PC/4 ENERGY SAVING: THE USE OF THERMAL SCREENS IN GLASSHOUSES
(Previously ADAS Project GP26/07745: Tomato, computer control of thermal screens)

FINAL REPORT

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The work reported on here forms part of a series of ADAS Development Farm investigations at the nurseries of Bunting & Sons that began in 1979. Since 1985, these have been concerned with the efficient use of thermal screens in association with environmental control computers and they have been an important component of a coherent programme of research and development within the ADAS/AFRC Integrated Project on Energy Saving in Greenhouses.

This report presents the conclusions from experiments in three growing seasons (1985, 1986, and 1987). The HDC supported the work in the final season to ensure the satisfactory completion of the project which might otherwise have ended prematurely and with incomplete results.

OBJECTIVE:

To develop control strategies for use with thermal screens that will achieve the economic optimisation of crop production in insulated greenhouses.

SUMMARY:

1. Experiments over three seasons demonstrated that drawing a Tyvek thermal screen over a tomato crop at night had no adverse effect on yield when compared with the productivity of crops in compartments having identical screens that were not drawn at night (unscreened).

2. The Tyvek screen reduced energy consumption at night by 60% when drawn over the crop, and reduced it by 39% over the whole period of its use.

3. Relative humidity at night was generally 4 to 5% higher under the Tyvek screen than in the unscreened compartments. The average relative humidity was no more than 85% in January and February and experiments at Efford EHS have since shown that average levels of 90% or more would be required in those months to produce a detectable reduction in yield.

4. In the light of the Efford results, it is not surprising that the use of a computer programme to limit the increase in relative humidity above 80% had little beneficial effect on yield. Such a programme might still be of value to ensure that relative humidity did not rise above 90% for prolonged periods.

5. In conjunction with other evidence from investigations at IHR Littlehampton, it is concluded that light loss by day from the parked screen is the main cause of loss of yield in comparison with the productivity of crops in houses without a screen fitted. Further work might concentrate on developing systems of screening that produce even less light loss by day and screen materials that have even better insulation properties.

6. The use of "anti-condensate" polythene as a mobile thermal screen did reduce yield in April and May, mainly because it generated high relative humidities both by day (c 90% in January) and by night (> 85% in January and February). This is consistent with observations on the effects of high

humidity at Efford EHS. In addition, water condensed on the polythene and fell on the crop when the screen was moved.

7. Energy saving by the polythene screen was more difficult to assess. It was estimated to be between 23 and 29% at night and about 35% by day. Overall, using the screen by day and by night reduced energy consumption by about 22% to 26%, and by 9 to 16% when used only at night.

8. At present, the best use of polythene is as a cheap fixed screen but further research and development may enable other strategies to be developed.

BACKGROUND:

Since the introduction of movable thermal screens in the mid 1970s, much has been done to define the ideal physical properties required of the screen material to maximise energy saving, but various trials have shown that crops can yield less when thermal screens are used and the value of the lost yield may cancel out the value of the fuel savings. The yield losses may be due to loss of light during the day, especially if the screen material is bulky and will not park neatly when not in use, and to changes in the environment under the screen. Information available in 1984 indicated that atmospheric humidity was higher under a thermal screen which might depress growth and yield. It was suggested that environmental control computers could be used to give more precise control of the aerial environment under thermal screens by retracting them as necessary to maintain a desired air temperature or humidity. Other investigations, some funded by HDC, are in progress at IHR Littlehampton and Efford EHS to determine more precisely the effects of high humidity on growth and yield of tomato.

The previous work with Bunting & Sons under the initial Development Farm Project (1979-81) had shown that the nursery layout lent itself to large-scale experiments, that the recording procedures used by the grower were reliable, and that although there were differences in the yields produced in different glasshouse compartments, their effects could be minimised by suitable experimental designs.

The nursery comprises two main glasshouse blocks; one a block of four compartments arranged in a square and another block of four arranged in a line (Fig. 1). Each compartment covered an area of approximately 0.5 acre, was equipped with a thermal screen, and had full control and monitoring of the aerial environment and screen position by an Envirocon computer. In 1985, heat usage was assessed from Carlton heat meters but for the 1986 and 1987 seasons, the heating systems of each compartment were equipped with new flow meters, and water temperature in the flow and return pipes was continuously monitored to enable the computer to calculate heat use in each compartment, by day and by night. There were small differences in the sizes of individual compartments but these have been allowed for in the following analyses.

EXPERIMENTS:

In all three years, tomatoes were grown on rockwool as long-season, layered crops at a density of 2.5 plants m^{-2} (10,000 plants $acre^{-1}$). Conventional blueprint temperature regimes were used with CO_2 enrichment from pure CO_2 controlled to a level of 1200 vpm until May and, thereafter, controlled at ambient levels. Two fans were used in each compartment to assist with air movement and to minimise temperature gradients. Yields were recorded as the fruit passed through a commercial packing house.

The main screens used were of 'Tyvek', a permeable material with an aluminised coating on the upper surface. In the 1987 season, an "anti-condensate", impermeable, polythene material was also used as a moveable thermal screen in some compartments. Although commonly known as "anti-condensate", water does condense on the material which has been treated to encourage the condensation to run off rather than drop off. In all years, mobile screens of either 'Tyvek' or polythene were fitted from gutter to gutter above the crop and along the side and gable end walls in every compartment.

A. 1985 season. The tomato cv. Marathon was sown on 30 October 1984 and grown as described earlier. Two main screen treatments were maintained until 19 May.

1) The 'Tyvek' screen was drawn at dusk and withdrawn gradually at dawn to minimise thermal shock. This was the "standard programme" (S).

