

**Project title:** Assessing the benefits of deleafing in peppers

**Project number:** PC 285

**Project leader:** Dr Steve Adams

**Report:** Annual; March 2009

**Previous reports:** None

**Key workers:** Warwick HRI:  
Dr Steve Adams – Project leader  
Dr Veronica Valdes – Photosynthesis measurements  
Angela Hambidge - Crop recording  
Jayne Akehurst – Crop recording

ADAS:  
Dr Tim O'Neill – Plant pathology

FEC Services:  
Jon Swain & Tim Pratt – Benchmarking of compartments

**Location:** Valley Grown Nurseries, Paynes Lane  
Nazeing, Essex, EN9 2EX

**Project co-ordinator:** Gary Taylor, Valley Grown Nurseries

**Start date:** 1 April 2008

**Completion date:** 31 March 2010

**Key words:** Sweet peppers, deleafing, water use, humidity, energy, yield, disease

**Signed on behalf of: Warwick HRI**

**Signature:** ..... **Date:** .....

**Name:** Professor Simon Bright  
Director and Head of Department

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The results and conclusions in this report are based on an investigation conducted over one year. The conditions under which the experiment was carried out and the results obtained 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 interpretation of the results especially if they are used as the basis for commercial product recommendations.

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## GROWER SUMMARY

### Headline

- Deleafed sweet peppers left with just 1.6 m of leaf at the top of the plants, had no detrimental affect on yield.
- Benefits of water ,energy use and disease will be examined in second year work.

### Background and expected deliverables

Sweet pepper crops are characterised by a large leaf area which increases continuously throughout the growing season. Towards the end of the season the leaf area can be 8 times that of the floor area. However, measurements of leaf photosynthesis in peppers carried out as part of PC 269 showed that lower leaves tended to be unresponsive. Many lower leaves were respiring more than they were photosynthesizing and appeared to be net sinks, rather than sources of assimilates. Hence there might not be a detrimental impact on yield if these leaves were removed.

Although there is interest in deleafing peppers in The Netherlands and Spain, to date there are few published trials. Dueck *et al.* (2006) examined leaf photosynthesis and transpiration at different heights in a sweet pepper canopy. In the period from August through to October it was estimated that the top 12.5% of the canopy was responsible for 89.9% of the photosynthesis but only 34% of the crop transpiration. The bottom 62.5% of the canopy was a net sink (-0.3% of photosynthesis) but predicted to be responsible for 37% of the transpiration.

Leaf removal may be a useful tool for improving water (and fertiliser) use efficiency in sweet peppers. There may also be implications for energy use as less heat will be needed to drive transpiration. However, a balance is required as the transpiration is beneficial for cooling in summer. Deleafing could reduce air humidity slightly which, given that around 20% of energy use in high wire crops is for humidity control, in turn may further reduce energy use.

There may also be advantages from deleafing in terms of reduced disease risk due to lower RH's, and the fact that lower stems should be cleaner and dryer following the removal of old leaf. However, there is also a potential risk that deleafing may increase stem fungal diseases due to the creation of an increased number of wound sites. The two fungi most commonly found causing stem lesions of pepper in the UK are *Fusarium* sp. and *Botrytis cinerea*. It seems unlikely that deleafing will greatly influence the microclimate around flowers and

developing fruit, but this cannot be excluded, and if so there may be an effect on Fusarium fruit rot, caused by *Fusarium* species.

The first year experiment (reported here) aims to explore how much leaf can be removed in sweet peppers without reducing light interception and yield. In the second year, a larger block will be deleafed in order to quantify the benefits in terms of water use, energy use and incidence of disease.

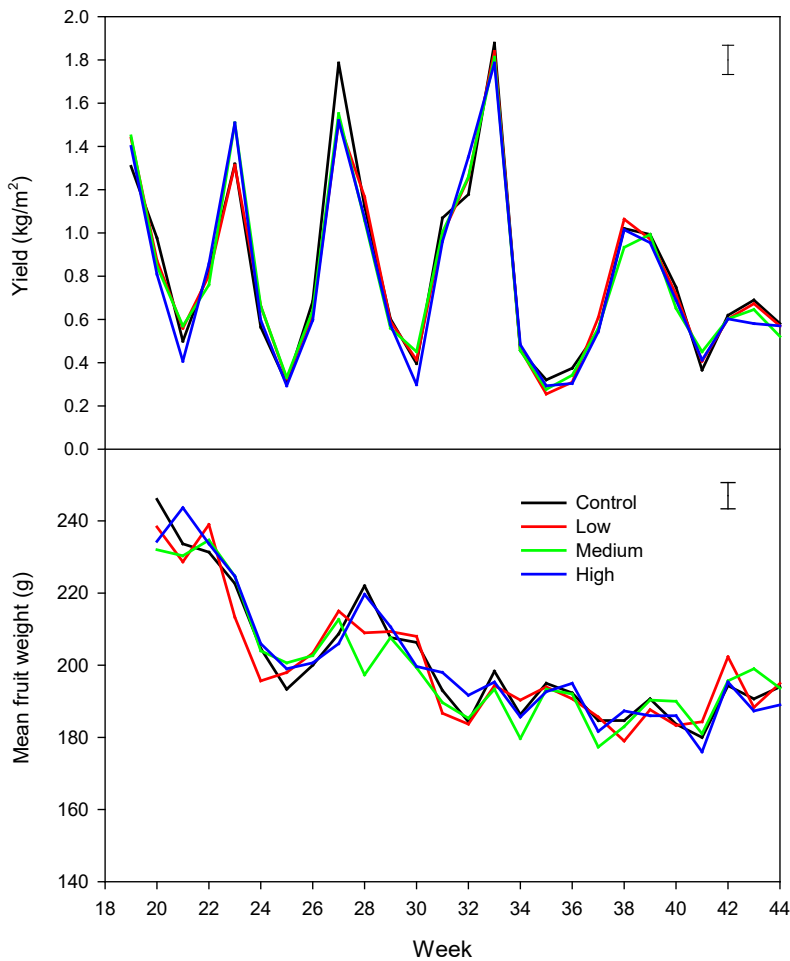
### **Summary of the project and main conclusions**

Four different deleafing treatments were applied to individual rows (three replicate rows per treatment) of peppers grown within a commercial block of cultivar Special at Valley Grown Nurseries, Essex. Treatments included a control (no leaf removal), and three levels of deleafing where either 1.6 m (high), 2.0 m (medium) or 2.4 m (low) of leaf was left on the top of each shoot (Figure 1). Deleafing commenced in May, July and August for the high, medium and low deleafing treatments, respectively, and plants were deleafed on a monthly basis thereafter.



**Figure 1.** Photograph of a high deleafed row (1.6 m of leaf) taken on 23 September 2008.

The total yield for each row was recorded separately to provide replication for statistical comparison. The mean cumulative yield at the end of the season was 21.7 kg/m<sup>2</sup> and there was no significant effect of the deleafing treatments. Similarly the treatments had little impact on the weekly pattern of yield (Figure 2). Average fruit weight was also unaffected.



**Figure 2.** Weekly yield and mean fruit size for four deleafing treatments. The bars represent pooled standard error of differences for comparison of two values in any given week.

Nursery staff kept crop records for 20 shoots per treatment. This included weekly growth (stem length), number of flowers, number of fruits set, and the number of fruits cut. There were no significant differences in the total number of flowers and fruits (set and cut), and there was little impact on the weekly patterns.

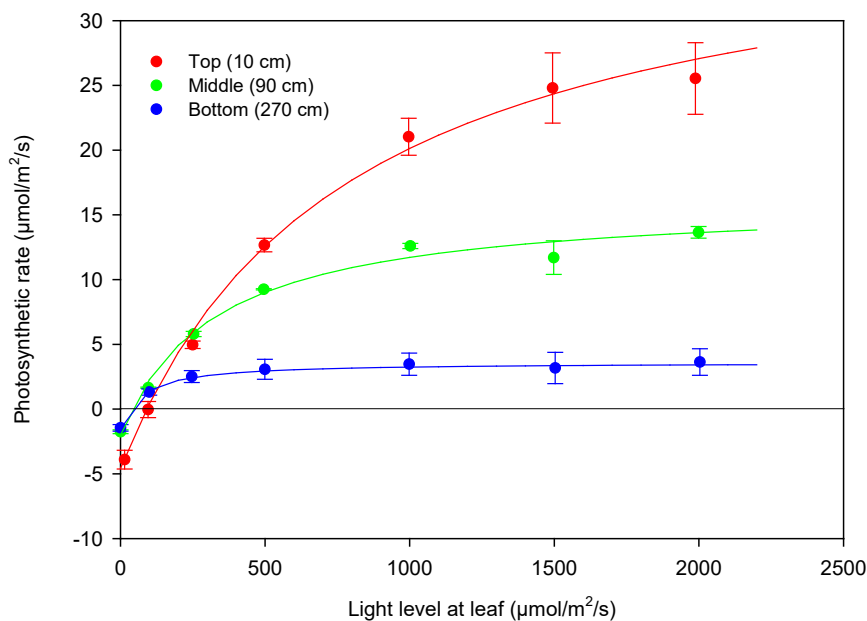
Disease monitoring was carried out to assess whether leaf removal affected the incidence of stem diseases or fruit rot. The crop was examined for disease on three occasions. No stem lesions were observed on 13 May or 17 July. On 9 October, four stem lesions were found, two in the high deleafing treatment and two in the medium deleafing treatment. *Fusarium* sp. was recovered from two of the stem lesions; no *Botrytis cinerea* was observed on or isolated from these stem lesions. These very low values indicate that deleafing pepper cv. Special does not result in production of wound sites on stems that are highly susceptible to *Fusarium* sp. or *B. cinerea*.

