°C.

- The Luminance THB screen increased the vapour pressure deficits (VPD) during the day due to an increase in air temperature and a reduction in light transmission (which would reduce transpiration, and hence the water released into the environment).

- Vegetative growth and flower development generally did not differ significantly when grown under the screen. The exceptions were reductions in height of up to 7% and a trend towards increased leaf area development under the screen. The former was attributed to possible alterations to the far red ratio or increased daytime VPD under the screen, which could have reduced plant height. The latter, was attributed to the more diffuse light environment under the screen (indicated by the lack of shadows) which was more conducive to leaf area development.

Action points for growers

- An internal screen mechanism needs to be designed for minimising ventilation rate reductions so that the benefits of reduced heat load from the selective infrared filter material can be achieved.

- From a practical point of view, Luminance THB was shown not to have any detrimental effects on growth and flower development of AYR Chrysanthemums. There was also evidence to suggest that properties of the screen were beneficial to height control and leaf area development. This suggests that if sufficient ventilation can be achieved, this material would be suitable as an internal screen to reduce heatloads.

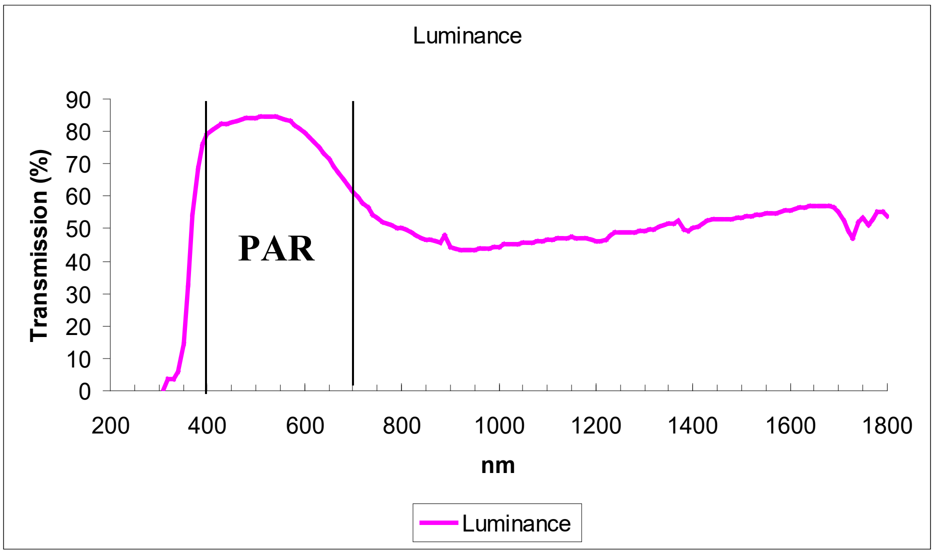
Practical and anticipated financial benefits

This was the first work looking at possible benefits of using Luminance THB as a screen under glass, in an attempt to reduce the heat load on the crop beneath. However, the impervious nature of the screen material reduced normal ventilation, resulting in an increase in temperature rather than the hoped reduction. Further work is therefore necessary to improve screen design to allow adequate ventilation before it can be fully evaluated.

SCIENCE SECTION

Introduction

Luminance THB is a polyethylene film, which incorporates a chromophore, designed to selectively reduce the transmission of the infra-red component of solar radiation. Transmission data (Pearson, *pers. comm.*, see graph at bottom of Page 5) indicates the material allows about 75% of Photosynthetically Active Radiation (PAR, 400 - 700 nm) to pass through it, but only about 45% of infra-red radiation (700 - 2000 nm). This results in an increased proportional screening of radiation which contributes to the heating of the greenhouse environment (infra-red) than of visible radiation used by plants for photosynthesis (and which also contributes to heating the environment). The material is being actively marketed as a greenhouse cladding material, particularly in southern areas of Europe, where there is a need to reduce the heat load in greenhouses in summer. When used in this way, Luminance has been reported (Pearson *pers. comm.*) to reduce the heat load in plastic structures by approximately 10 - 20%. Since the material diffuses about 95% of radiation passing through it, the potential reduction in photosynthesis may be less than is suggested by the transmission figures above. Other estimates (Pearson *pers. comm.*) suggest that effective PAR is reduced by only 4%. If these estimates prove accurate, summer cropping of heat-sensitive crops in Luminance-clad structures could increase markedly in southern production areas and increase the competition faced by UK producers.



Percentage radiation transmission through Luminance THB, showing magnitude of reduction in the PAR component (Data supplied by Reading University).

The question arises, does Luminance THB have the potential to benefit summer glasshouse production in the UK where product quality can be affected by excess heat load? In this case Luminance THB would be used as an internal glasshouse shade screen since the vast bulk of high-input protected cropping in the UK is in glasshouse structures. Conventional shade screen materials (such as ULS 15F) would be expected to give a greater reduction in total Infra-Red radiation than Luminance THB, but this would be at the cost of a much greater reduction in PAR.

The screen would have to be retractable (like other commercial screens) since it would be counter-productive to use the screen and increase the loss of PAR (over that excluded by the glass itself) at times when the heat load was not great. When utilised in this mode it could be used:

- To reduce high summer air and plant temperatures within the glasshouse to more equable levels with little adverse effect on visible (PAR) radiation reaching the crop, so improving product quality.

- To moderate the glasshouse environment for glasshouse workers without seriously compromising crop growth.

- To enable vents to be kept closed for longer (with temperatures similar to those currently experienced) to allow the increased use of cost-effective summer CO_2 enrichment.

The project aims to test the effect of Luminance THB as an internal screen in summer, on the growing environment below the screen. Ventilation requirements were examined, as adequate levels would have to be achieved to prevent heat build-up below the screen. This could be a problem as Luminance THB is an impermeable material (unlike other commercially available shade screens), and it is not possible at present to predict reliably the air flow through openings in shade screens. The project is seen as generic in that many summer-grown glasshouse crops should benefit from the results obtained. This trial used AYR spray chrysanthemums as a model crop for a number of reasons. Firstly, the requirements for optimal growth are better understood for chrysanthemum than for any other ornamental crop grown in the UK. Secondly, particular interest was expressed by this sector of the industry as screens are already widely used for photoperiod control and, when gapped, for amelioration of the daytime environment.

Objectives

1. To determine the physical effects of utilising Luminance THB as an internal shade screen on the growing **environment** below the screen and also on the aerial environment above the screen.

2. To determine the effect of the internal screen on **ventilation rates** in order to optimise the potential benefits of using infra red spectral filters as internal screens within glasshouses.

3. To determine the effects of using Luminance THB as an internal screen on a **growing crop** of all year-round chrysanthemums.

MATERIALS AND METHODS

The experiment was conducted in identical sized glass compartments (F-Block) at HRI Efford, with and without an internal screen. These are referred to as un-screened and screened hereafter for clarity. F Block is an east west orientated house, composed of 12 compartments divided equally into a north and south array (compartments used were in the centre of the south array). Each compartment had two vents with a maximum opening angle of 80°, and the vent angle fixed to achieve comparable venting characteristics to those in commercial houses using recommendations from SRI.

Environmental set-points in the house were controlled by a Priva computer, taking measurements from a aspirated screen located in the middle of each house, just above crop height (and therefore below the Luminance THB screen). Carbon dioxide enrichment was supplied as pure carbon dioxide controlled through the Priva computer by a solenoid and fed into clear plastic tubing, which was laid down the length of each bed. The target level for enrichment was to maintain ambient levels of 350 ppm during the day. The temperature heating set points were 18°C night and 19°C day with venting at 23°C. A high temperature alarm was set at 32°C to warn if the temperature became dangerous for the plants in any house. Night-length control was achieved by black plastic sheeting, supported over each bed during the blackout period.

The Luminance screen (Plates 1 & 2 : Appendix 3) was fitted at a height of 2.83 m from the ground in compartment F9, with a automatic screen movement system integrated to the Priva control computer. The screen was programmed to be moved over the crop when external light levels exceeded 400 Wm^{-2} for more than 15 minutes. Conversely, the screen was removed when light levels decreased below 400 $W\ m^{-2}$ for more than 15 minutes. This time lag prevented patchy cloud conditions moving the screen prematurely. The electric motor moved the screen over the compartment in 72 seconds, a distance of approximately 12 metres.