2) The 'Tyvek' screen was drawn at dusk but could be withdrawn again proportionally if either the relative humidity (r.h) or the external temperature rose above certain values. For humidity, the screen began to open at 80% r.h. and reached a set maximum gap of 12% (60 cm) at 90% r.h., while with external temperature, it began to open at 10°C and was opened to the 12% gap at 12°C above which, it was withdrawn completely. This was the "enhanced programme" (E).

The enhanced programme was used in compartments B and D and the standard in compartments A and C. The standard treatment was also given in compartments E to H to obtain a measure of the variation along this linear block of compartments.

B. 1986 season. The tomato cv. Marathon was sown on 15 October 1985 and grown as before with the exception that young plants were placed for 21 days under high-pressure sodium lamps (3500 lux for 16 h d^{-1}) before they were moved to the growing houses in mid-November.

Three main screen treatments were maintained from 11 January to 11 May 1986.

1) The 'Tyvek' screen was not drawn but remained in its parked position within the compartment at all times (U).

2) The 'Tyvek' screen was drawn as in the standard programme (S).

3) The 'Tyvek' screen was drawn as in the enhanced programme (E).

C. 1987 season. The tomato cv. Counter was sown on 17 October 1986 and grown as in earlier years. The young plants were placed under high-pressure sodium lamps (3500 lux for 15 h d^{-1}) until stood out in the growing areas after 25 days.

The effects of three main treatments were compared. The enhanced programme was not used as it had given little benefit in 1985 and 1986 (see Results). The main comparisons were:

1) The 'Tyvek' screen was not drawn but remained in its parked position within the compartment at all times (U).

2) The 'Tyvek' screen was drawn as before in the standard programme (S).

3) An "anti-condensate", clear polythene screen was fitted and operated as a movable screen but controlled only in relation to atmospheric humidity and outside temperature and not on time at dusk or dawn. It operated, therefore, on a modification of the "enhanced programme" and was drawn over the crop continuously night and day, unless either the humidity rose above 85%, in which case it opened proportionally until at 95% r.h. it was 12% open (60cm), or the outside temperature rose above 10°C, when it opened progressively to a 12% gap at 12°C and was withdrawn completely when outside air temperatures exceeded 12°C (P).

The treatments began in week 49 and were under full computer control from week 51. The full polythene treatment was terminated on 6 February, after which it was used with the enhanced programme but at night only until 19 March, when it was terminated. The 'Tyvek' screen treatment terminated on 5 April.

The complete allocation of treatments over three years is shown in Table 1.

Table 1. The allocation of screening treatments to compartments in different years

	Compartments							
Year	A	B	C	D	E	F	G	H
1985	S	E	S	E	S	S	S	S
1986	U	S	E	U	S	E	S	E
1987	S	U	U	S	P	-	P	S

S = standard screen programme U = unscreened programme
E = enhanced screen programme P = polythene screen programme

RESULTS:

A. Aerial Environments

1. Temperature

There was little variation in temperature between compartments that received the same treatment, and so temperatures are presented as averages for each treatment. The records for 1985 are incomplete. Average air temperatures at night were slightly higher under the standard screen programme than the unscreened one in February and March 1986 (Table 2), and there was little difference between the standard and enhanced programmes. In 1987, however, the air temperature at night was 0.5°C higher under the 'Tyvek' screen and almost 0.4°C higher under polythene between January and March (Table 3). These differences were not evident in April after the treatments had been discontinued.

There was little difference between treatments in day temperature in either February, March or April 1987, as no screens were drawn over the crop by day in this period, but the day temperature was 0.5°C higher under polythene in January, when this screen was drawn over the crop for at least part of each day (Table 3).

Table 2. The average temperature (°C) at night under different thermal screen programmes in 1986.

	Treatment		
Month	Unscreened	Standard	Enhanced
January	15.9	15.7	15.7
February	15.4	15.6	15.6
March	15.7	15.9	15.8
April	16.1	16.0	16.0

Table 3. The average temperature ($^{\circ}C$) by day and by night under different thermal screen programmes in 1987.

	Month	Treatment Unscreened	Standard	Polythene
a) Day	January	17.5	17.6	18.0
	February	18.4	18.4	18.3
	March	18.1	18.3	18.4
	April	18.3	18.4	18.5
b) Night	January	16.1	16.6	16.5
	February	16.2	16.6	16.4
	March	16.4	17.1	16.9
	April	16.7	16.7	16.9

2. Relative humidity

The enhanced programme did reduce relative humidity under the thermal screen at night in 1985 and 1986, and reduced it to values that were similar to those in the unscreened houses in March and April 1986 (Table 4). In 1987, humidity at night was higher under the screen in January and February but not March (Table 5). It was also higher under polythene, especially in January, when this screen was in place by day as well as by night. Day humidities were much higher under the polythene screen in January, even though the screen could be retracted to some extent when humidities exceeded 85% r.h. The polythene screen was not used by day in February, March and April, and so had little effect on day humidity in these months.

Table 4. The average relative humidity (%) at night under different thermal screen programmes in 1986

Month	Treatment Unscreened	Standard	Enhanced
January	71	79	80
February	73	83	77
March	82	87	81
April	82	87	82

Table 5. The average relative humidity (%) by day and by night under different thermal screen programmes in 1987.

	Month	Unscreened	Treatment Standard	Polythene
a) Day	January	81.1	83.2	89.6
	February	86.5	87.2	87.2
	March	85.3	83.2	83.0
	April	84.5	83.3	81.5
b) Night	January	73.2	77.7	84.9
	February	80.6	84.5	85.9
	March	78.0	76.8	77.3
	April	82.2	81.8	80.4

These differences in the aerial environment must be taken into account when considering differences in yield between compartments.