On 9 October, 50 visibly healthy class II fruit were collected from each treatment and examined in the laboratory the following day. *Fusarium* sp. was found within a proportion of

fruit from all treatments; however, infection did not differ significantly between treatments, and there was no trend in the level of *Fusarium* infection associated with the degree of deleafing.

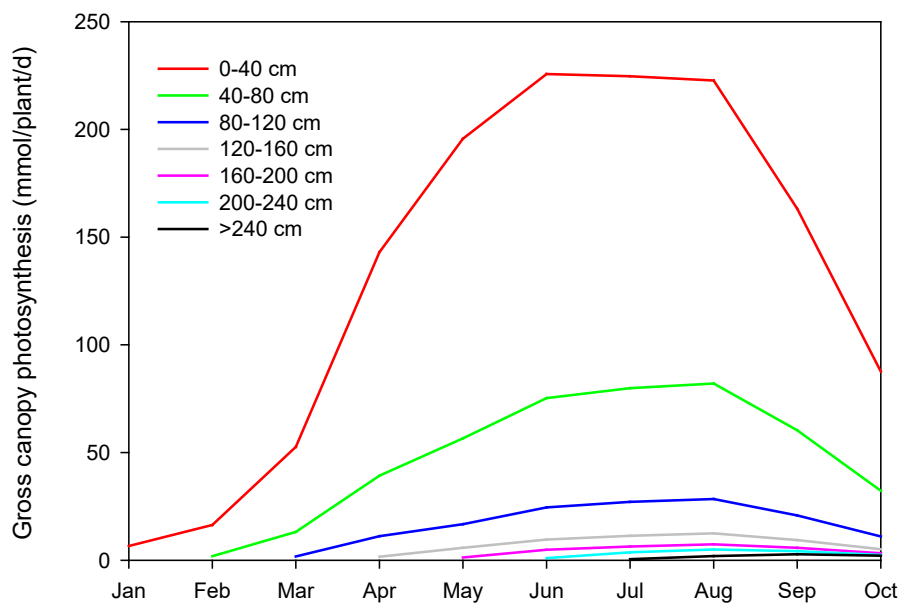
To gain a better understanding as to which leaves were working the hardest, we also measured leaf photosynthesis at different heights and light levels. These data were then used to develop a simple model of canopy photosynthesis. Firstly we needed to predict how much light would be available in the canopy. To do this we repeatedly measured the amount of light in the canopy at different heights expressed as a proportion of that above the crop. This fell sharply with height; half of the light was typically intercepted within the top 25 cm of canopy, and by 1 m from the top, light levels were around 6% of those above the canopy. Nevertheless even at the bottom of the canopy there was a small amount of light available, due to the pathways.

We then assessed how efficient the leaves were in terms of their ability to photosynthesize. For a given height and light level, photosynthesis remained more or less the same throughout the year. The big difference was with the height of the leaf from the top of the canopy (Figure 3). When photosynthesis was examined in relation to light level, the initial slope (light utilisation efficiency) was unaffected by leaf height. However, the amount of photosynthesis at high light levels (determined by the leaf conductance to CO<sub>2</sub>) decreased considerably with leaf height.



**Figure 3.** The effect of height on photosynthetic efficiency. Top represents the average of 3 leaves measured on 22 May. Middle represents 2 leaves on 22 May, and bottom represents the mean of 7 leaves recorded on 22 October.

Finally we needed to multiply the predicted photosynthesis per square meter of leaf by leaf area to estimate canopy photosynthesis. To do this we measured the length and breadth of leaves at different heights regularly throughout the experiment. We then used these measurements to estimate the change in leaf area over time based on a calibration curve. As a result of this exercise we predicted the photosynthesis for various heights in the canopy (see Figure 4). Our simulations suggest that the top 40 cm usually accounts for over half of the gross canopy photosynthesis, and that the top 160 cm accounts for over 95% of the gross photosynthesis. Given that some assimilates will be used to maintain leaves, it is therefore not surprising that leaf areas can be dramatically reduced without reducing yield, supporting the results from the trial.



**Figure 4.** Predicted gross canopy photosynthesis for different crop layers. Heights are expressed as cm from the top of the canopy.

### Financial benefits

- We anticipate that there should be benefits in terms of water use, energy use and possibly disease. These benefits will be quantified in the second year.

### Action points for growers

- It would appear to be safe to deleaf peppers providing that at least 1.6 m of leaf is retained, although it might be beneficial to leave slightly more leaf in summer than at other times of the year.
- Clear recommendations can not be made until the second year's work is completed.



## SCIENCE SECTION

### Introduction

Sweet pepper crops are characterised by a large leaf area which increases continuously throughout the growing season. Towards the end of the season the leaf area can be 8 times that of the floor area. However, measurements of leaf photosynthesis in peppers carried out as part of PC 269 showed that lower leaves tended to be unresponsive. Many lower leaves were respiring more than they were photosynthesizing and appeared to be net sinks, rather than sources of assimilates. Hence there might not be a detrimental impact on yield if these leaves were removed.

Deleafing is used in tomato crops and Adams *et al.* (2002) found that despite having about 50% of the leaf area, highly defoliated rows (leaving 16 leaves >10cm long) produced the same yield as low defoliation (28 leaves remaining). While Slack (1986) found that leaf removal to the level of two trusses above the ripening truss significantly reduced fruit yields, Cooper *et al.* (1964) showed no significant loss of yield when leaves were removed up to three trusses above the picking truss. Similarly other workers have shown that around 50% of the older leaves can be removed in tomato without any loss in yield (Jones, 1979; Stacey, 1983; Wolk *et al.*, 1983). Adams *et al.* (2002) showed that although lower leaves had a reduced photosynthetic capacity, the main reason for the lack of photosynthesis was because the lower leaves of tomato are exposed to small amounts of light. Acock *et al.* (1978) found that the uppermost third of a tomato canopy, which accounted for 23% of the total leaf area, assimilated 66% of the net CO<sub>2</sub> fixed by the canopy. In cucumber it appears that although older leaves do not contribute as photosynthetic organs, they do act as sources of mobile elements that can be exploited by younger, well-lit leaves (Hopkinson, 1966). Consequently, removing these leaves can affect dry matter accumulation. This appears not to be the case in tomato, but there is no data to suggest whether this is the case in sweet peppers.

We are aware that there is some interest in defoliation peppers in The Netherlands and Spain, although there are few published trials. Dueck *et al.* (2006) examined leaf photosynthesis and transpiration at different heights in a sweet pepper canopy. In the period from August through to October it was estimated that the top 12.5% of the canopy was responsible for 89.9% of the photosynthesis but only 34% of the crop transpiration. The bottom 62.5% of the canopy was a net sink (-0.3% of photosynthesis) but responsible for 37% of the transpiration. A study by Bhatt and Srinivasa Rao (1993), where young pepper plants grown in pots were defoliated, suggested that plants had the ability to compensate for

defoliation by increasing the photosynthetic efficiency of the remaining leaves. As a result plants with up to 50% defoliation had a higher total dry matter and leaf area at the end of the experiment when compared with the non-defoliated controls. Defoliation caused no significant difference in the fresh and dry weight of fruits. Therefore, clearly there is potential to reduce leaf area in pepper without sacrificing yield.

Despite the fact that lower leaves may not make a positive contribution to net canopy photosynthesis they still transpire. Adams *et al.* (2002) demonstrated that higher deleafing reduced the water uptake of tomatoes. Leaf removal may be a useful tool for improving water (and fertiliser) use efficiency in sweet peppers. There may also be implications for energy use as less heat will be needed to drive transpiration. However, a balance is required as the transpiration is beneficial for cooling in summer. Deleafing could reduce air humidity slightly which, given that around 20% of energy use in high wire crops is for humidity control, in turn may further reduce energy use.

There may also be advantages from deleafing in terms of reduced disease risk due to lower RH's, and the fact that lower stems should be cleaner and dryer following the removal of old leaf. However, there is also a risk that deleafing may increase stem fungal diseases due to the creation of an increased number of wound sites. The two fungi most commonly found causing stem lesions of pepper in the UK are *Fusarium* sp. and *Botrytis cinerea*. It seems unlikely that deleafing will greatly influence the microclimate around flowers and developing fruit, but this cannot be excluded, and if so there may be an effect on *Fusarium* fruit rot, caused by *Fusarium* species.

The first year experiment (reported here) aims to explore how much leaf can be removed in sweet peppers without reducing light interception and yield. In the second year, a larger block will be deleafed so as to enable the benefits in terms of water use, energy use and incidence of disease to be quantified.