The dimensions of each compartment were, width 6.7 m, length 12.0 m, height to gutter 3.25 m and height to ridge 4.7 m, so that the ground area was 80.4 m^2 and the internal volume was 320 m^3. The height of the screen was at 2.83 m so the volume below the screen was 228 m^3.

At planting the screen area as a percentage of the ground area of the greenhouse was 85% (i.e. ventilation gap 15%). Modifications were made to the end pelmets on 30 June (week 26) which increased the ventilation gap to 23% and on 29 July the side pelmets were moved to increase the ventilation gap further to 37%. Changes in the ventilation gap were made in attempt to ameliorate the heatload within the compartment.

The crop was planted in 1999 on 21 June (week 25) and harvested on 1 September (week 35).

Environment

Environmental sensor equipment was installed in each compartment 0.5 m above crop height and 3.5 m from the ground (above the screen in compartment 9) and outside the compartments. Air temperature was measured by precision platinum resistance thermometers placed in a ventilated screen, global solar radiation (irradiance) was measured by tube solarimeters and the concentration of carbon dioxide (CO_2) by a multiplexed Infra Red Gas Analyser (IRGA). The sensors were scanned by a data logger (Campbell Scientific – model 21x) at 10 sec intervals and logged every five minutes. Leaf temperature was measured by attaching to the underside of leaves four pairs of thin-wire (0.1 mm) copper-constantan thermocouples wired in series and referenced to air temperature.

Air temperature, relative humidity and the concentration of CO_2 for both compartments and irradiance, air temperature, wind speed and direction, vent opening positions (leeward and windward) and concentration of CO_2 for outside the compartments were logged at five minute intervals by the Priva environmental controller.

Ventilation rates

Ventilation rates were determined using a tracer gas technique. The static method, in which the tracer gas is injected at a constant rate, was used, which allowed information on the effect of windspeed to be obtained in one experiment. The CO_2 supply to the screened compartment was used for the tracer gas study and the flow rate measured on the Campbell logger by a mass flow meter. These studies took place at the end of the season when the crop had been removed. This avoided the complication of estimating the CO_2 uptake by the crop. Approximately five days of data were collected between 19 and 25 November 1999 during which time there was a wide range of windspeeds. The screen was in place throughout with a ventilation gap of 37% (i.e. in the position used for most of the experiment). Vent positions were fixed with the windward vent closed and the leeward vent opened at 70% of the maximum opening. The experiment was repeated for a further five occasions between 29 November and 6 December 1999, with the screen in the 'parked' position and with the same fixed vent positions. Again there was a wide range of windspeeds during the recording period.

Under conditions of constant injection rate the mean ventilation rate in a ventilated enclosure v_a over a time interval t_1 to t_2 is given by (Sherman, M.H., 1990):

$$v_a = \left[\frac{v_t}{C_i - C_o}\right] - \frac{V}{t_2 - t_1} \ln\left[\frac{C_{2i} - C_{2o}}{C_{1i} - C_{1o}}\right]$$

where V is the enclosure volume , v_t is the mean volumetric injection rate of the tracer gas over the time interval, C_i and C_o are the fractional volume concentration of the tracer gas inside and outside the enclosure. The volume concentrations of the tracer gas inside and outside the enclosure are C_{1I} and C_{1o} at time t_1 and C_{2I} and C_{2o} at time t_2. Rates were determined for ventilation from below the screen (inside) to above the screen (outside) and from above the screen (inside) to outside the compartment (outside). The same procedure was used for the experiment with the screen 'parked' (drawn back). The data were subdivided into 1 m/s windspeed intervals and the mean ventilation rate determined.

Growing crop

A crop of AYR spray chrysanthemums (*Dendranthema grandiflora* cv Dark Splendid Reagan & White Reagan) was established in both compartments on 21 June 1999. The materials and methods for the establishment of the crop were identical between the screened and unscreened compartments.

Cuttings (approximately 8cm in height) were supplied rooted into peat blocks (5 x 5 x 3 cm in size) suitable for planting. The growing substrate was a sand hydroponic system based on previous MAFF funded work (HH 1344), using trays (20 x 40 x 5cm in depth) filled with sand to create beds in each compartment, each row measuring 9.5 x 1.0 m (28.5 m^{-2} cropped area per compartment, Appendix 1).

The ground below the trays was lined with a permeable membrane (Mypex) to allow drainage of waste water through holes in the trays above. Irrigation and feed was supplied by perforated tubing laid down the length of the beds (Appendix 1). An automatic feeding unit supplied hourly feeds from 06.00 hours to 19.00 hours, each for a duration of 2 minutes (during long days) increasing to 4 minutes during short days when plants had increased in size (the composition of the feed is given in Appendix 2). Netting was positioned over each bed to help achieve uniform planting and to support plants later on in development.

Cuttings were planted on to the 'beds' in accordance with the layout (Appendix 1) on 21th June 1999, at a planting density of 65 plants per m^{-2}. Each of the beds was divided into two equal areas (north and south) and planted either Dark Splendid Reagan or White Reagan cuttings (A photograph of plant material in the screened house is given in Appendix 3 – Plate 3).

After planting, plants were given long days until the average height was 30cm, (achieved on 14 July) after which short days were applied. The interruption of 5 days commenced on 24 July, this was timed on the basis of light integral from starting short days as described previously (Langton, 1992). Plants were harvested when they reached a commercially marketable stage, this was defined as when the maximum number of flowers were open, but before pollen was shed in the outer row of disc petals of the uppermost flower.

The following assessments were made of the crop during production, the sample population (n) is given in brackets. Assessments were made on two occasions, at the end of long days and at final harvest.
At the end of long days (n = 100 unless otherwise specified)

- Plant height (cm)
- Leaf number
- Leaf area (cm^2) (n =10)

At final harvest (n = 100 unless otherwise specified)

- Plant height (cm)
- Leaf number
- Fresh weight (g)
- Dry weight (g)
- Flower number per stem
- Bunch weight (5 stems) (g)
- Stem width (mm) (n = 10)
- Leaf area (cm^2) (n = 10)
- Flower colour (Using Royal Horticultural Society colour cards)

From the leaf area data and the known planting density of 65 plants per m^{-2} the Leaf Area Index (LAI) value was calculated as shown below. Fully functional canopies capable of intercepting more then 90% of incident radiation typically have LAI values of between 4 to 5.

$LAI = L_A / P$ Where L_A = Area of green leaf material per plant (m^{-2}).
P = Area of land occupied by plant (m^{-2}).

Leaf area values were measured in cm^2 but converted to the same units as the planting density (m^2) as the measurement (LAI) was a ratio of plant leaf area to the area of ground the plant occupied.

RESULTS AND DISCUSSION

Environment

The results are presented as the mean daily values over the growing season (*seasonal*) and the values during the course of a day of high irradiance, high air temperature and low windspeeds (*12 July*) when the screen ventilation gap was 23%. There were no days with similar environments in the later period of the experiment when the screen ventilation gap was increased to 37%.

Seasonal

Figure 1 (Page 18) presents the daily values of radiation integral measured outside the compartments and the transmission (the ratio of inside to outside) above and below the height of the screen. The mean external irradiance over the growing season was 17.0 MJ/m^2/d. The average transmission was 0.56 above the screen and 0.54 below the screen in the unscreened compartment whereas in the screened compartment the average transmission was 0.64 above the screen and 0.44 below the screen. The reasons for the increase transmission above the screen are uncertain and probably due to a number of factors. These may include the reflection of radiation by the screen, direct light falling on the sensor without passing through the glass when the vents are fully open and cleanliness of the glass. The loss in transmission above and below the screen of about 30% is due to the reduction in total radiation by the screen material, and the support and control mechanisms for the screen.

Figure 2 presents the daily mean values of air temperature recorded by the Campbell logger. The difference in the mean temperatures above and below the height of the screen was small. This is due to the consequences of averaging over the whole season which included nights and periods of low irradiance when the screen was not in place. During periods 2 and 3 the differences in the average daily temperatures were 0.7ºC (there was insufficient data in period 1 to make the same comparison, periods 1-3 refer to different percentages of screen ventilation used, Page 7). There were consistent differences of about 0.8ºC between air temperature logged by the Campbell and Priva systems (Figure 3).

Even though there were differences in the air temperature between the two compartments, the relative humidity (RH) was very similar (Figure 4). Averaged over the season RH in the screened compartment was less than 1% lower than in the unscreened compartment. At the time when the screen gap increased to 37% the fall in air temperature and rise in RH was almost certainly due to the drop in average outside air temperature.