B. Yields

A major problem with investigations on commercial nurseries is that it is unusual for all compartments to have the same exposure to light, wind and other aspects of the natural environment. Within the linear block of compartments (E to H), E has a hedge and other compartments to its south and so might be expected to receive less light than F (Fig. 1). Both of these compartments also have buildings along their south-eastern wall, which will cast more shade than the wooden vinery houses adjacent to G and H (Fig. 1). Within the square block of compartments, B appears to be more favourably placed than D for light (Fig. 1) while A should receive less light than C, especially in the morning in spring and summer, because of the hedge along its south-eastern wall.

Research at IHR, Littlehampton, within the ADAS/AFRC Integrated Project, has confirmed the close relationship between light receipt and yield of tomato, especially in the period up to the end of May. Differences in light transmission alone, therefore, would be expected to produce proportionally similar differences in yield, though the impact of these positional differences can be minimised by suitable experimental designs.

Examination of the trend graphs of cumulative yield against time showed that there were no marked changes in the relative differences between compartments in different months up to September. More variation was encountered in October, however, and so the results from that month have not been used in the following analyses.

1. Standard and Enhanced Programmes

All compartments in the linear block received the same screen treatment in 1985 and yields to the end of April were also similar in all compartments (Fig. 2). By the end of September, however, a gradient of increasing yield was evident from E to G, with H yielding slightly less than G (Fig. 2). In 1986, E and G received the standard programme and F and H the enhanced one. Although the average yield under the standard programme was slightly higher than that from the enhanced to the end of April 1986, the differences between appropriate pairs of compartments were similar to those in the previous year when all compartments had received the same treatment (Table 6).

Table 6. Average yields of tomato (tons acre^{-1}) in different pairs of compartments in different years.

	Year	Compartments E + G	F + H	Difference
To April				
	1985	23.59 (S)	23.11 (S)	- 0.48
	1986	22.83 (S)	22.22 (E)	- 0.61
To September				
	1985	125.4 (S)	126.7 (S)	+ 1.3
	1986	131.1 (S)	130.7 (E)	- 0.4

S = standard programme E = enhanced programme

Yields to the end of September showed a similar pattern. Compartments F + H gave a slightly higher yield than E + G when they all received the standard treatment and a slightly lower yield when F + H received the enhanced programme. There was no significant evidence that the enhanced programme gave an improvement in yield when tested within the linear block.

It is more difficult to assess positional effects within the square block as a whole as the compartments received different treatments in different years. Taking the pair of compartments B and C, however, while B received the enhanced programme and C the standard in 1985, this allocation was reversed in 1986. Yields averaged over two years confirmed that there was little difference between the standard and enhanced treatments (Table 7).

Table 7. Yields of tomato (tons acre^{-1}) under the standard and enhanced screen programmes

	Compartment	Standard	Enhanced	Mean
To April				
	B	25.48	24.81	25.15
	C	23.63	24.08	23.86
	Mean	24.56	24.45	
To September				
	B	141.5	135.2	138.4
	C	130.3	138.8	134.6
	Mean	135.9	137.0	

A statistical analysis of yields from all compartments in all years indicated that there was no significant difference between the standard and enhanced programmes. A linear regression model which was based on this analysis and took account of differences between years and compartments predicted that the average yield to the end of April would be 24.61 tons acre^{-1} in the standard programme and 24.18 tons acre^{-1} in the enhanced and would be 131.55 and 130.25 tons acre^{-1} respectively, to the end of September. Thus, although the enhanced programme did reduce humidity it had no apparent effect on yield.

2. Standard v Unscreened Programmes

As there was effectively no difference between the standard and enhanced programmes they can be regarded as being the same for the purpose of analysing the effects of the standard and unscreened programmes. Over three years of experimentation, each compartment in the square block (A to D) had the unscreened treatment in one year and either the standard or the enhanced programme in the other two years. Thus, the average yields over three years within each compartment provide a measure of the effect of position, assuming that there were no interactions between treatments and years. This analysis (Table 8, Fig. 3) shows that D yielded less than other compartments up to the end of either April or September, while A yielded less than either B or C to the end of September.

Table 8. Yields of tomato (tons acre^{-1}) in different compartments in different years

		Compartment				
	Year	A	B	C	D	Mean
To April						
	1985	24.44	24.81	23.63	22.06	23.74
	1986	23.32	25.48	24.08	21.73	23.65
	1987	27.81	27.28	27.50	26.21	27.20
	Mean	25.19	25.86	25.07	23.33	
To September						
	1985	128.8	135.2	130.3	122.3	129.2
	1986	136.9	141.5	138.8	132.9	137.5
	1987	132.5	137.0	140.1	131.9	135.4
	Mean	132.7	137.9	136.4	129.0	

Despite these positional effects, the effects of treatments can be assessed by ensuring that each treatment is equally represented in all positions. Such an arrangement existed within the square block in the 1986 and 1987 seasons. In these years, the screened and unscreened programmes were compared with two replicates of each treatment in each year. The allocation of treatments to compartments was then reversed in the second year.

The results showed that the average yields from the two treatments were very similar up to either April or September (Table 9). The average yield to April was slightly higher in the standard treatment and the data for the two years suggest that the higher night temperatures under the screen (Tables 2 and 3) contributed to this. Other factors, such as higher pipe temperatures and thereby higher rockwool slab temperatures in the unscreened compartments, may also have been involved, for the plants in this treatment were assessed to be more vigorous and with poorer fruit set in March 1986.