## **Materials and methods**

### Crop trial at VGN

Four different deleafing treatments were applied to individual rows (three replicate rows per treatment, each comprising 225 plants, each with two shoots) of peppers grown within a commercial block of cultivar Special at Valley Grown Nurseries, Essex (block 3). Treatments included a control (no leaf removal), and three levels of deleafing where either 1.6 m (high), 2.0 m (medium) or 2.4 m (low) of leaf was left on the top of each shoot. Details of the

experimental layout can be seen in Appendix 1. Deleafing commenced in May, July and August for the high, medium and low deleafing treatments, respectively, and plants were deleafed on a monthly basis thereafter.

The total yield for each row was recorded separately so as to provide replication for statistical comparison. For each row the average fruit weight was also recorded. Furthermore, nursery staff kept crop records for 20 shoots per treatment (from 1 row per treatment). This included weekly growth (stem length), number of flowers, number of fruits set, and the number of fruits cuts.

No fungicides were applied to the crop for control of stem or fruit diseases.

#### Disease monitoring

Disease monitoring was carried out to assess whether leaf removal affected the incidence of stem diseases or fruit rot. The crop was examined for disease on 13 May, 17 July and 9 October 2008. All of the experimental rows were walked and examined for stem disease and external fruit rot. At the final visit 50 visibly healthy class II fruit were collected from each treatment and examined in the laboratory the following day for visible *Fusarium* sp. sporulation within them. Standard errors (SE) of the proportion of fruit infected were calculated using the formula for binomial data:

$$SE = \sqrt{p \times q/n} \quad (\text{eqn. 1})$$

where  $p$  = % fruit with *Fusarium*,  $q$  =  $100-p$  and  $n$  = total number of pepper fruit examined. The 95% confidence limits were calculated as  $p \pm (1.96 \times SE) + 50/n$ .

#### Modelling crop photosynthesis

In order to develop a simple canopy photosynthesis model for optimising deleafing strategy, additional plant growth and leaf photosynthesis measurements were carried out by staff from Warwick HRI. This involved estimating the increase in leaf area over time. This was done by counting the number of leaves and measuring leaf length and breadth at different times and estimating canopy area based on a calibration curve produced from leaves measured on a Delta T leaf area meter. The leaf number in control rows was counted on eight occasions, between April and October. Between eight and thirteen randomly selected shoots were used for these measurements, except in April when only two shoots were recorded. Leaf length and breadth of every 3 to 5 leaves was also measured in May, August and October, on ten, two and eight shoots, respectively. Plant height and length of stem with leaves left on were also measured for ten shoots of each row at the end of the season.

Light penetration in the canopy was measured using two ceptometers, which integrate the output from an array of light sensors. One ceptometer was positioned at the top of the canopy. The other ceptometer was used to measure the light at a range of heights and this was related to the incoming light at the top of the canopy. These measurements were done on five occasions between the end of April and beginning of October, at different times of the day.

Leaf photosynthesis and transpiration was measured using portable infra-red gas analysers (CIRAS-1). The relationship between light and leaf photosynthesis was investigated (light response curve) by exposing leaves at different heights to a range of light levels (0 to 2000  $\mu\text{mol}/\text{m}^2/\text{s}$ ), starting with high light levels to encourage stomatal opening. For the same reason bottom leaves were lit for at least 20 min with light levels of over 1000  $\mu\text{mol}/\text{m}^2/\text{s}$  before taking measurements; however, on many occasions the stomata on the bottom leaves did not open sufficiently, limiting photosynthesis at these light levels (ideally stomatal conductance would have been greater than 250  $\text{mmol}/\text{m}^2/\text{s}$  as found in PC 269).  $\text{CO}_2$  concentrations in the chamber were controlled so as to avoid fluctuations caused by  $\text{CO}_2$  dosing in the glasshouse. The mean  $\text{CO}_2$  concentration in the chamber was 526 ppm (with a standard deviation 12 ppm). The temperature was ambient, and humidity was set to 70% of ambient. Some measurements were also taken under ambient light conditions at different heights in the canopy.

To gain an indication of the effect of the treatments on transpiration and water uptake, sap flow was measured using a heat balance method with commercially available gauges (SGA10, SGA13, SGB13 Dynamax Inc.) on two occasions between September and October. Four sensors were placed on four control shoots and four sensors on four high deleaf shoots; all shoots were facing east during the first period and west during the second period. The sensors were attached to the bottom of the shoots, usually just above the V. Sensors were positioned on sections of stem that were relatively straight and cylindrical. Although it is recommended by the manufacturers, no insulating compound (silicon grease) was applied to the area of the stem to be covered by the gauge as it was found that on pepper (PC 269) this encourages infection with *Fusarium oxysporum*, presumably due to reduced gas exchange. The outputs from these gauges were scanned every 60 seconds and the mean value was logged every 30 minutes using a Campbell CR 10X datalogger and an AM416 multiplexer. The sheath conductance (Ksh), which was needed for sap flow calculations, was estimated by looking at minimum values at night.

## Results

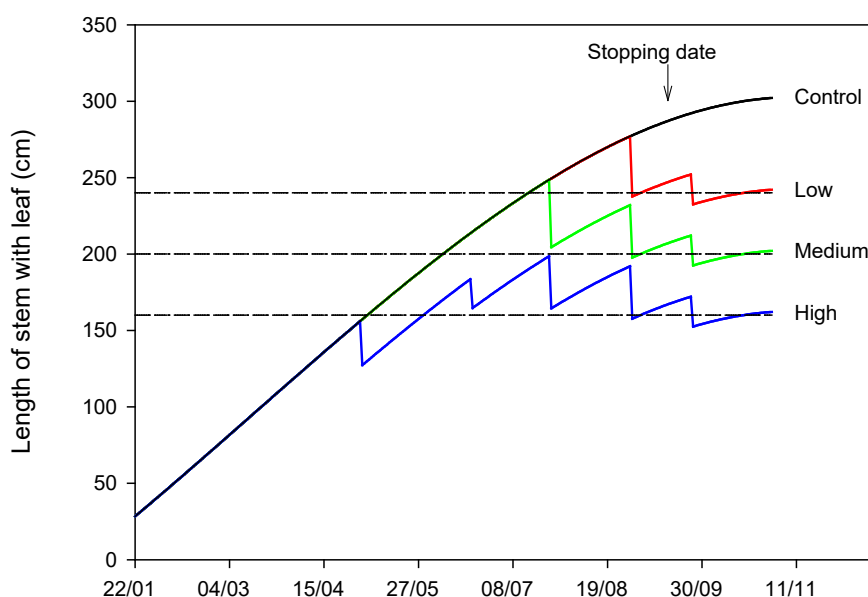
### Crop trial at VGN

#### *Effect of the treatments on the amount of leaf*

The amount of leaf that was removed from each of the treatments can be seen in Table 1 and this is expressed graphically in Figure 1. While no leaf was initially removed from the control rows, the bottom 20 cm or so had senesced and fallen off naturally by the end of the season. Given that the plants eventually reached almost 3 m, in the highest deleafing treatment (1.6 m of leaf) almost half of the stem was bare at the end of the season.

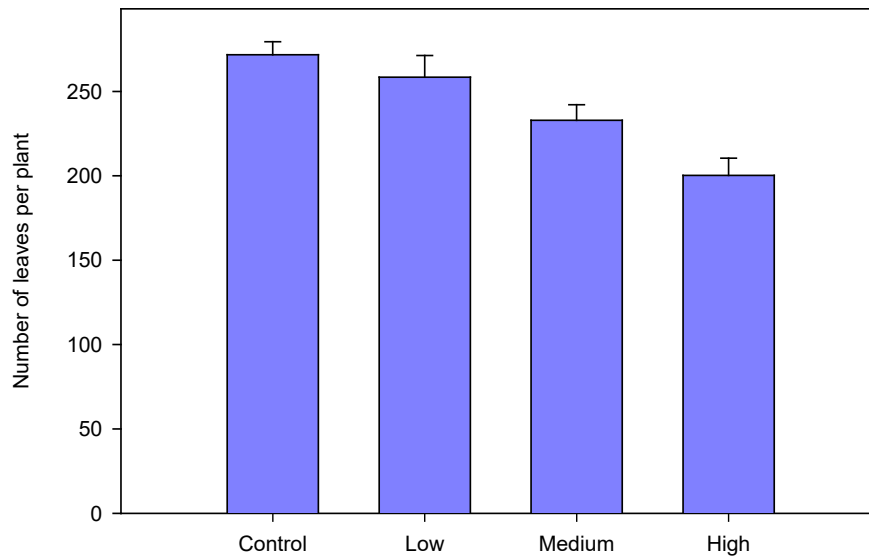
**Table 1:** *The amount of leaf removed over the course of the experiment. The values represent the length of stem that was deleafed on each occasion*

	2 May	20 June	25 July	30 Aug	26 Sept
High	30 cm	20 cm	35 cm	35 cm	20 cm
Medium	-	-	45 cm	35 cm	20 cm
Low	-	-	-	40 cm	20 cm
Control	-	-	-	-	-



