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THE EFFECTS OF TEMPERATURE ON BEDDING PLANTS

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RELEVANCE TO GROWERS AND PRACTICAL APPLICATION

Application

The objectives of this project were to increase our understanding of the effects of temperature and light on the growth and development of bedding plants. Particular emphasis was placed on quantifying responses to a wide temperature range and developing sowing date schedules. Plants considered were pansy, primrose, petunia, impatiens and geranium. The results showed that a plants response to temperature is diverse and complex. Generally, time to flowering was increased with higher temperatures, but quality was enhanced by lower temperatures. Schedules were developed that can be used by growers to determine sowing dates for crops of pansy, geranium and petunia. Growers can also apply the results to determine optimal growing conditions for each of the crops studied.

Summary of Implications for Growers:

This study has clearly demonstrated some of the complexities of plant responses to temperature. The most notable effect was that the optimum temperature conditions for various aspects of plant growth varied within a species and between species. Though generally the optimum temperature for maximum quality was lower than the optimum for flowering. Thus, a dilemma exists in selecting the correct set point temperature that optimises quality, but also increases output and minimises fuel consumption. Furthermore, in the majority of bedding production a range of species are grown in the same greenhouse, so the set point temperature has to be optimal for all the species grown, or at least not detrimental to growth of any one of the species mix. This project has gone a considerable way to addressing these questions. Growers can now begin to predict the effects of growing plants at a range of temperatures. The optimum temperatures that maximise profit have yet to be determined. We intend to address this problem in the next phase of the project.

Summary of Crop Responses:

4.1 Pansy

This study has improved considerably our understanding of the effects of the environment on the growth and development of Pansy. Much of this increased understanding can be applied to the benefit of growers. The work has shown that for general plant culture, temperatures above 14°C will lead to a rapid reduction of plant quality, since flower size is reduced and plant height increased. These reductions in plant quality were found to be predictable. Models of the effects of the environment on Pansy quality have, therefore, been developed. These can be applied to predict fresh weight, leaf area, leaf number, branch number and flower size in response to any set of environmental conditions. It is hoped that a program containing these models will be released in the near future. A cropping schedule has also been developed for Pansy. The relationship can be used to predict the maturity of any crop. The study has also shown that potential exists for using night break lighting on Pansy to decrease flowering, since Pansy was found to be a long day plant. However, the economics of such growing regimes and the effects on plant quality need to be investigated.

4.2. Primrose

This study has indicated a number of the factors that affect flowering and quality of Primrose. Quality, in terms of plant leaf area (large leaf areas being considered as representing poor quality) was affected by sowing date and temperature, such that late sowings and cool temperatures (approx. 10°C or less) led to smaller leaf areas. However, cool temperatures led to delays in flowering as well an increased cropping duration (i.e. time from 10 to 90% plants in flower). Blindness, i.e. the failure of plants to flower, was only noted in plants sown in July and grown at temperatures above 20°C. Surprisingly, late sowings (September) produced no blind plants and matured late, in April. Maturity dates in April are desirable since plants could be scheduled for the Mother's day market rather than for January and February as present. Thus, the project has indicated the potential for opening new markets. However, many of the factors that affect time to flowering are unknown (such as light and photoperiod), thus further work will be required prior to the development of sowing date schedules.

4.3 Geranium

This study has shown that geranium are very sensitive to temperature. Temperatures higher than 26°C were found to induce chlorophyll degradation. Thus, geraniums should not be produced in poorly ventilated structures during the summer. Quality was reduced at either cool (<15°C) or warm (>24°C) temperatures. The response to temperature in terms of quality was found to be quantitative and quite predictable. Unusally plant height was greatest at cooler temperatures (<20°C). Time to flowering was found to be very sensitive to temperature, but also light integral and photoperiod, such that geranium were found to be a long day plant. This suggests some potential may exist for the use of night break lighting to hasten flowering by about two weeks. A production schedule has also been produced. The relationship to derive the schedule can also be used to predict maturity dates of different batches of the crop. Further work required will be the development of schedules for a wider range of varieties.

4.4 Impatiens

A considerable amount of information has been gathered on the factors affecting the growth and development of Impatiens. The data showed that optimum quality was obtained by growing the plants between 16 to 20°C. Temperatures of approximately 18°C were also observed to produce good leaf colour and zonation. Increasing temperatures tended to reduce plant compactness and cause flower abortion. Temperatures below 15°C severely retarded growth. Thus, a greenhouse that contains a mix of bedding species, including Impatiens ought not be set at temperatures of less than 15°C. The data also showed an effect of temperature on time to flowering, with an optimum temperature for fastest flowering at 24°C, but there is still no explanation why plug raised plants tend to flower prematurely. Thus, prior to the development of any schedules further work is required to understand factors affecting flowering, in particular abortion.

4.5 Petunia

The optimum temperature for maximum quality tended to be slightly lower for Petunia than Impatiens or Geranium. Maximum quality in terms of compact, short plants, with long branches and large leaf areas were noted at temperatures between 14 and 18°C. Quality was very sensitive to higher temperatures, such that increasing temperatures above 22°C led to rapid reductions in plant quality and compactness. However, time to flowering was also very responsive to temperature, such that time to flowering was prolonged from 66 days at 22°C to 76 days at 18°C. Thus, a trade off exists, as with the other species examined, between maximising quality and reducing cropping time. Photoperiod also affected time to flowering, such that flowering in plants grown in long days (15h) was 10-14 days earlier than others in short days (9h). A sowing schedule has been developed for Petunia. This considers the combined effects of temperature and photoperiod on time to flowering.

This study has made considerable progress to realising the following benefits for the industry;

i) The development of accurate crop schedules and thereby a reduction of wastage.
ii) Identification of the optimal temperatures for crop growth.
iii) Increased understanding of the effects of temperature on plant quality.
iv) The identification of new marketing opportunities.
v) The prediction of the maturity date.

The financial benefits of research to the industry are always difficult to quantify, but here they may be substantial, since a reduction in wastage of only 1% through improved scheduling equates to a saving of £2.5 - £4.0M. On top of the benefits gained that are listed above, this study has also provided a sound framework for further studies on the effects of environment on growth and development of bedding plants.

Further work, funded by MAFF and the HDC is now in progress to both consider the effects of temperature on a wider range of species and cultivars, and to clarify some of the more poorly understood responses noted here.

1. INTRODUCTION

Temperature is an environmental variable over which growers of protected crops have a considerable degree of control. However, although it has been the subject of considerable research, the effects of temperature on the growth and development of many plant species are still poorly understood. This is largely because plants respond to temperature in complex ways; for example, the optimum temperature for vegetative growth may not be the same as that for flowering. Also, previous experimental studies have tended to be limited in scope, considering only a few arbitrarily chosen temperature regimes and often over only a limited period of plant growth. Consequently, these studies have tended to give only a limited representation of plant responses. In addition, the interaction between temperature and other environmental variables such as light and daylength has been poorly described. Finally, as there are a vast range of commercially important bedding plant species, a general limitation of resources has meant that experimentation on each individual plant species has tended to be restricted.

The objectives of this HDC funded study were, therefore, to gain a better understanding of the effects of temperature, as well as other environmental factors such as light level and daylength, on the responses of five important bedding plant species, impatiens, geranium, pansy, primrose and petunia.

The potential benefits of this work include;

i) The development of accurate crop schedules with a consequent reduction in crop wastage.
ii) Identification of the optimal temperatures for crop growth.
iii) Increased understanding of the effects of temperature on plant quality.
iv) The identification of new marketing opportunities.
v) The prediction of the maturity date, so that sales can be prearranged.
vi) Optimising the use of fuel.

In economic terms, it has been estimated that a reduction in wastage by a mere 1%, that may be achieved by improved scheduling, will lead to a saving of approximately £2.5 - 4.0M.

The study will use modern mathematical modelling techniques to quantify plant responses to a wide range of temperatures. This modelling approach is being used increasingly, most notably in America, where numerous models have been developed to describe effects of environment on crops such as chrysanthemum and poinsettia. The advantages of modelling are that crop responses to the environment become predictable and models can be used as a tool for analyzing complex sets of data, such as those found here.

1.1 Review of Current Knowledge

1.1.1 Pansy (*Viola* X *wittrockiana*)

The value of the market for pansies is estimated at £20M. Currently, during the winter pansies are grown in cold greenhouses, in the summer they are frequently grown outdoors, with no environmental control.

There have been remarkably few studies on the growth and development of Pansy. The earliest by Withrow and Benedict (1936) showed that the close relative *Viola tricolor* was a long day plant; in that plants flowered after 123 days when daylength was extended to 21h d^{-1}, but plants in short days required 178 days prior to flowering. Hughes and Cockshull (1966) also report observations that flowering of *Viola tricolor* is earlier when night break lighting is applied. However, growers have suggested that the modern Pansy is largely day neutral. This is also indicated by the fact that pansies are a winter bedding plant, which flower even in the short days of winter.

Little is known regarding the flowering responses of pansies to temperature. Merritt and Kohl (1991) showed that pansy cv. 'Universal Mix' grown at a mean diurnal temperature of 21°C flowered 15 days earlier than those grown at 13.5°C. The optimum temperature for time to flowering has not been determined. Recent work at Efford has also shown that pansies are responsive to DIF (L. Sach *pers comme*). Effects of temperature on flower size, compactness, plant height, branch production and leaf area have not been studied.

1.1.2 Primula (*P. vulgaris* or *P. acaulis*)

Primula is an important winter bedding species worth an estimated £25M per annum. It is currently grown in cold greenhouses, with frost protection. Continuity of production is by sowing over a prolonged period and with a range of varieties that mature over an extended period. A reported problem with late sowing dates is blindness, whereby plants do not flower.

There have been very few studies on the effects of temperature on the growth and development of *P. vulgaris*. Welander and Selander (1981) examined the effects of temperature and photoperiod on the maturity of Primula grown in growth cabinets. They showed that *P. vulgaris* had an optimum temperature for flower initiation between 12 and 15°C. Flowering was delayed at a lower temperature of 9°C. They also showed that at lower temperatures (9°C) the spread in time to flowering of a population was greatly increased. *P. vulgaris* was also found to be a short day plant, but at 12°C decreasing the daylength from 16 to 9 hours only reduced the time to flowering by about 10 days. Karlsson and Hanscom (1993) have also shown that the optimum temperature for time to flowering is in the order of 14°C.

Other studies have examined the close relative *P. malacoides*. Post (1937) showed that *P. malacoides* grown at 10 to 15°C flowered 7 days earlier than those at 15 to 21°C. Runger and Wehr (1971), again on *P. malacoides*, examined the responses to temperature and daylength on time to flowering. They showed that the optimum temperature for time to flower initiation was 11°C. However, from initiation to flower opening the optimum appeared to be higher at 20°C.

For *P. denticulata, P. juliae, P. rosea* and *P. sieboldii*, Encke (1960) and Steib (1981) recommend a period of cold (6 to 8°C) for flowering. However, this may not be the case for *P. malacoides*, since plants at 11°C flowered earlier than those at 5°C (Runger and Wehr, 1971). Runger and Wehr also showed that *P. malacoides* was a short day plant, however, at temperatures of 11°C and below, reducing the daylength from 16 to 8 hours only shortened the time to flower initiation by about 4 days. Plants became more sensitive to short days at temperatures above 11°C. This explains why Primula do not flower in the summer, since when temperatures are high they require short-days for flowering.

1.1.3 Petunia (*P. X hybrida*)

Petunia is known to be a long day plant for time to flowering (Piringer and Cathey, 1960). Photoperiod also influences plant quality, in that plants in long-days tend to be tall and produce less side shoots than in short days (Piringer and Cathey, 1960). Temperature has a dramatic influence on time to flowering, such that at 26°C Petunia cv Snow Cloud require 48 days to flowering compared to 75 days at 14°C (Kacperski *et al.*, 1991). These authors also showed that the number of side shoots decreases with increasing temperature; 8 side-shoots compared to 4.5 were recorded at 14 and 26°C respectively. Cooler temperatures also reduces plant height (Kacperski *et al.*, 1991 Merritt and Kohl, 1991).

1.1.4 Impatiens (*I. wallerana*)

There is remarkably little information on factors affecting the growth and development of *Impatiens*, even though it is one of the most popular bedding plants. Zimmer (1980) showed that a temperature of 14 - 18°C produced plants with the best foliage colour, but flowering and bud formation were greatest at 18°C. Merritt and Kohl (1991) examined the effects of low night temperatures on the growth and flowering of *Impatiens*. They found that at a 27° day / 7° night temperature combination growth was severely stunted and flowering occurred 54 days later than at a 27/18° temperature combination. In terms of their photoperiod response, Hendriks and Ludolph (1992) stated that the plants were day neutral.

1.1.5 Geranium (*Pelargonium X hortorum*)

Of all the bedding plant species, Geranium has received the most attention. Hendriks and Ludolph currently recommend a growing temperature of 17 - 19°C. Time to flowering decreases with increasing temperature (Armitage *et al.*, 1981; Hopper *et al.*, 1985; White and Warrington, 1988; Welander and Hellgren, 1988). Hopper *et al.* (1985) report that the optimum temperature for shortest duration to flower initiation is 25°C compared to 27°C for floral development. This contrasts with Regal pelargoniums (*P X domesticum*), which require a period of cool temperature (10-12°C) before flowers are initiated (Nilsen, 1974; 1975). High temperatures also reduce the number of flowers and increase the leaf number and plant height (Welander, 1983; White and Warrington, 1988). A model of the effects of temperature on the growth and floral development of geraniums has been described by Hopper *et al.* (1985). Although the model accurately predicted vegetative growth, it was a poor predictor of time to flowering.

Geranium is considered to be day-neutral for flowering, however, flowering is delayed by low light integral (Armitage *et al.*, 1981; Welander and Hellgren, 1988; White and Warrington, 1988). White and Warrington (1988) reported that no flowering occurs at light integral of 3.3mol.d^{-1}.m^{-2} (equivalent to a February day) and below, but increasing light above 13 mol.$d^{-1}m^{-2}$ (equivalent to an April day) has little extra effect on time to flowering. Increasing light level leads to an increase in the number of flowers per plant, dry matter accumulation and leaf number (Wellander and Hellgren, 1988).

1.2 Outline of Experimental Plan

The objectives of this study were to examine the effects of a wide range of photo-thermal environments of the growth and development of these crops, and to develop mathematical models of their responses. Plants were grown at six temperatures and with a range of sowing dates. Time to flowering and aspects of plant quality were measured. Further experiments, part funded by the University of Reading, were performed on Pansy, in order to obtain a deeper insight into the growth of this species. Factors examined were the effects of temperature and photoperiod on time to flowering and final flower size.

2. MATERIALS AND METHODS

2.1 General Plant Culture

For all experiments, seed were sown in standard seed trays containing a proprietary peat based compost (Shamrock potting compost), and germinated in a Conviron S10H growth cabinet at a constant temperature of 17 ± 0.5°C with a 12 hour daylength and an irradiance of $150\mu mol.m^{-2}.s^{-1}$, provided from warm white fluorescent and supplemented with 33% tungsten light, determined on the basis of nominal wattage. Seedlings were maintained under growth cabinet conditions for three weeks, by which time the cotyledons had fully expanded and the first true leaf was emerging. Plants were then pricked out, into a Plantpak P84 plug-tray (volume of each cell, 40ml). When the plugs could be easily pulled from the trays without disturbing the roots, plants were transferred into 9cm pots .

For all experiments, plants were irrigated as necessary and fed twice weekly with a 200ppm solution of soluble fertiliser (Sangral 101). Biological control of white fly, thrips and red spider mite were used through-out. For the control of Scarid fly, Fernex was incorporated into the compost at a rate of 34g per 80l. Pots were re-spaced when the canopy closed, until they reached the final plant density of 40pots m^{-2}.

2.2 Experiment 1. The effect of temperature and sowing date on the time to flowering: Natural photoperiods.

This main experiment was conducted in the inner six, of a linear array of eight, 3 x 8m temperature controlled glasshouse compartments. The experimental compartments had set-point heating temperatures of 4, 10, 14, 18, 22 and 26°C. Ventilation occurred at temperatures 4°C higher than the set-point. The actual mean diurnal temperatures were recorded on a Combine data-logger (Murdoch, 1985), from measurements recorded with thermistors mounted within an aspirated screen within each compartment. The sowing dates of the various species are presented in table I.

Table I. Sowing dates used in experiment 1.

Plant Species	Sowing Dates
Pansy 'Universal Violet'	10.7.92
	4.9.92
	10.11.92
	23.12.92
Primrose 'New Europa Blue'	10.7.92
	4.9.92
Geranium 'Century Rose'	12.2.93
	8.3.93
	26.3.93
Impatiens 'Super Elfin Blue Pearl'	8.2.93
	1.3.93
	22.3.93
Petunia 'Express Blush Pink'	8.2.93
	1.3.93
	26.3.93

At each sowing 30 replicate plants of each species were grown in each temperature compartment. For Pansy and Primrose, measurements were made continually throughout the growth of each crop. Thus, at each measurement six randomly selected plants were dissected and fresh weight, leaf areas, branch numbers and flower numbers were determined. For the Spring crops, six plants were randomly selected, at 50% flowering, and measurements made to assess plant growth. All data presented graphically, unless stated otherwise, represent the means from the six selected plants. Regression analysis was used to analyze the data.

2.3 Experiment 2. Effects of photoperiod on time to flowering of pansy.

A further greenhouse experiment was conducted to examine the effects of photoperiod on time to flowering of pansy. These data form an essential component of the plant scheduling model. Pansy were grown at one of four daylength, 8, 10.6, 13.3 or 16 hours per day. Two temperature treatments were also imposed, 10 or 20°C night temperature, both combined with an 18°C day temperature. Time to flowering were measured.

2.4 Experiment 3. Effects of temperature on final flower size of pansy.

The objectives of this experiment were to determine when final flower size in pansy, is sensitive to temperature. This experiment, using reciprocal transfers, was conducted in Conviron S10H growth cabinets set at constant temperatures of 10°C and 25°C (± 0.5°C). An irradiance of $150\mu mol.m^{-2}.s^{-1}$ was provided by warm white fluorescent supplemented with 33% tungsten light, determined on the basis of nominal wattage, with a 14 hour daylength. All bulbs were renewed immediately prior to start of the experiment. Forty-nine seedlings were placed inside each growth cabinet on 21st April 1993. Three series of reciprocal transfers were made when the first flower bud, on the main stem, had attained a length of 5mm (visible bud), when both the flower bud was horizontal to the soil surface and the peduncle had started to expand and finally prior to anthesis when the corolla had started to show colour. Transfers were made when individual plants had attained the desired developmental stage. For each transfer, seven randomly chosen plants from each cabinet were moved to each of the other cabinets and remained until anthesis. One set (7 plants) of common controls, i.e. those plants that were not transferred but remained in the same compartment throughout.

To offset positional effects within the cabinets, plants were re-randomised on two occasions. Each plant was monitored at two day intervals and the date of anthesis of the first flower was recorded. Flowers were removed from the plants four days after anthesis, by which time the corolla was fully expanded, and areas were then measured on a Delta-T leaf area meter.

3. RESULTS AND DISCUSSION

3.1 Pansy

The effects of temperature on the growth and quality of pansy grown at one of four different temperatures are shown on Plate 1.

3.1.1. Time to flowering

The time to flowering in pansy was found to be modulated by three environmental factors, temperature, photoperiod and light integral, which act in a complex but quantifiable manner.

i) Photoperiod

Plants at 16hd^{-1} flowered 16 days earlier than those at 8hd^{-1} (see figure 1), indicating that pansy are a weak long day plant. These experiments also revealed that a large proportion of the variation in the time to flowering (i.e. time from 10-90% flowering) amongst a population is brought about by growing plants in short days (see figure 1). This information is important in two ways; firstly, it shows that there **may** be potential for giving the crop brief periods of night break lighting to increase crop uniformity and to bring forward maturity, and secondly, there is potential for breeding a day-neutral pansy, since some of the plants grown under short days flowered at the same time as those under long-days. Breeding a day neutral pansy would be desirable, as presently pansies are grown under short winter days, whilst it is adapted to long-days and therefore time to winter flowering is prolonged.

Plate 1. The effect of temperature on the quality of Pansy cv. Universal Violet. The temperatures shown on the photograph are set point temperatures.

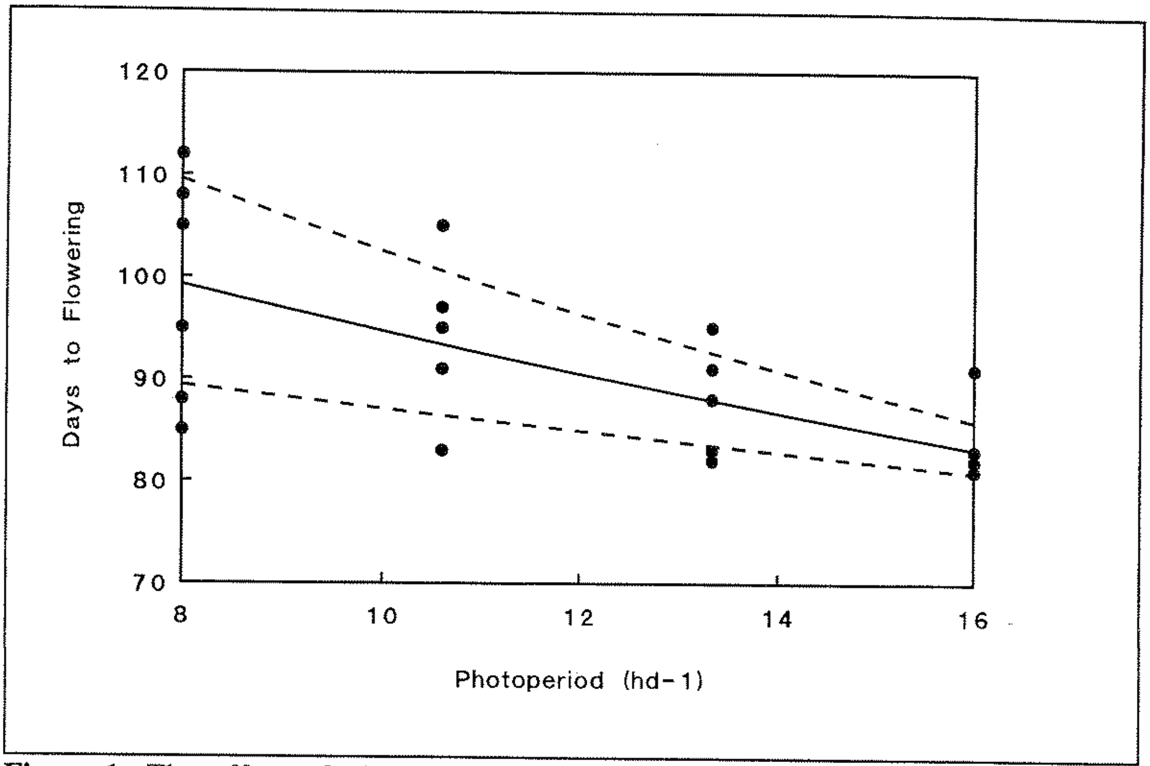

Figure 1. The effect of photoperiod on the time to flowering of Pansy 'Universal Violet'. Each point represents a single plant.

ii) Temperature

Increasing the temperature reduced the time to flowering in pansy, however, the response was relatively weak. For example, pansy Universal Violet grown, in growth cabinets, at 10, 17.5 and 25°C required 88, 84.8 and 82 days for flowering, respectively.

iii) Light integral

Based on our experiments at controlled photoperiods and temperatures we produced a model to determine sowing schedules for pansy. To examine the accuracy of the model over a wide range of conditions, the model was tested on flowering date data gathered from the sowing date and temperature experiment (Expt. 1). However, this validation exercise revealed that a model only accounting for temperature and photoperiod could not accurately predict time to flowering in pansy.

This failure illustrates one of the advantages of developing models since, if a model does not work it indicates that factors you have not considered or researched influence the system. The model was therefore extended and based on the data, from the sowing date experiment, it was clear that the over riding factor influencing time to flowering was light integral (i.e. the total quantity of light received over a day). The analysis revealed that once the daily light integral dropped below $5MJm^{-2}d^{-1}$ (total solar radiation or $2.5MJm^{-2}d^{-1}$ photosynthetically active radiation), which equates to that received on a typical January day, the time to flowering was greatly retarded. A new model for predicting time to flowering was then developed which incorporated the effects of light integral, temperature and photoperiod. The model could predict the maturity date of a crop, given the actual light integral, temperature and photoperiod, to within ±7 days (Figure 2). This is accurate considering that some crops took over 200 days to flower and that the model's maximum theoretical accuracy, given a typical pansy crop, is in the order of plus or minus 2.5 days.