Table 9. Yields of tomato (tons acre^{-1}) under the standard and unscreened treatments in 1986 and 1987.

	Compartment	Treatment Standard	Unscreened
To April			
	A	27.81 (87)	23.32 (86)
	B	25.48 (86)	27.28 (87)
	C	24.08 (86)	27.50 (87)
	D	26.21 (87)	21.73 (86)
	Mean	25.90	24.96
To September			
	A	132.5 (87)	136.9 (86)
	B	141.5 (86)	137.0 (87)
	C	138.8 (86)	140.1 (87)
	D	131.9 (87)	132.9 (86)
	Mean	136.2	136.7

A statistical analysis of yields from all compartments in all years showed that there was no significant difference between the standard and the unscreened programmes. The linear regression model mentioned earlier, predicted that the average yield to the end of April would be 23.82 tons acre^{-1} in the unscreened programme and 24.61 tons acre^{-1} under the standard screened programme. Yields to the end of September would be 132.44 and 131.55 tons acre^{-1} respectively.

3. Polythene screens

The effects of the polythene screen treatment are more difficult to assess as the treatment was given only in 1987, and only to the linear block in which compartment F was not used for growing tomato. All compartments of the linear block received the same treatment in 1985 to assess variation along the block (Fig. 2). The standard and enhanced programmes were compared within the block in 1986 and as these treatments did not differ significantly, the results from both years have been pooled to improve the assessment of positional effects. The average values for both years are shown in Table 10 and compared with the results in 1987 when the polythene treatment was given to E and G and the standard programme to H.

Table 10. Yields of tomato (tons $acre^{-1}$) under the polythene and standard screen treatments.

	Year	Compartment E	Compartment G	Compartment H
To April				
	1985 + 1986	22.43	23.99	22.78
	1987	23.91	25.02	25.67
	Difference	-1.48	-1.03	-2.89
To May				
	1985 + 1986	45.40	49.01	46.06
	1987	43.75	43.82	45.06
	Difference	1.65	5.19	1.00
To September				
	1985 + 1986	123.5	133.0	129.4
	1987	123.8	126.5	128.8
	Difference	-0.3	6.5	0.6

The yield of fruit from compartments E and G in 1987 was 1.26 tons $acre^{-1}$ more on average to the end of April than in 1985 + 1986, whereas in compartment H it was 2.89 tons $acre^{-1}$ more. This suggests that the polythene screen actually caused a loss of yield of about 1.63 tons $acre^{-1}$.

Yields to September averaged 3.1 tons $acre^{-1}$ less in E and G in 1987 as compared with 1985 + 1986, whereas the reduction was only 0.6 tons $acre^{-1}$ in H. The overall loss due to the polythene, therefore, was about 2.5 tons $acre^{-1}$. It is apparent, however, that compartment G was more adversely affected than E and that this pattern was already evident at the end of May (Table 10).

Records for May have been presented because recent work within the ADAS/AFRC Integrated Project at Efford EHS has shown that exposure to high humidity in January and February can produce a subsequent reduction in fruit production in April and particularly May. Closer inspection of the environmental records, showed that, although the values of air humidity in compartments E and G were usually similar, in the period from 29 December 1986 to 25 January 1987, there were differences between them. While the average relative humidity over this period was 87.8% by day and 81.9% by night in E, it was 92.0% by day and 89.3% by night in compartment G.

These differences in humidity may well account for the differences in productivity and imply that the high humidity under polythene in January was a major cause of loss of yield in May. These effects are consistent with those observed at Efford.

A statistical analysis of yields from all compartments in all years showed that yield in the polythene treatment was significantly lower than that in the standard treatment in both April and May. The linear regression model predicted that the average yield to the end of April would be 22.49 tons $acre^{-1}$ as against 23.82 tons $acre^{-1}$ in the unscreened and to the end of September would be 127.7 and 132.4 tons $acre^{-1}$ respectively. It is important to note, however, that due to the very limited replication available, there are large standard errors associated with the predicted yields under polythene, viz. 0.60 and 2.59 tons $acre^{-1}$ for the April and September totals respectively.

No records of fruit quality were taken in these investigations though the grower's assessment was that fruit quality was adversely affected and occasional spot checks indicated that fruit size was smaller in the polythene treatment.

4. Conclusions - Yield

4.1 The Tyvek screen, when drawn over the crop at night, did increase air temperature and humidity but these environmental changes caused no loss of yield when compared with compartments in which the screen was not drawn at night. This arrangement ensured that the loss of light by day, due to the presence of a parked screen, was the same in both treatments.

4.2 The results implicate light loss as being the major cause of the loss of yield observed in other investigations where comparison has been made between crops grown in houses either with a thermal screen or without a screen fitted.

4.3 As using a Tyvek screen caused no loss of yield, it was not surprising that using a computer to regulate the screen's position, and so limit the increase in humidity under the screen, had no beneficial effect on yield.

4.4 When an anti-condensate polythene screen was drawn over the crop by day and by night, humidity rose markedly, even though the screen could be withdrawn a little in an attempt to limit this increase. In view of results from Efford EHS on the effects of humidity on yield of tomato, it seems likely that the increase in humidity by day and by night in January, contributed greatly to the loss of yield observed in the polythene treatment in April and May. Light loss from using the polythene screen by day in January might also have contributed a little to the loss of yield but this effect would have been offset to some extent by the accompanying increase in day temperature (Table 3).

C. Energy Usage

When considering energy usage under different treatments, the following points must be considered.

1. All compartments do not have the same area of external glass surface. E and H have three external walls, while the remaining compartments have only two.