**Figure 1:** *Increase in plant height over time and the amount of the stem with leaves*  
While the highest deleafing treatment involved removing a considerable amount of leaf, the reduction in terms of the percentage of leaves that were removed was less extreme (Figure

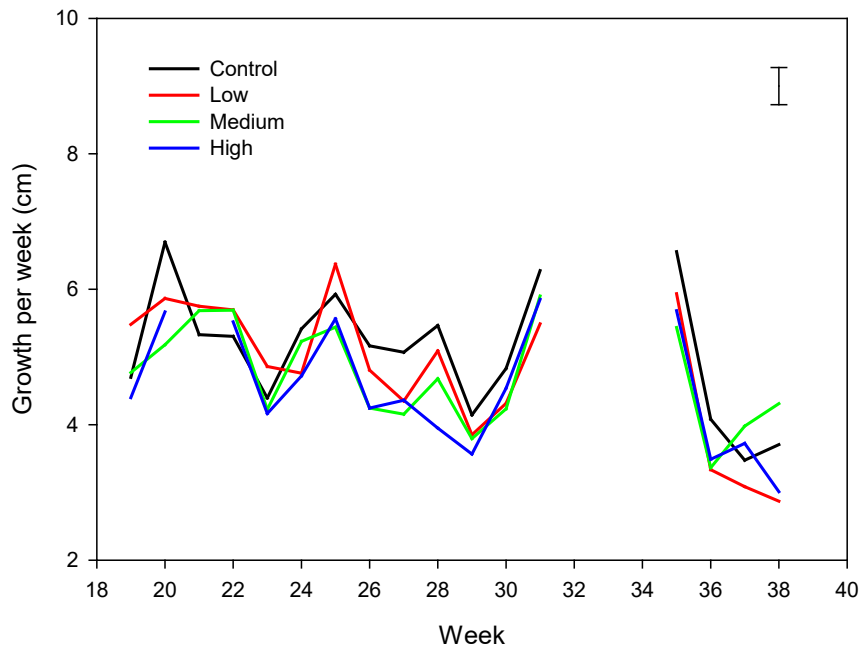
2). This was due to all treatments having more side shoots in the upper canopy, and as a result the high deleafing treatment only reduced the leaf number by 26%.



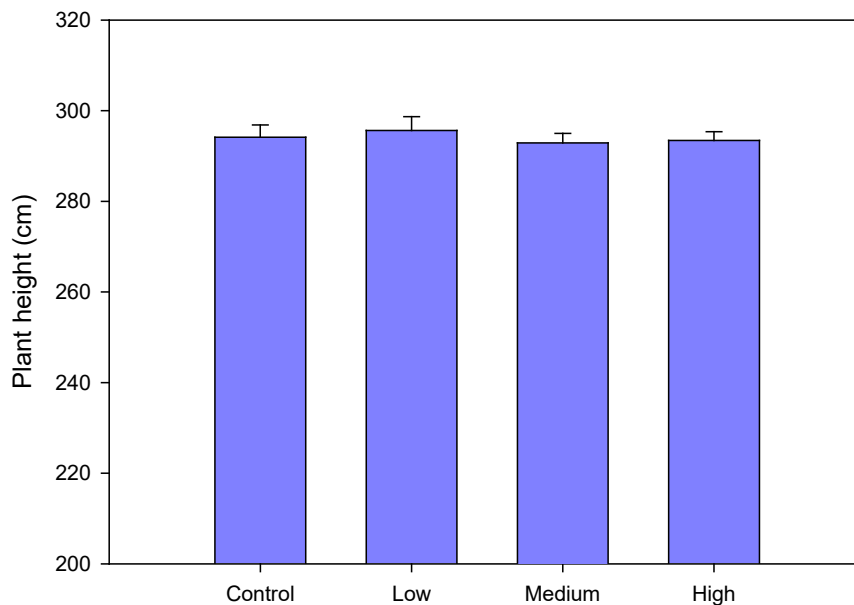
**Figure 2:** The total number of leaves (> 1 cm in length) on plants from each deleafing treatment on 22 October. Each column is the mean of 30 shoots (10 per row) and the error bars represent the standard error of the mean

#### *Crop recording data*

Weekly plant growth (increase in height) was similar in the four deleafing treatments (Figure 3). The differences between treatments were only significant in weeks 28 and 38 ( $P < 0.05$ ), and there were no consistent trends. The crop recording data indicated significant differences in the final height, with the control plants being the tallest and the medium deleafing being the shortest. However, there were marked differences in height at the beginning of the season, before the deleafing treatments were applied, suggesting that this might have been due to the plants that were selected for recording. To confirm this, 10 shoots from each row were recorded on 22 October and no significant differences in height were found ( $P > 0.05$ ). The average height at this time was 294 cm (Figure 4).



**Figure 3:** Weekly crop growth (increase in height) recorded over time for 20 shoots in one row



**Figure 4:** The height of plants recorded on 22 October. Each column is the mean of 30 shoots (10 per row) and the error bars represent the standard error of the mean

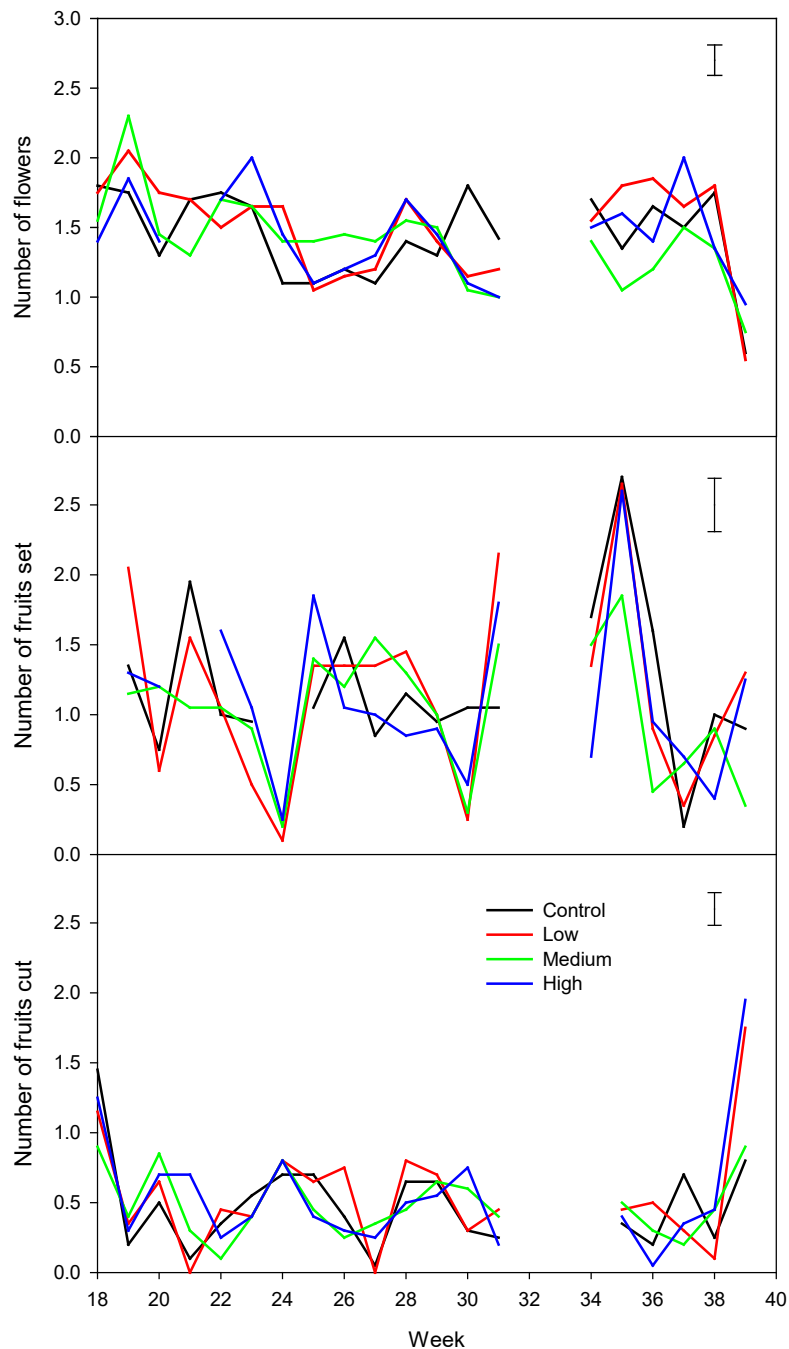
Similarly no significant differences were found between the treatments for the average number of flowers and fruits set per week (Table 2). Furthermore, there was no effect on the total number of fruits cut by the end of the growing season ( $P > 0.05$ ). For most weeks the

number of flowers, fruits set and fruits cut were very similar for the different treatments (Figure 5). There were a few weeks when there were significant differences, but no consistent pattern was found between the treatments.