During period 2 leaf temperature was below air temperature by about 0.8ºC in both compartments (Figure 5). During period 3 the difference between leaf and air temperature in the unscreened compartment was small, whereas in the screened compartment leaf temperature was on average 0.6ºC lower than air temperature.

Figure 6 presents the average vent position and the mean daily windspeed throughout the season and Table 1 the mean values for the three periods. For periods 1 and 3 there was no difference in the windward vent opening for both compartments but in period 2 the windward vent was more open in the screened compartment than in the unscreened one. The differences between the opening of the leeward vents during period 2 were less than in the other periods.

Table 1 Average vent position as a percent of the maximum opening.

Period	Leeward		Windward	
	No screen	Screened	No screen	Screened
1 (21.06.99 – 30.06.99)	53	82	19	19
2 (01.07.99 – 29.07.99	63	66	36	41
3 (30.07.99 - 01.09.99)	38	59	31	31

CO_2 concentrations were measured at crop height during the trial. Weekly daytime average values for both compartments (Table 2) show similar levels were achieved in both compartments. The daytime time interval was calculated from the sunrise and sunset times for each day. Analysis of Variance was used to examine any differences in the daily daytime CO_2 concentrations between the two compartments (21.06.99 to 01.09.99). Average values were 384.8 ± 7.3 ppm and 385.4 ± 7.2 ppm for unscreened and screened compartments respectively. No significant differences were found in CO_2 concentrations between compartments.

Table 2. Average weekly CO_2 concentrations (ppm) at crop height for the two compartments, Screened and No screen, from crop establishment (week 25) to harvesting (week 35).

Week Number 1999	(Average daytime CO_2 concentration, ppm)	
	Screen	No Screen
25 (21.06.99)	353	356
26	399	395
27	405	405
28	386	386
29	383	383
30	340	342
31	391	392
32	387	387
33	368	354
34	386	394
35 (01.09.99)	402	402
Average	**382**	**381**

12 July

This day was selected as extreme environmental conditions existed in the compartments as a result of the outside air temperature exceeding 28°C, the daily global radiation was 26.1 $MJ/m^2/d$ and the average windspeed was 1.4 m/s. The vents were fully open from 9:00 to 21:00. The ventilation gap was 23% on this day.

Figure 7 compares the diurnal variation of irradiance in the compartments with and without the screen. Shortly after 18:00 hours the blackout material reduced irradiance to zero. The large fluctuations in values of irradiance inside the compartments are due to shading by structural members. The transmission of total radiation measured above the height of the screen was 0.58 in the compartment without the screen and 0.64 in the compartment with the screen. The screen considerably reduced the transmission, which averaged 0.41 for the day compared to 0.52 in the unscreened compartment.

Figure 8 presents the diurnal variation of air temperature above the canopy and the difference between leaf and air temperature. At dawn air temperature was similar in both compartments with the screen increasing temperature by only about 0.2°C. This temperature difference increased during the day and from noon until early evening the temperature under the screen was on average 2ºC higher than the unscreened compartment. The maximum air temperature in the compartment with the screen was 34.5°C whereas in the compartment without a screen the maximum was 31.2°C.

At night leaf and air temperatures were similar, but during the day leaf temperatures were lower than air temperature by as much as 2°C in the compartment with the screen when irradiance was at a peak in early afternoon. At the same time, in the compartment without a screen leaf temperature was lower than air temperature, although the difference was smaller at about 1°C. This effect can be explained by the reduction in heat load on the leaves as a result of the loss of radiant energy beneath the screen, which demonstrates the potential of luminance as an internal screen.

A notable feature was the rapid increase in leaf and air temperature at the time the plants were covered by the blackout material. Air temperature increased by 5°C in the compartment with the screen whereas the effect was less (about 2°C) in the other compartment. The black-outs used in the experiment were not commercial so the elevation in temperature would not be expected to the same extent under commercial conditions.

RH was similar in each compartment at night and during the blackout period (Figure 9). The maximum relative humidity occurred near to dawn and decreased gradually until later in the afternoon when differences between the two compartments were observed. The minimum RH in the compartment with the screen was 41% whereas the minimum in the compartment without the screen was 47%. Relative humidity is temperature dependent and does not relate to plant transpiration so well as vapour pressure deficit (VPD), which is a measure of the dryness of the air). However, as the air temperature was higher in the compartment with the screen the vapour pressure deficit was higher than in the other compartment. This effect was large during the part of the day when temperatures were high. At this time in the compartment with the screen the VPD was about 2500 Pa and in the no screen compartment was about 2000 Pa. There was no difference in the VPD during the night period.

Ventilation rates

Figure 10 compares ventilation rates in relation to windspeed with and without the Luminance THB screen in place. With the screen in the 'parked' position, the ventilation rates from the area below screen height to the area above the screen were very similar to the ventilation rate from the area above the screen to the outside. However with the screen in place the ventilation from the area below the screen was considerably reduced for windspeeds greater than 0.5 m/s. Ventilation rate increased only slowly in relation to windspeed above 2.5 m/s. Table 3 presents estimates of ventilation rate at different windspeeds with and without the screen.

Table 3. **Estimates of ventilation rate (from below the screen to the area above the screen) at different windspeeds with (*a*) and without a screen (*b*). The ventilation gap was 37%, the windward vent was closed and the leeward vent opened at 70% of the maximum opening. The percent reduction in ventilation rate due to the screen is estimated as 100(1-*a/b*).**

Windspeed (m/s)	Ventilation rate (m^3/s)		Reduction (%)
	Screen (*a*)	No screen (*b*)	
0	4.6	6.1	25
1	9.9	14.4	31
2	13.7	21.4	36
3	15.7	27.0	42
4	16.3	31.4	48

Even with the large ventilation gap of 37% the reduction in ventilation rate due to the internal screen was very large ranging from 25% in still conditions to 48% for a windspeed of 4 m/s. The reduction in ventilation explains the reason for the increased air temperature under the luminance screen during the day when the radiation was high.

Larger gaps than those used in the latter part of the experiment are required to provide sufficient ventilation for internal screens placed horizontally above the crops. Gaps larger than those used could provide inadequate shading by exposing considerable areas of the crop to the direct beam of light. The determination of the size of gap required for adequate ventilation was beyond the scope of the design of this experiment.

A different design of screen, e.g. parallel to the greenhouse roof, is required that will provide adequate screening of the crop but with minimal interruption with the ventilation process so that the benefits of reduced heat load from the selective infrared filter material can be achieved.

Growing crop

The results are divided into two sections, the assessment at the end of long days (plants 30 cm tall) and the final harvest (plants approximately 90 cm tall).

At the end of Long Days (LD)

At the end of long days destructive assessments (Table 4) showed there were no significant differences between plants grown under screened and un-screened conditions. The lack of difference can possibly be attributed to the fact plants had only been subjected to 21 days under the different treatments (during long days).

Final harvest

The final assessment at maturity was made on 1 September 1999 for all treatments. The crop response was 7 weeks, with an overall crop duration of 10.3 weeks. By the final destructive harvest some differences in the vegetative growth had emerged between treatments (Table 5). The most notable difference was reduced height with crops grown under the screen. Other studies using far red absorbing spectral filters (Khaltak, Pearson & Johnson, 1999 ; Clifford, 1999) have also demonstrated height control can be achieved, suggesting the height reduction could possibly be linked to some adjustment of the far red ratio by the spectral filter. Alternatively, VPD values greater than 1000 Pa have been observed to have detrimental effects on plant growth (Langton, *pers. com*), on the 12 July (Fig 9) levels approached 3000 Pa in the screened compartment compared to lower levels of 2000 Pa in the unscreened compartment.

Table 4. Destructive assessment of plant growth and development at the end of long days (30 June 1999) confidence intervals ($P<0.05$) are given in brackets.