2. The average internal temperatures during the day and night periods were not identical in all compartments.

3. With the exception of compartments F and G (F was not included in the 1986/87 experiment), the disposition of the compartments was different (Fig. 1), consequently wind direction, as well as wind speed, could influence heat loss.

The following analysis was carried out on data from the 1987 season recorded from 16 December 1986 (day) and 19 December 1986 (night) until 16 March 1987. The polythene screen was not used during the day after 6 February

1987; prior to this it was normally drawn over the crop by day but records show that it did open partially on several occasions to reduce humidity.

It is also noteworthy that the Tyvek screens had been installed in August 1983 and so were in their fourth season of use when these analyses were made.

1. Energy use at night

Records of the quantities of energy required each night in the seven compartments were used to calculate heat transfer coefficients for the eight wind directions recorded (Table 11). These coefficients are independent of greenhouse surface area and internal temperature, and also enable the influence of the changing length of the night to be eliminated.

Table 11. Heat transfer coefficients at night for compartments A to H in 1987 ($W\ m^{-2}\ K^{-1}$)

	Wind direction								
Compartment	NE	E	SE	S	SW	W	NW	N	Mean
A	2.31	2.36	2.70	2.16	2.31	2.61	2.50	0.00	2.37
B	5.38	5.74	6.01	5.13	5.74	5.75	5.16	0.00	5.55
C	5.25	5.94	5.99	5.36	5.75	5.86	5.22	0.00	5.65
D	2.04	2.23	2.29	1.88	1.97	2.06	1.98	0.00	2.04
E	4.64	4.76	4.53	4.61	4.51	4.60	4.41	0.00	4.61
G	4.93	4.22	4.28	3.89	3.82	3.74	3.40	0.00	3.98
H	2.72	2.69	2.93	2.55	2.51	2.73	2.60	0.00	2.64
No. obs.	7	18	3	20	17	17	6	0	88
Wind speed ($m\ s^{-1}$)	1.57	2.71	2.40	2.32	5.58	4.52	2.67	0.00	3.46

A direct comparison of the heat transfer coefficients for the various wind directions is not valid because the mean wind speeds differ. Consequently, linear regressions of heat transfer coefficient on wind speed for each compartment and each wind direction were obtained and from these the heat transfer coefficients at the overall mean wind speed of 3.46 $m\ s^{-1}$ were calculated (Table 12).

Table 12. Heat transfer coefficients at night for compartments A to H in 1987 at the mean wind speed of 3.46 m s^{-1}

	Wind direction							
Compartment	NE	E	SE	S	SW	W	NW	N
A	2.59	2.36	2.64	2.72	2.27	2.55	2.68	0.00
B	5.95	5.91	6.14	5.40	5.54	5.58	5.40	0.00
C	5.76	6.09	6.10	5.66	5.45	5.58	5.48	0.00
D	2.18	2.22	2.72	1.90	1.85	2.02	2.09	0.00
E	4.35	4.78	3.70	4.67	4.39	4.45	4.41	0.00
G	3.49	4.11	3.66	3.97	3.86	3.67	3.50	0.00
H	2.50	2.68	2.77	2.50	2.48	2.69	2.76	0.00

These data indicate that easterly winds produced a higher heat loss than westerly and southern winds for the unscreened compartments B and C. There was, however, no detectable influence on the other compartments where thermal screens were drawn. The regressions for east and west winds for compartment B have standard errors of 0.57 and 0.77 W m^{-2} K^{-1} respectively, and the heat transfer coefficients at the mean wind speed of 3.46 m s^{-1} were 5.91 and 5.58 W m^{-2} K^{-1}. The difference between these two is statistically significant.

As the differences between the mean heat transfer coefficients for the screened and unscreened compartments were considerably greater than the influence of wind direction on the two unscreened compartments and there was no influence on the screened compartments, the influence of wind direction was not included in the subsequent analysis.

The comparison of the pairs of unscreened and Tyvek-screened compartments in the square glasshouse block is straightforward as the respective pairs of mean heat transfer coefficients are similar (Table 11). Comparing the average values (5.6 and 2.21 W m^{-2} K^{-1}) showed that the Tyvek screen reduced the heat requirement at night by 60% (Table 13).

Comparing the results from the polythene-screened compartments in the linear block (Table 11) indicated that the outer compartment E had a heat transfer coefficient which was 16% larger than for the inner compartment G. An estimate of the performance of the polythene screen during the night can be obtained by comparing the heat transfer coefficients of compartments E and G with those of the unscreened compartments B and C. This suggests that polythene screens reduce the rate of heat loss by 23% (Table 13). However, there are dangers in making a comparison between the square and linear blocks because of differences in geometry and exposure, as there are when comparing the relative performance of outer and inner compartments of the linear block. These are exemplified by comparing compartments D and H, both of which contain Tyvek thermal screens, but the heat loss coefficient of H was 29% greater than that of D. Similarly, it has already been demonstrated that the outer compartment (E) of the linear block lost 16% more heat than the inner compartment (G). If allowance is made for this, the energy saving of the polythene screen could be as high as 29% at night.

Table 13. Comparison of heat transfer coefficients at night

	Unscreened		Standard			Polythene	
Compartment	B	C	A	D	H	E	G
Mean heat transfer coefficient	5.55	5.65	2.37	2.04	2.64	4.61	3.98
Average values	5.60		2.21			4.30	
Ratio	1.00		.40			.77	
Relative energy saving	0		60%			23%	

2. Energy use during the day

During the day, energy is supplied to the glasshouse by solar radiation but not all the radiation entering the glasshouse is effective in raising the air temperature; some is reflected by the crop, some is absorbed by the floor and some is used to provide transpiration. The relative proportions depend on the leaf area of the crop, and so change as the crop grows. As the proportion of the external solar radiation which contributed to raising the glasshouse temperature is not known, it is not possible to calculate heat transfer coefficients for the compartments during the day.