**Table 2:** *The effect of deleafing treatment on flower numbers and the number of fruits set and cut per shoot*

<b>Deleafing treatment</b>	<b>Average no. of flowers/week</b>	<b>Average no. of fruits set/week</b>	<b>Total no. of fruits cuts</b>
Control	1.4	1.2	12.6
Low	1.5	1.2	13.0
Medium	1.4	1.0	11.9
High	1.4	1.1	13.1
Significance	N/S	N/S	N/S





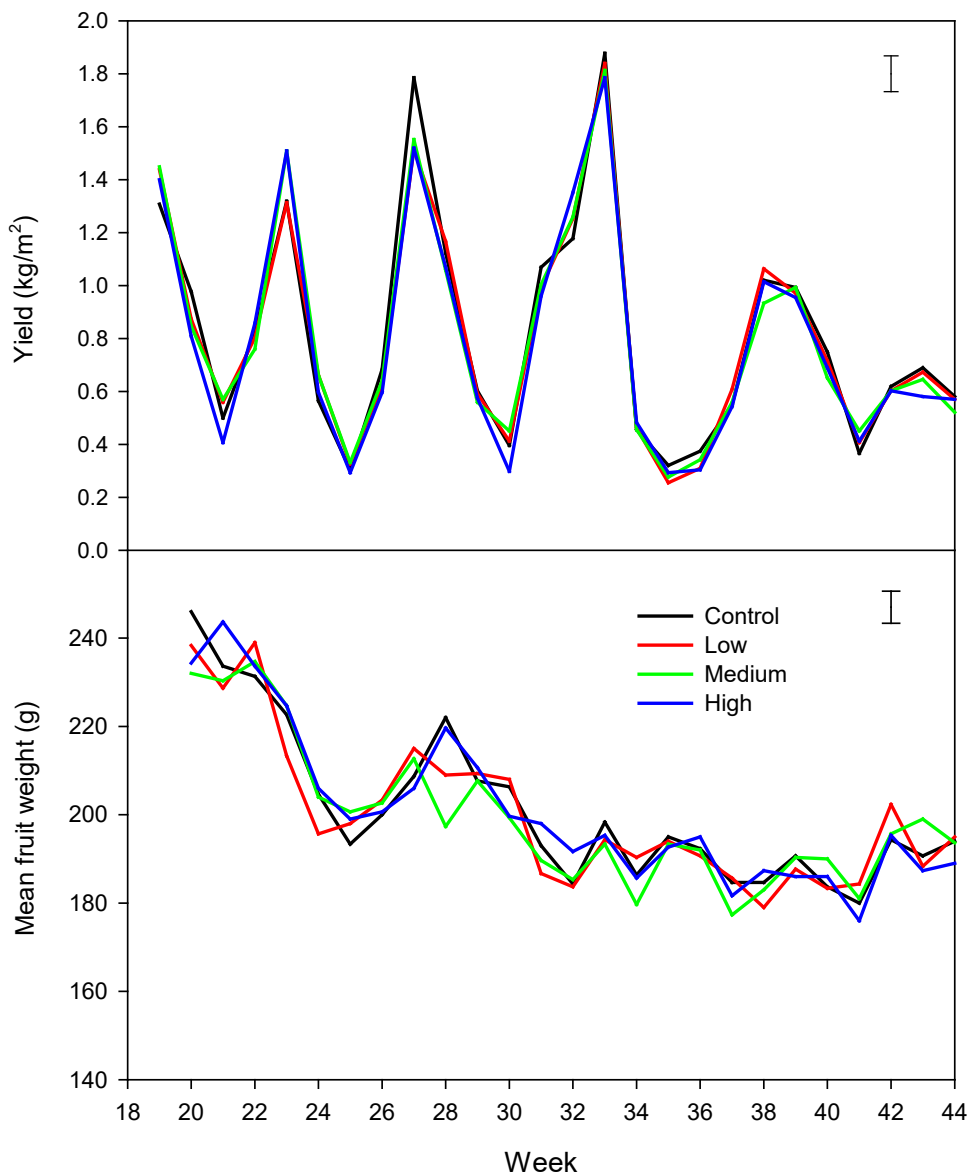
**Figure 5:** The number of flowers, fruits set and fruits cut per week. Data are the average for 20 shoots per treatment and the bars represent a pooled standard error of difference for comparing two means in any given week

#### Weekly yield and fruit size

The weekly yield was recorded for each of the experimental rows so as to enable the data to be analysed using ANOVA. The mean cumulative yield at the end of the season was 21.7 kg/m<sup>2</sup> and there was no significant effect of the deleafing treatments ( $P > 0.05$ ). While the high deleafing treatment had the lowest yield, this was due to a low yield in one particular

row, and did not appear to be a consequence of the treatment. Similarly there was no significant effect of deleafing treatments on the mean fruit size for the year; the average fruit size was 200.5 g.

The weekly yields and mean fruit sizes are shown in Figure 6. The treatments had little impact on either the pattern of yield or pattern of fruit size. The differences between the treatments were rarely significant when analysed one week at a time. There were odd exceptions, such as the mean fruit size in week 28, where the control and medium deleafing treatments had significantly larger fruits ( $P < 0.05$ ) than the low deleafing treatment, however, such differences were infrequent and there was no consistent trend.



**Figure 6:** The effect of deleafing treatment on the weekly yield and mean fruit size. The bars represent pooled standard error of differences for comparison of two values in any given week

## Disease monitoring

### *Stem lesions*

No stem lesions were observed on 13 May or 17 July. On 9 October, four stem lesions were found, two in a high deleafing treatment and two in a medium deleafing treatment. None were found in the other treatments (Table 3). Two of the four affected plants were wilting badly.

**Table 3:** *Effect of deleafing on occurrence of stem lesions and fusarium internal fruit rot in pepper – 9 October 2008*

<b>Deleafing treatment</b>	<b>Mean no. of nodes deleafed/stem</b>	<b>Total no. of stem lesions (on 1,350 stems)</b>	<b>Mean % fruit infected internally by Fusarium (95% confidence limits)</b>	
Control	0	0	20.5	(7.5-33.4)
Low	10.0	0	8.9	(0-18.4)
Medium	13.8	2	24.0	(11.2-36.8)
High	20.8	2	18.4	(6.6-30.2)

*Fusarium* sp. was recovered from two of the stem lesions; no *Botrytis cinerea* was observed on or isolated from these stem lesions. This result is consistent with previous work on the nursery where a *Fusarium* sp. was isolated from some but not all stem lesions.

The stem lesions all occurred on deleafed areas of stem and appeared to originate at nodes around 1.5 – 2.0 m above the stem base. It was not possible to determine whether infection originated at deleafing or side-shoot wounds. The mean number of deleafed nodes in the four treatments at this time (average of five plants) were 0, 10, 13.8 and 20.8 respectively. The proportion of stems affected by stem lesions in the medium and high deleafing treatments was 0.15%; the proportion of deleafed nodes affected was less than 0.01%. These very low values indicate that deleafing pepper cv. Special does not result in production of wound sites on stems that are highly susceptible to *Fusarium* sp. or *B. cinerea*.

Given the very low incidence of stem lesions, it is not possible to draw any conclusions as to the effect of deleafing on occurrence of stem lesions. In previous disease monitoring on the nursery, *Fusarium* stem lesions have been found at nodes of non-deleafed plants (wound sites are regularly created on the stem of non-deleafed plants by removal of side-shoots).

### *Internal fruit rot*

No external fruit rot was observed when plants were examined in May, July and October. *Fusarium* sp. was found within a proportion of fruit from all treatments (Table 3). The incidence of *Fusarium* infection did not differ significantly between treatments, and there was no trend in the level of *Fusarium* infection associated with the degree of deleafing.

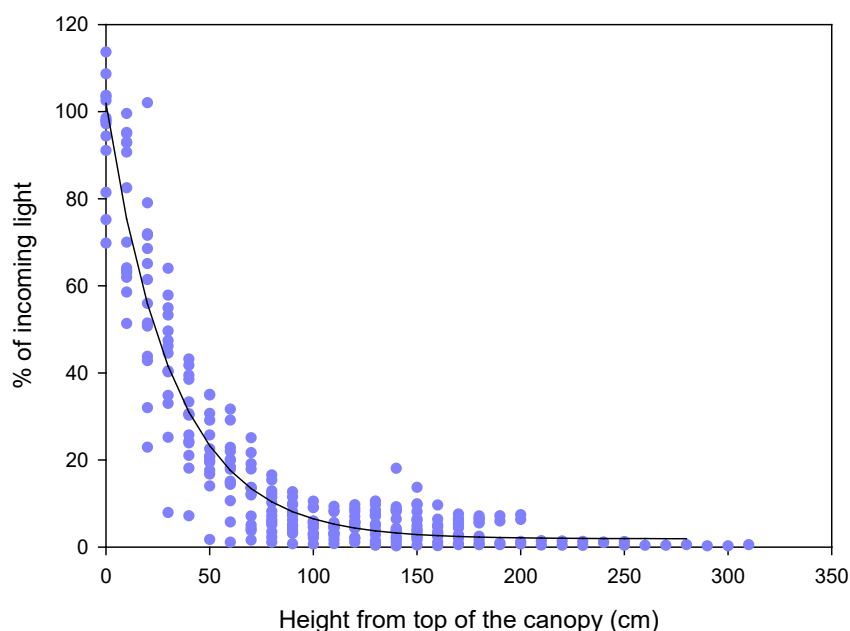
Within fruit, *Fusarium* sp. was predominantly found on seeds (55% of total occurrences), the side wall (25%) and at the flower end (18%); it was rarely found at the stalk end (2%). The *Fusarium* sp. recovered from within fruit was peach-coloured in culture and appeared identical to that isolated from stem lesions.