	Plant height (cm)	Leaf number	Leaf area (cm^2)	LAI
Unscreened				
Dark Splendid Reagan	27.5 (± 0.38)	16.5 (± 0.24)	203.5 (± 5.71)	1.3 (± 0.13)
White Reagan	26.7 (± 0.56)	15.1 (± 0.22)	185.6 (± 6.20)	1.3 (± 0.10)
Screened				
Dark Splendid Reagan	28.7 (± 0.39)	17.1 (± 0.23)	207.0 (± 6.28)	1.3 (± 0.12)
White Reagan	26.3 (± 0.36)	15.5 (± 0.20)	191.2 (± 5.38)	1.4 (± 0.13)
Unscreened average	27.1 (± 0.56)	15.8 (± 0.22)	194.6 (± 6.20)	1.3 (± 0.08)
Screen average	27.5 (± 0.46)	16.3 (± 0.28)	198.7 (± 5.71)	1.3 (± 0.09)

Fresh and dry weights were not significantly different between screened and un-screened treatments, despite the reduction in total radiation transmission (of 20 %) by the spectral filter. This is in contrast with other studies on some spectral filters, which have actually reduced plant dry weights (Rajapakse & Kelley, 1992). Despite dry weights being equivalent there was some evidence to suggest increased partitioning into leaves (as increased leaf area, Table 6) in screened treatments. Under the spectral filter the light environment appeared more diffuse, due to the lack of shadows, and such an environment would increase the utilisation of radiation by the canopy (Healey *et. al,* 1998), which could explain the trend towards increased leaf area under the screen. Overall, it appears that the more diffuse light environment (which is more conducive to canopy photosynthesis) may compensate decreased radiation transmission through the screen.

Flower development between treatments did not differ significantly in terms of speed, quantity or final quality. Under both treatments stems produced were of marketable quality. A dark flower variety (Dark Splendid Reagan) was used to determine if the spectral filter influenced petal colour. No differences were found in the colour of petals between the dark coloured variety in the two treatments.

Table 5. Destructive assessment at marketing (1 September 1999) of plant height, flower number fresh and dry weights (confidence intervals ($P<0.05$) are given in brackets)

	Plant height (cm)	Flower number	Fresh weight (g)	Dry weight (g)
Unscreened				
Dark Splendid Reagan	90.0 (± 1.52)	12.3 (± 1.19)	83.3 (± 5.24)	13.3 (± 0.77)
White Reagan	91.0 (± 0.96)	11.5 (± 0.95)	88.5 (± 4.64)	13.4 (± 0.71)
Screened				
Dark Splendid Reagan	88.4 (± 0.90)	11.9 (± 1.09)	82.2 (± 6.33)	13.1 (± 3.26)
White Reagan	85.2 (± 0.90)	12.2 (± 0.97)	88.6 (± 5.80)	13.5 (± 0.83)
Unscreened average	90.5 (± 1.27)	11.9 (± 1.08)	85.9 (± 4.97)	13.4 (± 0.74)
Screen average	87.7 (± 1.04)	11.2 (± 0.97)	84.9 (± 5.80)	13.1 (± 0.83)

Table 6. Destructive assessment at marketing (1 September 1999) of leaf number per plant and Leaf Area Index (LAI), confidence intervals ($P<0.05$) are given in brackets.

	Leaf number	LAI
Unscreened		
Dark Splendid Reagan	27.2 (± 2.26)	4.5 (± 0.35)
White Reagan	29.4 (± 0.41)	4.4 (± 0.65)
Screen		
Dark Splendid Reagan	29.6 (± 1.46)	4.9 (± 0.51)
White Reagan	28.3 (± 0.42)	4.8 (± 0.61)
Unscreened average	28.3 (± 0.59)	4.4 (± 0.36)
Screen average	29.9 (± 0.42)	4.9 (± 0.39)

4. CONCLUSIONS

1. The Luminance THB screen reduced the transmission of total radiation from 0.64 to 0.44 over the season.

2. Even with a ventilation gap of 37% the Luminance THB screen considerably reduced ventilation rates, although as windspeed increased these rates improved from 25% in calm conditions to 48% for a windspeed of 4 m/s.

3. Reduced ventilation rates resulted in air temperature over the season being 0.7°C higher beneath the Luminance THB screen. On a hot sunny day, the temperature excess was 2°C averaged from noon to early evening. The maximum excess temperature recorded was 3.3°C.

4. The effect of the screen on leaf temperature was less extreme than on air temperature. For high irradiance conditions, leaf temperature under the Luminance THB screen was about 2°C lower than air temperature whereas the difference without the screen was about 1°C.

5. The Luminance THB screen increased the vapour pressure deficits during the day due to an increase in air temperature and a reduction in light transmission (which would reduce transpiration).

6. The internal screen must be designed to allow adequate ventilation rates so that the benefits of reduced heat load from the selective infrared filter material can be achieved.

7. Vegetative growth and flower development generally did not differ significantly when grown under the Luminance THB screen. The exceptions were reductions in height of up to 7% (White Reagan) and a trend towards increased leaf area development under the screen. The former was attributed to possible alterations to the far-red ratio by the screen or the increased peak VPD values in the screened compartment. The latter was attributed to the more diffuse light environment under the screen (indicated by the lack of shadows) which was more conducive to leaf area development.

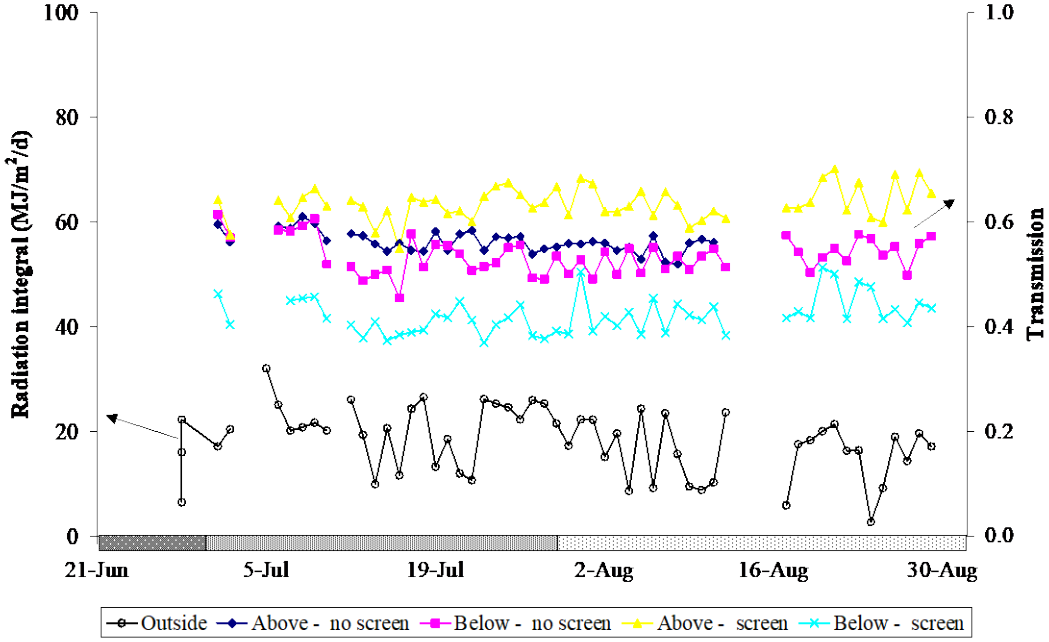


Figure 1. *Seasonal*: Daily mean radiation integral and light transmission. The hatching indicates the periods with different ventilation gaps in the screen.

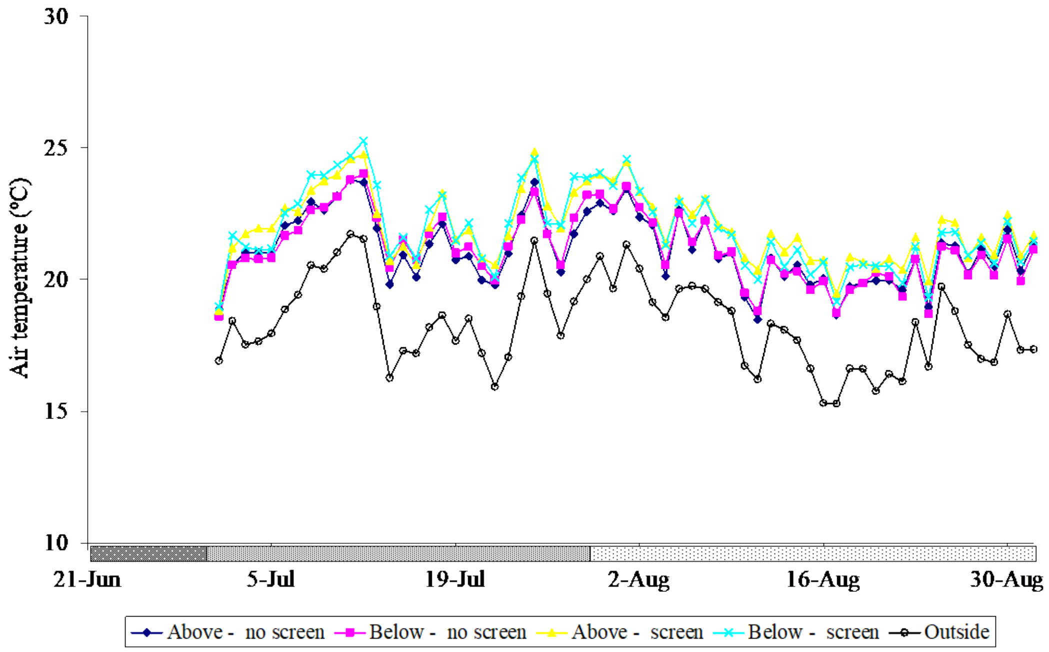


Figure 2. *Seasonal*: Daily mean air temperature. The hatching indicates the periods with different ventilation gaps in the screen.