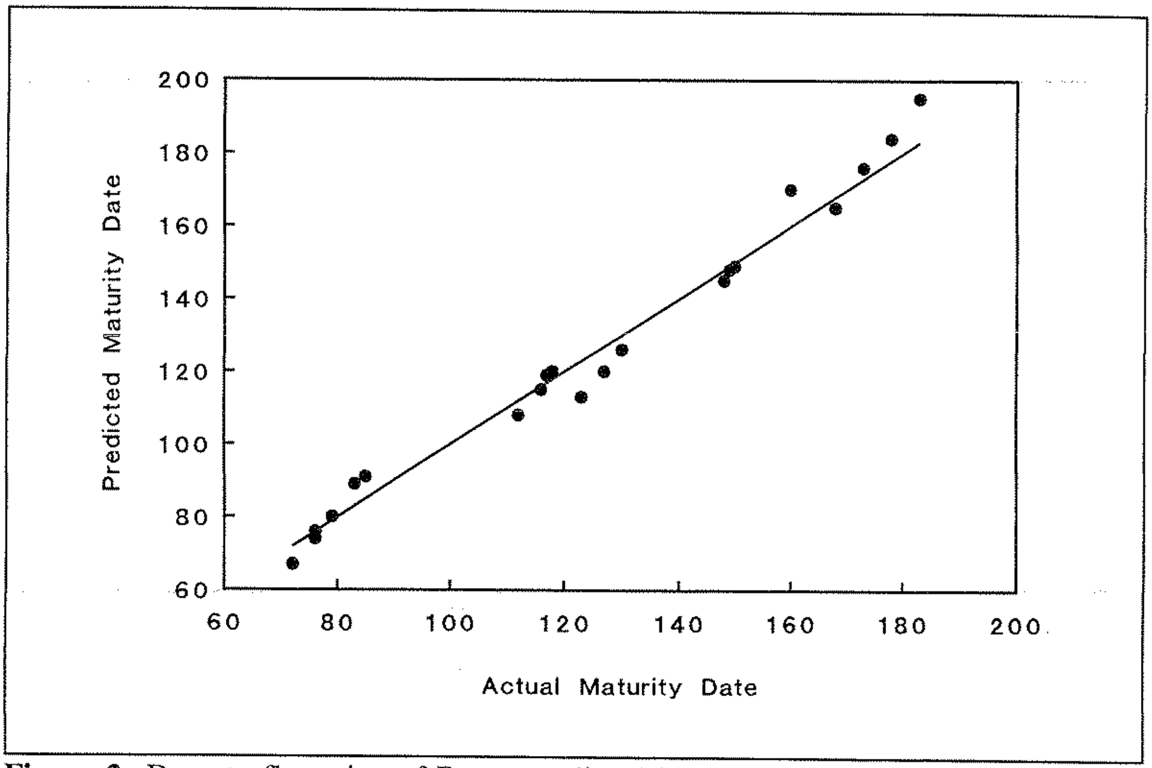

Figure 2. Days to flowering of Pansy predicted by the model compared to the actual 50% maturity dates.

This model was applied to develop a sowing schedule (Figure 3). The model shows that for pansies to mature in the autumn they must be sown by the latest on 3 August, sowing dates 14 days later will result in spring maturities. Such a sharp response is confirmed by previous experiments at Lee Valley EHS.

One of the most useful applications of a model are the prediction of maturity dates. These can be used to assess whether the crop's maturity will deviate from the planned schedule and how the environment could be adjusted to achieve the desired target. The information on predicted maturity dates can also be used to assist with the marketing of the crop. A computer program to enable such forecasts will be forthcoming.

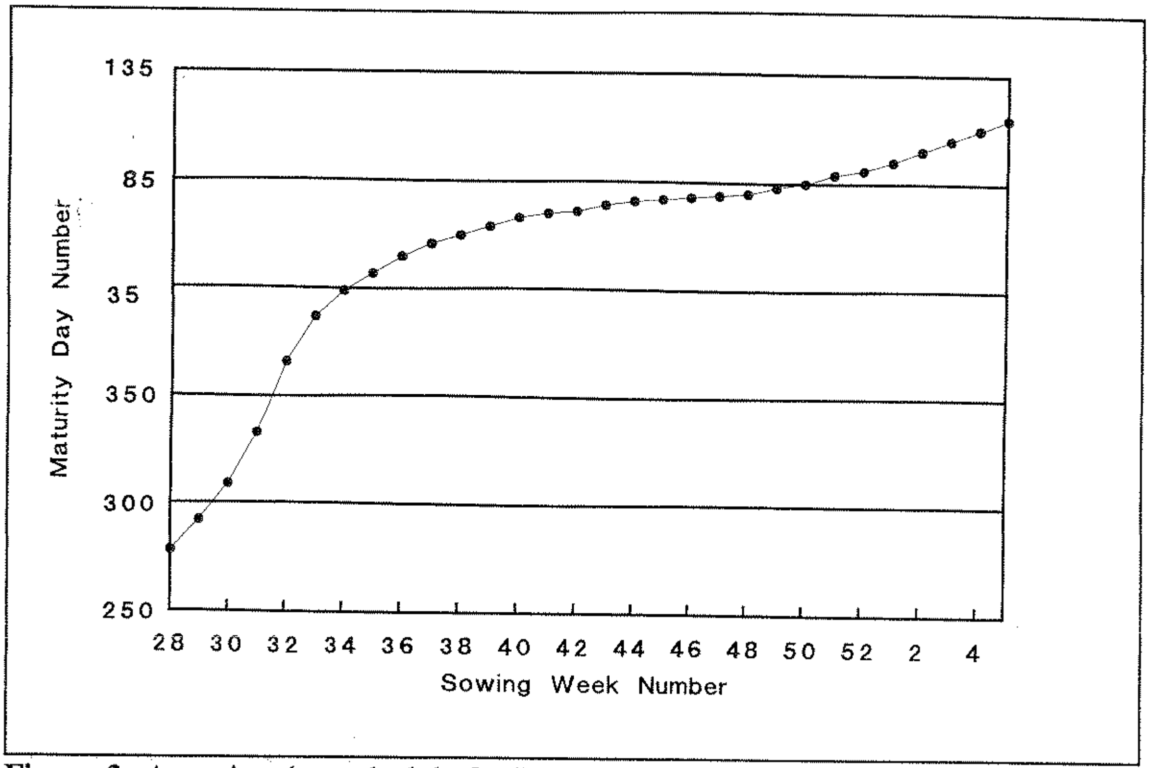

Figure 3. A sowing date schedule for Pansy developed using the flowering model and assuming the glasshouse set point temperature is 10°C.

3.1.2 Flower size

One of the important aspects of pansy quality is flower size. There is no previously published data indicating how or if this is affected by the environment. However, our experiments showed temperature had a substantial effect on final flower size, such that higher temperatures led to smaller flowers (figure 4).

The effect of temperature at different stages of floral development was also examined. This work was conducted to examine whether temperature manipulations during plant growth would affect quality. The experiment was conducted, in growth chambers at 10 and 25°C, by transferring plants between each chamber at one of three different stages of floral development; i.e. floral initiation, flower stalk expansion, showing colour and also an untransferred control. The analysis revealed that the response to temperature was quantitative, such that the longer the plants remained at high temperatures (above 10°C) the smaller the final flower became (Figure 5a). Furthermore, short exposures to very high temperatures (25°C) at any stage of floral development led to reductions in final flower size. The responses were quantified with a simple model which accurately predicted the flower size of pansies grown at a range of temperatures during floral development (Figure 5b). Thus, increasing the temperature after flower initiation to temperatures above at least 10°C, for any duration, will lead to a reduction in final flower size. The magnitude of the reduction being dependent on the temperature and the duration of the exposure.

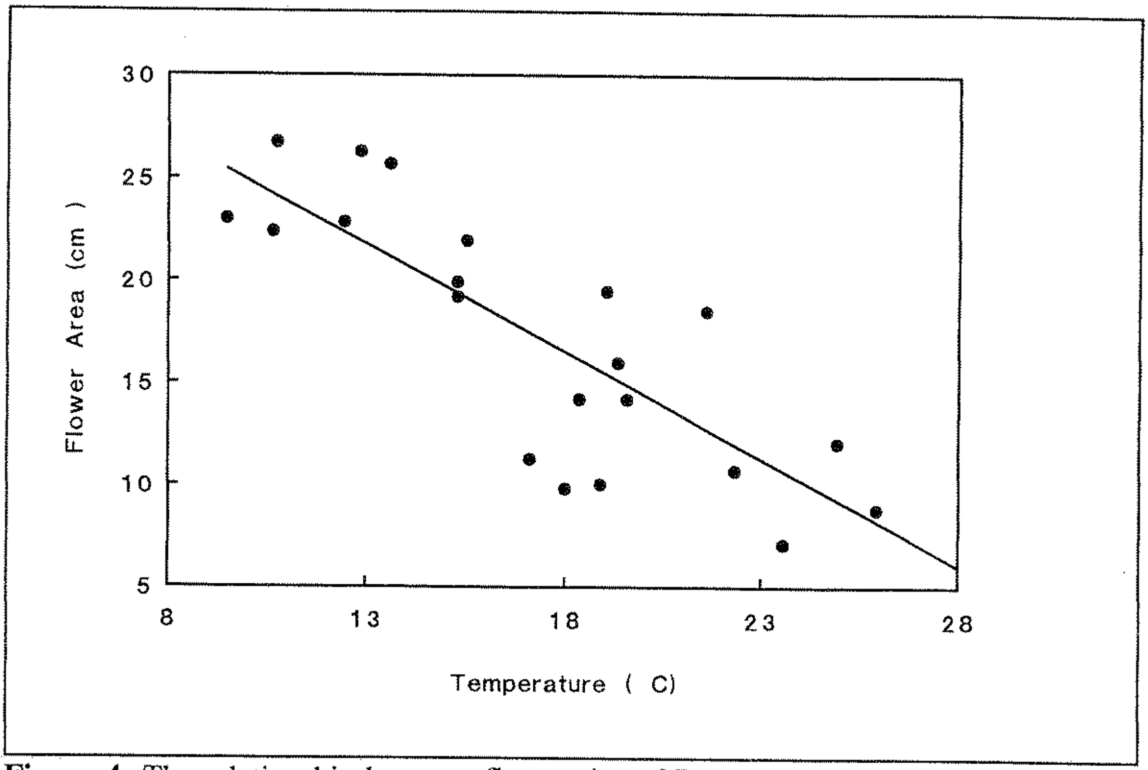

Figure 4. The relationship between flower size of Pansy and mean temperature.

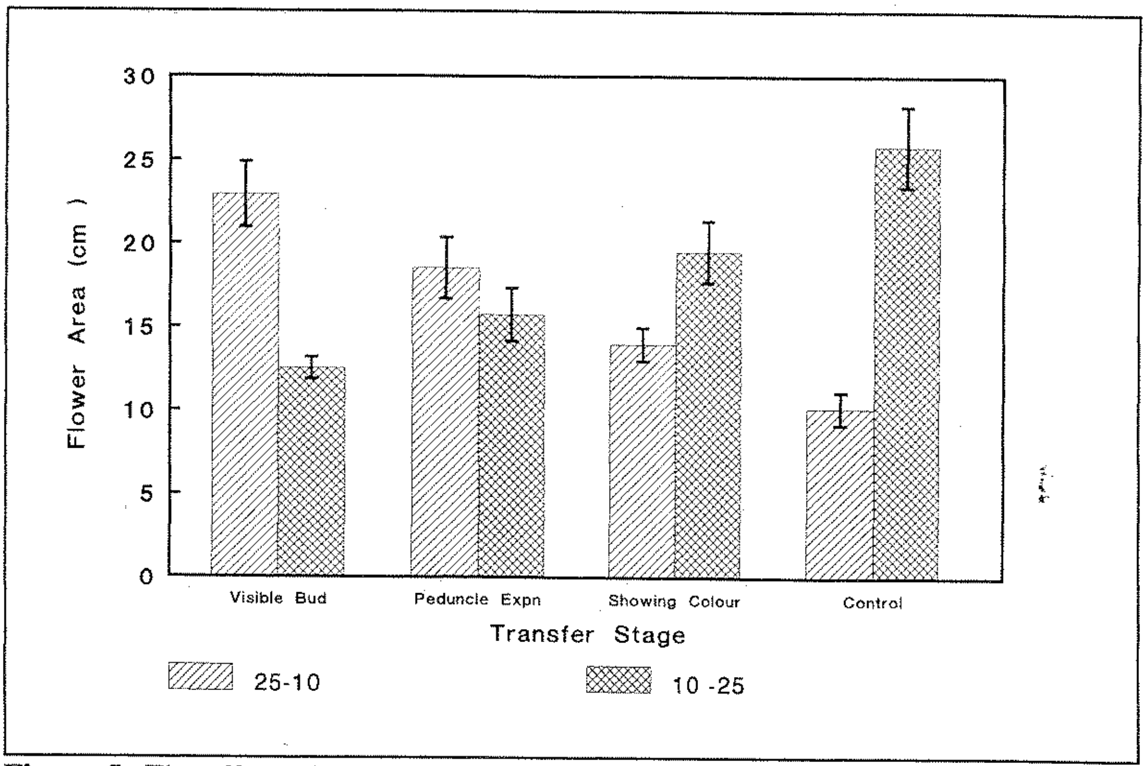

Figure 5. The effect of transfers between a growth cabinet at 10°C to 25°C and vice-versa, at various stage of flower development of Pansy, on final flower size.

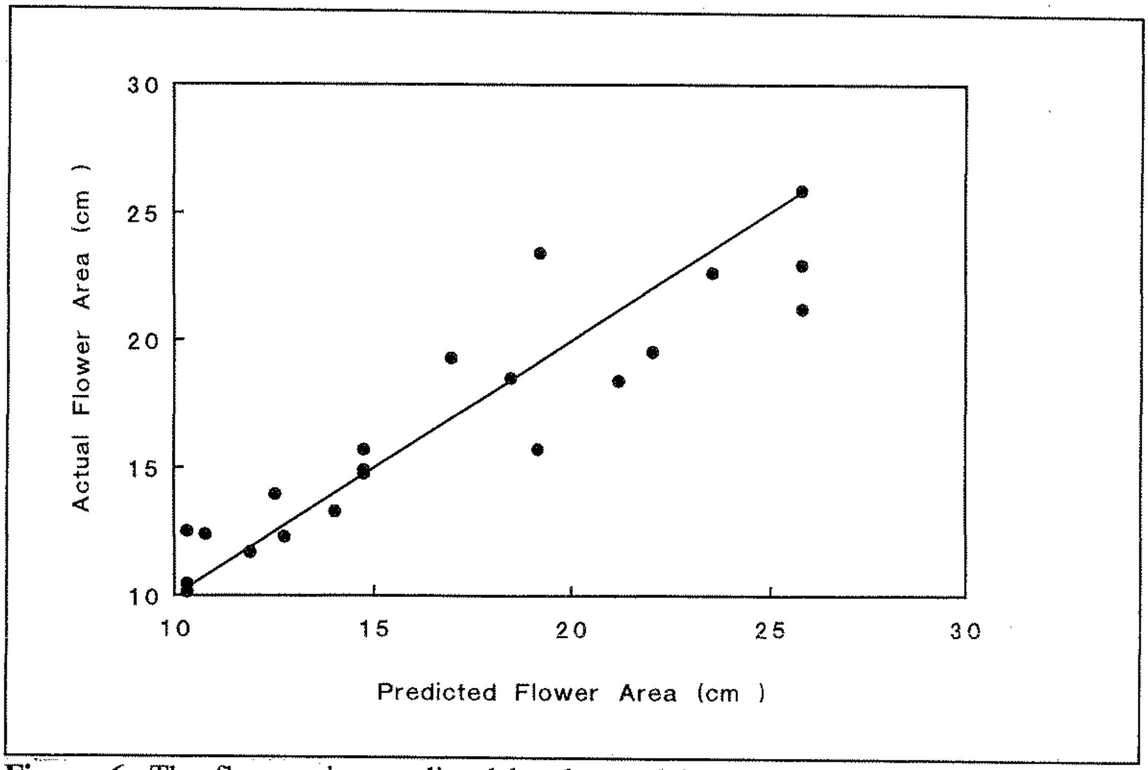

Figure 6. The flower size predicted by the model compared to measurements from Pansy's grown at a range of temperatures.

This work has important implications for both the production of high quality pansies, but also in understanding how the crops temperature can be manipulated during growth. As this response has been modelled we now have the ability to predict the effect of proposed environmental changes on flower size, an important aspect of quality.

3.1.3 Fresh Weight

Temperature had considerable affect on the rate of fresh and dry matter production (figure 7). The optimum set-point temperature for maximising fresh weight production was in the order of 18°C. A similar optimum temperature was also noted for dry matter production.

Light integral also had considerable influence on the rate of fresh and dry matter production. This is illustrated by figure 8 which shows the rate of fresh matter production for pansies sown on two different sowing dates, but maintained at the same set point temperature (14°C). Thus, the July sown plants, which experienced high light levels grew at a considerably greater rate than those sown in September. A model has been constructed to predict fresh weight in response to temperature and light. This model is currently under validation and will be released through a computer program in the near future.

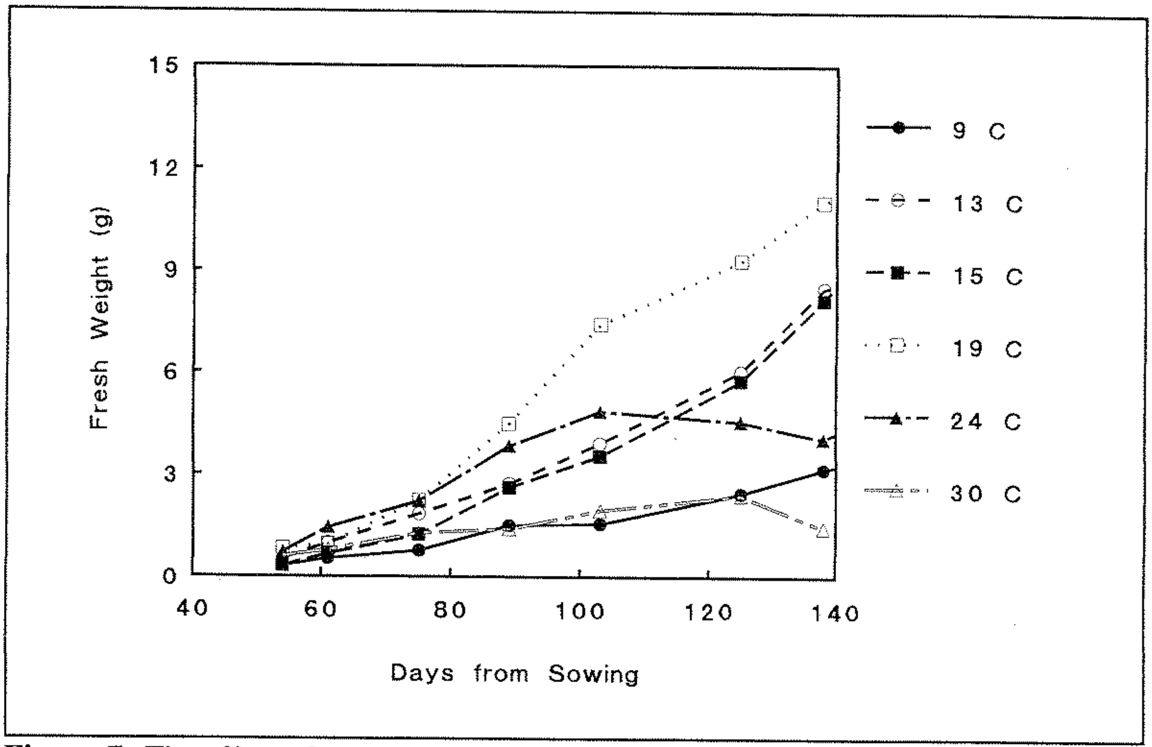

Figure 7. The effect of temperature on the increment in Pansy fresh weight over time.

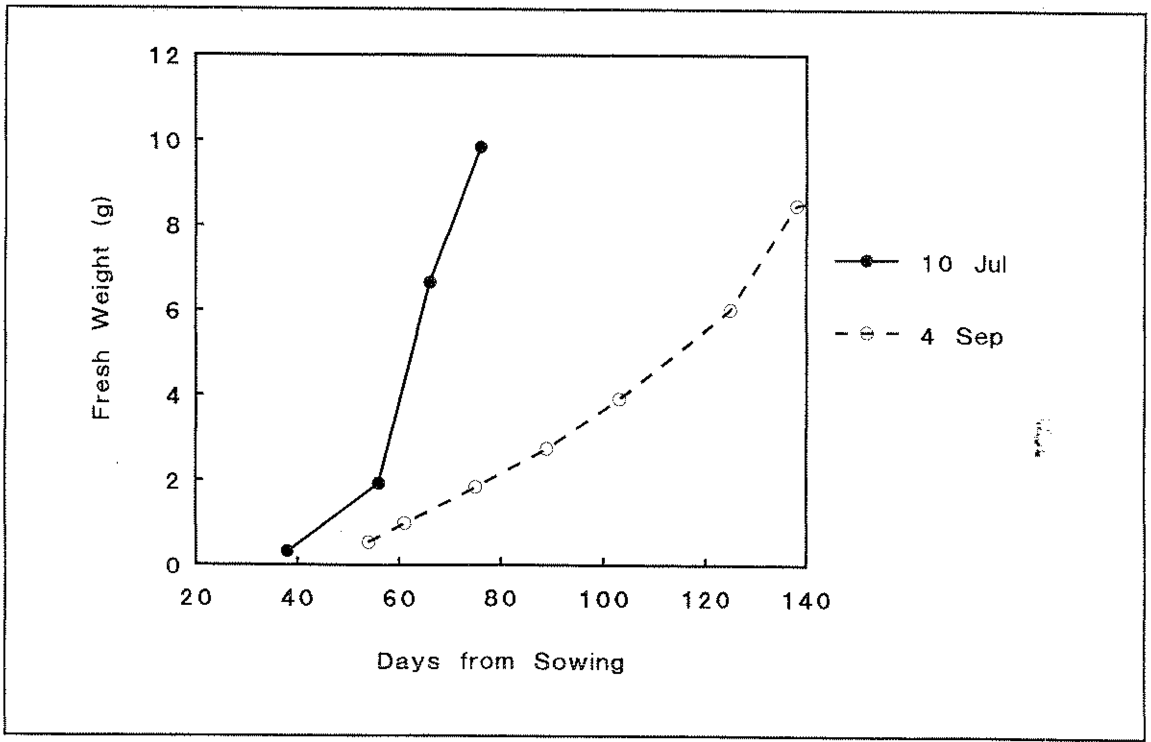

Figure 8. The increase in plant fresh weight over time of two pansy crops grown at the same temperature, but sown on different occasions.

3.1.4 Leaf Area

Temperature and light significantly affected the rate of leaf area expansion in pansy. Leaf area expansion increased up to an optimum of 14-18°C and declined thereafter. This is similar to that noted for fresh and dry matter production, presumably because the majority of the plants mass is in the form of leaves. A model for leaf area expansion in pansy has been constructed and will be released in the near future with the other models for aspects of pansy quality.

3.1.5 Leaf number

The initiation of leaves was again dependent on the temperature and light integral. However, the optimum temperature for leaf production was quite high and in the order of 22°C (figure 9).

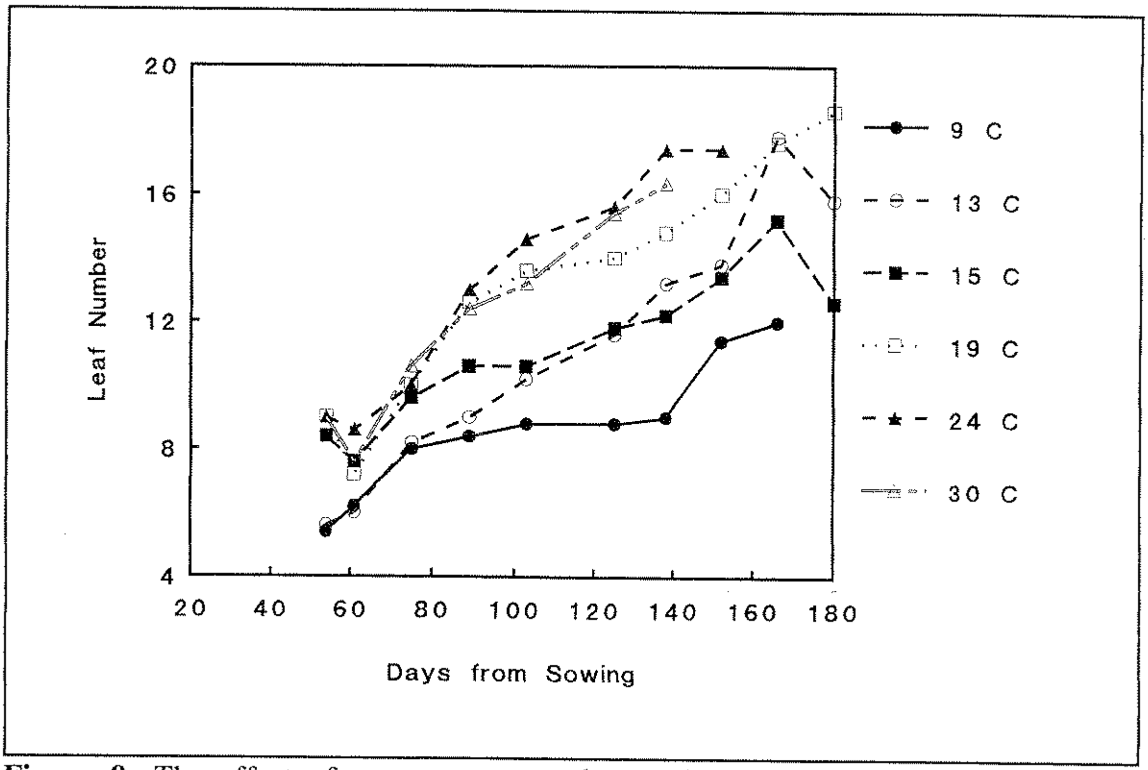

Figure 9. The effect of temperature on the number of leaves produced by Pansy Universal Violet.

3.1.6 Plant Height

Plant height increased at higher temperatures. High temperatures led to considerable extension growth and thus poor quality crops. Quality, in terms of plant height, was unacceptable when plants were grown at temperatures greater than 14°C (figure 10). Of all the aspects of pansy quality prediction of plant height has been the most difficult. This is possibly because pansy plants are known to respond to DIF (Sach *pers comme*), and this factor was not considered in the experimental design.