### Modelling crop photosynthesis

There were a number of discrete steps required to develop a canopy photosynthesis model. The light levels available in the canopy had to be measured and modelled, as did the photosynthetic efficiency of the leaves. The leaf area was then required to sum the photosynthesis for different layers of the canopy. These steps will be discussed one by one.

#### *Light availability in the canopy*

The light within the canopy fell more or less exponentially with the height from the top of the canopy (Figure 7); 50% of the light was usually intercepted by the top 25 cm of the canopy and by 1 m the available light was only around 6% of that at the top of the canopy. However, there was always a small amount of light at the bottom of the canopy due to the fact that light was penetrating via the pathways.



**Figure 7:** *The availability of light at different heights in the canopy, expressed as a percentage of that incoming at the top of the canopy. Each point represents an individual measurement and the line shows the fitted relationship*

The relationship between height from the top of the canopy ( $h$ ) and the proportion of the incoming light ( $PAR$ ) that is transmitted ( $TPAR/PAR$ ) was modelled using a light extinction coefficient ( $k$ ). To take into account the fact that there was always some light from the pathways a constant proportion of the incoming radiation ( $a$ ) was added at heights more than 1 cm from the top of the canopy.

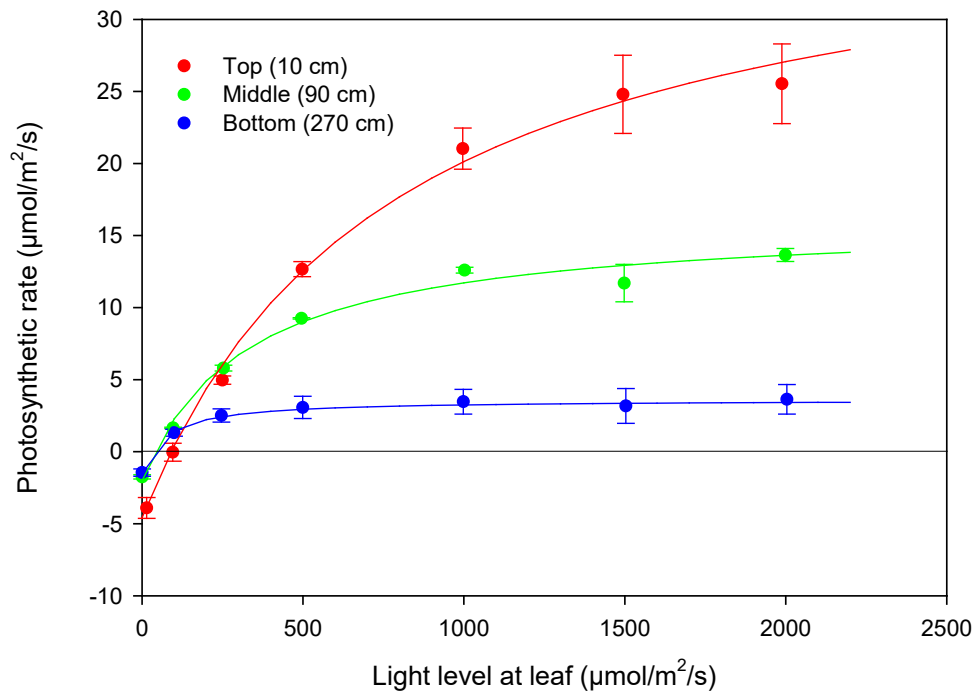
$$TPAR/PAR = a + \exp^{-kh} \quad (\text{eqn. 2})$$

This relationship was fitted using Genstat (10<sup>th</sup> edition) and the optimised values of  $a$  was 0.01898 and  $k$  was 0.03085. The accuracy of the fitted relationship can be seen in Figure 7.

Given the low light levels in the lower canopy, little photosynthesis is likely to be taking place even if the leaves are capable of doing so.

#### *Modelling of photosynthetic efficiency*

For a given height in the canopy, there was little evidence to suggest that photosynthetic efficiency changed over the course of the experiment. However, there were large differences in photosynthesis recorded at different heights in the canopy for a given light level. This is illustrated in Figure 8, where light response curves are shown for representative top, middle and bottom leaves. Even when the middle and bottom leaves were lit at high light levels, their level of net photosynthesis fell well below that of young leaves at the top of the canopy.

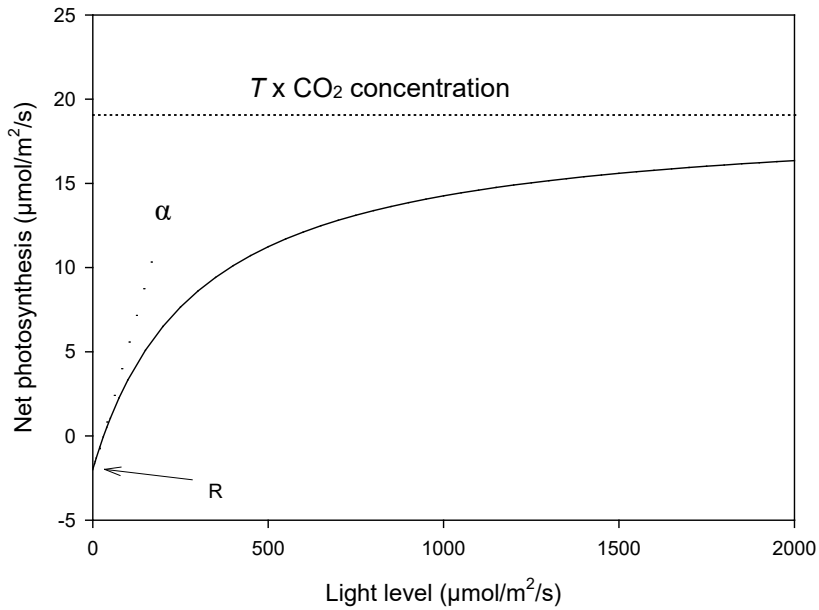


**Figure 8:** The effect of height on photosynthetic efficiency. Top represents the average of 3 leaves measured on 22 May. Middle represents 2 leaves on 22 May, and bottom represents the mean of 7 leaves recorded on 22 October

To model the change in photosynthetic efficiency with canopy height, light response curves were fitted to numerous data sets using a simple photosynthesis model (Acock, 1991):

$$P_n = \alpha I C / (\alpha I + \tau C) - R \quad (\text{eqn. 3})$$

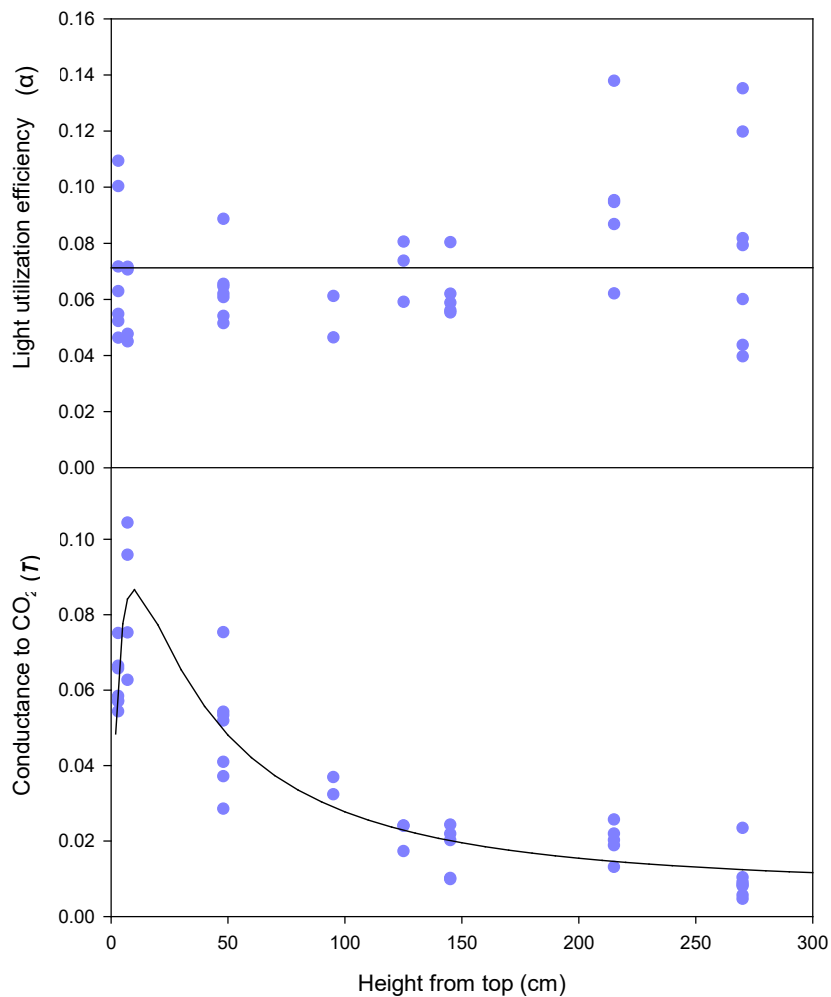
where the increase in net leaf photosynthesis ( $P_n$ ) with intercepted light ( $I$ ) and  $\text{CO}_2$  concentration ( $C$ ) is determined by the light utilisation coefficient ( $\alpha$ ) and leaf conductance to  $\text{CO}_2$  ( $\tau$ ). The gross photosynthesis ( $P_g$ ) can be calculated by subtracting the respiration rate ( $R$ ). The effect of these parameters on the shape of a light response curve can be visualised in Figure 9. When plotted against light level,  $\alpha$  is the initial slope and  $\tau$  determines the upper asymptote.