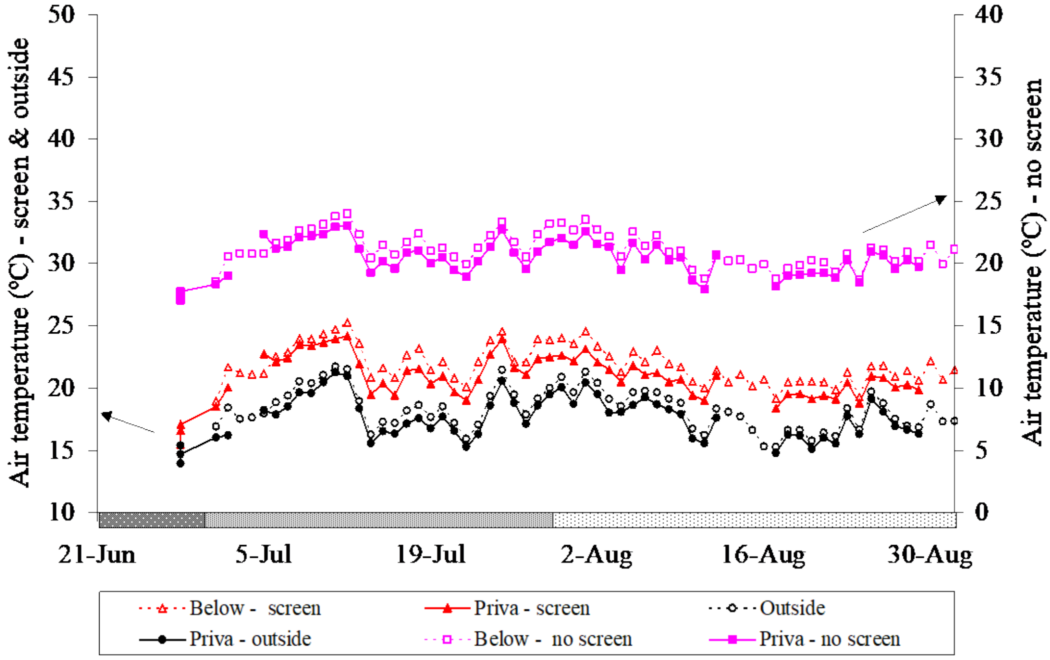


Figure 3. *Seasonal*: Comparison of daily mean air temperature recorded by the Campbell and Priva systems. . The hatching indicates the periods with different ventilation gaps in the screen.

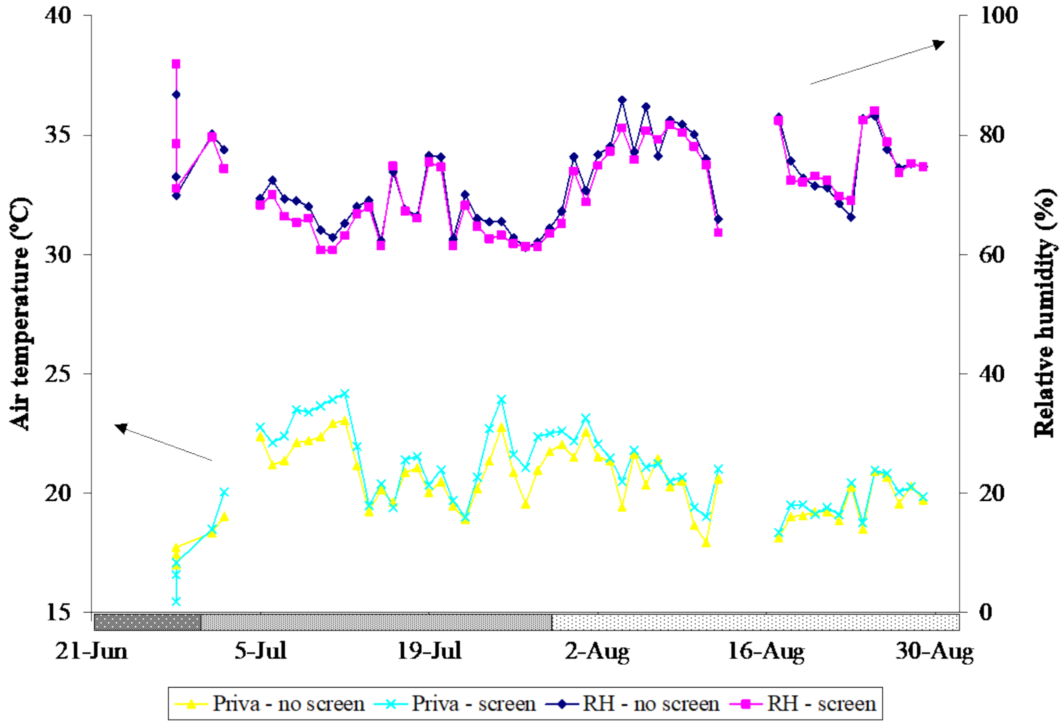


Figure 4. *Seasonal*: Daily mean air temperature and relative humidity. The hatching indicates the periods with different ventilation gaps in the screen.

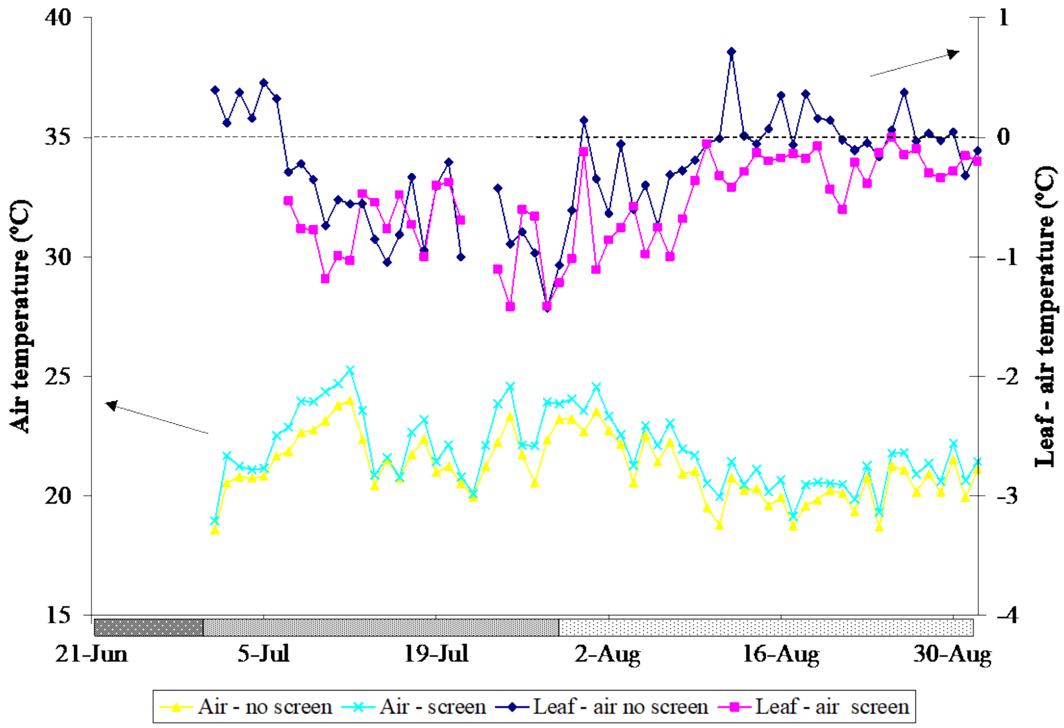


Figure 5. *Seasonal*: Daily mean leaf and air temperatures. The hatching indicates the periods with different ventilation gaps in the screen.