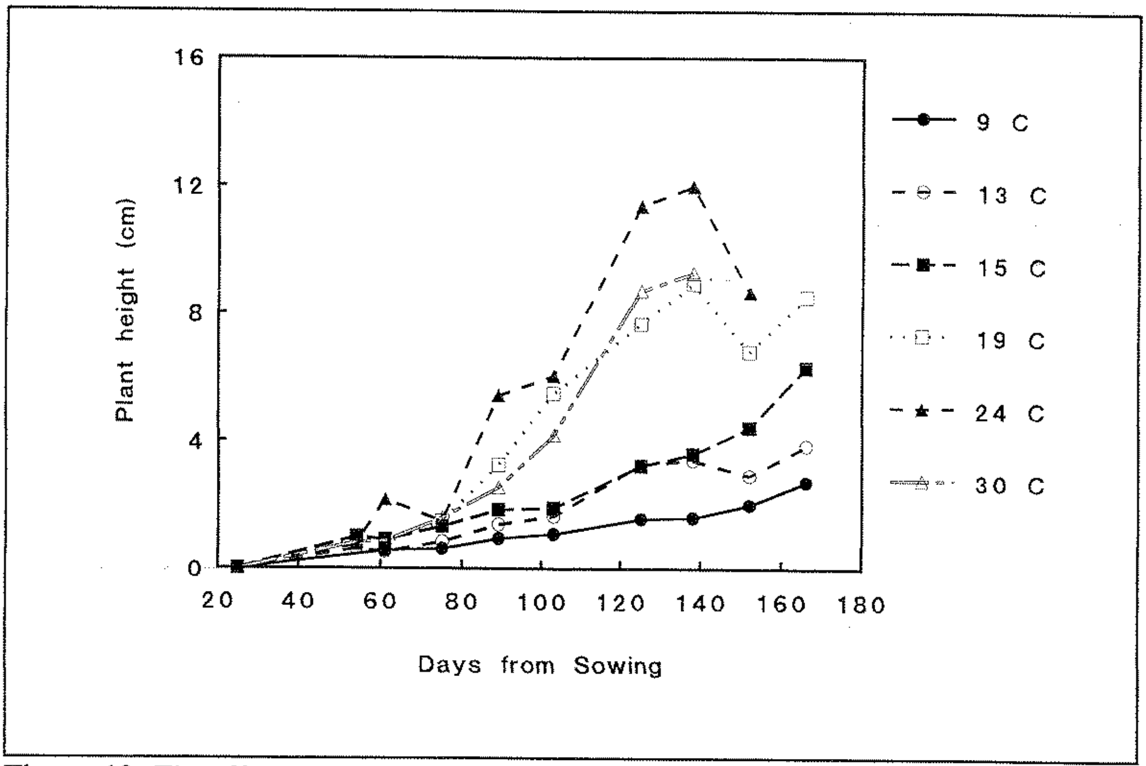

Figure 10. The effect of temperature on the increase in plant height of Pansy over time.

3.1.7 Branching

Temperature had a strong influence on branch production, an indicator of plant quality. The optimum temperature for maximum branch production was low (13.5°C) (figure 11). However, cooler temperatures also led to the production of a considerable number of branches and plants of high quality. The effects of temperature on branching were very predictable and modelled.

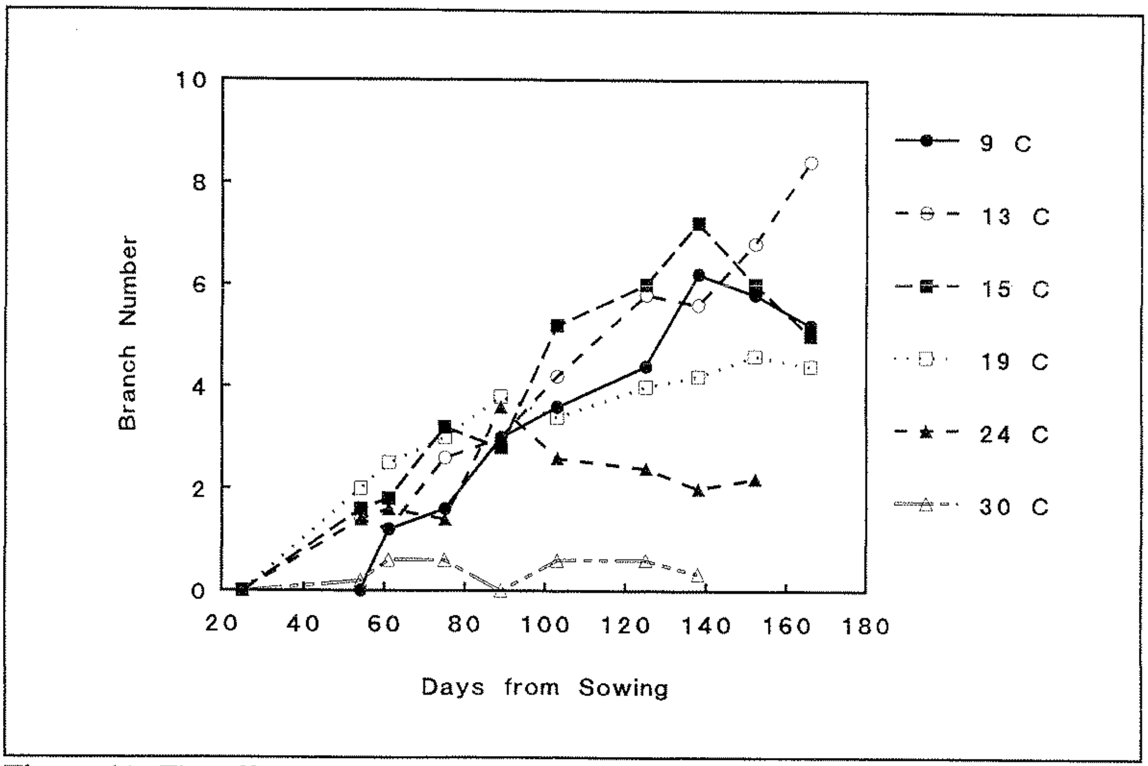

Figure 11. The effect of temperature on the branch production of Pansy over time.

3.2 PRIMULA

Plate 2 shows the effects of temperature on the growth and quality of Primula. This, in particular, shows a considerable effect of temperature on the flower stalk length and flower size; increasing temperature led to reduced peduncle length and flower size. Increasing temperature also appeared to increase the anthrocyanin content of the flower, thus plants at higher temperatures had more intense flower colour than cooler ones.

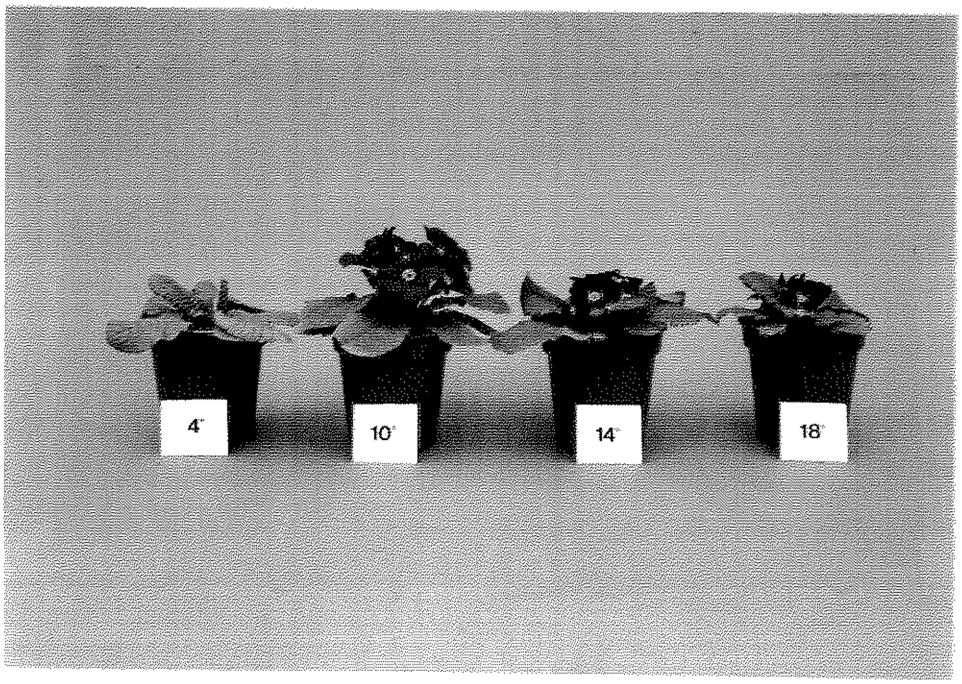

Plate 2. The effect of temperature on flowering and quality of Primrose.

3.2.1 Time to Flowering

Time to flowering decreased with increasing temperature up to 20°C (Figure 12). Thus, plants grown at an average of 20°C flowered approximately 30 days earlier than those at 10°C. The optimum temperature we found (20°C) for flower opening was higher than that noted by other workers who have reported an optimum of 14°C for flower *initiation* (Karlsson and Hanscom, 1992). The discrepancy is probably due to the fact that the optimum temperature for flowering increases after flower initiation (as shown by Runger and Wehr, 1971, for *P. malacodies*). Thus, our data may be misleading, since we have studied a combined effect of temperature on flower initiation with one on flower development, where in reality each phase may have completely different responses to environment. Further work is required to increase our understanding of the effects of temperature on flowering of Primula.

There was also a considerable effect of sowing date on time to flowering, thus July sown plants matured after approximately 145 days, but September sown plants required in the order of 245 days. The reason for this difference is unknown, but it's likely to be related to either decreasing light intensity or photoperiod.

Blindness, a problem noted usually with late sowings was only seen here in plants grown at 20°C from the July sowing date, where 85% of the plants did not flower. All plants at cooler temperatures eventually flowered, however, there was a suggestion that temperature affected the duration of the flowering period, for example plants grown at an average of 10°C took 46 days from 10 - 90% flowering, however, those at approximately 14°C required only 24 days. This may have important implications if growers wish to increase uniformity in time to flowering of the crop.

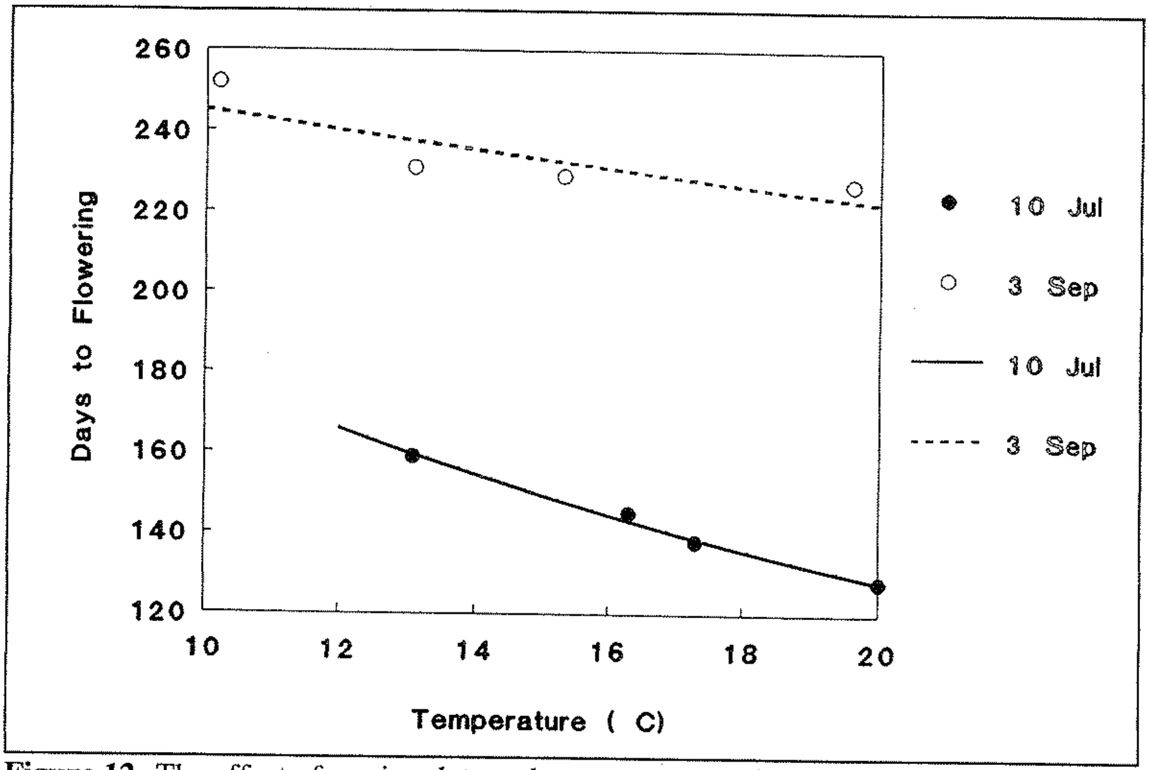

Figure 12. The effect of sowing date and temperature on time to flowering of Primrose. The lines were fitted by regression analysis.

3.2.2 Fresh Weight

The effect of temperature on the increment of plant fresh weight is demonstrated with data gathered from July sown plants on figure 13. This shows that temperature above 20°C led to very slow growth and eventually plant death. Optimal temperatures, that led to fastest rate of growth, and largest fresh weight at flowering, were between 15 - 18°C. Higher and lower temperatures led to smaller plants at flowering.

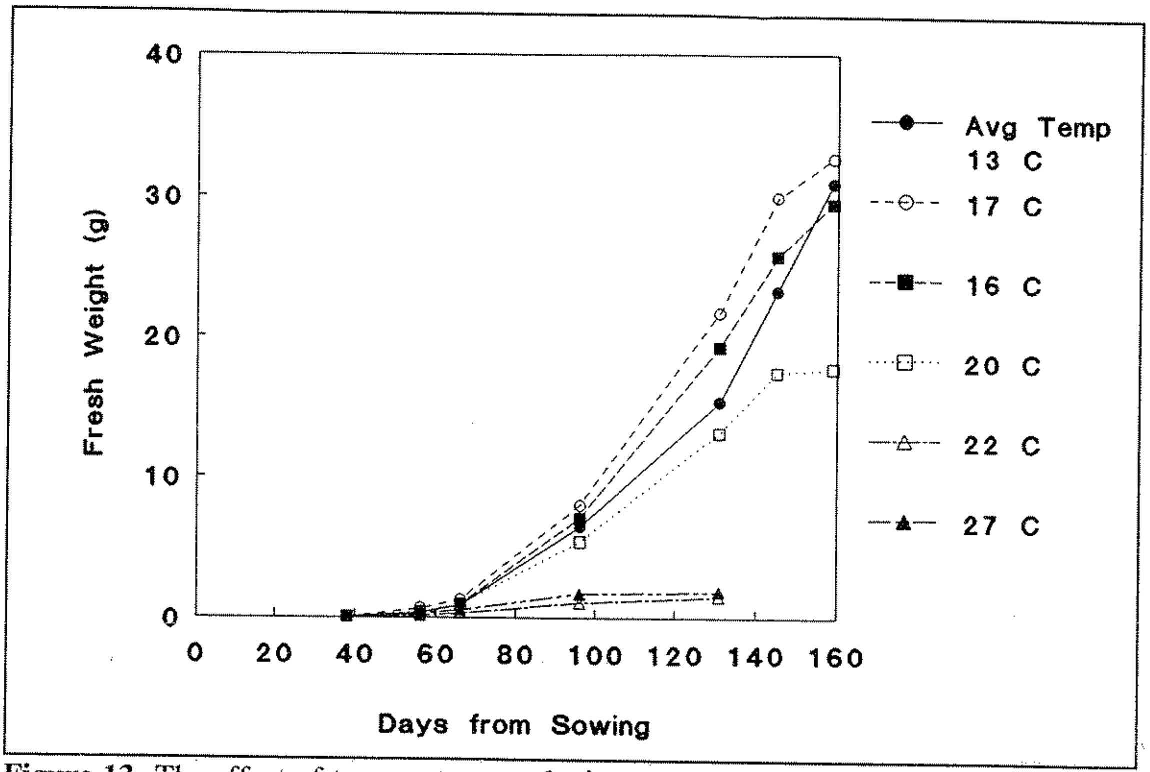

Figure 13. The effect of temperature on the increment of plant fresh weight of Primula over time.

3.2.3 Leaf Number

Little effect of temperature was noted on leaf production (Figure 14). However, there was an indication that 20°C appeared to be optimal for leaf production, higher temperature greatly reduced leaf production.

3.2.3 Leaf Area

The effects of temperature on leaf area of Primrose reflected the effects noted for fresh weight (Figure 15). The optimum temperature for leaf area was in the order of 15-18°C and a lower temperature (10°C) led to a smaller leaf area at flowering.

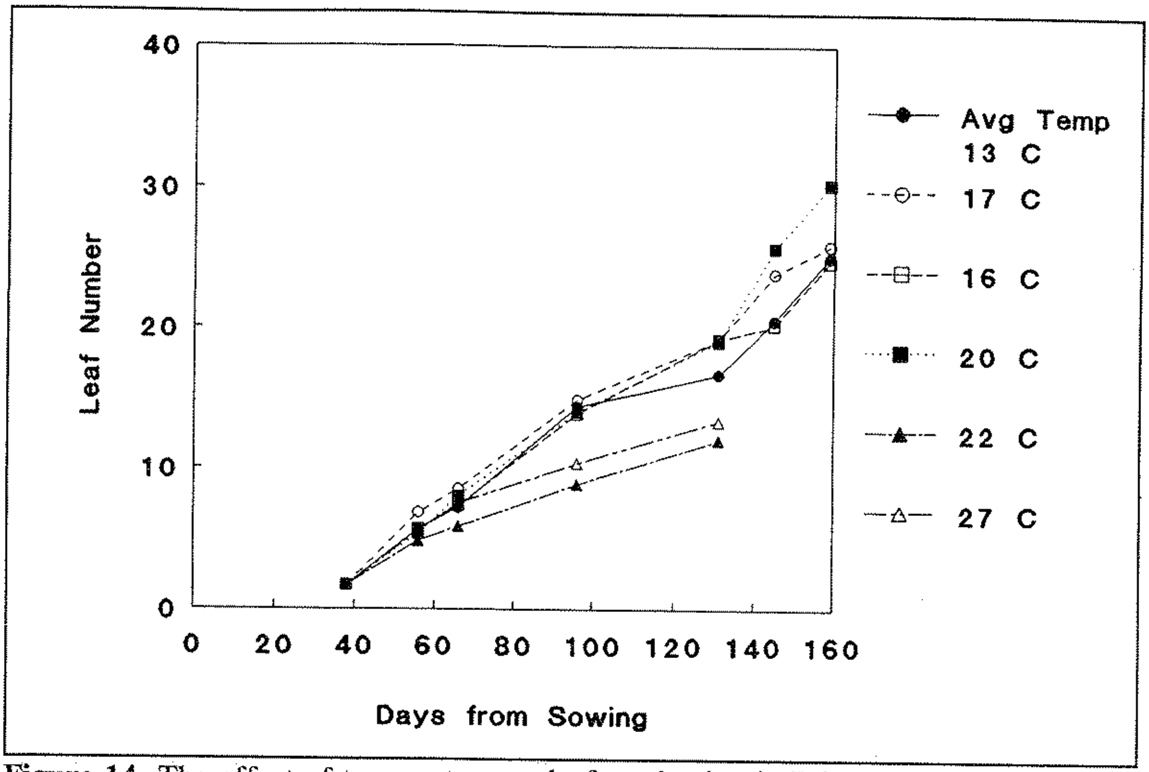

Figure 14. The effect of temperature on leaf production in Primrose over time.

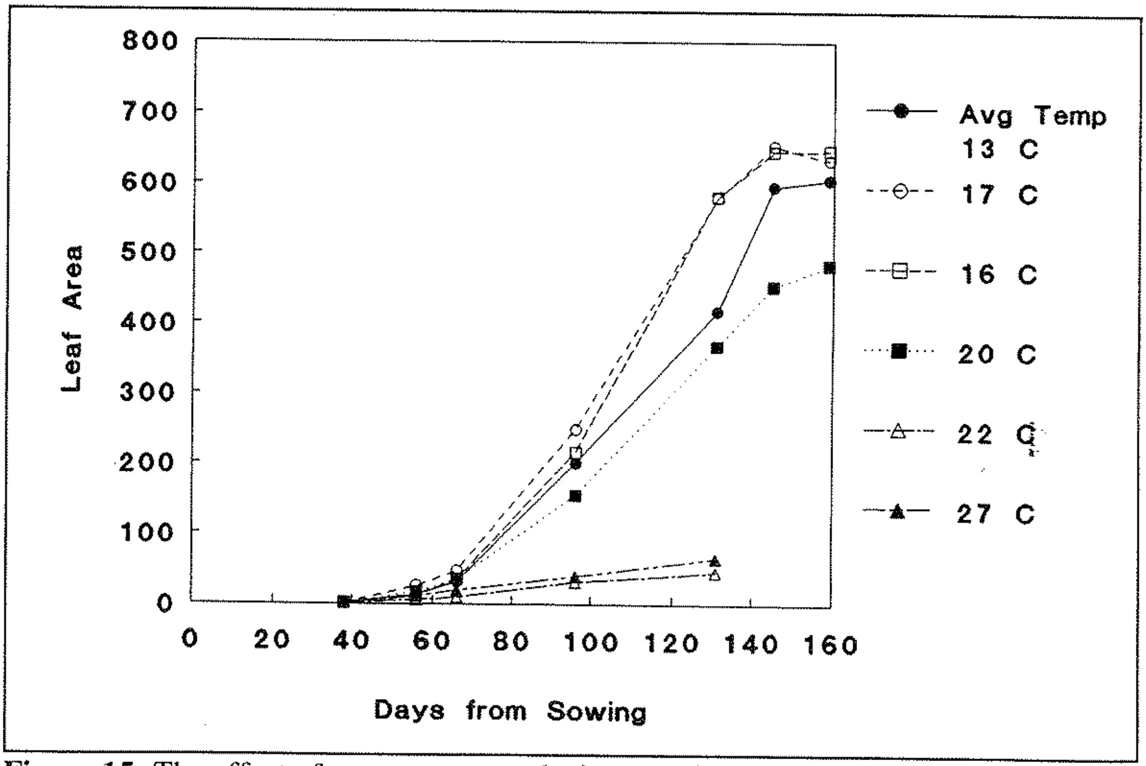

Figure 15. The effect of temperature on the increase in leaf area of Primrose over time.

Leaf area at flowering was also dramatically affected by sowing date. Thus, the leaf area of July sown plants was in the order of three times larger than others sown in September (Figure 16).

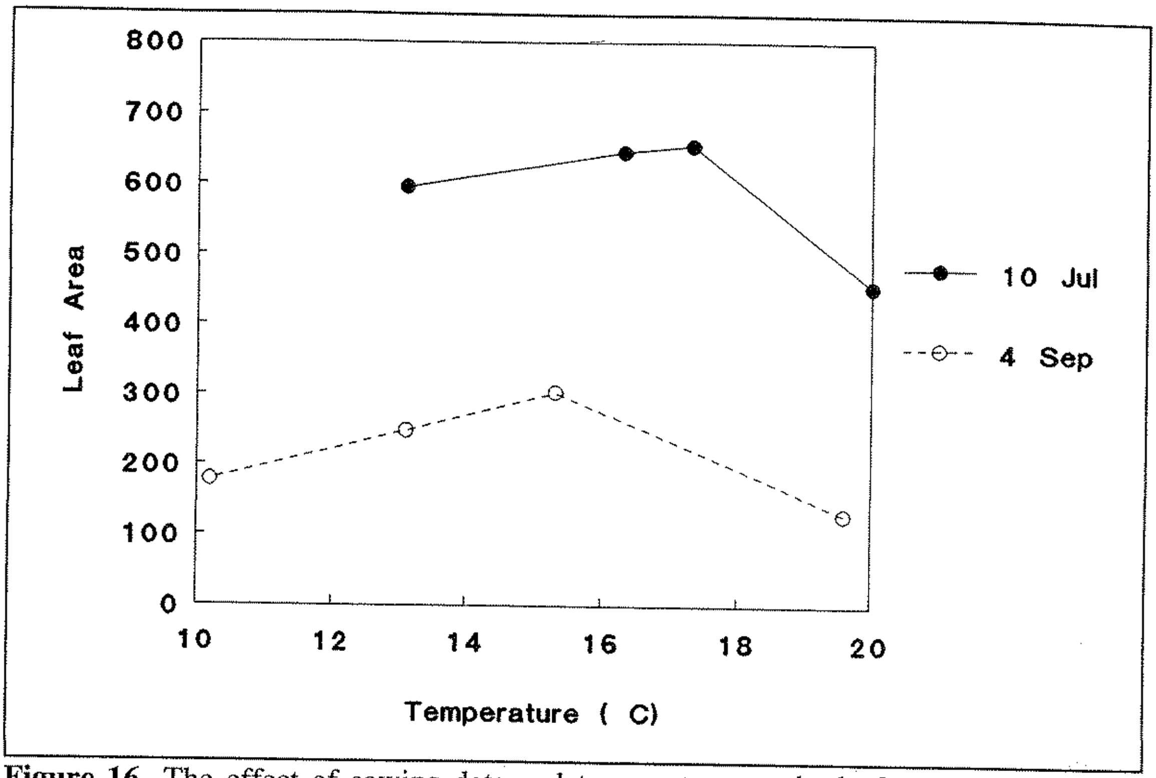

Figure 16. The effect of sowing date and temperature on the leaf area of Primula at flowering.

These results, on leaf area, are important in terms of plant quality, since too leafy plants are considered undesirable. Thus, the data suggests that vegetative growth can be partially controlled by either later sowings or growing at cool temperatures.