**Figure 9:** Schematic diagram which shows how the parameters in the photosynthesis model affect the shape of a light response curve

For each light response curve (40 in total) these parameters were fitted using Genstat. The way in which these optimised parameters changed with canopy height was explored. The light utilisation coefficient ( $\alpha$ ) did not appear to change with height and so was assumed to remain at 0.0713 (the average value) in the model (see Figure 10). However, the leaf conductance to  $\text{CO}_2$  ( $\tau$ ) changed with height (Figure 10). This increased initially as the leaf expanded, was maximal at around 10 cm from the top of the canopy, and thereafter declined with height from the top of the canopy. This relationship was described using the following formula:

$$\tau = 0.0076 + 0.07903 \exp^{(-0.5 * (\ln(h / 9.951) / 1.396)^2)} \quad (\text{eqn. 4})$$



**Figure 10:** The influence of height from the top of the canopy on the parameters of the photosynthesis model. Each point represents an individual measurement and the lines show the fitted relationships

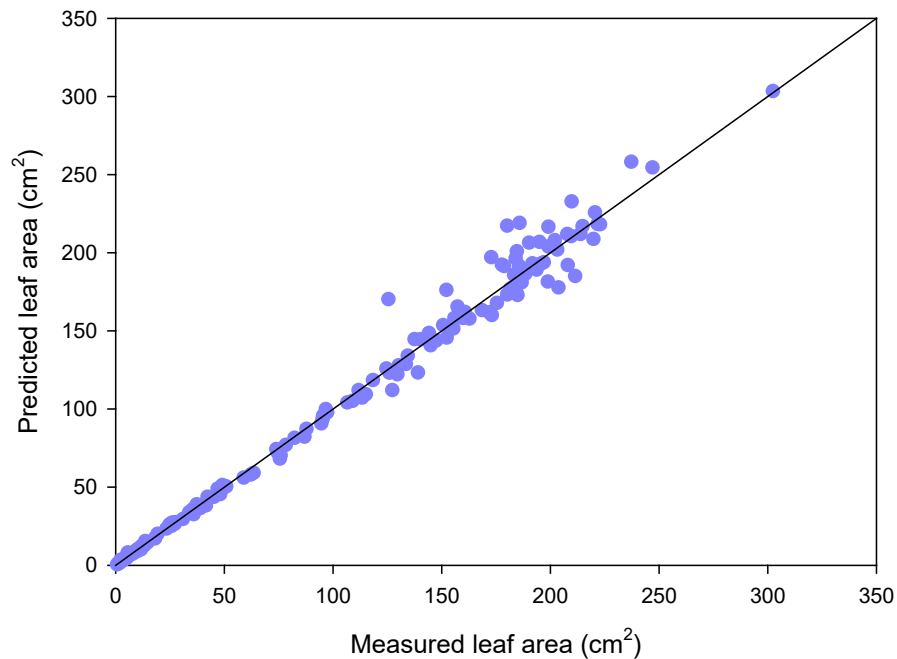
#### Estimation of leaf areas

A calibration was developed so that leaves did not need to be removed from the trial area for the estimation of leaf areas. This related leaf area to leaf length and breadth. Leaves that had fallen off plants were collected on a few occasions and taken back to Warwick HRI. For each leaf the length and breadth (at the widest point) was measured and then the leaf area was measured using a Delta T leaf area meter. The relationships between these data were then explored and the following equation best related leaf area ( $A$ ) to length ( $L$ ) and breadth ( $B$ ):

$$A = \exp^{(-0.3831 \times 0.982 \cdot \ln(L) \times 1.024 \cdot \ln(B))} \quad (\text{eqn. 5})$$

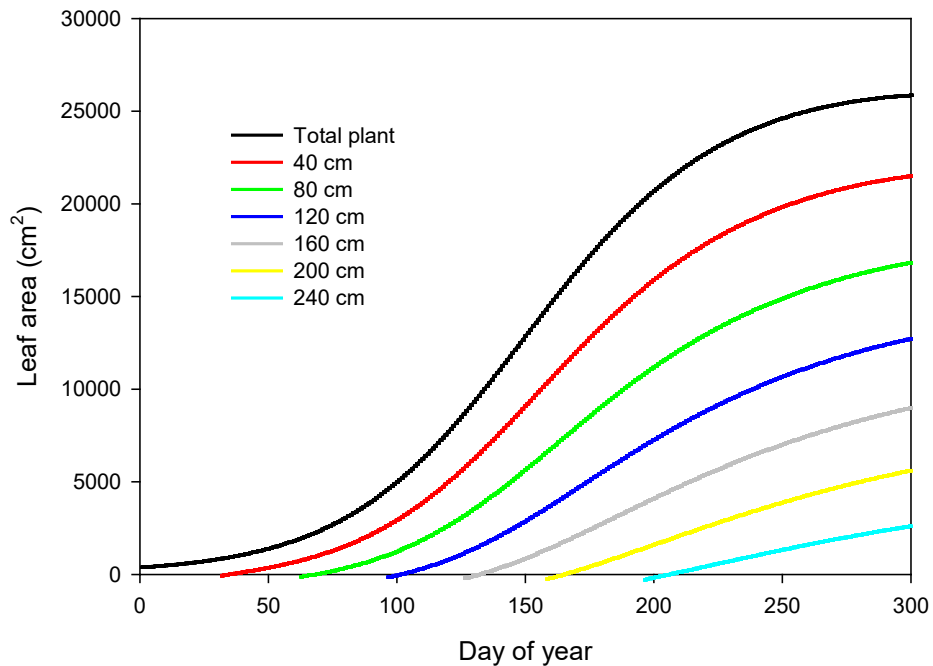


This relationship gave a good fit to the data ( $r^2 = 0.99$ ) and the accuracy of the relationship between the predicted and measured leaf areas can be seen in Figure 11.



**Figure 11:** *The accuracy of the calibration to convert leaf length and breadth into an estimate of leaf area. Each point represents an individual measurement and the line shows the line of identity on which all of the points would fall for a perfect fit*

This relationship was then used to convert measurements of leaf length and breadth at different heights in the control plots into profiles of leaf area. The canopy was divided up into 40 cm layers. The percentage of the leaf area in each layer was then calculated for each date when the measurements were made. The percentage of leaf area within, for example, the top 80 cm started at 100% when the plant height was 80 cm or less, and this then fell as the plants grew taller than this and an increasing number of leaves were below this level. The leaf areas predicted using the model that was developed can be seen in Figure 12. It was not just the top of the canopy where the leaves were initiating and expanding, lower down in the canopy there was an increase in leaf area over time as a result of side shoots.

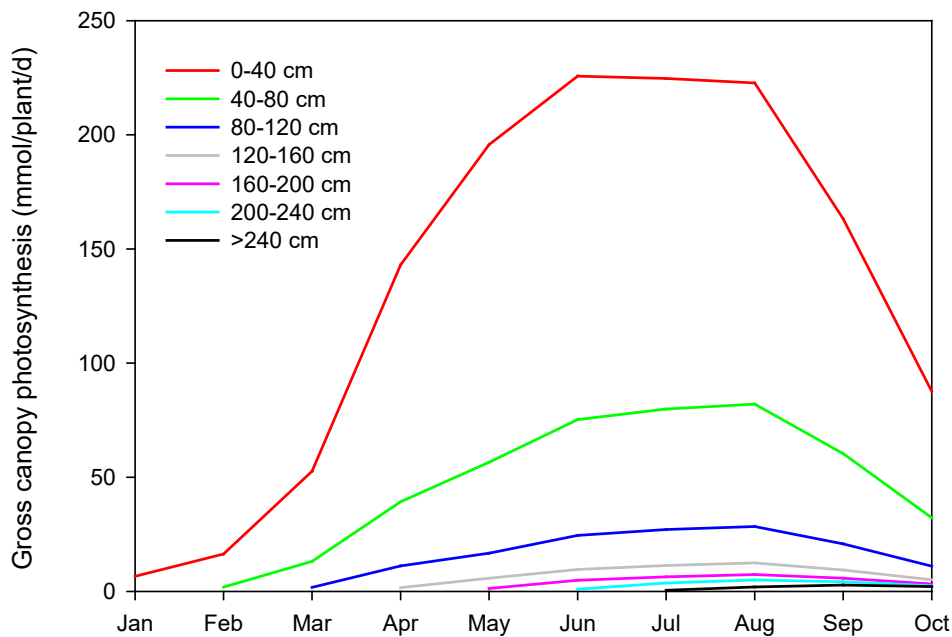


**Figure 12:** Prediction of the leaf area for different canopy layers over time. The heights in the legend are from the top of the plant and the lines represent the leaf area below this. Therefore, the area of layer 40 to 80 cm from the top of the canopy is shown as the differences between the red and green lines

#### Prediction of gross photosynthesis

The gross photosynthesis for different layers of the canopy was then predicted for a full season based on hourly light data collected at Wellesbourne in 2007. A 70% light transmission into the glasshouse was assumed, and the light available at different heights in the canopy was calculated accordingly. The photosynthesis per m<sup>2</sup> of leaf was estimated using the photosynthesis model and this was converted to a plant basis by multiplying with the predicted leaf area.