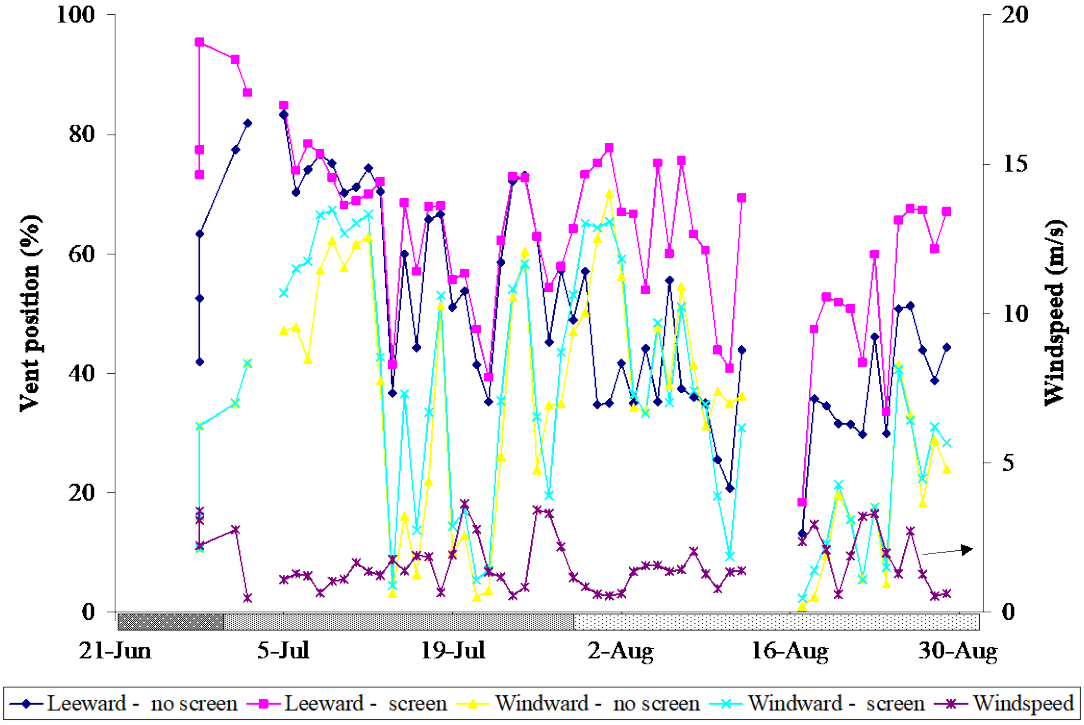


Figure 6. *Seasonal*: Daily mean vent position. The hatching indicates the periods with different ventilation gaps in the screen.

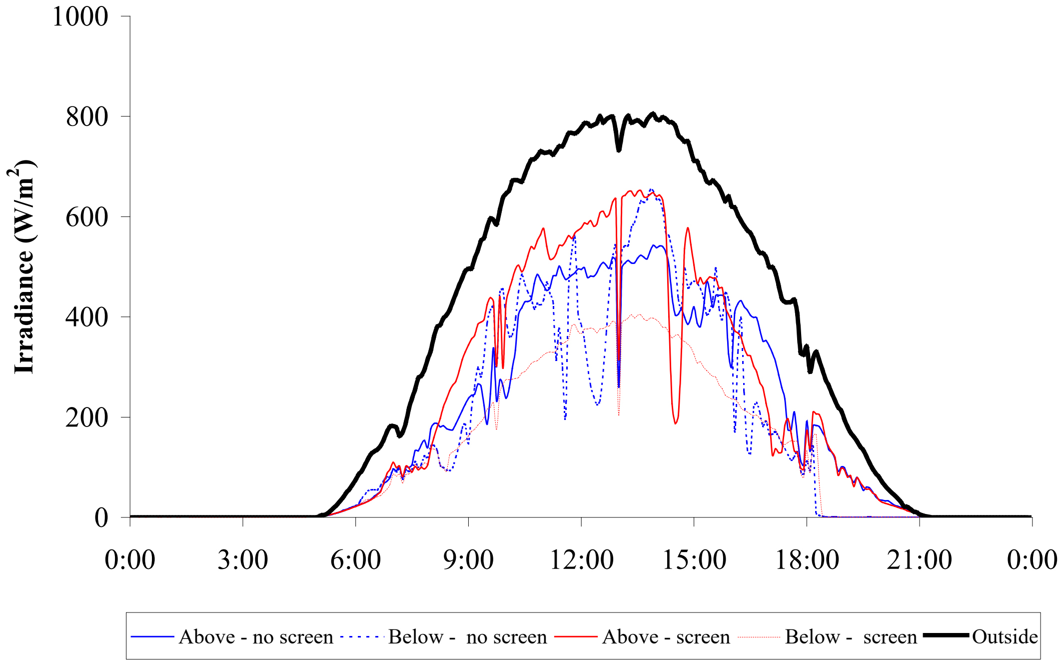


Figure 7. *12 July*: Irradiance.

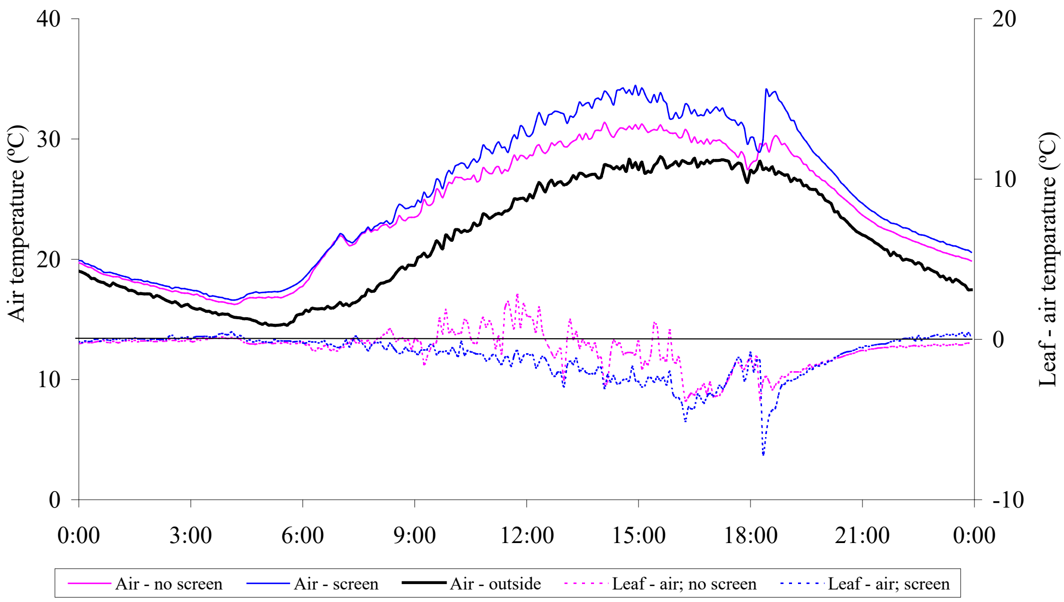


Figure 8. *12 July*: Air temperature and leaf (minus) air temperature.