The average day-time temperature is achieved by the combined effects of solar input and the energy supplied by the heating system. As the solar input is not known it is not possible to apply a correction to the energy supplied by the heating system for deviations from the desired temperature. In fact the only correction which can be applied to the energy input is for the differences in the sizes of the glasshouse compartments.

After applying this correction by expressing the total heat usage relative to the surface area of the appropriate compartment, the influence of wind direction was assessed (Table 14). The polythene screens were closed during the day until 6 February, unless they were opened by the computer control system because either the humidity or the internal or external temperature rose above set values. No detailed records were kept of the degree and duration of screen opening but inspection of the computer printout from selected days showed that the screen did open and close progressively in relation to changes in internal humidity. Interpreting the data is not straightforward because the influence of day-to-day temperature differences within and between compartments is still present. Also the mean wind speeds were different for the different wind directions. However, it appeared that the highest heat consumptions occurred with winds from the south-east quadrant. The relatively low heat requirement which occurred with the south-west and west winds was due to the lower temperature lifts which existed. Thus the mild conditions associated with southwest winds more than offset the influence of the higher wind speed. It is clear that the heat loss from compartment A was less affected by the wind direction than any of the other compartments.

Table 14 Heat loss per unit surface area (MJ m^{-2}) by day for compartments A to H in 1987

Compartments	Wind direction NE	E	SE	S	SW	W	NW	N	Mean
A	2.32	2.38	2.50	2.61	2.28	2.20	2.74	0.00	2.39
B	2.67	3.19	3.33	3.16	2.48	2.61	2.76	0.00	2.88
C	2.63	3.27	3.39	3.19	2.52	2.61	2.73	0.00	2.92
D	2.39	2.98	3.10	2.85	2.23	2.23	2.50	0.00	2.61
E[a]	2.14	2.57	2.38	2.44	2.06	2.06	2.17	0.00	2.25
E[b]	3.30	3.56	4.08	4.08	2.87	2.98	0.00	0.00	3.51
G[a]	1.92	2.57	2.12	2.17	1.80	1.82	1.81	0.00	2.04
G[b]	2.91	3.31	3.51	3.56	2.25	2.51	0.00	0.00	3.07
H	2.98	3.51	3.67	3.40	2.65	2.71	3.05	0.00	3.12
No. obs.	8	22	4	17	16	16	4	0	87
Wind speed ($m\ s^{-1}$)	1.81	3.80	5.45	3.23	6.46	5.67	2.83	0.00	4.42

[a] Polythene screen closed by day except when opened to limit humidity or temperature (before 7 Feb.)
[b] Polythene screen permanently open by day (after 6 Feb.)

Table 15. Temperature rise above ambient during the day for each compartment

Compartments	Wind direction NE	E	SE	S	SW	W	NW	N	Mean
A	15.76	17.02	17.50	16.36	11.27	13.10	16.83	0.00	15.01
B	15.61	16.53	16.83	16.04	11.22	13.02	16.77	0.00	14.75
C	15.81	16.93	17.38	16.39	11.32	13.09	16.68	0.00	14.99
D	15.76	17.18	17.55	16.46	11.35	13.14	16.90	0.00	15.10
E[a]	15.00	19.14	19.25	17.14	12.03	13.35	16.98	0.00	15.49
E[b]	16.10	15.18	16.20	15.63	10.23	12.43	0.00	0.00	14.20
G[a]	15.24	19.44	19.65	17.64	12.13	13.47	17.05	0.00	15.72
G[b]	16.50	15.28	16.25	15.83	10.50	12.78	0.00	0.00	14.41
H	15.59	16.80	17.40	16.31	11.22	12.99	16.65	0.00	14.89
Mean	15.66	17.00	17.48	16.34	11.29	13.09	16.84	0.00	15.01

[a] Polythene screen closed except when opened to limit humidity or temperature (before 7 Feb.)
[b] Polythene screen permanently open (after 6 Feb.)

The comparison of the heat consumption of the compartments during the day (Table 14) showed that A had the lowest value, probably due to its relative insensitivity to easterly winds. Compartment E required 10% more heat than compartment G when the polythene screens were in use by day and 14% more when they were not. This is consistent with the more reliable results obtained during the night on the relative heat consumption of the inner and outer compartments of the linear block.

A more satisfactory estimate of the performance of the polythene screens can be made during the day than was possible at night. In compartments E and G, the screens were used during the day until 6 February, but not thereafter. Comparing the values of heat loss per unit surface area before and after 6 February, shows the screens reduced the rate of heat loss by 36 and 34% in the two compartments respectively (Table 14). When the polythene screens were closed, however, the average day temperature was 1.3 °C higher than when they were open (Table 15). It is assumed this occurred because of the improved retention of absorbed solar energy and was not due to additional heat from the heating system. Comparing the daytime heat loss data of compartments E and G with that of the four compartments in the square block, suggests the polythene screens gave reductions of 17 and 24% respectively. However, the same comments made previously about comparing results between the linear and square blocks apply here and the values of 36 and 34% are considered to be the more reliable estimates of the performance of the polythene screens.

3. Total energy use

The average heat loss from each compartment by day, by night, and in total is shown in Table 16, together with the average lift in temperature in each compartment. The data show that in compartments E and G, heat loss at night was similar both before and after 6 February, whereas the daytime heat loss was 35% less when the polythene screen was in use by day up to 6 February.