Figure 13 shows the predicted gross photosynthesis for each 40 cm layer of the canopy. Due to the fact that the top 40 cm both intercepts most of the light, and has the most efficient leaves, this accounted for over 60% of the gross photosynthesis. The lower leaves were predicted to photosynthesize little, especially below 160 cm. When respiration is taken into account (to give net canopy photosynthesis) all of the lines would be lower, and some of the lower leaves would often be below the compensation point. However, net photosynthesis has not been shown due to the difficulties in accurately assessing respiration and not knowing how much of this is associated with the maintenance of the leaves.

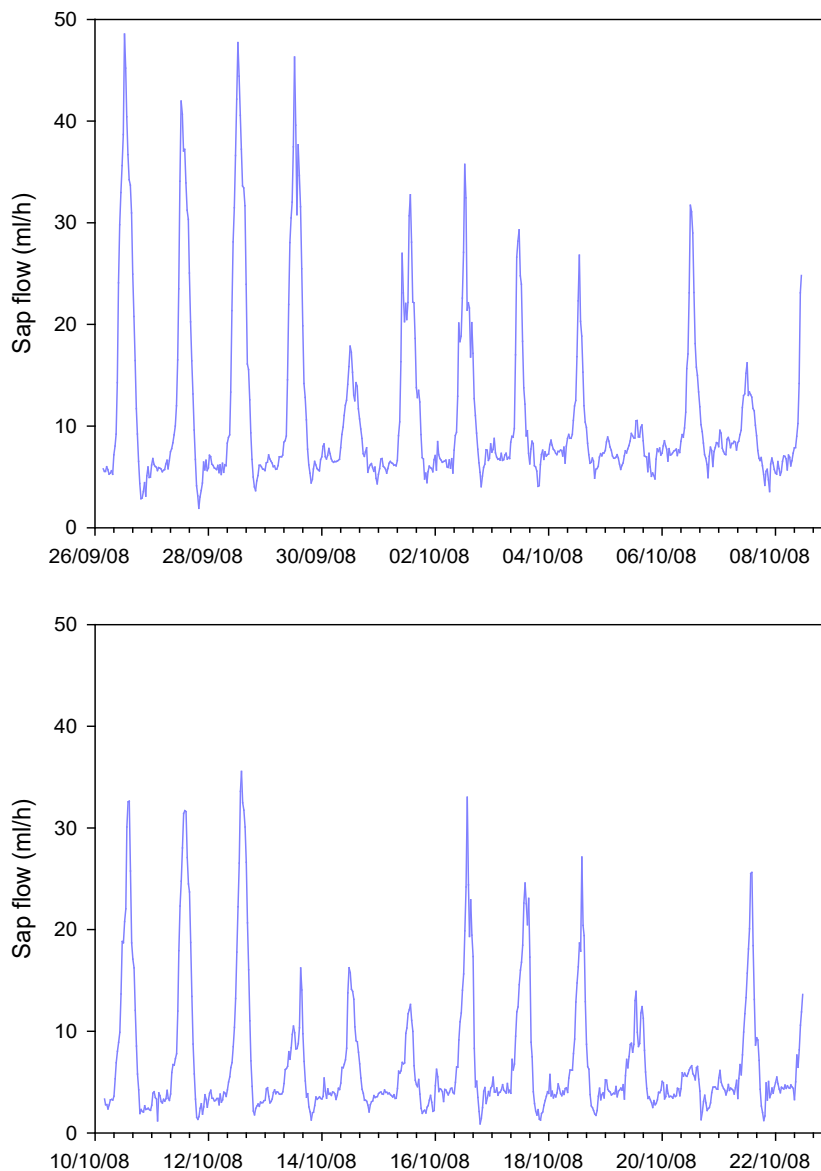


**Figure 13:** Predicted gross canopy photosynthesis for different crop layers. Heights are expressed as cm from the top of the canopy

### Transpiration

The transpiration values measured when determining the light response curves were fairly high, due to the fact that the leaves had been pre-lit to open the stomata in order to minimise the effect of stomatal conductance on the measurements. Some measurements were also made under ambient conditions and these transpiration values will be more typical. The transpiration of the upper leaves varied depending on the conditions, with values up to 4.5 mol/m<sup>2</sup>/s. However, the lower leaves, were typically closer to 0.5 mol/m<sup>2</sup>/s. Therefore, the lower leaves are clearly transpiring, and removing them should reduce water use, although the reduction in water use will be much smaller than any reduction in leaf number or leaf area.

Sapflow sensors were used in an attempt to quantify the reduction in water uptake due to leaf removal. While the sensors showed sensible outputs with the transpiration being related to the solar radiation (Figure 14), due to the fact that we were unable to use silicon grease to improve the thermal contact, and a few sensors failed during the course of the experiment, there was insufficient precision to detect the treatment effects. Water uptake will be explored further in year 2.



**Figure 14:** *The average sap flow for all treatments (water uptake) recorded over two periods in September–October*

## Discussion

The initial assumption that the leaf area in sweet peppers can be reduced without sacrificing yield has been proved correct. Even the most severe deleafing treatment that was applied did not appear to reduce the yield. Furthermore, this was backed up by the model of canopy photosynthesis which indicates that the top 40 cm of canopy probably account for over 60% of the gross photosynthesis. While it might be possible to leave less than 1.6 m of leaf and still not affect yield, this has not been tested experimentally. Based on the first year's data, leaving 1.6 m of leaf would appear to be fairly safe, and will form the basis of the experiment in year 2. However, as illustrated in the canopy photosynthesis model, slightly more leaf is desirable in summer to intercept the additional light. Furthermore, crop transpiration can be

desirable to cool the glasshouse in summer. Consequently, in year 2 slightly more leaf will be retained in July and August.

Although no firm conclusions of the effect of deleafing on stem rot can be drawn due to the low incidence of stem disease (four lesions), it would appear that wound sites created by deleafing are not highly susceptible to *Fusarium* sp. or *Botrytis cinerea*, the two fungi most commonly found causing stem lesions of pepper in the UK. However, the benefits of potentially lower RH's will not be observed until all of the plants in a block are deleafed in the same way. Furthermore, there was no effect of deleafing on the incidence of fruit rot. Cultures of the *Fusarium* sp. isolated from fruit and stem were morphologically identical.

Assuming that transpiration is reduced as a result of deleafing, there will be a trade off between reducing energy use and achieved RH. If the humidity control strategy remains unchanged then at times the achieved RH may be similar, although with less energy use. Whereas if the same amount of energy is used it should be possible to achieve a lower RH. These potential benefits will be quantified further in the third year.

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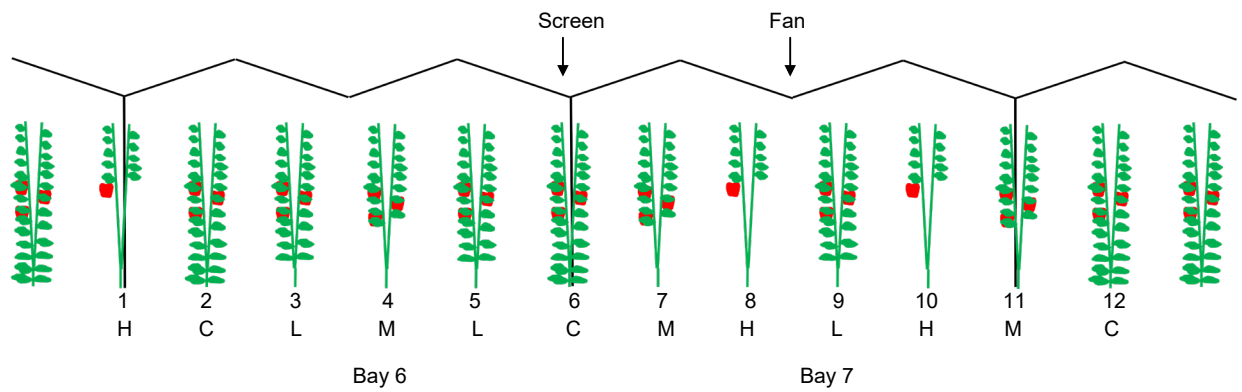
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**Appendix 1 – Experimental plan:**

Block 3 at Valley Grown Nurseries



Where:

C = Control with no leaf removal

L = Low deleafing leaving 2.4 m of leaf

M = Medium deleafing leaving 2.0 m of leaf

H = High deleafing leaving 1.6 m of leaf