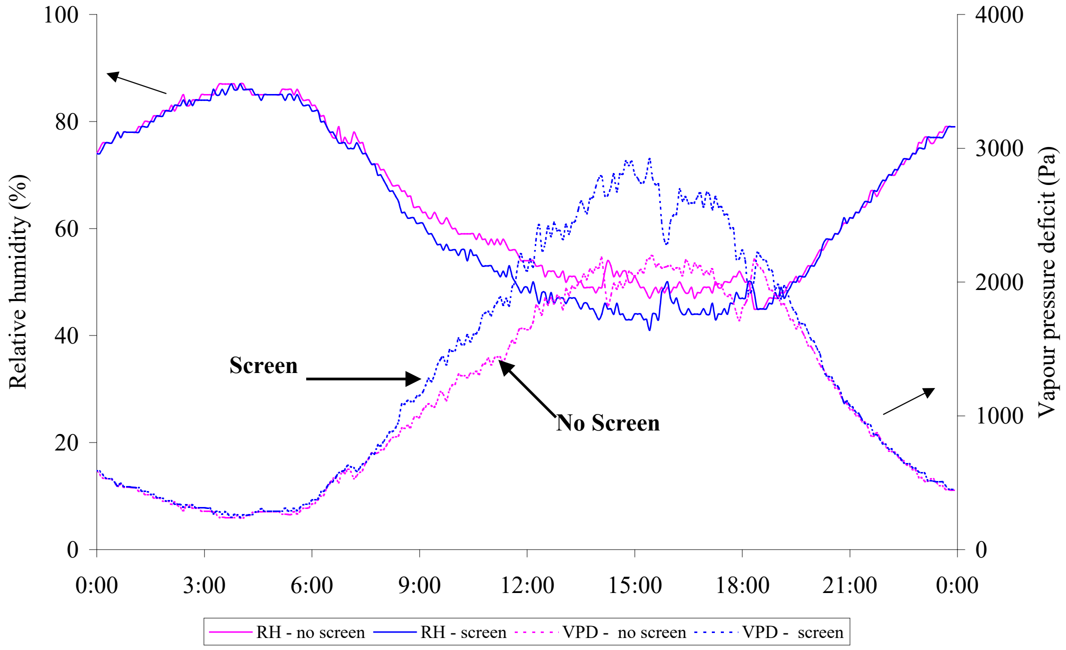
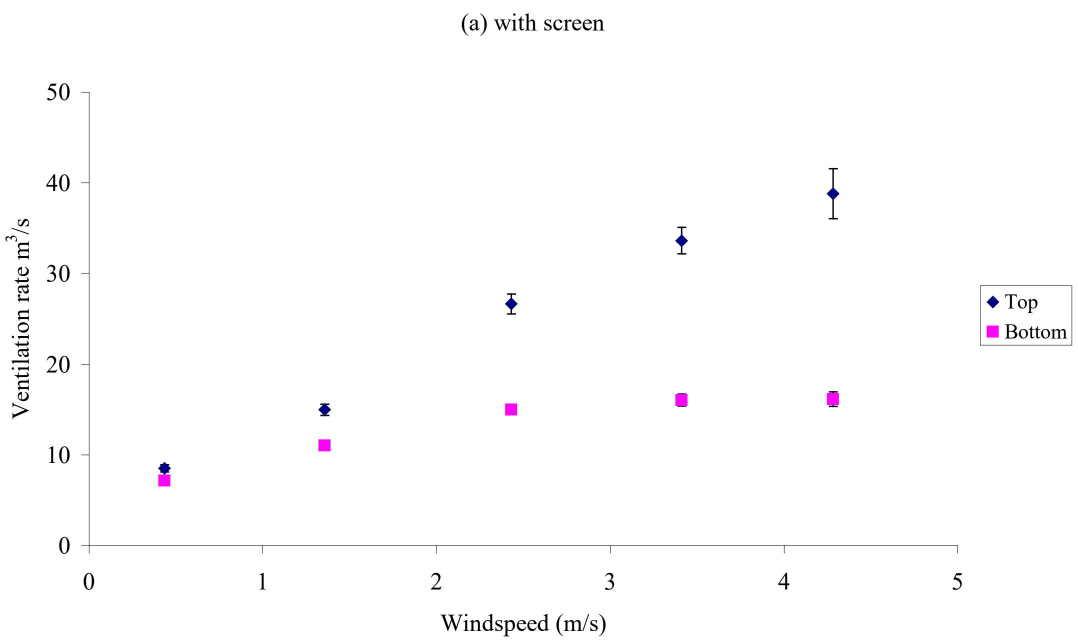


Figure 9. *12 July*: Relative humidity and vapour pressure deficit (VPD).



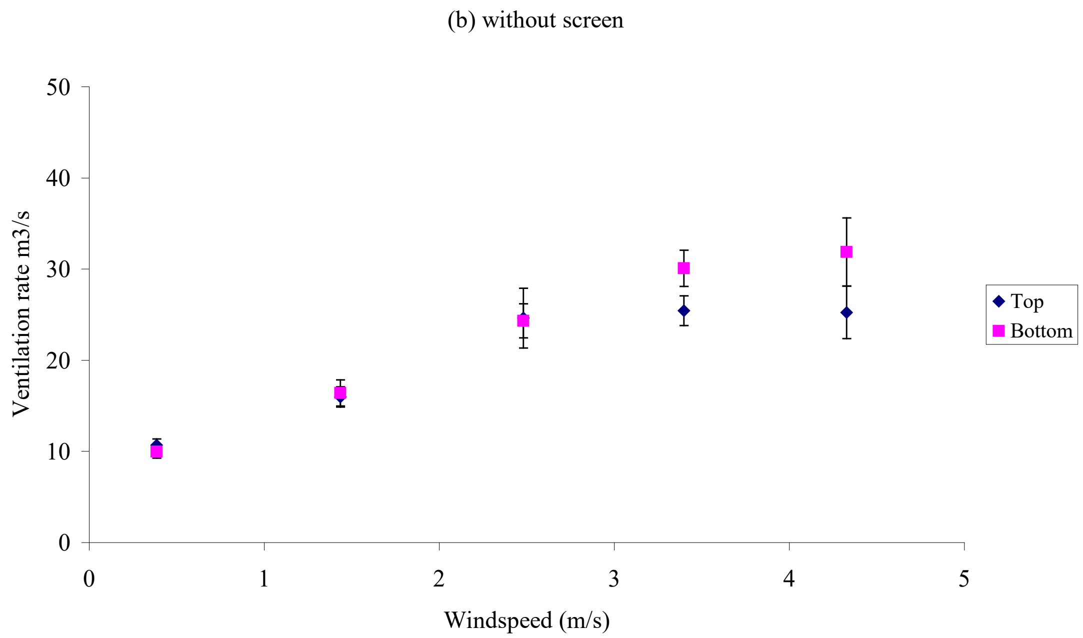


Figure 10. *Ventilation:* Ventilation rates in relation to windspeed (a) with the screen in place (with 37% ventilation gap) and (b) without the screen (in the 'parked' position). The error bars indicate 95% confidence level; top refers to ventilation rate from the space above the screen to the outside and bottom refers to ventilation rate from the space below the screen to the space above the screen.