The values for total daily energy consumption show that the use of a Tyvek screen at night gave an overall reduction of 39% in energy usage. The polythene screen, on the other hand, apparently gave an overall reduction of 22% in energy usage when it was used continuously night and day, and an overall reduction of 9% when used only at night. There are good reasons for believing the values for polythene are underestimates. Not only do the calculations involve comparisons between glasshouse blocks with different exposure and geometry, it was also shown earlier that the end compartment (E) required 10% more heat than the inner compartment (G) when the screens were in use by day and 14% more when they were not. If allowance is made for this, the overall energy saving from a polythene screen used in the manner described, would be increased to 26% when used night and day, and 16% when used only at night.

Table 16. Daily heat loss per unit surface area (MJ m^{-2}) and temperature lifts (K)

Compartment	A	B	C	D	E[a]	G[a]	E[b]	G[b]	H
Day									
Energy	2.39	2.88	2.92	2.61	2.25	2.04	3.51	3.07	3.12
Temperature	15.01	14.75	14.99	15.10	15.49	15.72	14.20	14.41	14.89
Night									
Energy	1.87	4.17	4.31	1.63	3.59	3.25	3.59	2.85	2.09
Temperature	15.02	14.33	14.55	15.02	14.88	14.81	14.65	14.67	14.99
Total									
Energy	4.26	7.05	7.23	4.24	5.84	5.29	7.10	5.92	5.22
Unscreened		7.05	7.23						
Tyvek	4.26			4.24					5.22
Polythene									
before 6 Feb					5.84	5.29			
after 6 Feb							7.10	5.92	

Average daily energy consumption:	Unscreened	7.14	
	Tyvek	4.57	reduction of 39%
	Polythene		
	(used night and day)	5.56	reduction of 22%
	(used night only)	6.51	reduction of 9%

[a] Polythene screen closed by day except when opened to limit humidity or temperature (before 7 Feb.)
[b] Polythene screen permanently open by day (after 7 Feb.)

4. Conclusions - Energy usage

4.1 Use of the Tyvek screen at night was estimated to reduce the night-time heat requirement of the glasshouse by 60%. The screens on which these assessments were made were in their fourth season of use.

4.2 The effect of the polythene screen was less certain but it was estimated to reduce the heat requirement of the glasshouse by 35% during the day and by between 23 and 29% at night, when used as described with "gapping back" to limit increases in humidity and temperature.

4.3 Estimates of the total daily energy consumption (day and night) indicated that using the Tyvek screen only at night gave an overall saving of 39% while using the polythene screen by day and by night as described, gave an overall energy saving of between 22 and 26%, which was reduced to between 9 and 16% when used only at night.

4.4 At night, the unscreened compartments B and C had significantly higher heat transfer coefficients for east winds (5.91 and 6.09 $W\ m^{-2}\ K^{-1}$) than for west winds (5.58 and 5.58 $W\ m^{-2}\ K^{-1}$) at the same wind speed. Wind direction had no detectable influence on the heat transfer coefficients of the screened compartments.

4.5 During the day, the heat requirement of the unscreened compartment A was not as affected by easterly and southern winds as the other compartments.

4.6 The heat requirements of the end compartment (E) of the linear block were 16% higher than an inner compartment (G) at night, and 10-14% higher during the day.