3.3 GERANIUM

3.3.1 Time to Flowering

The work has shown that the primary determinant of time to flowering in Geranium is temperature. There was a curvilinear relationship between days to flowering and temperature (figure 17a), with an optimum temperature (in terms of earliest time to flowering) of approximately 26°C. This indicates that producing a crop at 22°C will result in 10-14 days earlier maturity than a temperature of 18°C. Also shown on figure 17a, for comparison, are data gathered from growth cabinet experiments by Hopper *et al.*, (1985) and White and Warrington (1988). These data follow a similar trend as that gathered in this study, and therefore provides validation of the temperature response curve.

Further data gathered as part of project PC74a has also shown that photoperiod significantly affects time to flowering (plants grown at a daylength of 15hd^{-1} flowered 10-14 days earlier

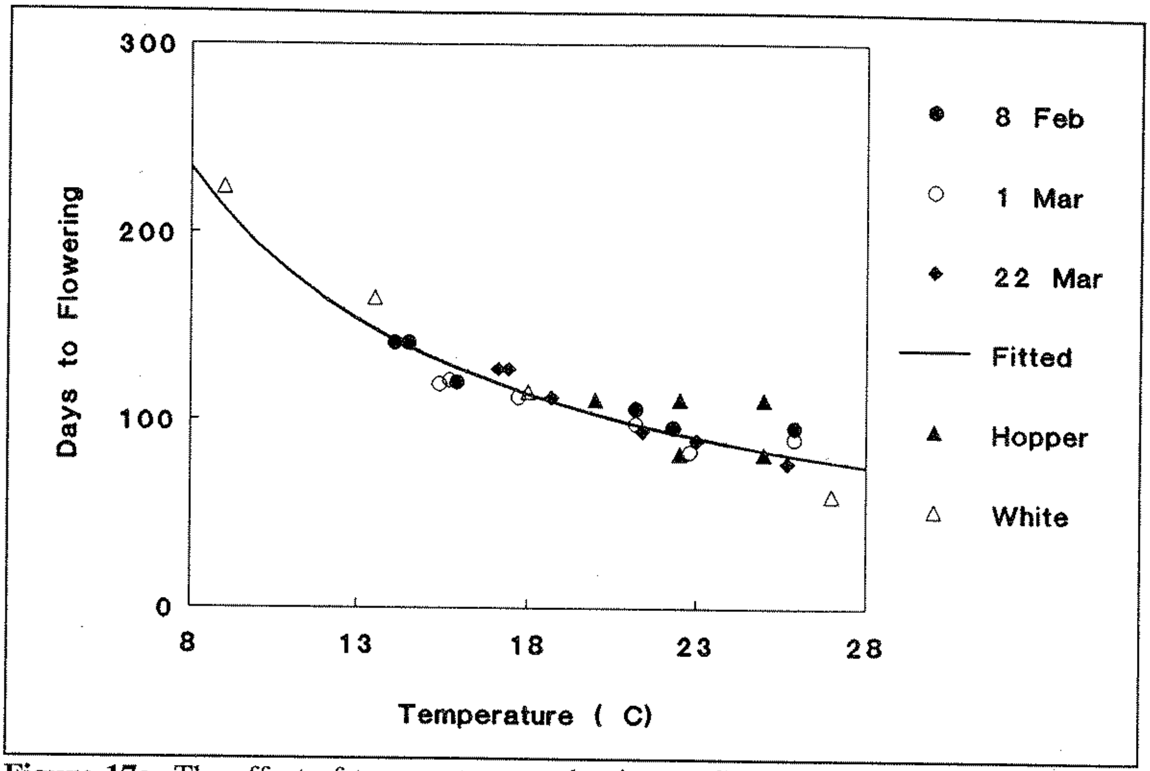

Figure 17a. The effect of temperature on the time to flowering of Geranium. The line was fitted by regression, where days to flowering = $1/(0.000646 + 0.00045T)$, $r^2 = 0.71$, 26d.f.

than those at $9hd^{-1}$). Numerous other studies have also shown that daily light integral affects time to flowering (Armitage *et al.*, 1983; Hopper *et al.*, 1985; White and Warrington, 1988), for example Armitage *et al.*, (1983) showed that Geraniums (cv. Ringo) grown at approximately $3MJm^{-2}d^{-1}$ (February light levels) flowered after 112 days, but only required 98 days at $18MJm^{-2}d^{-1}$ (equivalent to June light levels).

Data gathered, here and in the literature, on the effects of temperature, photoperiod and light integral on time to flowering were used to construct a model to predict time to flowering in Geranium. This model was accurate and accounted for 83% of the variation in time to flowering. The model was independently validated on 18 crops of geranium grown under a range of temperature conditions. This validation exercise showed that the model was accurate and could predict maturity to within ± 7.2 days (Figure 17b).

The model has been used to construct a sowing date schedule (Figure 18) for geranium. It can also be applied to predict the maturity of geranium crops from sowing to flowering. The schedule shows that set-point temperature has a considerable influence on time to flowering, particulary during the early part of the season.

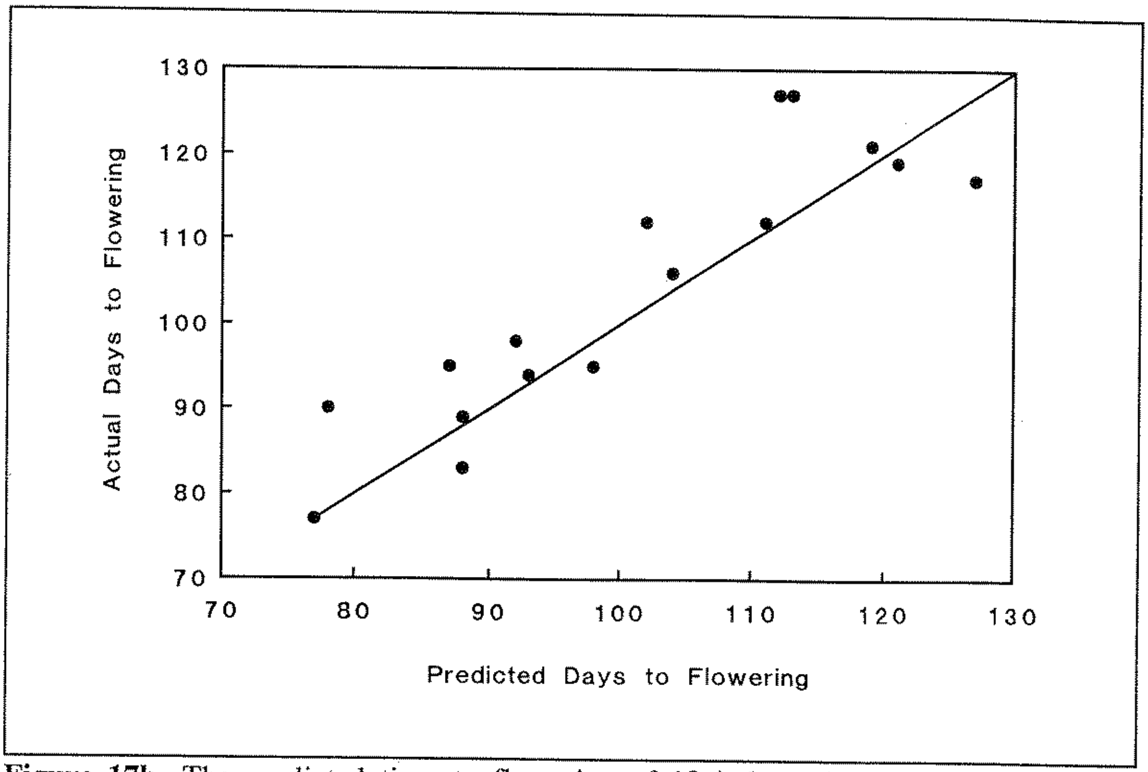

Figure 17b. The predicted time to flowering of 18 independent crops of Geranium versus the recorded flowering dates.

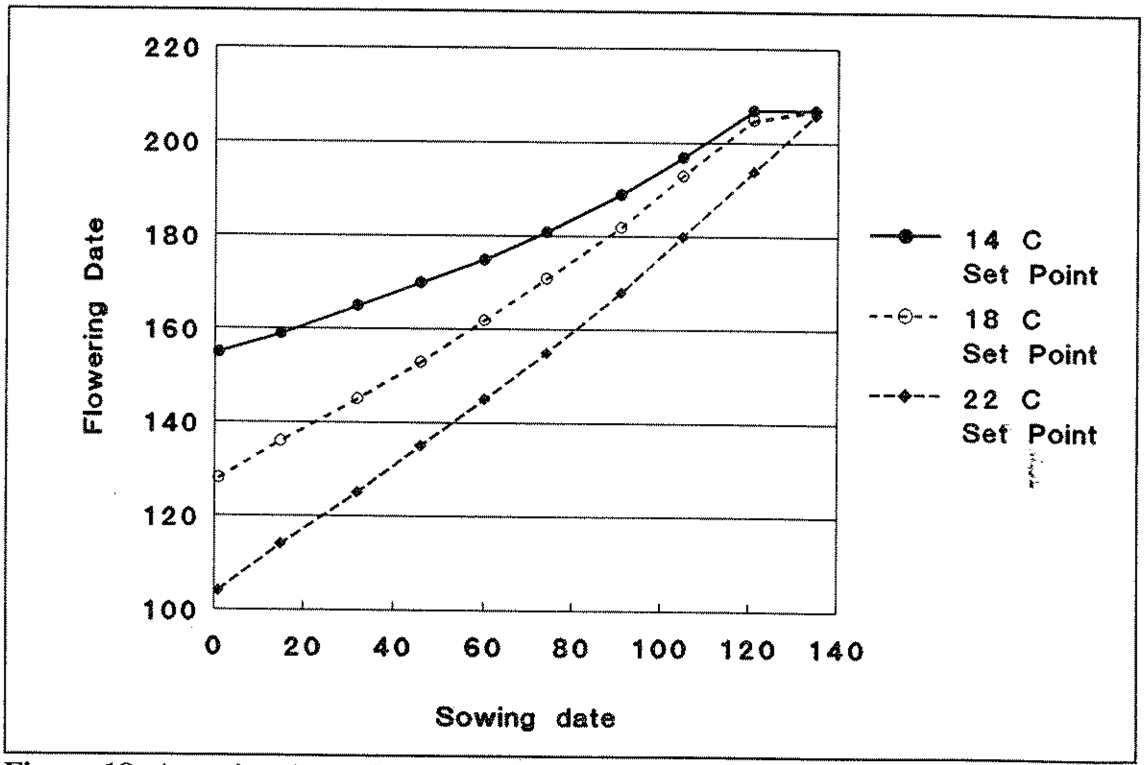

Figure 18. A sowing date schedule for Geranium determined from the flowering model.

3.3.2 Fresh Weight

Figure 19 shows that there was a curvilinear relationship between fresh weight at flowering and temperature for each of the geranium crops grown. For all crops, there was an optimum temperature of 14-18°C for maximum fresh weight. As temperature increases above the optimum, the fresh weight decreases rapidly, such that final weight was approximately halved at 26°C compared to 16°C. Some of the reduction in fresh weight at high temperatures was attributable to high temperature chlorophyll degradation. The symptoms occur once temperatures exceed 26°C.

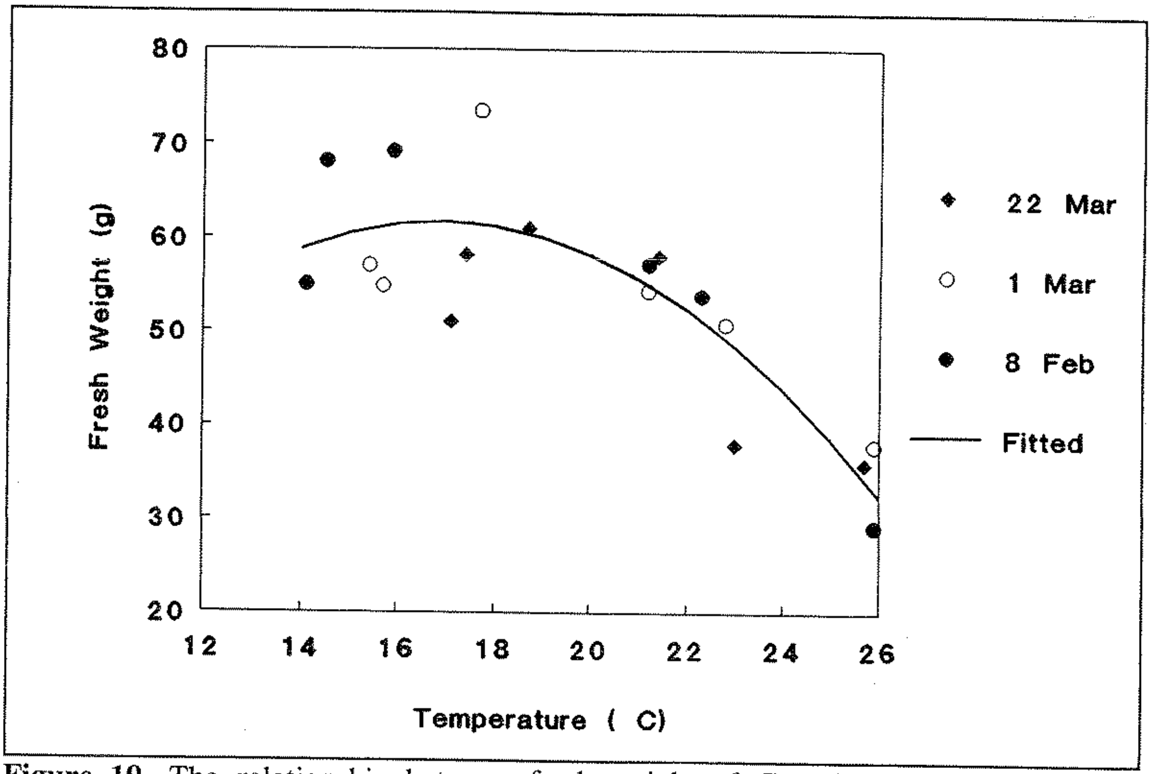

Figure 19. The relationship between fresh weight of Geraniums at flowering and temperature. The line was fitted by regression where FW = $-38+11.83T-0.3501T^2$, r^2 =0.72, 15d.f.

3.3.3 Leaf Number

Figure 20 shows the relationship between leaf number at flowering and temperature. Temperature generally had little effect, but leaf number was maximal at temperatures of approximately 21°C. Light integral also affected leaf number, such that final leaf number decreased significantly with increasing integral.

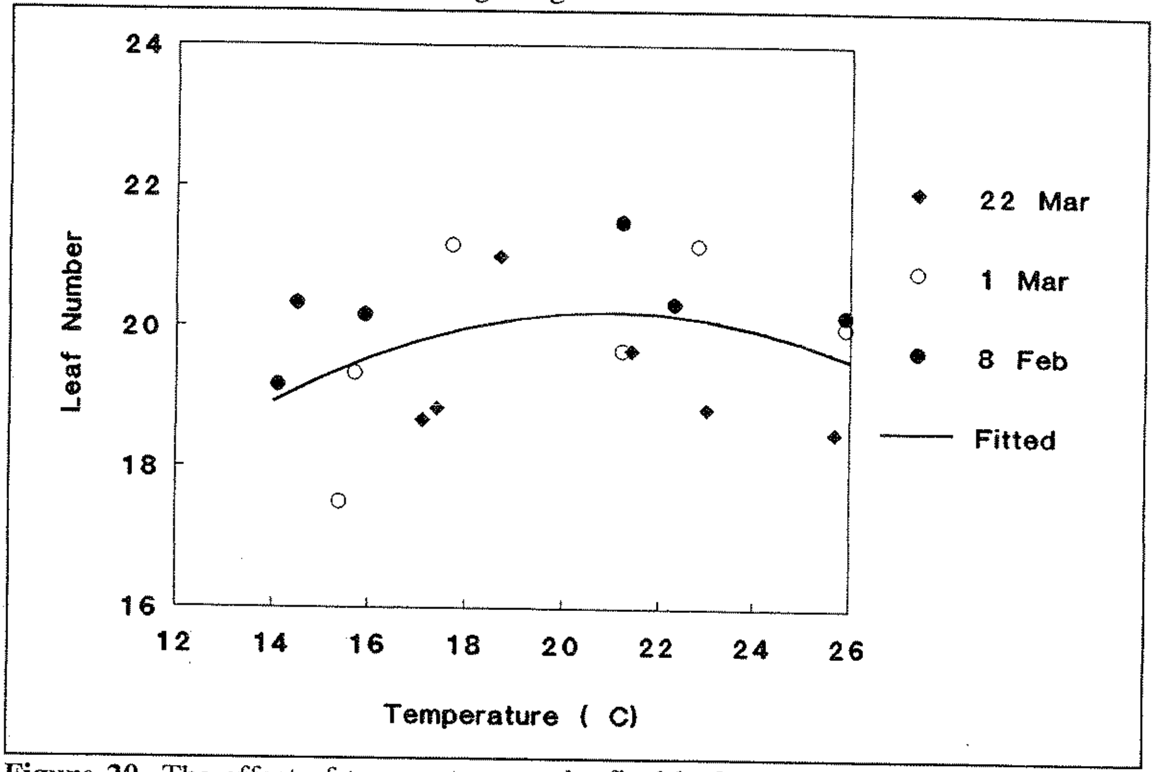

Figure 20. The effect of temperature on the final leaf number of Geranium. The line was fitted by regression, thus LN = 8.55 + 1.11T - 0.026T^2, r^2 = 0.13, 15d.f.

3.3.4 Leaf Area

Leaf area at flowering increased with temperature to 19°C and declined curvilinearly thereafter (Figure 21), so that leaf area was in the order of 75% greater at 19°C compared to 26°C. Considering that there were relatively small differences in leaf number with increasing temperature, the increase in leaf area with temperature is therefore largely due to an increase in individual leaf size, rather than number.

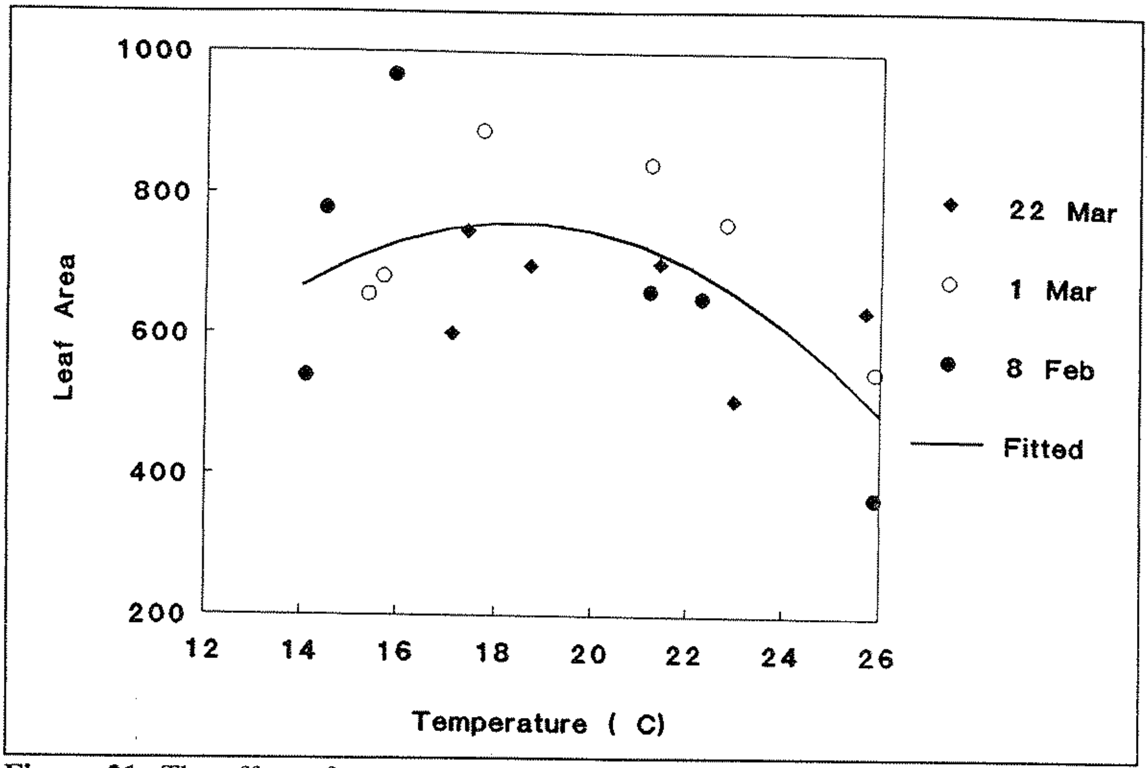

Figure 21. The effect of temperature on the leaf area of Geranium at flowering. The line was fitted by regression, where LA = -829 + 172.5T - 4.68T^2, r^2 =0.37, 15d.f.

3.3.5 Plant Height

Temperature had considerable influence on plant height to the apex (Figure 22). Tallest plants at flowering were those maintained at cooler temperatures in the order of 14°C. Plants were shortest at higher temperatures, such that at 26°C plants were only half the height of those at 14°C. Much of this effect was due to delayed flowering at low temperatures and plants therefore had a longer duration for stem elongation. Effects of temperature on height were mainly due to differences in internode elongation, since temperature had little effect on leaf number. Consequently, contrary to the findings on Impatiens, Pansy and Petunia, increasing temperature for geranium can provide some growth control of the finished plant.

3.3.6 Compactness

The most compact plants, in terms of leaf area per unit height, were produced at temperatures above 18°C (Figure 23). Lower temperatures produced poorer quality plants, since they were tall with smaller leaf areas.

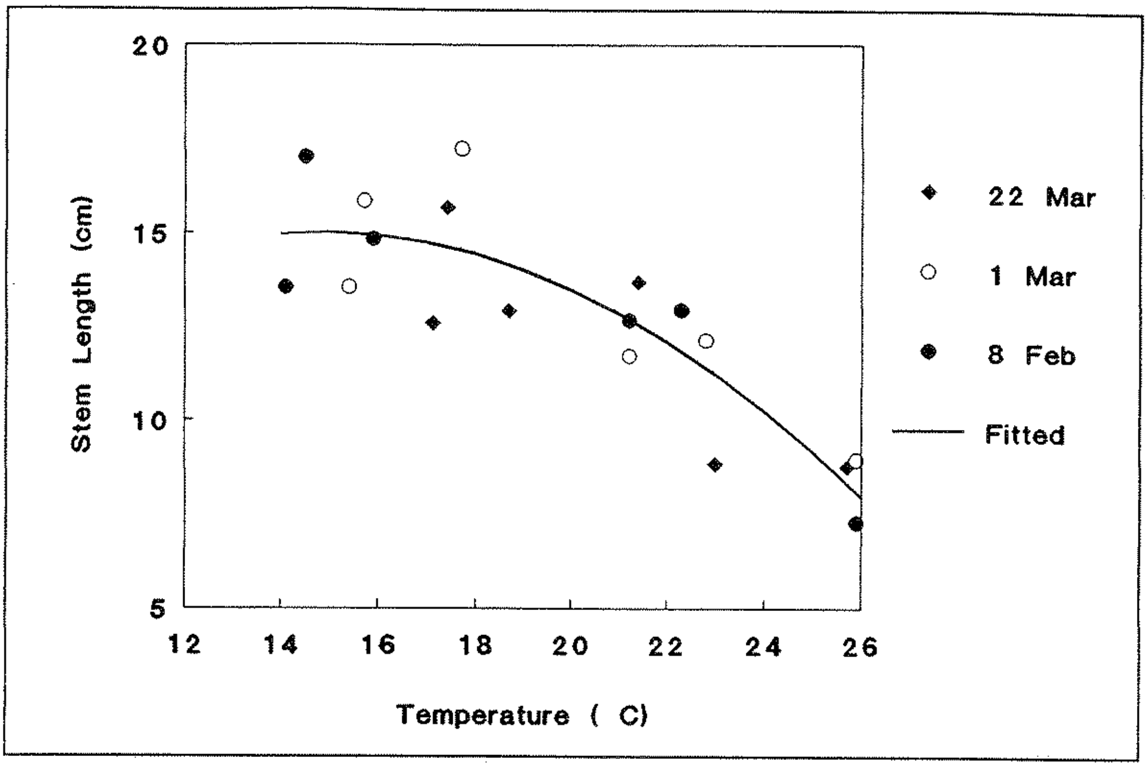

Figure 22. The effect of temperature on plant height of Geranium at flowering. The line was fitted by regression, where PH = 2.53 + 1.68T - 0.057T^2, r^2 = 0.75, 15 d.f.