5. REFERENCES

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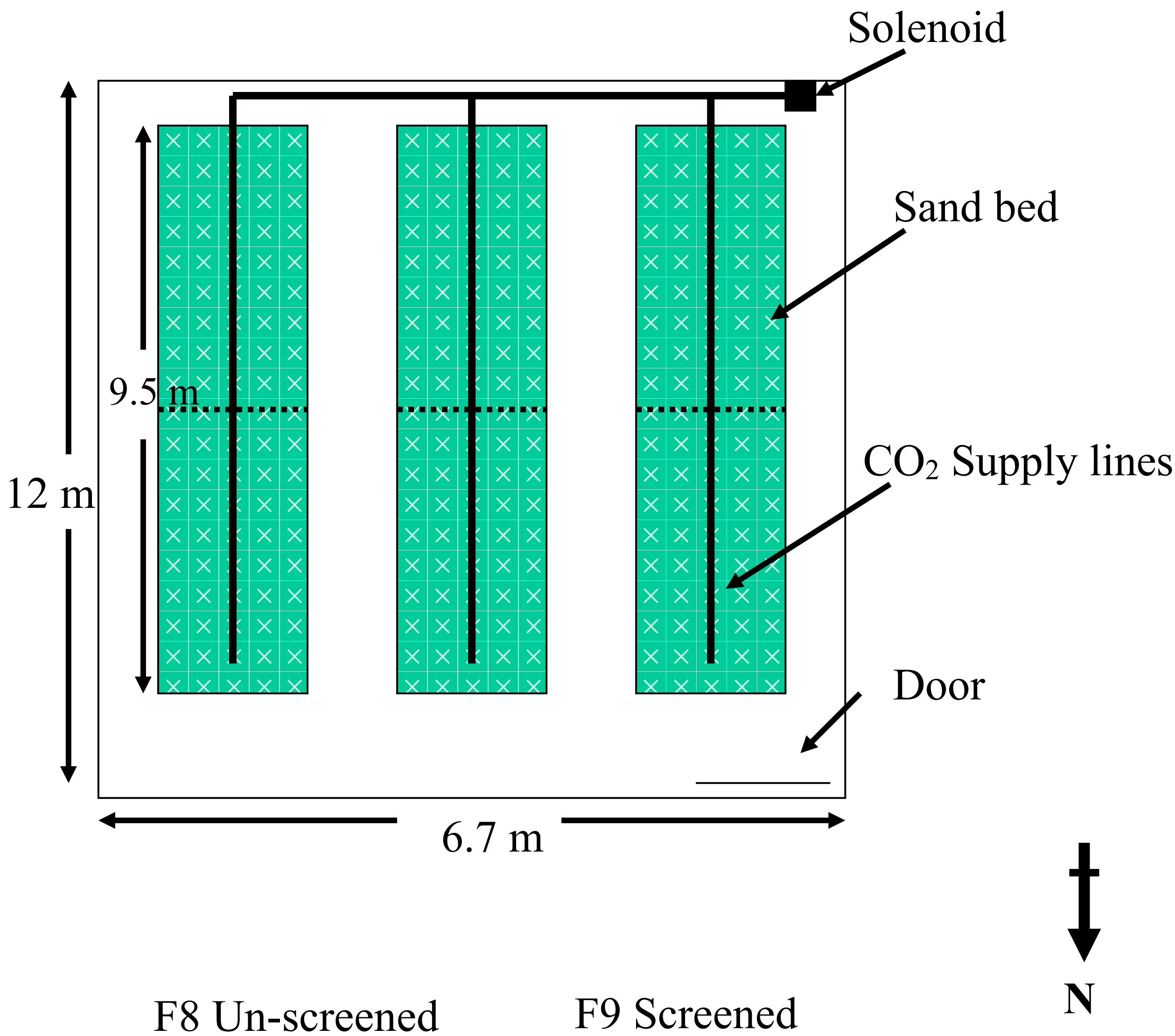
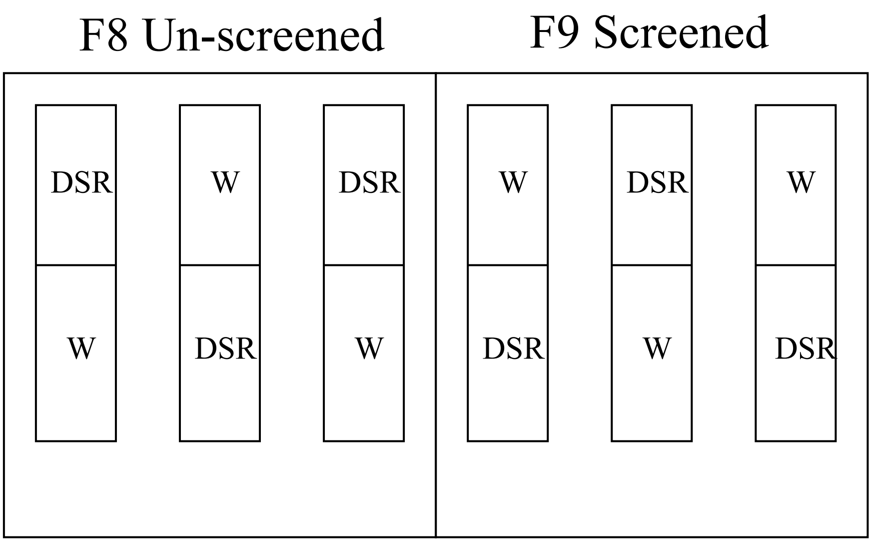
Appendix 1 – Plan view of (a) growing crop arrangement within experimental house F9 (Screened) and (b) layout of different variety treatments within both houses.

(a)



(b)



Codes: W = White Reagan
DSR = Dark Splendid Reagan

Appendix 2 – Composition and target nutrient levels of feed used for hydroponic growth of AYR chrysanthemum crop.

The feed was mixed separately in two feeds of A and B, which were then mixed in equal proportions a stock tank prior to feeding on the bed. The target pH and conductivity values (EC) were 6.7 and 1.5 µS respectively.

Feed composition per 100 litres of water		Target nutrient levels for dilute feed (mg/l)	
A Feed			
Calcium nitrate (NORSK)	2.5 kg	N	157
Potassium nitrate	3.3 kg	K	250
Fe EDTA (13% Fe)	340 g	Ca	120
B Feed		Mg	30
Potassium nitrate	3.3 kg	P	35
Potassium sulphate	1.0 kg	Fe	3
Magnesium sulphate	4.1 kg	Mn	1
Ammonium nitrate	420 g	Cu	0.1
Monopotassium phosphate	2.3 kg	B	0.3
Manganese sulphate	54 g	Mo	0.05
Copper sulphate	6 g		
Borax	31 g		
Ammonium molybdate	1.4 g		

Appendix 3 Colour plates of growing trial

Plate 1 – Internal view of F-Block compartment 9 (Screened house) with screen and side pelmets visible.

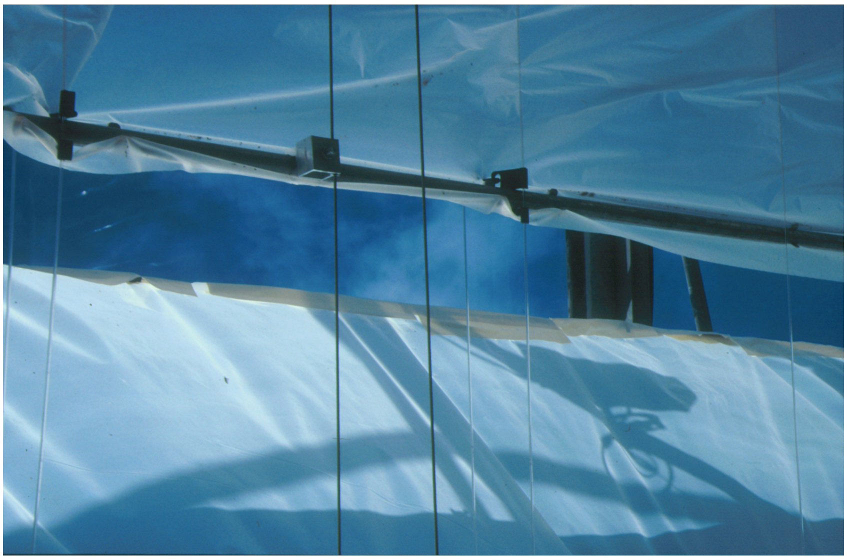


Plate 2 – Ventilation gap in Luminance screen at south end of compartment (F9).

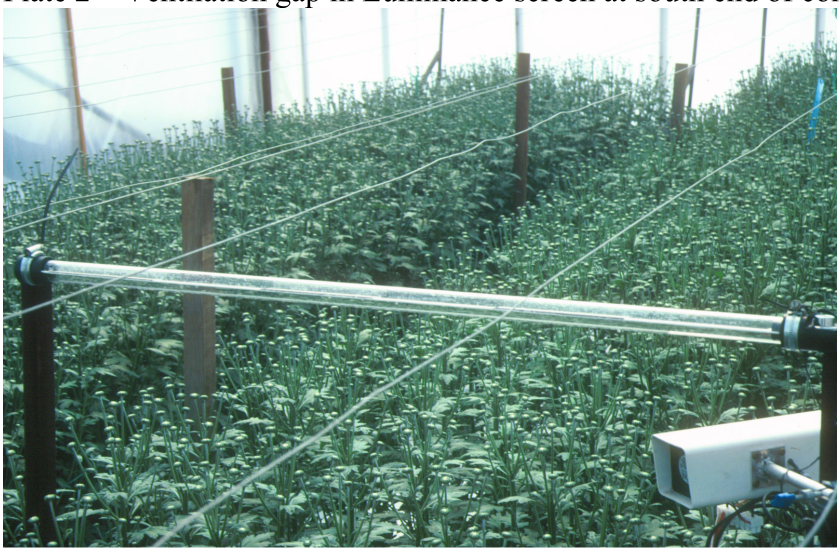


Plate 3 – Photograph of growing crop in screened house (F9) with tube solarimeter (clear glass pole) used to measure incident radiation below the screen clearly visible. The white box to the right of the picture is an aspirated screen used to sample air temperature and CO_2.