Plan of nursery

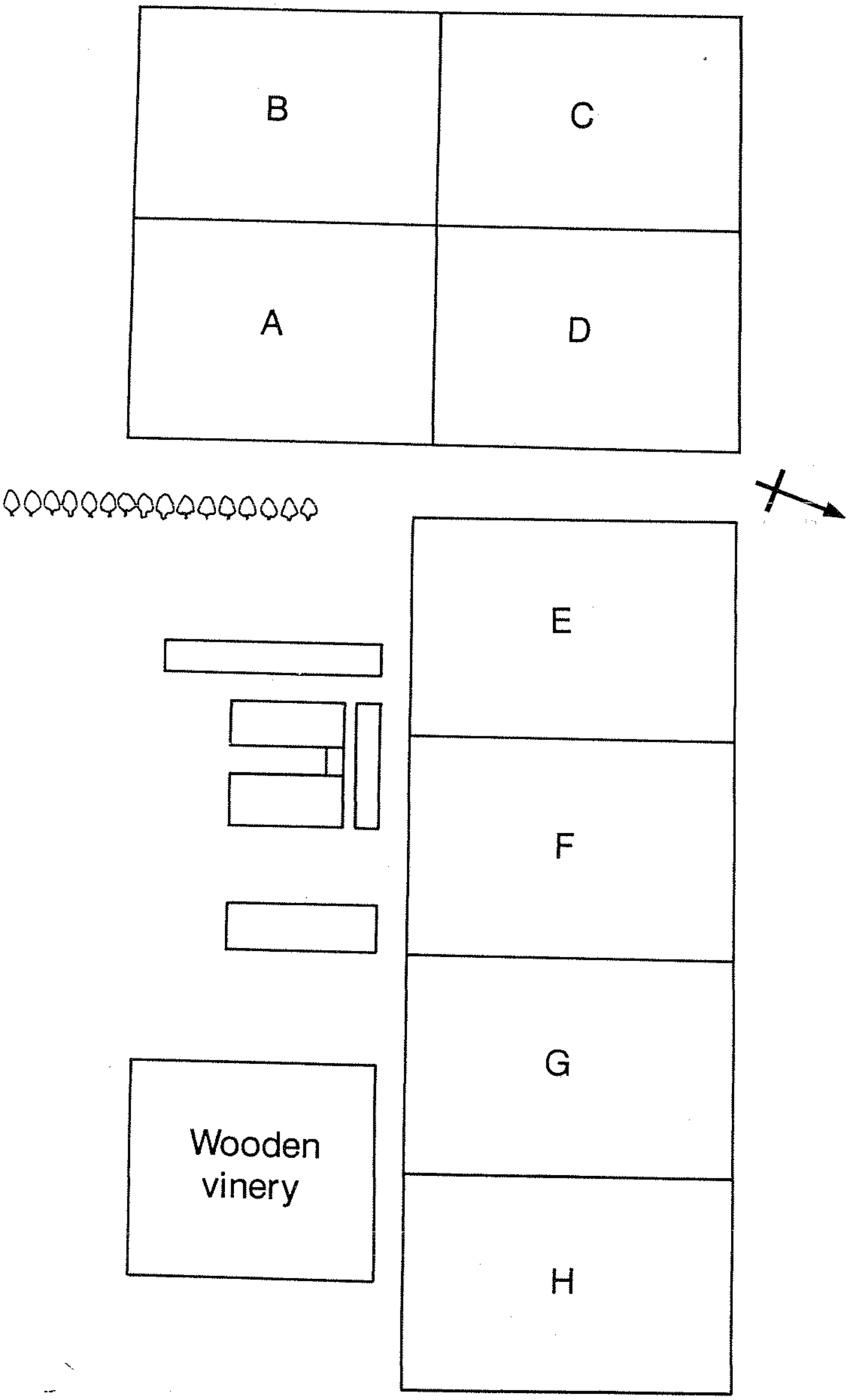

Fig 2. The variation in yield along the linear block of compartments in 1985

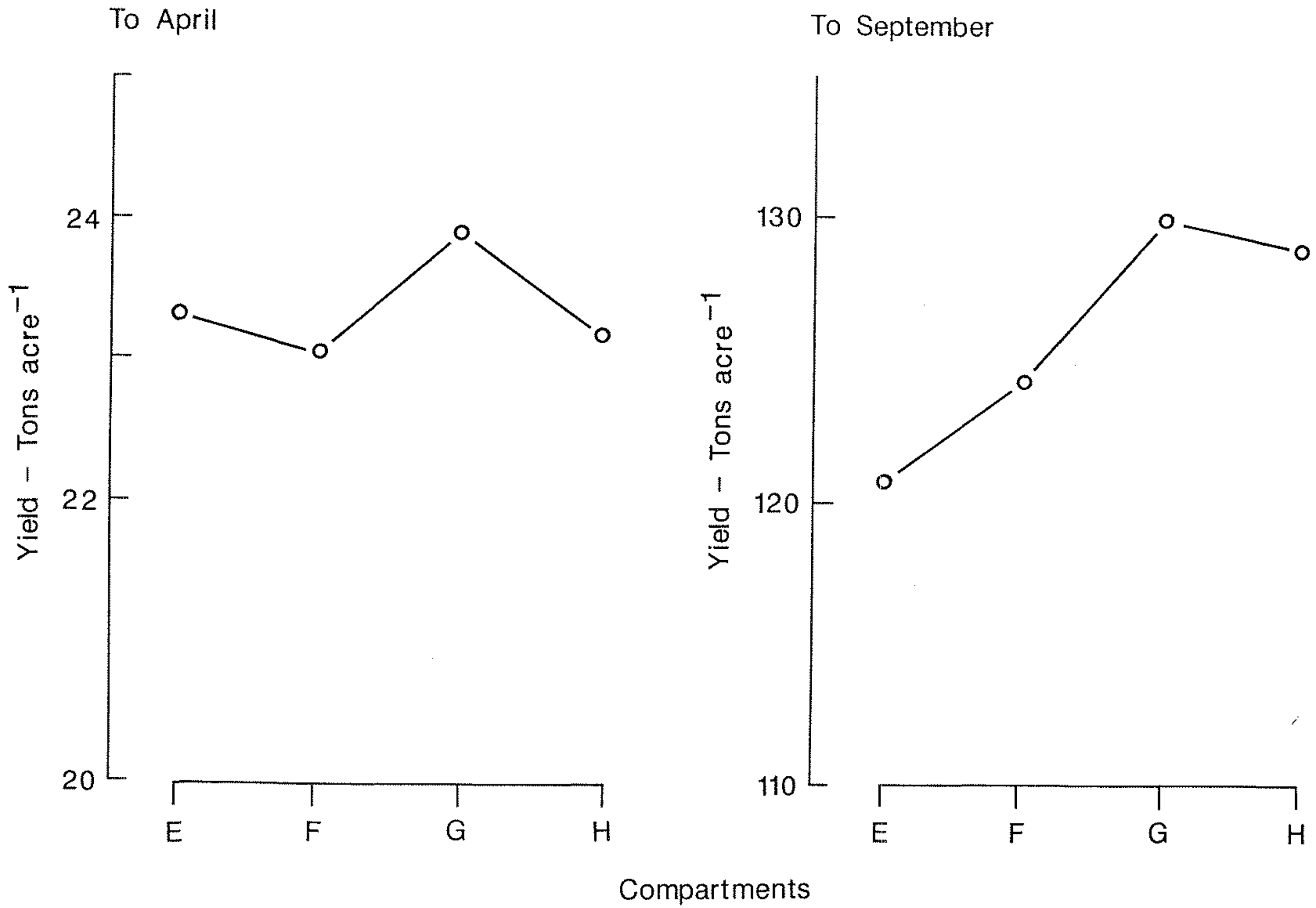

Fig 3. The variation in yield within the square block of compartments in 1985–1987