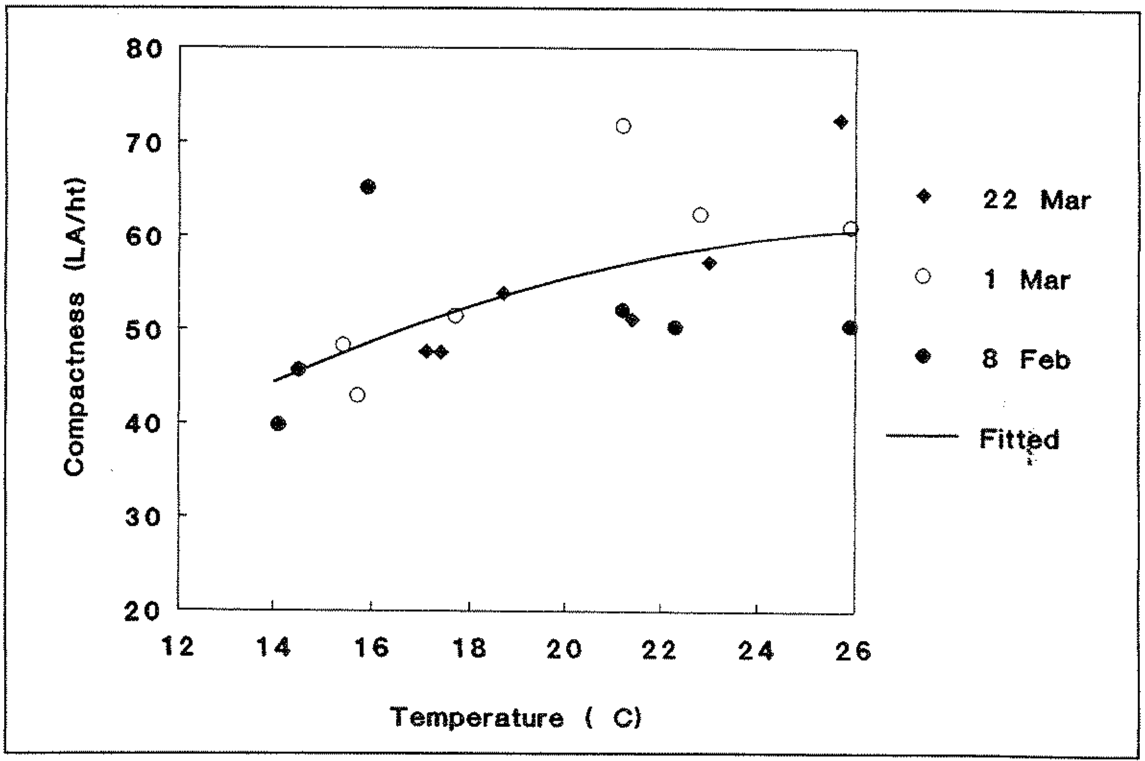

Figure 23. The effect of temperature on compactness of Geranium at flowering. The line was fitted by regression, where -5.05 + 4.709T - 0.084T^2, r^2 = 0.35, 15d.f.

3.3.7 Peduncle Length

The length of the flower stalk was considerably affected by temperature, such that flower stalks were longer as temperatures increased. The greatest reductions in flower stalk length occurred as temperatures exceeded 22°C (Figure 24). This affect may be important in terms of the appearance and therefore overall quality of the final product, long flower stalks being desirable, since the flower will be clearly visible above the foliage.

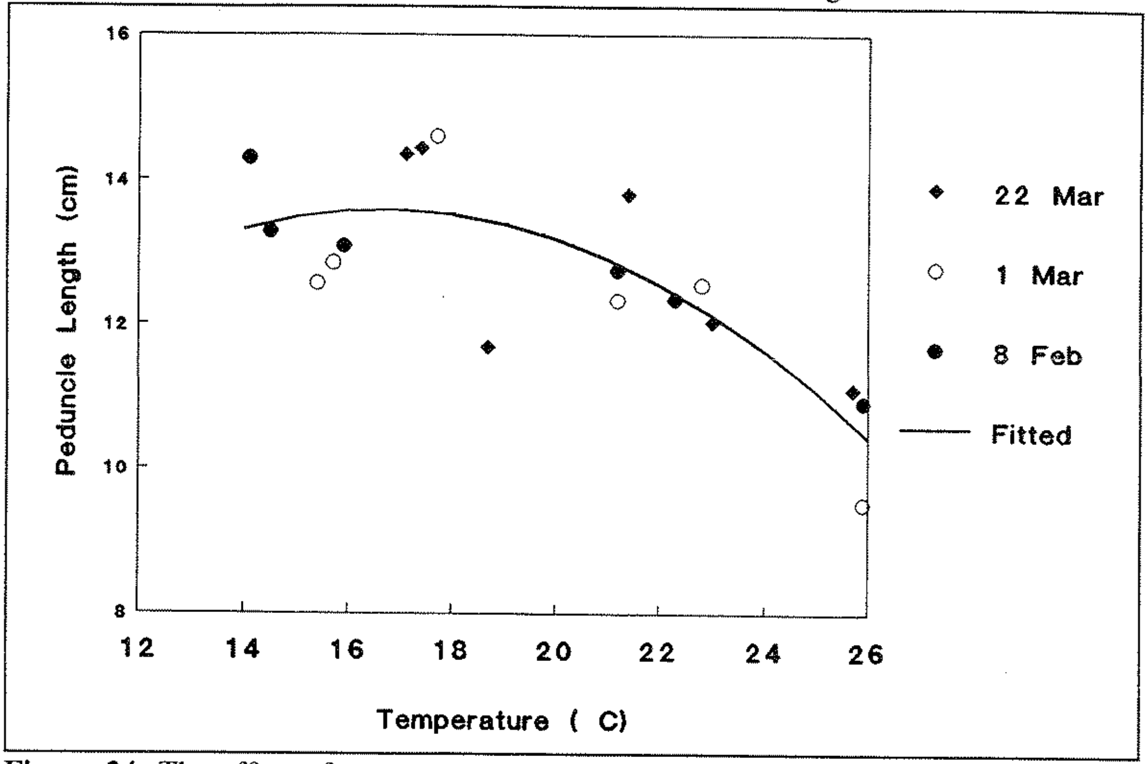

Figure 24. The effect of temperature on the length of the flower stalk of Geranium at flowering. The line was fitted by regression, where Ped = 3.41 + 1.21T - 0.036T^2, r^2 = 0.65, 15 d.f.

3.3.8 Flower Number

In this study no data were collected on effects of temperature on flower number. However, for completeness figure 25 shows a reproduction of the effects of temperature on flower number of geranium reported by Erwin and Heins (1994). This shows that flower number decreases considerably with increasing temperature.

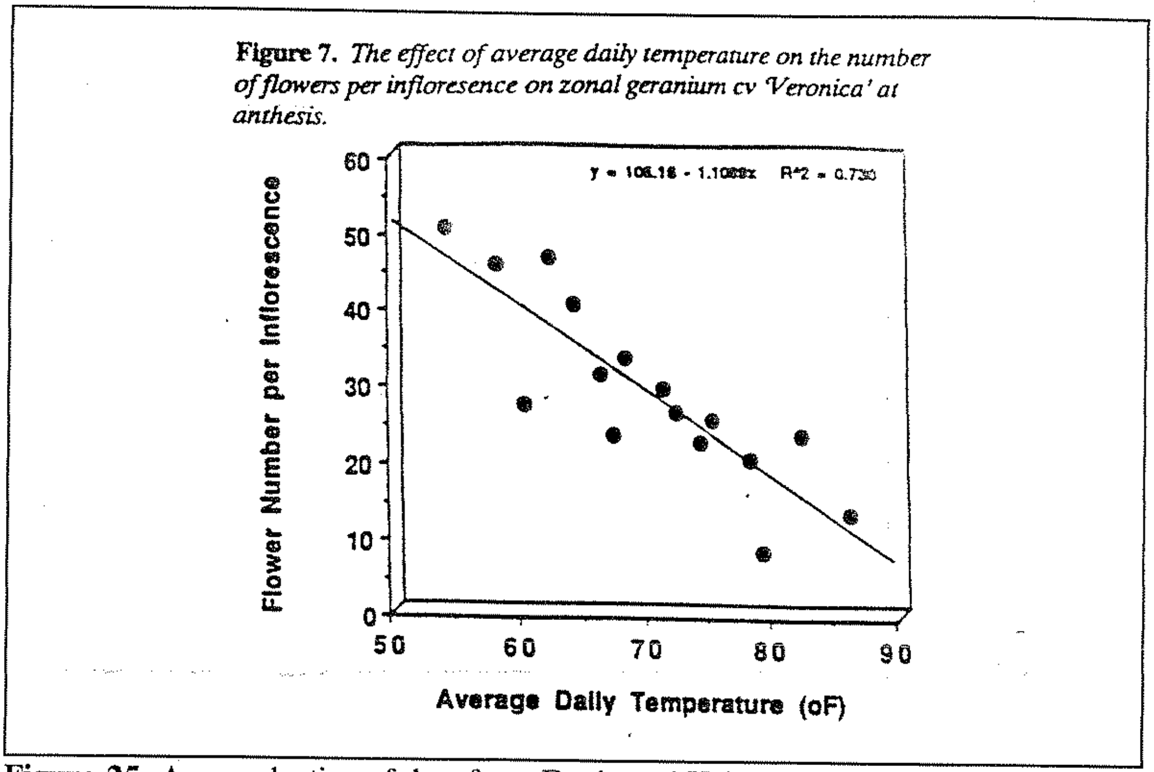

Figure 7. *The effect of average daily temperature on the number of flowers per infloresence on zonal geranium cv 'Veronica' at anthesis.*

Figure 25. A reproduction of data from Erwin and Heins (1994) showing the effect of temperature on flower number of Geranium.

3.4 IMPATIENS

The effects of temperature on the growth and quality of *Impatiens* are demonstrated on Plate 4.

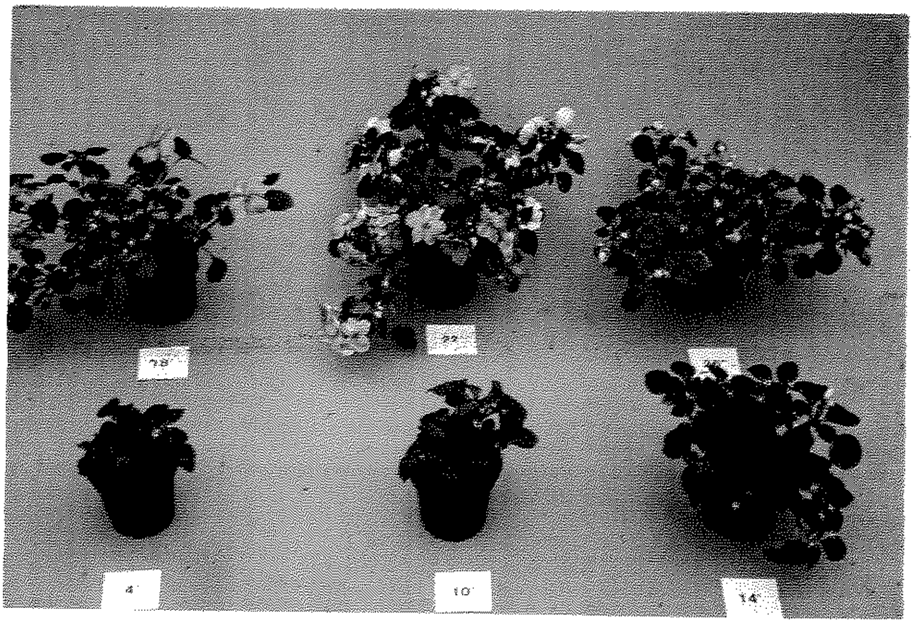

Plate 4. The effect of temperature on the growth and development of Impatiens.

3.4.1 Flowering

The prediction of flowering in Impatiens is complicated by their unusual morphology, such that they initiate flowers very readily with at least one in every node, but a large proportion are aborted. Observation suggested that at higher temperatures there was considerable flower abortion. Therefore to understand factors affecting flowering of Impatiens, flower abortion must be considered, and this is not currently understood. However, our data also suggests that temperature influences time to flowering, such that flowering occurred earliest at temperatures approaching 24°C (Figure 26) and increasing the temperature from 18 to 24°C lead to 16 days earlier flowering. Thus, as with Geranium and Petunia, small changes in temperature can have a considerable impact on the production time. Photoperiod was found to have no affect on flowering in Impatiens (authors unpublished data). A relationship was developed to predict flowering in Impatiens for crop scheduling. However, this model does not explain why flowers open on apparently juvenile plug plants. Therefore, as the model is not reliable, at the present time no schedules have been produced for Impatiens. These will be reported following further experimentation.

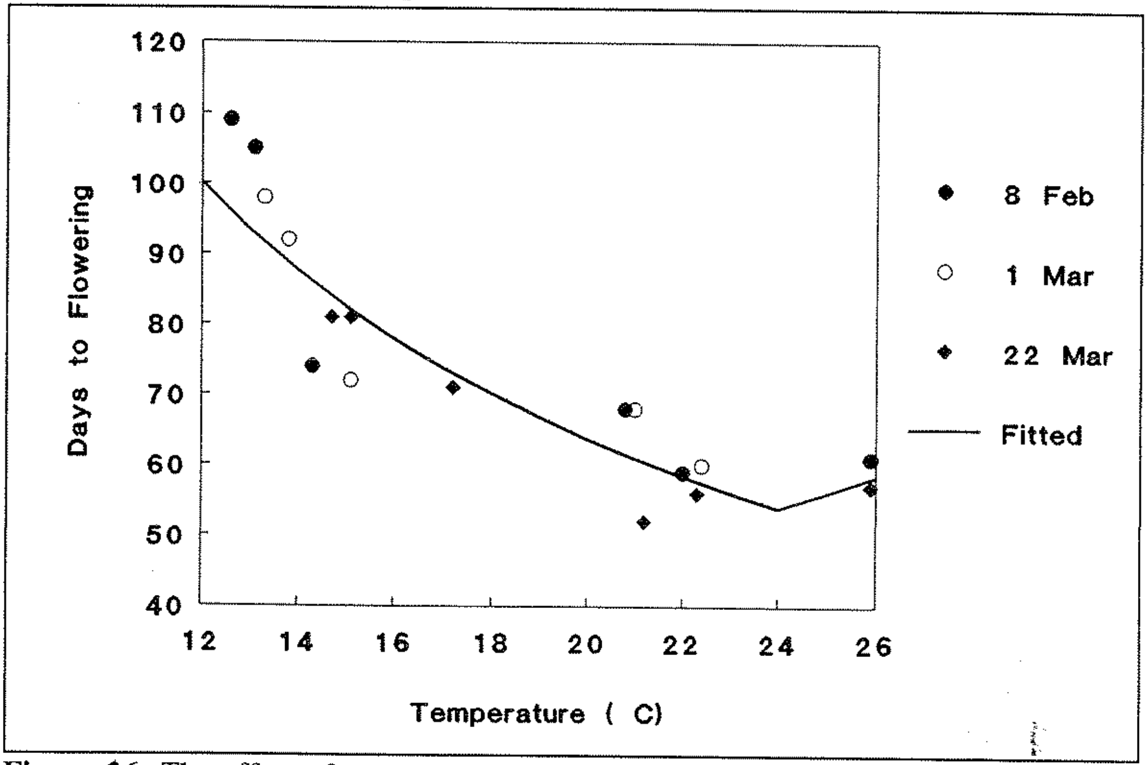

Figure 26. The effect of temperature on the time to flowering of Impatiens. The line was fitted by regression, where days to flowering = 1/(0.00145 + 0.00071T), r^2 = 0.84, 15d.f.

3.4.2 Fresh Weight

Final fresh weight at flowering increased sharply with temperature up to approximately 18-22°C and declined thereafter (Figure 27). Observations indicated that growth virtually ceased, once the temperature dropped below 12°C.

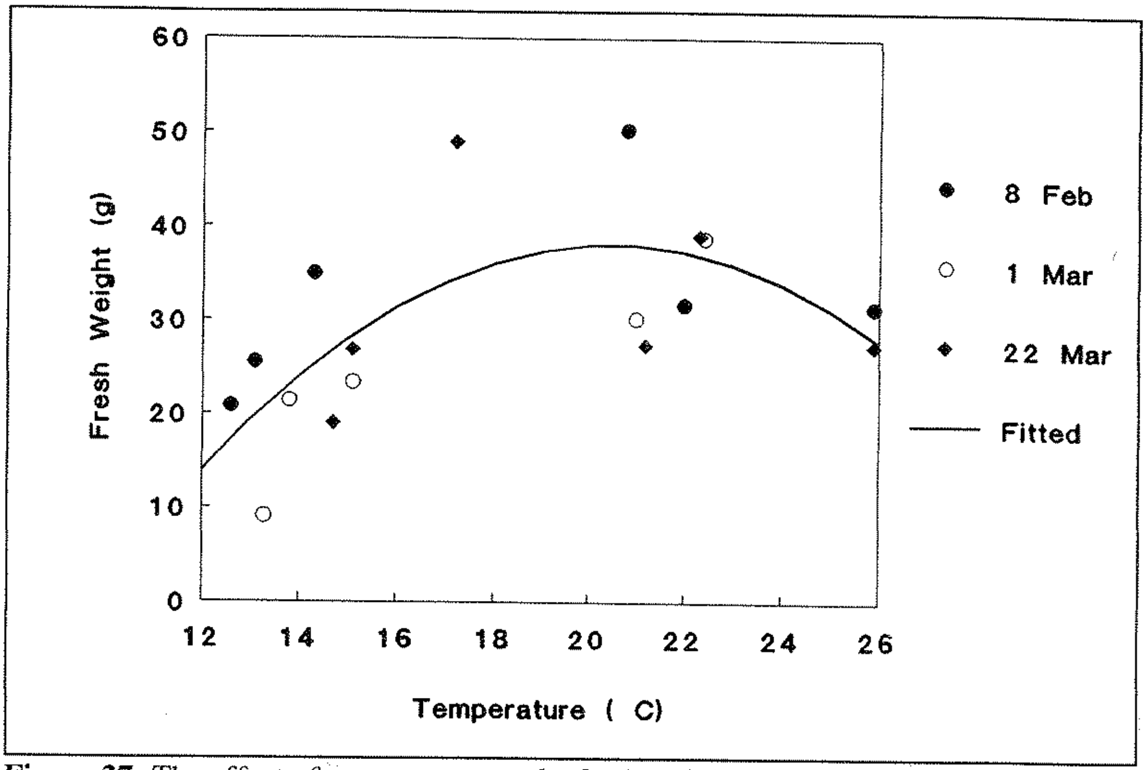

Figure 27. The effect of temperature on the fresh weight of Impatiens at flowering. The line was fitted by regression, where FW = -103.39 + 13.82T - 0.337T^2, r^2 = 0.45 14 d.f.

3.4.3 Leaf Number

Temperature had little affect on the leaf number of the central stem prior to flowering (Figure 28).

3.4.4 Leaf Area

Temperature did, however, have considerable affect on the leaf area (Figure 29). Leaf area, at flowering showed a similar response to temperature as fresh weight so that, it was four times greater at around 18°C compared to plants grown at 13°C. This demonstrates that Impatiens are very sensitive to low temperatures. The effects of temperature on leaf area were attributable to differences in leaf size, since leaf numbers were similar, and warmer temperatures tended to produce a greater number of branches (see below). Observations also indicated that leaf zonation (i.e. dark bands of green surrounding the leaf veins) was greatest at temperatures in the order of 18°C. This affect improved the visual appearance of the plants and therefore their quality.

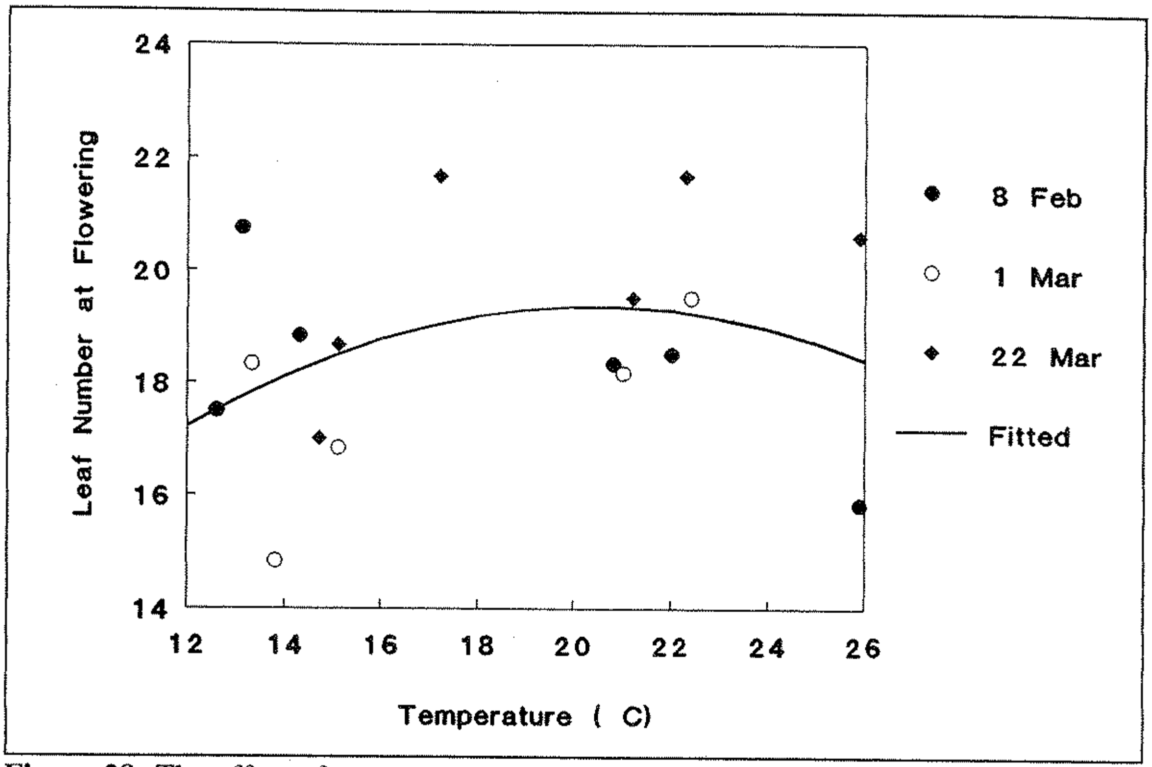

Figure 28. The effect of temperature on the leaf number of Impatiens at flowering. The line was fitted by regression, where LN = 6.75 + 1.23T - 0.03T^2, r^2 = 0.11, 14d.f.

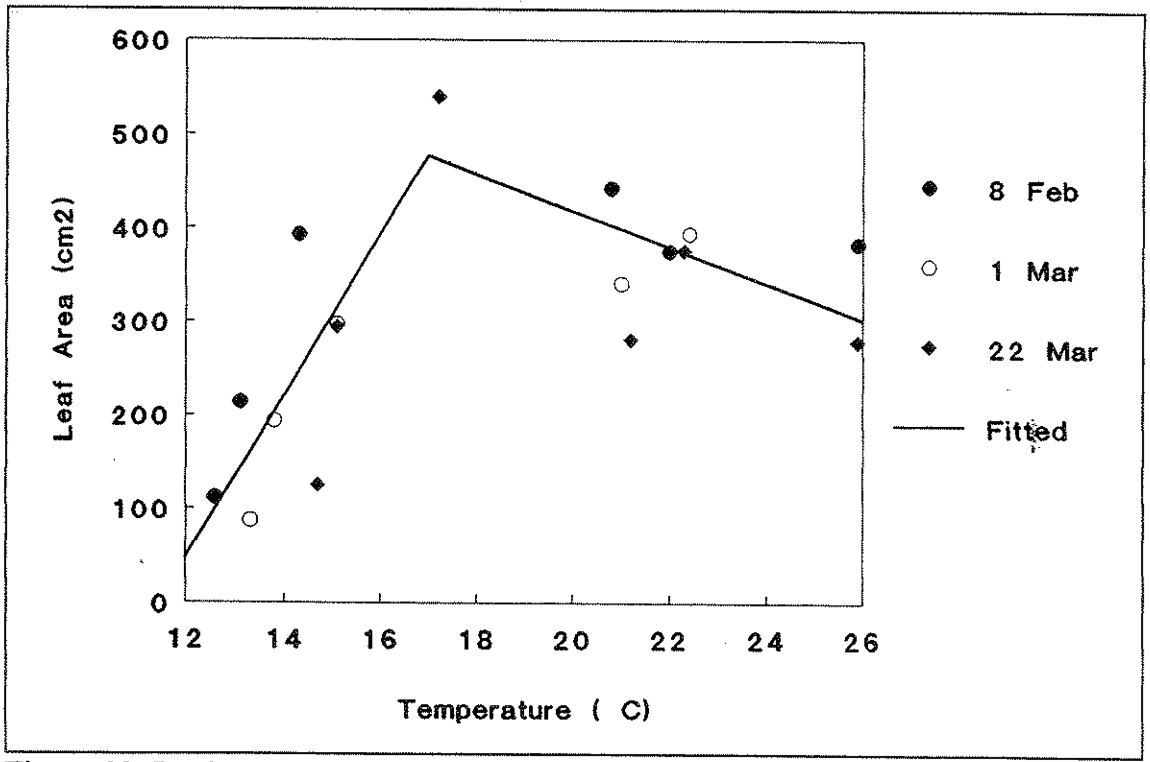

Figure 29. Leaf area of Impatiens at flowering. The line was fitted by regression, where for 12-17°C LA = -992 + 86.6T and 17-26°C LA = 807 - 19.37T, r^2 = 0.64, 14 d.f.

3.4.5 Branch Number

The number of branches, greater than 1cm, per plant increased linearly with increasing temperature (Figure 30). Plants at 12°C produced about 18 branches compared to 25 at 26°C.

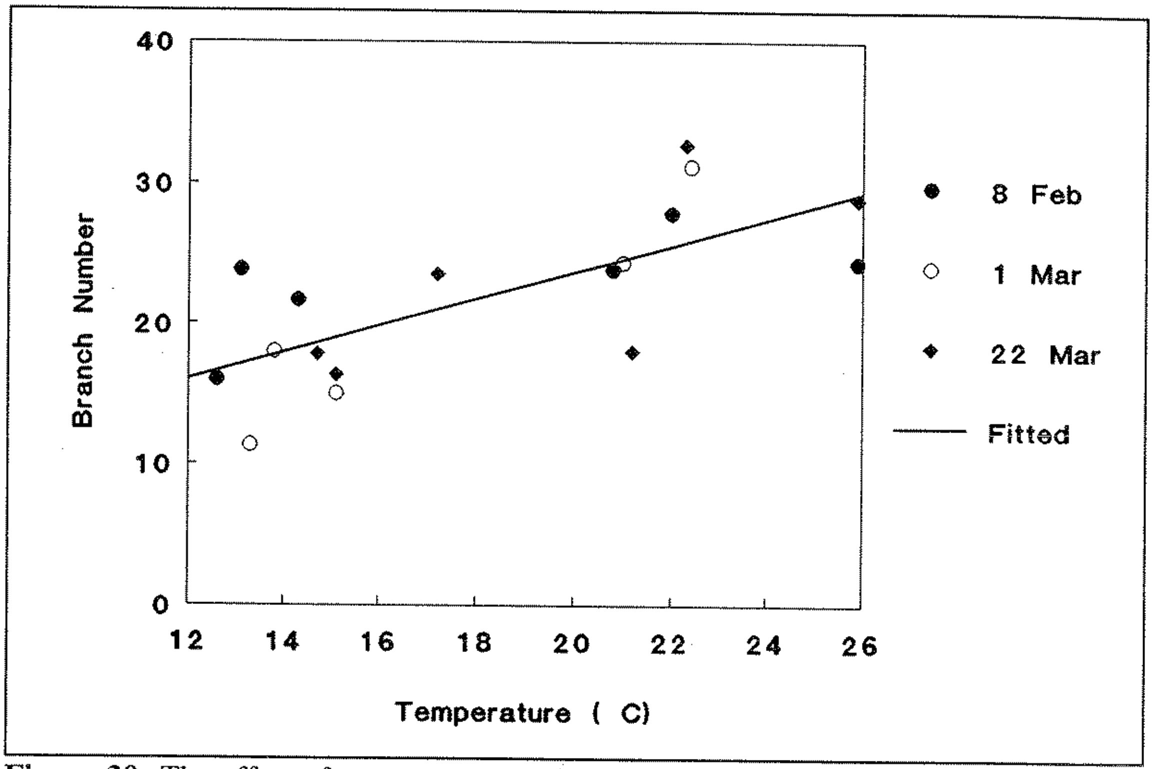

Figure 30. The effect of temperature on the branch number of Impatiens at flowering. The line was fitted by regression, where BN = 4.68 + 0.948T, r^2 = 0.53, 15 d.f.

3.4.6 Plant Width

Measurements of plant height in Impatiens have little relevance, since it has a prostrate habit. Therefore to assess the amount of lateral growth, measurements were made of the length of the central stem, which reflects the diameter of the plant. These showed that the stem length increased with increasing temperature (Figure 31). Thus, stem length was doubled, and therefore quality reduced, in plants grown at 26 compared to 12°C. The effect of temperature on stem length was, however, largely only expressed as temperature decreased below 20°C. Plants from the first sowing date tended to be shorter than those from the second and third sowings. This was explained by an effect of light integral, such that higher light integral produced marginally but significantly longer stems.

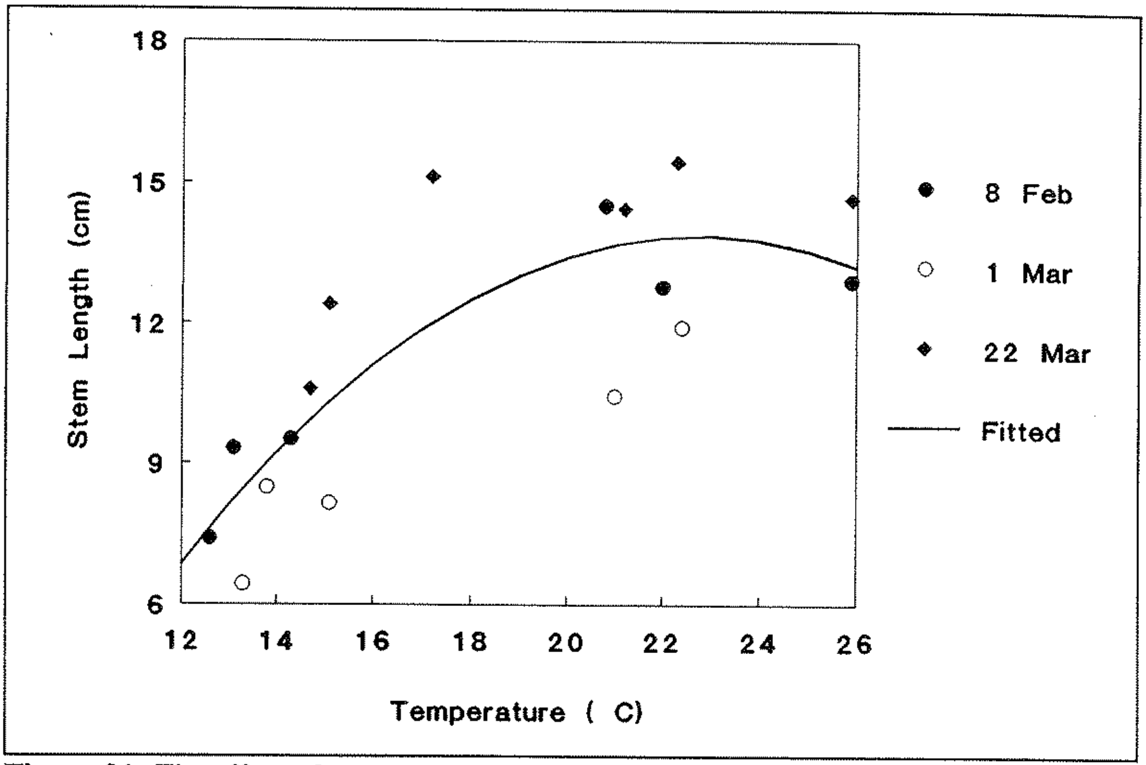

Figure 31. The effect of temperature on stem length of Impatiens at flowering. The line was fitted by regression, where $SL = -17.64 + 2.77T - 0.061T^2$, $r^2 = 0.68$, 14 d.f.

3.4.7 Compactness

The analysis showed that the most compact plants, in terms of the leaf area per unit stem length, were those maintained at 15°C (Figure 32). Decreasing the temperature led to a dramatic reduction in the plants compactness, primarily due to the large reduction in leaf area at low temperatures. This again demonstrates the extreme sensitivity of Impatiens to low temperatures. Thus, temperatures below 15°C are clearly unsuitable for the production of Impatiens. Temperatures above 15°C also led to reductions in plant compactness, again as a result of the reduction in leaf area, but the response was less dramatic, and therefore quality plants could be produced at a range of temperatures above 15°C.

3.4.8 Flower Area

Temperature affected final flower size, such that flower area was greatest at approximately 12-16°C (Figure 33), but declined thereafter. Indeed, it was halved at 26°C compared to 16°C. Light integral also significantly and considerably affected flower size, such that high light reduced flower size.

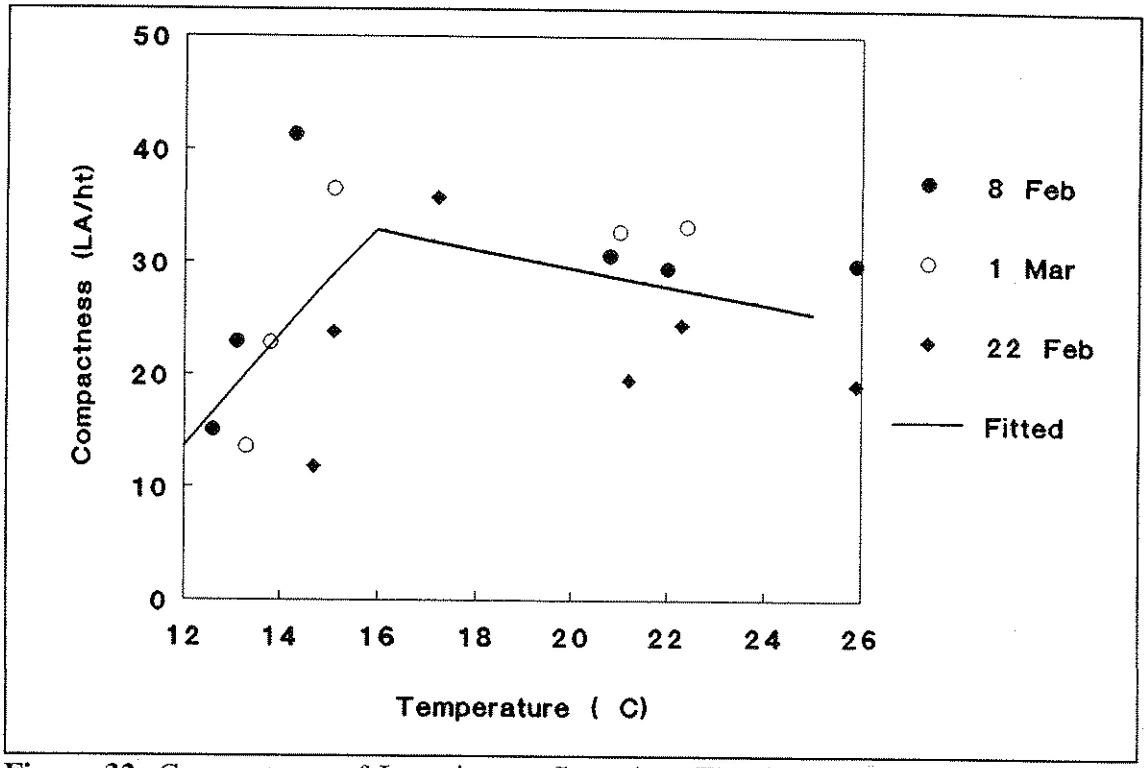

Figure 32. Compactness of Impatiens at flowering. The line was fitted by regression, where for 12-16°C, $C = -45.78 + 4.94T$ and 16-26°C, $C = 45.69 - 0.81T$, $r^2 = 0.28$ 14d.f.

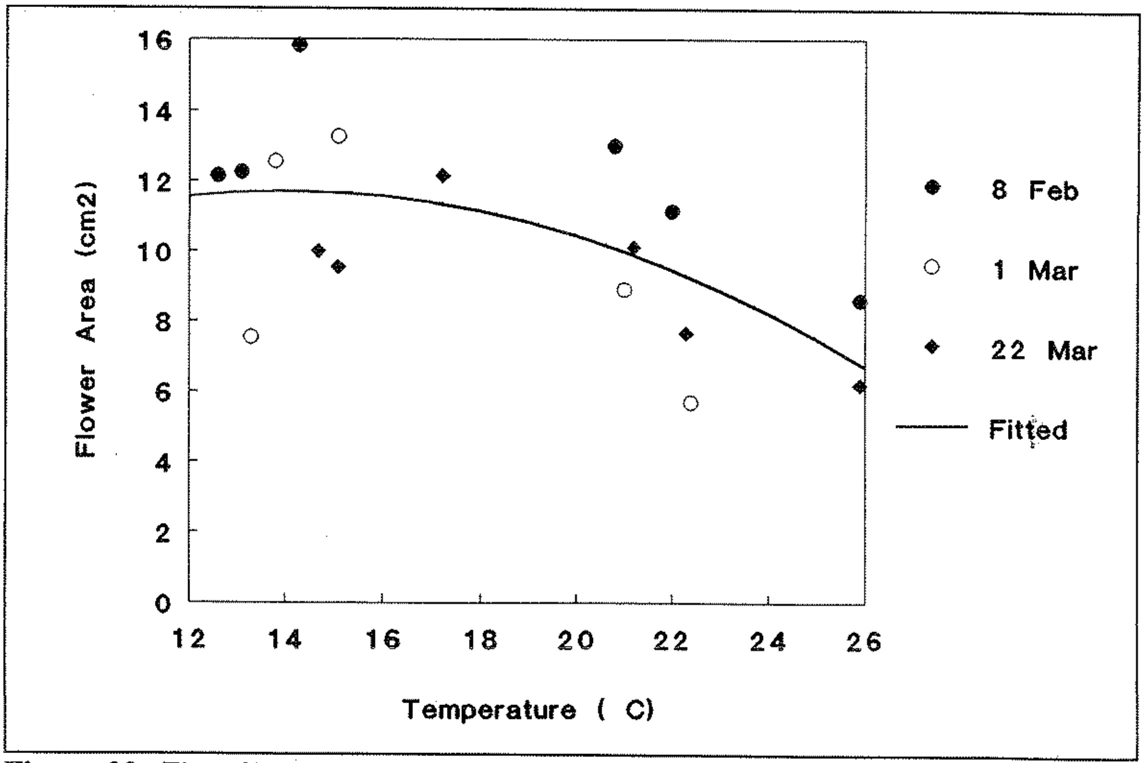

Figure 33. The effects of temperature on the flower size of Impatiens. The line was fitted by regression, where $FA = 4.91 + 0.97T - 0.034T^2$, $r^2 = 0.36$, 14 d.f.

3.5 PETUNIA

The effects of temperature on the growth and quality of *Petunia* are shown on Plate 5.

Plate 4. The effects of temperature on the growth and development of Petunia.

3.5.1 Flowering

Temperature had a considerable effect on the time to flowering (Figure 34a), such that time to flowering decreased with increasing temperature up to 26°C. Thus, plants grown at 18°C took approximately 76 days to flower compared to 66 days at 22°C. Also shown on Figure 34a is the relationship between temperature and time to flowering of *Petunia* cv. Snow Cloud determined from plants grown in growth cabinets by Kaczperski *et al.* (1991). This shows a close fit to the data gathered here and therefore provides some independent validation of the data, and evidence of its robustness. Figure 34a also suggests that plants from the earliest sowing date required more days to maturity than those sown later. This effect is because *Petunia* are long day plants, since further experiments (authors unpublished data) have shown that *Petunia* grown with a 15 hour daylength flowered 10 to 14 days earlier than those grown with a 9 hour daylength. Thus, plants from early sowing dates, when days are short, will require more time to flowering than those sown later.

These data on photoperiod responses, combined with that of Kaczperski *et al.*(1991) was used to construct a model to predict flowering of *Petunia* in response to photoperiod and temperature. This model was validated, independently, on data gathered from the experiments reported here. The model was shown to be accurate and predicted flowering date of 18 crops to within ± 3.2 days (Figure 34b). The model was then applied to construct sowing date schedules for crops grown at a range of set point temperatures (Figure 35). This schedule shows that different set point temperatures can have considerable effects on the time to maturity, especially for early sowing dates. The model developed to construct the schedule can also be used to forecast crop maturity dates following sowing. It is hoped that a computer program enabling such forecasts will be forthcoming shortly.

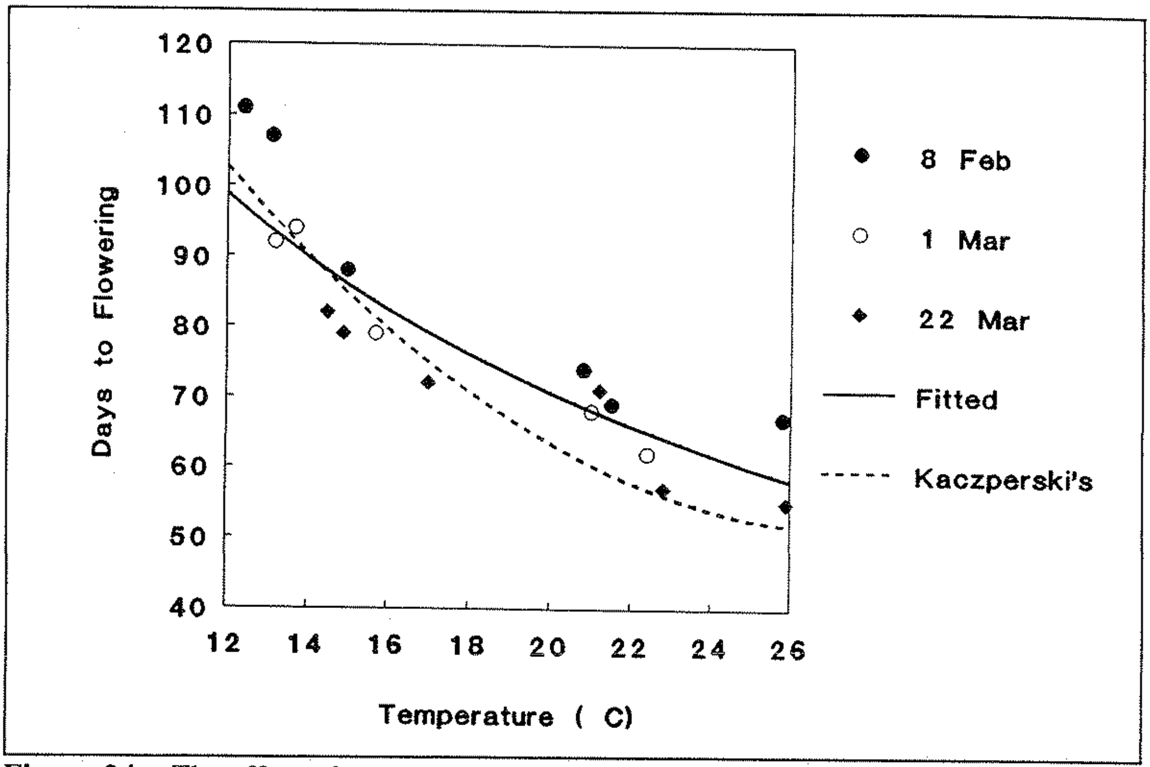

Figure 34a. The effect of temperature on the time to flowering of Petunia. The line was fitted by regression, where days to flowering = 1/(0.00404 + 0.000504T), $r^2 = 0.84$, 16d.f.

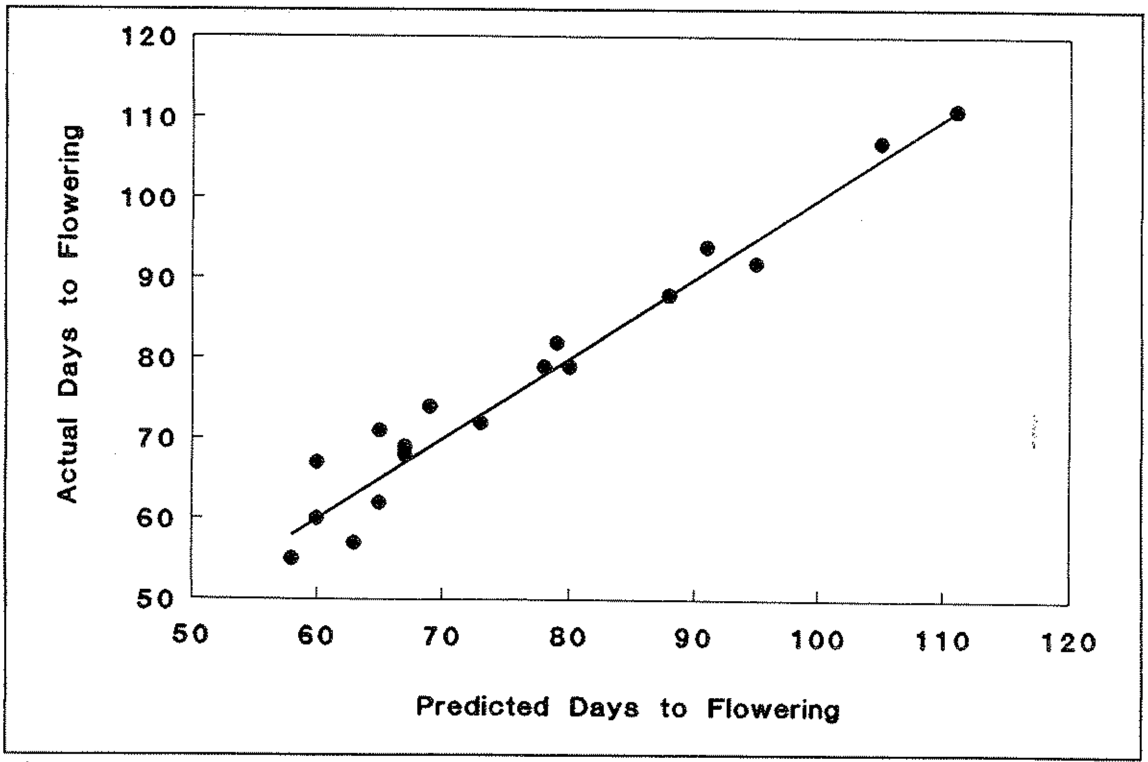

Figure 34b. The predicted days to flowering of Petunia, by the model, versus measurements made on 18 independent crops.

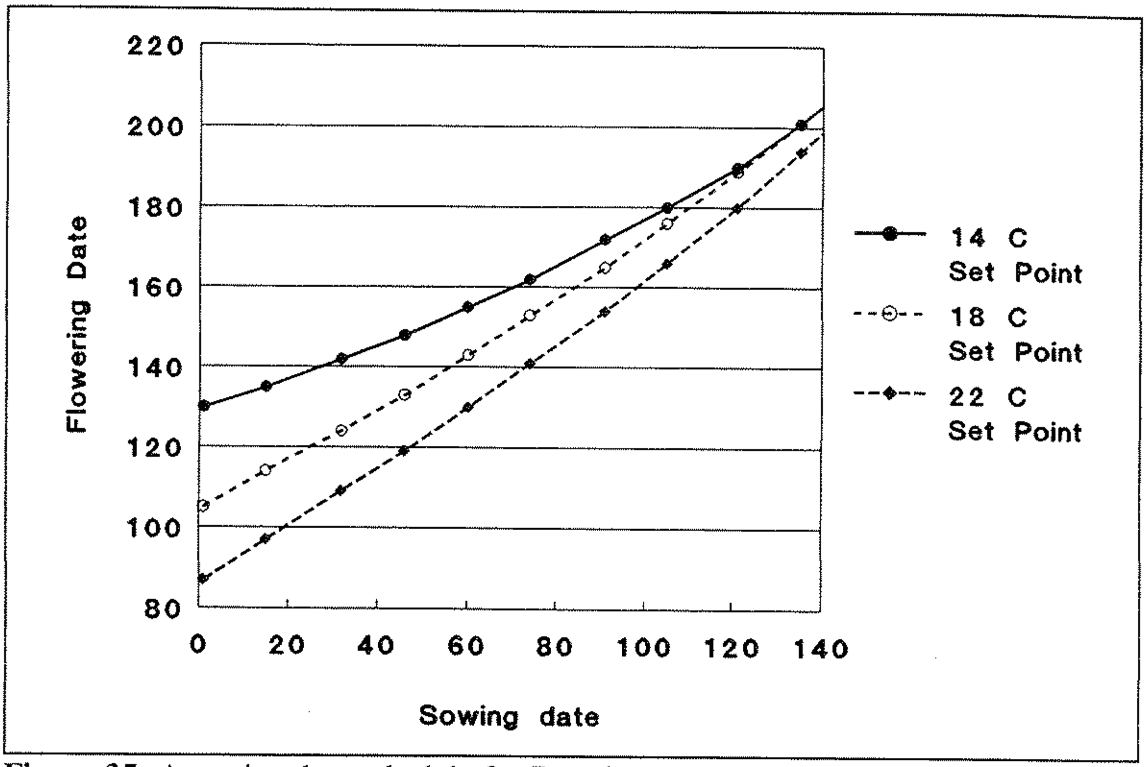

Figure 35. A sowing date schedule for Petunia.

3.5.2 Fresh Weight

Fresh weight at flowering was inversely proportional to temperature. Thus, fresh weight decreased linearly as temperature increased (Figure 36). Plants at 26°C attained only half the weight as those at 14°C. The greater fresh weight at cooler temperature may be partially attributable to the fact that those plants took considerably longer to flower than others in warmer environments. Thus, cool temperatures provide more time for growth and fresh weight gain.

3.5.3 Leaf Number

Temperature had little influence on the final leaf number prior to first flowering (Figure 37). Thus, plants from all sowing dates and temperatures produced approximately 31 leaves prior to the first flower.

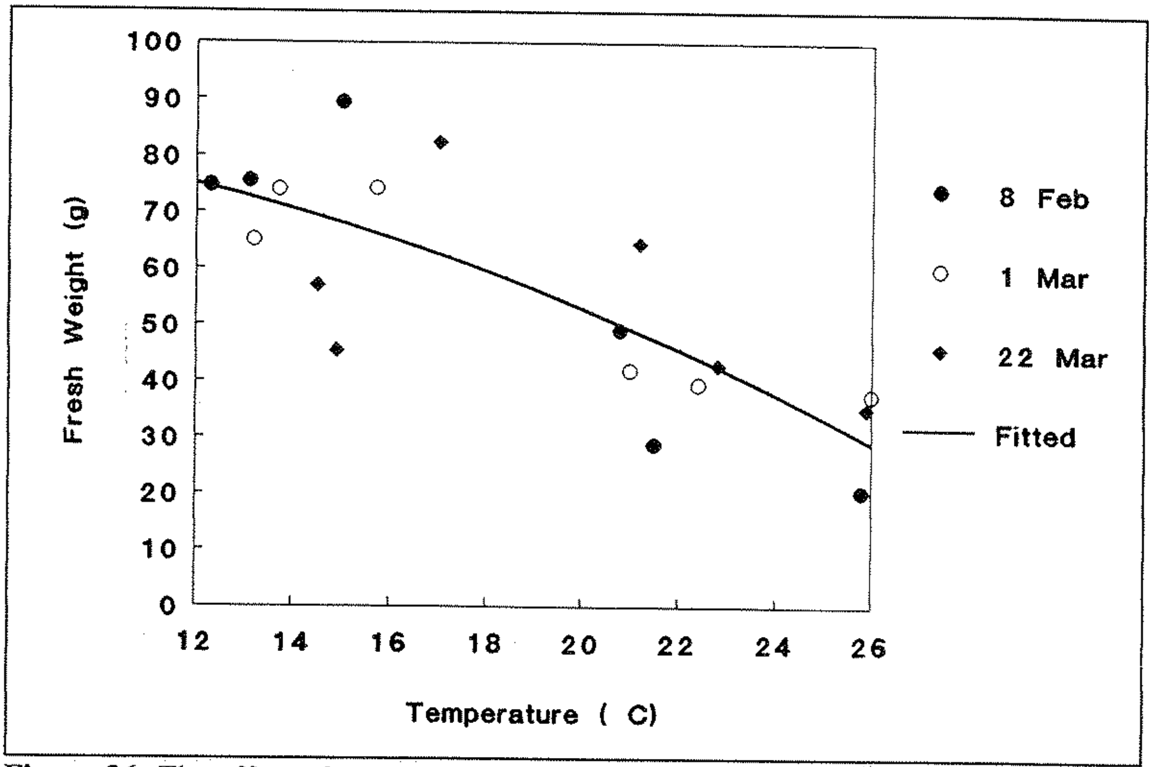

Figure 36. The effect of temperature on the fresh weight of Petunia at flowering. The line was fitted by regression, where FW = 87.6 - 0.086T, r^2 = 0.63, 16d.f.

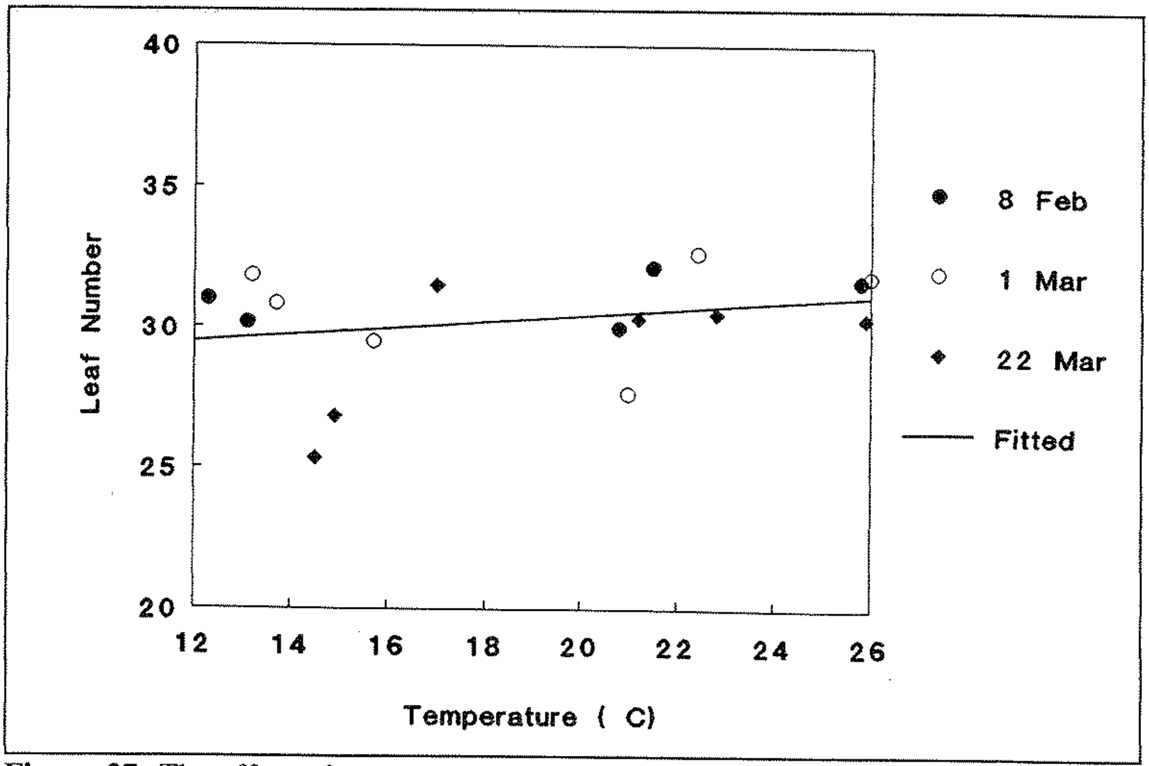

Figure 37. The effect of temperature on the leaf number of Petunia at flowering. The line was fitted by regression, where LN = 28.1 + 0.117T, r^2 = 0.09, 16d.f.

3.5.4 Leaf Area

Temperature had considerable influence on the final leaf area per plant (Figure 38). Final leaf area per plant declined with temperatures higher than 16°C. Plants at 14°C produced almost double the leaf area as those grown at 26°C.

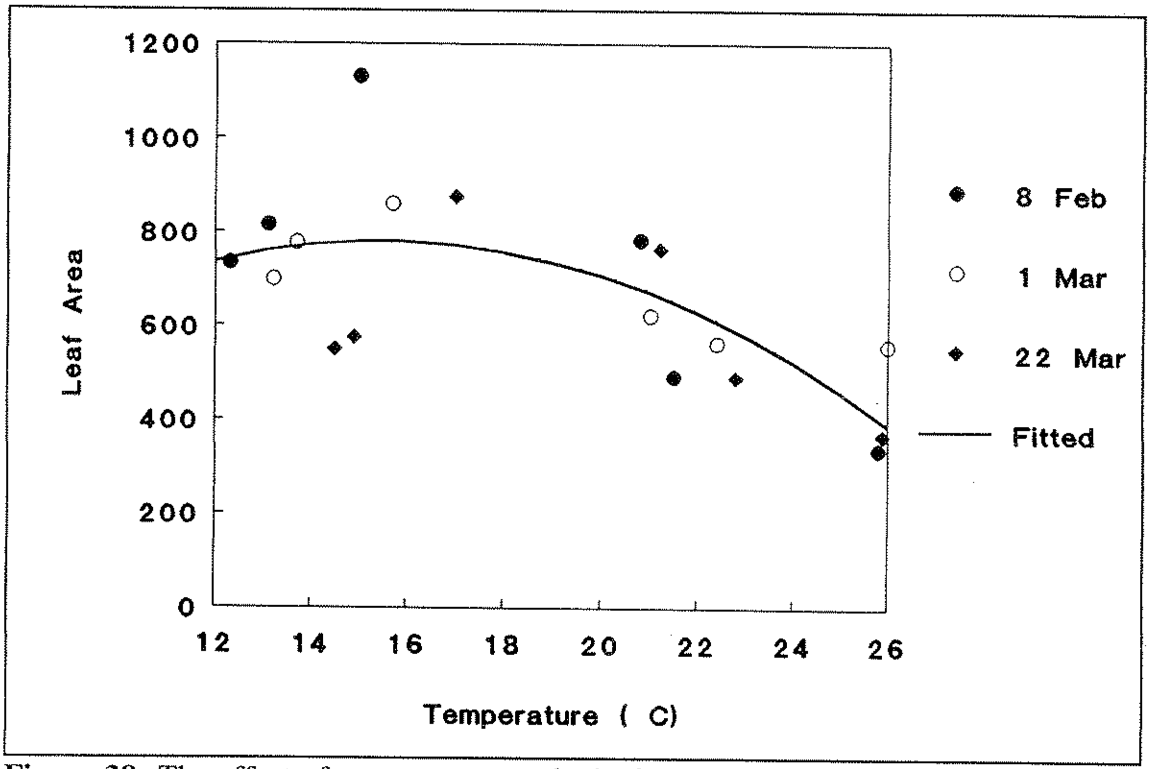

Figure 38. The effect of temperature on the leaf area of Petunia at flowering. The line was fitted by regression, where LA = -60.5 + 108.7T - 3.51T^2, r^2 = 0.49, 15d.f.

3.5.5 Branch Number

Temperature appeared to have little affect on the number of branches produced (Figure 39). Thus, plants from all sowing dates and temperatures produced approximately 10 branches at flowering. This contrasts to the data provided by Kaczperski *et al.* (1991) who indicated that branch number decreased with increasing temperature. The discrepancy may be due to the fact that they used a different cultivar to that here, or that branches of different sizes to Kaczperski were included in this study.

3.5.6 Branch Length

Temperature did, however, have a considerable effect on branch length (Figure 40). Longest branch lengths were recorded in plants grown at cool temperatures, thus plants at 14°C produced 10 branches compared to 5 at 26°C. Thus, plants at cooler temperatures appeared to have a better branching habit, and were therefore of greater quality, than those at higher temperatures, even though the actual branch numbers were the same.

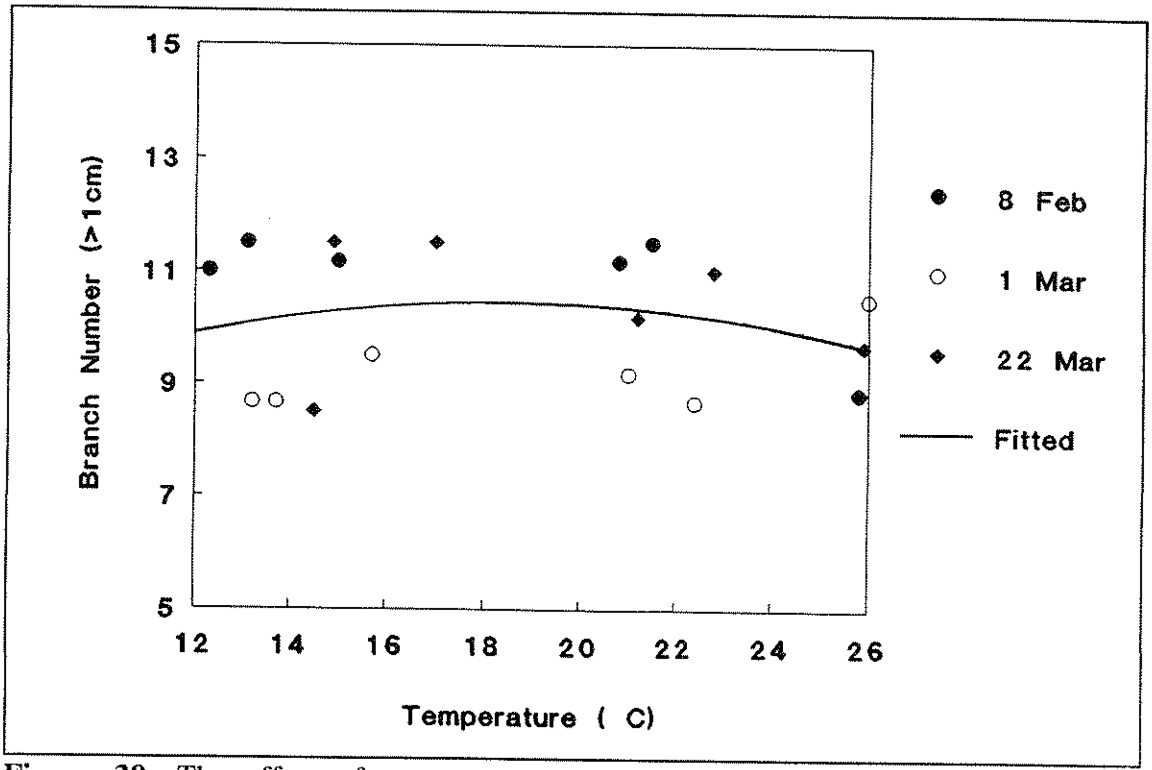

Figure 39. The effect of temperature on branch number (>1cm) of Petunia at flowering. The line was fitted by regression where, $BN = 5.88 + 0.49T - 0.0134T^2$, $r^2 = 0.04$, 15d.f.

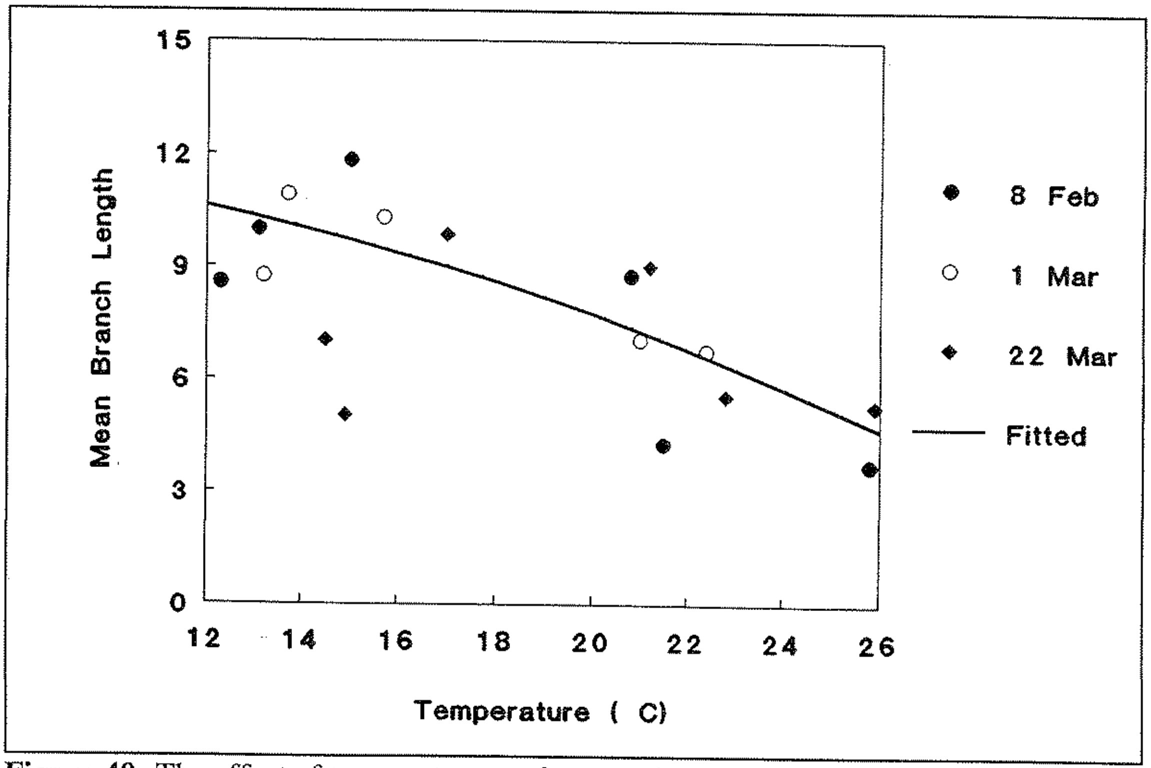

Figure 40. The effect of temperature on the mean branch length of Petunia at flowering. The line was fitted by regression, where $BL = 12.25 - 0.0112T^2$, $r^2 = 0.7$, 14 d.f.

3.5.7 Plant Height

For last two sowing dates, plant height at flowering generally increased with increasing temperature (Figure 41). However, for the earliest sowing date, temperatures above 21°C led to a reduced final plant height. This may be due to an interaction with photoperiod; since studies on the photoperiod responses of *Petunia* (authors unpublished data) suggest that plant height increases with photoperiod (see Plate 6). Thus, plants sown early when days are short may be expected to be shorter than those sown on later dates.

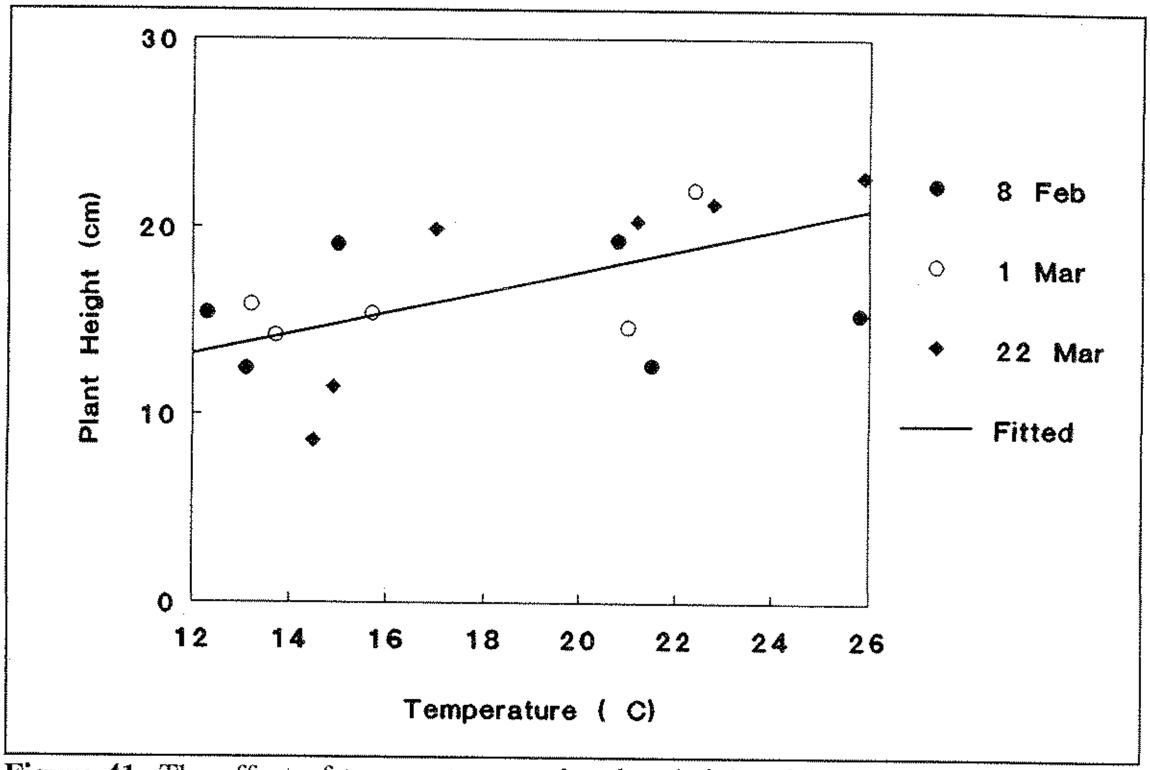

Figure 41. The effect of temperature on the plant height of Petunia at flowering. The line was fitted by regression, where PH = 6.61 + 0.55T, r^2 = 0.37, 16d.f.

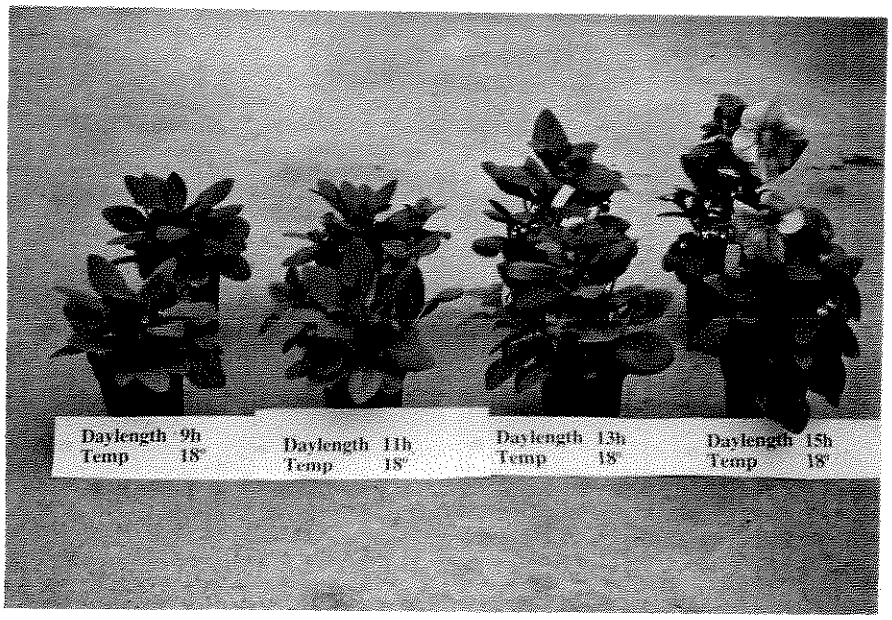

Plate 5. The effect of photoperiod on plant height of Petunia (from the authors unpublished data).

3.5.8 Compactness

Figure 42 shows that cool temperatures led to the most compact plants at flowering. Plants at 14°C had more than twice the leaf area per unit height than those maintained at 26°C. Thus, greatest quality is achieved by growing the plants at cooler temperatures, however, this is at the expense of prolonged production times.

3.5.9 Flower Area

Temperature had a relatively small effect on flower area, relative to the response noted with Pansy and Impatiens (Figure 43). Flower size appeared to be greatest at 16°C.

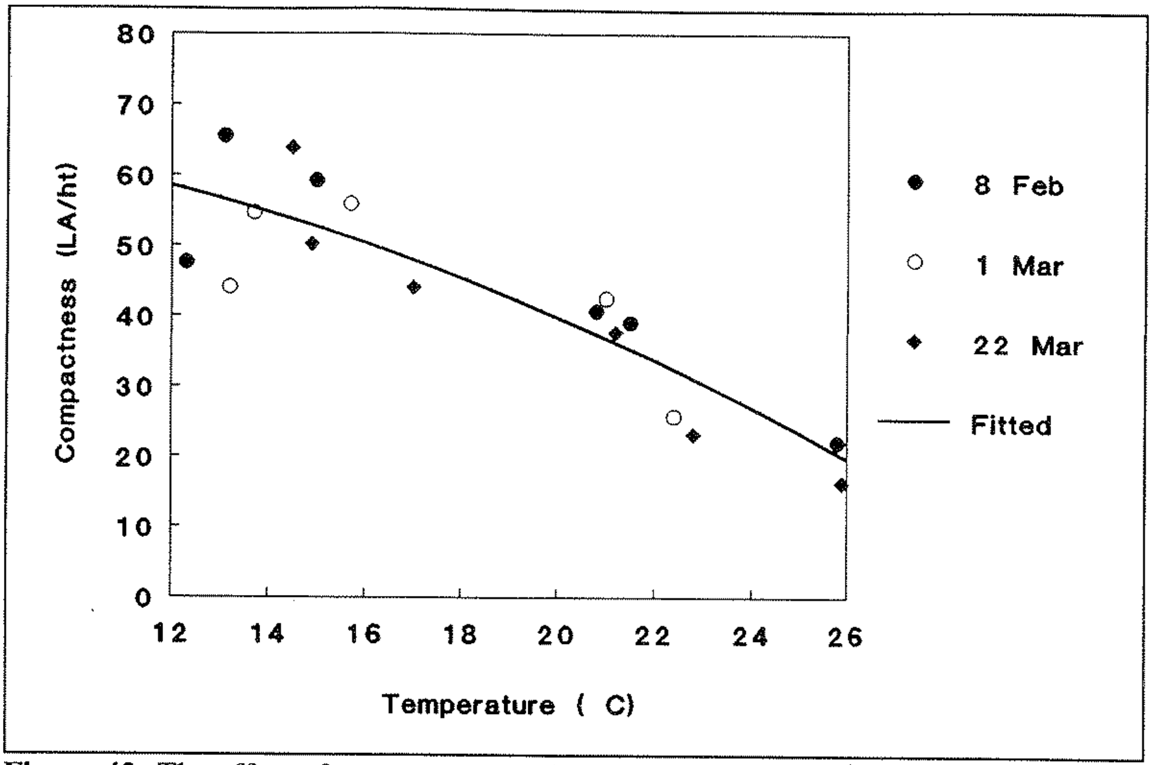

Figure 42. The effect of temperature on the plant compactness of Petunia at flowering. The line was fitted by regression, where C = 69.2 - 0.073T^2, r^2 = 0.81, 16 d.f.

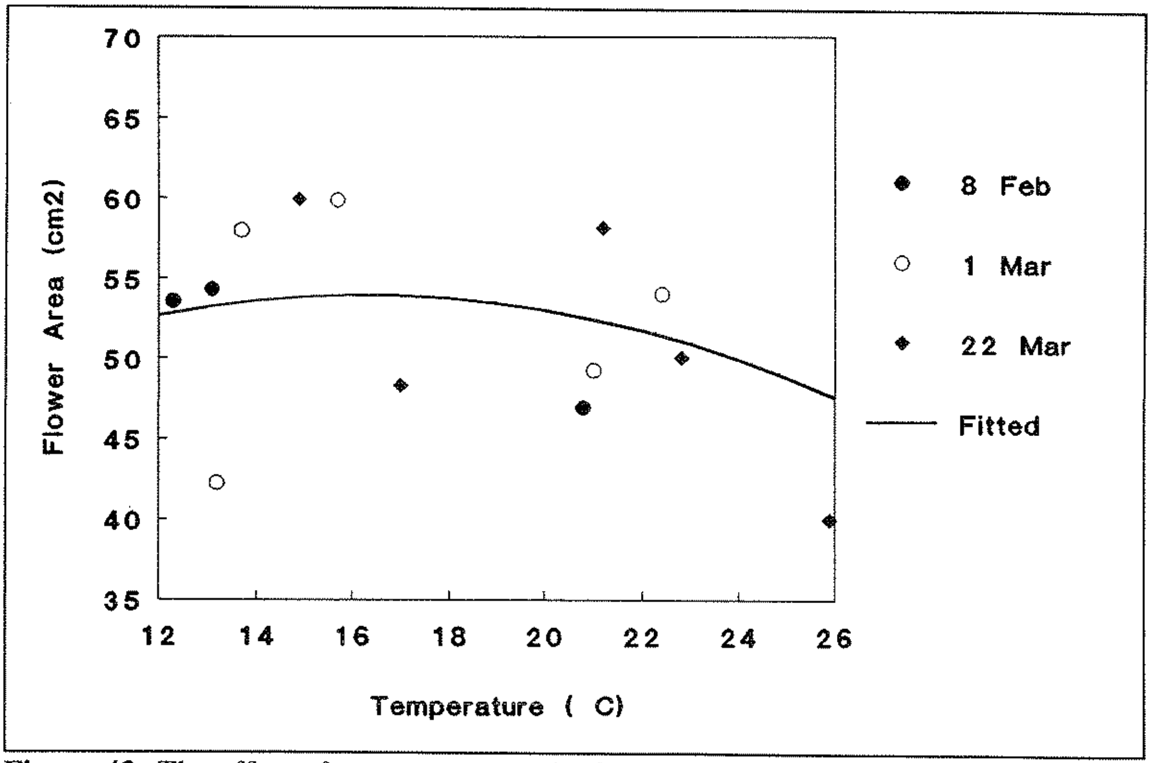

Figure 43. The effect of temperature on the flower area of Petunia. The line was fitted by regression, where FA = 36 + 2.2T - 0.067T^2, r^2 = 0.11, 11 d.f.

4.0 CONCLUSIONS

This study has clearly demonstrated some of the complexities of plant responses to temperature. It has also demonstrated the optimal temperatures for the growth of a diverse range of bedding plants. The most notable effect reported was that the optimum temperature conditions for various aspects of plant growth varied within a species and between species. Though generally the optimum temperature for maximum quality was lower than the optimum for flowering. Thus, a dilemma exists in selecting the correct set point temperature that optimises quality, but also increases output and minimises fuel consumption. Furthermore, in the majority of bedding production a range of species are grown in the same greenhouse, so the set point temperature has to be optimal for all the species grown, or at least not detrimental to growth of any one of the species mix. This project has gone a considerable way to addressing these questions. Growers can now begin to predict the effects of growing plants at a range of temperatures. The optimum temperature that maximise profit have yet to be determined. We intend to address this problem in the next phase of the project. This will be by incorporating the models developed here into computer programs. Simulations will then be un to determine optimal environments for growing a range of crops that maximise returns.

The study has shown that a number of areas of plants responses are still poorly understood and require research attention. These include;

1) How temperature effects different cultivars of the plants examined here.
2) Effects of environment on other bedding species, such as Anthirrinhum, Salvia, Marigold etc.
3) Effects of temperature on flowering of Primrose, increased understanding would help scheduling for Mothers Day crops.
4) Factors affecting flower abortion and premature flowering in Impatiens.
5) There is little information on the interaction between photoperiod and light integral, especially during low light conditions. Improved understanding of these interactions will help scheduling.
6) Effects of changing temperature during plant growth on subsequent plant quality, these experiments were performed in constant conditions, there may be benefits from changing set points at different stages of development.

Further work, funded by MAFF and the HDC, is now in progress to both consider the effects of temperature on a wider range of species and cultivars, and to clarify some of the more poorly understood responses noted here.

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6.0 Acknowledgements

We would like to thank the help and encouragement of all those who have supported this study, in particular Stuart Coutts and Brian Crosby.

7.0 Appendix: Publications From the Project

7.1 Articles Published

1. Pearson, S., May, D.R., Hadley, P. (1992). Scheduling bedding crops for better quality, *HDC Project News*, May 1993, p1.

2. Tuffs, L. (1994). Crystal balls for greenhouses. *Horticulture Week*, **215**(5), 25-28.

3. Pearson, S., Hadley, P., Parker, A. and May, D.R. (1993). Scheduling Pansy crops for better quality. *HDC Fact Sheet*, 4pp.

4. Pearson, S., Hadley, P., Parker, A. and May, D.R. (1994). Scheduling Spring Bedding. *HDC Fact Sheet*, 6pp.

5 Pearson, S., Parker, A., Adams, S.R. Hadley, P. and May, D.R. (1995). The effects of temperature on flower size of pansy (*Viola X wittrockiana* Gams.). *Journal of Horticultural Science*, (In Press).

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Journal of Horticultural Science (1995) **70** (?) 000–000 ?

The effects of temperature on the flower size of pansy (*Viola × wittrockiana* Gams.)

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SUMMARY

The effects of temperature on the flower size of pansy were investigated in two experiments under both glasshouse and controlled environment conditions. Under glasshouse conditions, flower size (mm^2) decreased linearly with increasing temperature between 9 and 31°C ($r^2 = 0.72$). A transfer experiment showed that the decrease in flower size was proportional to the magnitude of the increase in temperature and to the duration of exposure. Thus, prolonged exposures to higher temperatures led to progressively smaller flowers. Temperature prior to visible bud stage had little effect on final flower size, but all subsequent stages were equally sensitive to increased temperatures. Thus, a period of high temperature had the same affect regardless of the stage of floral development. A proportion of the reduction in final flower size to temperature could be attributed to changes in the duration of flower development with temperature. A model was developed which showed that final flower size could be accurately predicted assuming that it was a simple function of mean temperature during flower development and that temperature affected flower size equally throughout development. Fastest rate of flower development from visible bud was found at temperatures greater or equal to 25°C.

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PANSIES (*Viola × wittrockiana* Gams.) are grown as autumn and spring bedding plants, and are also raised for the summer and winter markets. Although the closely related species *Viola tricolor* is thought to be a long-day plant (Withrow and Benedict, 1936; Hughes and Cockshull, 1966), the effects of temperature, photoperiod and irradiance, and their possible interaction, on the vegetative and reproductive growth of *Viola × wittrockiana* have not been studied. Consequently, little is known of the effects of environment on the flower size of pansy, an important element of plant quality, although it has been noted by growers that flower size typically decreases during the summer, and increases again in the spring and autumn.

Studies on chrysanthemum (*Dendranthema grandiflora*, Vince, 1960; Karlsson *et al.*, 1989), *Helichrysum bracteatum* (Sharman *et al.*, 1989), *Anemone coronaria* L. (Ben-Hod *et al.*, 1989) and *Impatiens wallerana* (Lee *et al.*, 1990) have shown that flower size generally decreases with increasing temperature. However, there is little information to indicate when the flower is sensitive to temperature. Garrod and Harris (1974) showed that in carnation, decreasing the flower bud temperature before appearance led to a greater number of petals.

It would be useful to know at which stage pansy flowers are sensitive to temperature, since growers might be able to manipulate temperature to increase flower size and therefore quality. The objectives of this study were, therefore, to investigate the responses of flower size of *Viola × wittrockiana* to temperature, for plants grown under both natural and controlled environment conditions.

MATERIALS AND METHODS

General plant culture

Seed of pansy cv. Universal Violet were sown in standard seed trays containing a proprietary peat based compost (Shamrock potting compost), and germinated in a Conviron S10H growth cabinet at a constant temperature of 17± 0.5°C with a 12 h daylength and an irradiance of 150 µmol m^{-2} s^{-1}, provided from warm white fluorescent lamps and supplemented with 33% tungsten light, determined on the basis of nominal wattage. For all experiments, seedlings were maintained under growth cabinet conditions for three weeks, by which time the cotyledons had fully expanded and the first true leaf was emerging. Depending on the experiment, plants were then either pricked out into a Plantpak P84 plug-tray (volume of each cell, 40 ml), or into a 9 cm pot (volume 0.37 l), containing a proprietary peat based compost (Shamrock Special). Plants which were pricked out into the plug-trays were later transferred into 9 cm pots.

For all experiments, plants were irrigated as necessary and fed twice weekly with a 200 ppm solution of soluble fertilizer (Sangral 101). Biological control of white fly, thrips and red spider mite were used throughout. For the control of scarid fly, Fernex was incorporated into the compost at 34 g per 80 l. Pots were re-spaced when the canopy closed, until they reached the final plant density of 40 pots per square metre.

Experiment 1. The effect of temperature and sowing date on the time to flowering: Natural photoperiods

This experiment was conducted in the inner six of a linear array of eight, 3 × 8 m temperature controlled glasshouse compartments. The experimental compartments had set-point heating temperatures of 4, 10, 14, 18, 22 and 26°C. Ventilation occurred at temperatures 4K higher than the set-point. The actual mean diurnal temperatures were recorded on a Combine data-logger (Murdoch, 1985), from measurements recorded by thermistors mounted within an aspirated screen within each compartment. The experiment was repeated on four occasions, each with a different sowing dates; 10 July 1992, 4 September 1992, 11 November 1992 and 23 December 1992. To simulate commercial practice, seedlings from the growth cabinet, were initially pricked out into one of six Plantpak P84 plug-trays. One tray was placed into each of the six glasshouse compartments. When the plants had reached the fifth true-leaf stage, they were potted on into 9 cm pots. The area of the first fully expanded flower of five guarded plants in each treatment were measured using a leaf area metre (Delta-T Devices, Cambridge, UK), 4 d after anthesis.

Experiment 2. Transfer experiment to investigate the sensivity of stage of flower development to temperature

This experiment, using reciprocal transfers, was conducted in three Conviron S10H growth cabinets set at constant temperatures of 10°C, 17.5°C and 25°C (± 4K). An irradiance of 150 µmol m^{-2} s^{-1} was provided by warm white fluorescent lamps supplemented with 33% tungsten light, determined on the basis of nominal wattage, with a 14 h daylength. All lamps were renewed immediately prior to start of the experiment. Forty-nine seedlings were placed in each growth cabinet on 21 April 1993. Three series of reciprocal transfers were made when the first flower bud, on the main stem, had attained a length of 5 mm (visible bud), when both the flower bud was horizontal to the soil surface and the peduncle had started to expand and finally prior to anthesis when the corolla had started to show colour. Transfers were made when individual plants had attained the desired developmental stage. For each transfer, seven randomly chosen plants from each cabinet were moved to each of the other cabinets and remained until anthesis. One set (seven plants) of common controls, i.e. those plants not transferred, remained in the same compartment throughout. The transfers were between cabinets at 10 and 17.5°C, 10 and 25°C and 17.5 and 25°C and *vice-versa*. Thus, the experimental design consisted of 24 combinations of three initial temperatures, three final temperatures and three transfer stages.

To offset positional effects within the cabinets, plants were re-randomized on two occasions. Each plant was monitored at 2 d intervals and the date of anthesis of the first flower was recorded. Flowers were removed from the plants 4 d after anthesis, by which time the corolla was fully expanded, and areas were then measured on a Delta-T leaf area meter.

Analytical approach: effects of temperature on final flower size

Due to the complicated design of transfer experiments, their analysis is frequently problematic. To overcome this problem models are frequently used to analyze the data. For example, Ellis *et al.* (1992) developed a model to analyze phases of sensitivity and insensitivity to photoperiod in transfer experiments with soya-bean (*Glycine max* Merril.; Ellis *et al.*, 1992) and rice (*Oryza sativa*; Collinson *et al.*, 1992). Here, an analogous model is used to analyze the effects of temperature, at different stages of floral development, on final flower size. This model is based on the hypothesis that cool temperatures lead to larger flowers, but high temperatures during any stage of development will reduce final flower size. The magnitude of the reduction depends on the temperature imposed and its duration. Thus, the model assumes that maximum flower size (F_m) will be attained when temperature is at the optimum (T_{oF}) throughout floral development and that final flower size (F) under any other temperature regime is determined by mean temperature during flower development, thus:

$$F = F_m \cdot T_{oF} / \bar{T} \qquad T_{oF} \leqslant \bar{T} \qquad (1)$$

where $\bar{T}$ is the mean temperature recorded over the duration of floral development. The model predicts, therefore, that supra-optimal temperature conditions, over the duration of flower development will reduce final flower size, by increasing $\bar{T}$. Higher temperatures will lead to relatively greater reductions in flower size, as will longer durations of exposure to supra-optimal temperatures. Where definitive evidence of an optimum temperature is not found the model can be used, and is valid, by assuming T_{oF} is a reference temperature. F_m then becomes the flower size at the reference temperature. The model is therefore simple and biologically meaningful whether or not an optimum is found, since the only inputs are the flower size recorded at a given temperature.

RESULTS

Experiment 1. Flower size under glasshouse conditions

Figure 1 shows that the average flower size decreased as mean temperature increased (P<0.001). A linear regression accounted for 72% of the variation in final flower size. The range of temperatures encountered reflect those experienced in commercial cultivation, since set points were at 4 to 26°C. Over the range of recorded mean temperatures (9 to 31°C), there was no evidence for an optimum temperature for flower size. The relationship between light integral and flower size was not analysed, since there was little variation in the light integrals received up to flowering for each of the last three sowing dates.

Experiment 2. Temperature transfer experiment

For the control plants, which were not transferred, the final flower size decreased signifi-

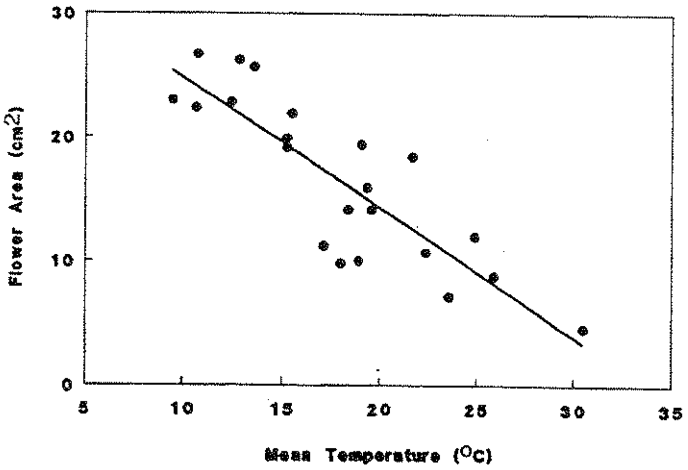

FIG. 1
The relationship between flower size and the mean temperature recorded between the sowing date and time to flowering. The solid line was fitted by regression analysis, where flower size = 35.3 − 1.05T, (r^2 = 0.72, 20 d.f.).

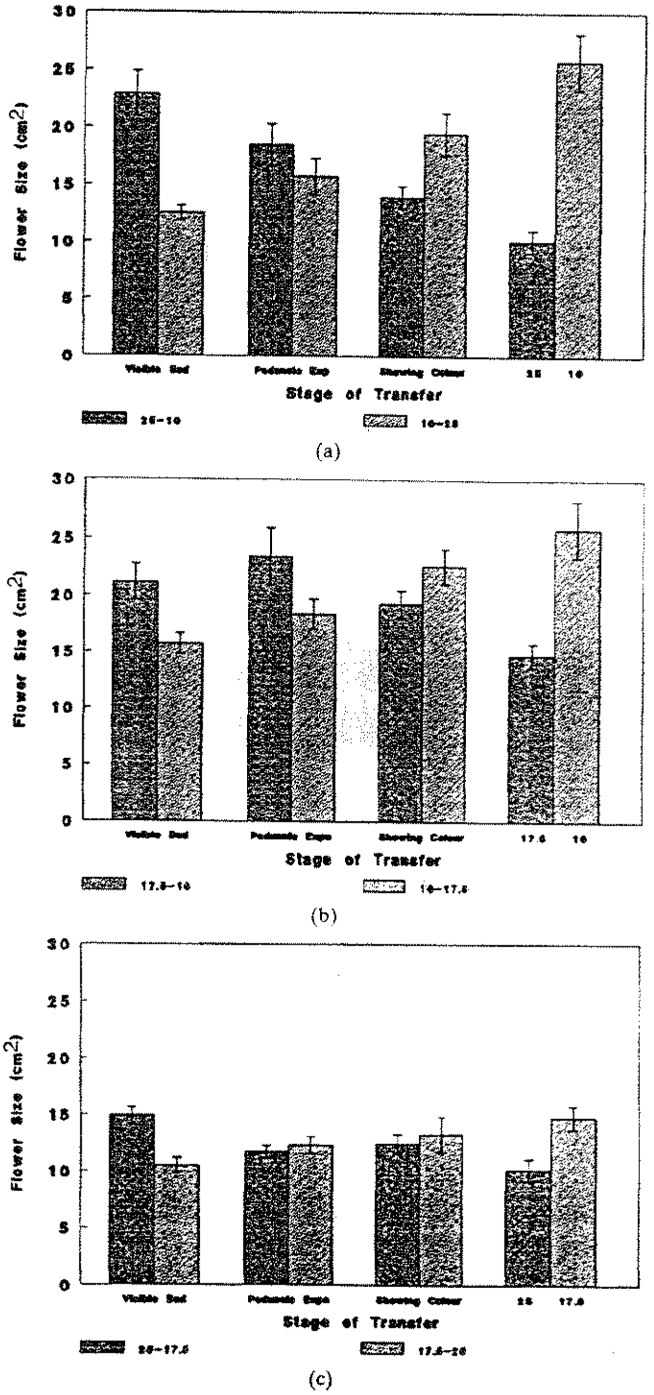

FIG. 2
Final flower size of pansies transferred to and from growth cabinets at three stages of floral development and different temperatures; a) 10°C to 25°C; b) 10°C and 17.5°C; c) 17.5°C and 25°C. The bars represent standard errors of means.

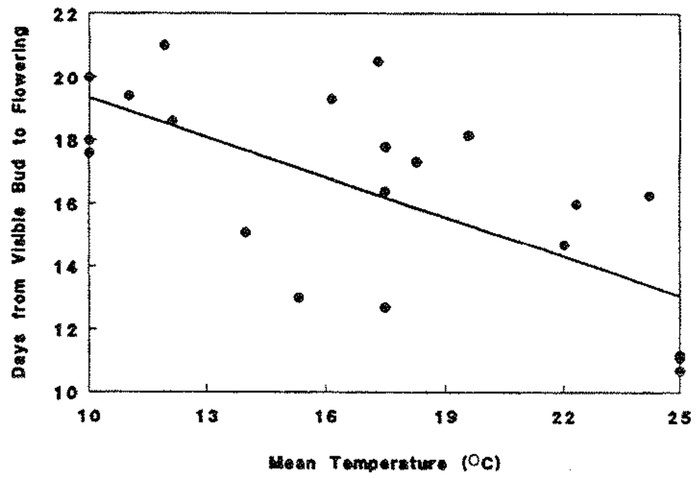

FIG. 3
The effects of the mean temperature, determined from visible bud to flowering, on the days from visible bud to flowering. The solid line was fitted by regression analysis. where Days = 23.5 − 0.42T, (r^2 = 0.49, 22 d.f.).

cantly ($P<0.001$) with increasing temperature, such that final flower areas at 10°C, 17.5 and 25°C were 25.8 ± 2.4, 14.8 ± 1.0 and 10.1 ± 1.0 cm^2, respectively. Figure 2a shows final flower size of plants from transfers between the 10°C and 25°C cabinets and *vice-versa*. This indicates that when plants were initially maintained at cool temperatures and transferred to warm conditions at the visible bud stage, final flower size is similar to that of plants maintained at warm temperatures throughout. Thus, temperature prior to visible bud had little, if any, influence on final flower size. Conversely, when plants were maintained at warm temperatures and then transferred to cool conditions at visible bud, final flower sizes were similar to those of plants maintained under cool conditions throughout. Transfers at later stages of development produced intermediate size flowers. Thus, for transfers at later stages of development, the initial periods of cool or warm had a greater influence on flower

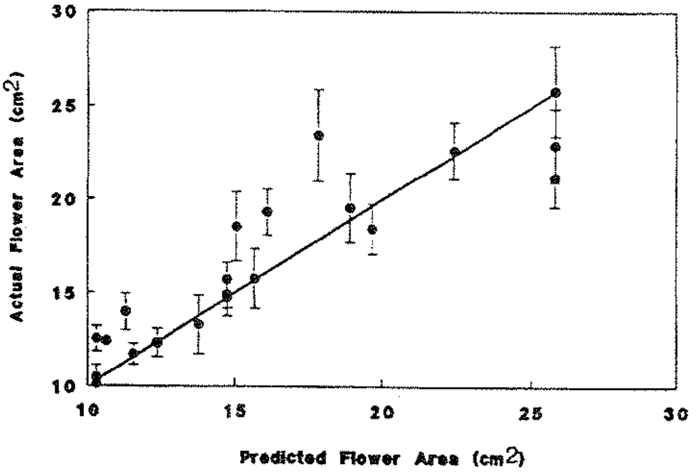

FIG. 4
Validation of the model to predict final flower size, data are those gathered from each of the transfer experiment treatments. The solid line is the line of identity. Each point represent the mean of seven plants, together with standard error bars.

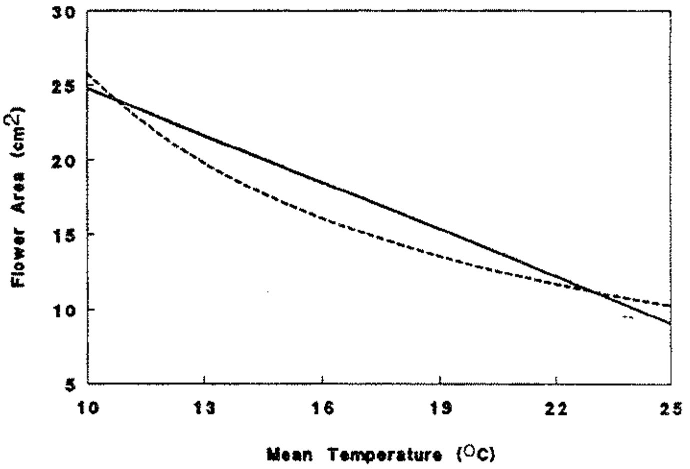

FIG. 5
A comparison of the effect of temperature on flower size determined by the simulation model developed here (dashed line), and fitted to data from a growth cabinets, with an empirically derived relationship (see legend to Figure 1) fitted to data from glasshouse experiments (full line).

size, since flowers were either larger or smaller than when the plants were transferred at earlier stages of development.

Similar responses were recorded for reciprocal transfers between cabinets at 10 and 17.5°C (Figure 2b) and 17.5°C and 25°C (Figure 2c). However, the actual flower sizes varied with the overall temperature imposed. Thus, mean flower sizes for the transfers between the 17.5 and 25°C were smaller than those between the 10°C and 17.5°C cabinets.

To investigate the basis of the variation in final flower size with temperature, days from visible bud to flowering were plotted against the mean temperatures recorded over that period for all the transfer treatments, Figure 3. This showed that the duration for flower development decreased linearly ($P<0.001$) with temperature from visible bud to flowering. A linear regression fitted to the data accounted for 49% of the variation in time to flowering. This suggests small flower size at high temperatures may be partially attributable to a reduced duration of floral development. The data also showed that the fastest rate of flower development of pansy from visible bud occurred at 25°C.

The model for final flower size (eqn 1) was tested on the data gathered in the growth cabinets. As only three temperatures regimes were examined, there was little clear evidence for an optimum temperature for final flower size (T_{oF}), a constituent of the model. To test the model, the optimum (more appropriately the reference temperature) was assumed to be 10°C, the lowest temperature studied. The maximum flower size, F_m, was assumed to be that measured for the plants maintained at 10°C throughout, 25.8 cm^2. For any treatment, the onset of flower sensitivity to temperature (day 0 in the model) was assumed to begin when the buds were first visible. This is valid, since the transfer experiment showed that temperature primarily influenced flower size after this stage of development. The model accurately predicted the flower size obtained during the transfer experiment (Figure 4), accounting for 86% of the variance in final flower size. The error bars on the diagram represent standard errors of a mean. If the model were valid, we would expect approximately two-thirds of the points to have error bars intercepting the line of identity, which is the case.

To validate the simulation model with data from the experiment 1, Figure 5 compares the relationship between mean temperature and flower size for the simulation model developed here (equation 1) and the regression relationship determined from experiment 1. Both show very similar responses, suggesting that the data gathered in the growth cabinets, and therefore the simulation model, provided a realistic representation of the response of pansies to temperature.

DISCUSSION

Under glasshouse conditions during the typical production period for cv. Universal Violet, higher temperatures led to smaller flowers, which explains why growers frequently report smaller flowers during the summer months compared with the autumn or spring periods, since temperatures are generally cooler over the latter periods. The first experiment, however, did not provide information on when the flower was sensitive to temperature. The transfer experiment revealed that the flower is sensitive to temperature only at the onset of, or after, the visible bud stage. There was little evidence that different stages of development were more sensitive to temperature than others, since the model, which assumed equal sensitivity throughout development, accurately predicted final flower size.

Final flower size of any determinate organ is a product of the duration of growth and the rate of growth. It was not possible to examine the effects of temperature on the rate of flower growth, however, the smaller final flower size at high temperature can, at least, be partially attributed to shorter durations for growth. This reduced duration may have influenced the time for cell division within the flower or the time for cellular expansion. However, the effects of temperature were primarily exerted after the visible bud stage, by which time presumably most cells had divided.

Little is known about effects of temperature on final flower size. Other studies have shown the effects of temperature on both petal number and petal size, for instance in carnation Garrod and Harris (1974) showed that low temperatures increased petal number, and in chrysanthemum Vince (1960) showed that low temperatures had little effect on floret number but increased their length. These two studies also demonstrated that carnations and chrysanthemum had distinct periods of sensitivity to temperature. In carnation, the greatest response to low temperature was seen when the treatment was applied early during the flowers development, prior to visible bud (Garrod and Harris, 1974). In chrysanthemum, the flower was most sensitive after it became visible (Vince, 1960). However, for pansy the flower appears to be sensitive to temperature throughout its development.

This study has also attempted to model the effects of temperature on flower size. The model developed was relatively simple, and contrasts with that developed by Karlsson *et al.* (1989) to predict the final flower size of chrysanthemum. Although it was accurate, the latter model was empirical and contained a number of interacting day and night temperature terms. The model reported here was also accurate and showed that the flower was sensitive to mean temperature throughout its development. It predicts that the largest flowers, of the highest quality, will be achieved by growing the plant at low temperatures. Further improvements to the model could be achieved through incorporating other environmental factors into the model, such as irradiance and photoperiod, and by examining whether the true optimum temperature for final flower size is lower than the value of 10°C, which was assumed here.

This study has clarified the effects of temperature on the final flower size of pansy. This information will be of considerable value to growers, since flower size, and therefore plant quality, can be maximized by keeping the plant cool after flower initiation. Many growers increase temperatures during the later stages of development to hasten flowering. However, this may be counter-productive, since such treatments will reduce flower size and therefore quality.

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