Master project in the Horticultural Science Programme
2008:5, 30 hp (30 ECTS)

Climate management in tomato greenhouse market gardens

- Application and evaluation

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Project information

This is the result of a master thesis (30 ECTS) carried out at the department of horticulture within the horticultural programme at the Swedish University of Agricultural Sciences. The project includes both a literature study and a practical experiment. Beatrix Alsanius was the head supervisor, Inger Christensen assistant supervisor, and Rolf Larsen the examiner.

Abstract

An efficient climate management is essential to achieve a high production in tomato greenhouse market gardens. Temperature, especially, is very important since it has a large influence on both the vegetative and the generative growth. The main objective of the present study was to evaluate the effect of low temperature pulses (LTP) on the fruit growth. The study was carried out both through a literature study and through an empirical study done in three commercial greenhouse market gardens growing tomato. During a ten week period in the spring of 2007 weekly growth, stem diameter, leaf length, length of truss peduncle, peduncle diameter, number of fruits per truss, fruit diameter and height, total number of fruit on the plants, amount of harvested fruit, and individual fruit weights were measured. Climatic data was gathered from PRIVA environmental computers, which were used in all three market gardens. Due to reluctance from the participating growers to use LTPs, and a lack of literature on the subject, the question of whether LTP has an effect on fruit growth remains unanswered. The effect of night temperature and average temperature was also included in the study. There were correlations between night temperature and the number of fruit; the R^2 values were very low however, indicating that hardly any of the variation in the plant parameters can be explained by the night temperature. Lower average temperature lead to larger but fewer fruits, while a higher average temperature lead to slightly smaller first fruits, but a higher yield; this is confirmed in the literature. The harvest was closely related to the weekly average temperature where a high average temperature one week resulted in a high yield the following week.

Referat

En effektiv klimatstyrning är grundläggande för att uppnå en hög produktion i tomatväxthus. Särskilt temperaturstyrning är viktigt då temperaturen har en stor inverkan på både den vegetativa och den generative tillväxten av plantorna. Den huvudsakliga målsättningen med examensarbetet var att undersöka effekten av lågtemperaturpulser (LTP) på fruktutvecklingen. Studien omfattade både en litteraturstudie och en empirisk studie som utfördes hos tre tomatodlare i södra Sverige. Under en tioveckorsperiod våren 2007 mättes stamtillväxt, stamdiameter, bladlängd, klasstjälkslängd, klasstjälkdiameter, antal frukter per klase, fruktdiameter och –höjd, totalt antal frukter på plantan, skördemängd och individuella fruktvikter. Klimatdata samlades in från PRIVA klimatdatorer; ett system som alla tre odlarna använde sig av. På grund av odlarnas tveksamheter att använda LTP, samt bristen på relevant litteratur i ämnet, gjorde att frågan om huruvida LTP har en effekt på fruktutvecklingen förblir obesvarad. Effekten av nattemperatur samt medeltemperatur var också innefattat i studien. Det fanns korrelationer mellan nattemperatur och antalet frukter på plantorna; R^2 värdena var däremot så låga att i stort sett inga av variationerna i växtparametrarna kan förklaras av förändringar i nattemperaturen. Låg medeltemperatur ledde till stora men färre frukter, medans en högre medeltemperatur ledde till något mindre frukter men en totalt högre skörd; dessa resultat bekräftas i litteraturen. Skörden var nära förknippad med medeltemperaturen: en hög medeltemperatur under en vecka ledde till en hög skörd veckan därpå.

1 Introduction

A high production is absolutely essential for the profitability of commercial tomato market gardens. This means that an efficient climate management is necessary. Temperature is said to be the predominant cultural management factor to steer the production since it has a large influence on the vegetative and generative development (Heuvelink & Dorais, 2005). To achieve a balance between the vegetative and generative growth growers commonly use different temperature programmes where the day and night is divided into five or six periods. One of the more recent methods of controlling the growth is by using low temperature pulses. This master thesis has come about as an attempt to find the underlying theory of why low temperature pulses should be used, as well as studying the effect of commonly used temperature settings.

1.1 Purpose of the study

The overall purpose of the present study is to gain knowledge that can be used to increase the profitability in commercial tomato greenhouses by more efficient climate management. This is done by comparing the climate regime, in particular temperature, carried out by three commercial greenhouse market gardens in southern Sweden, and by studying the scientific basis for the employed procedures.

1.2 Hypotheses

- Low temperature pulses during early morning and pre-night has a positive effect on the fruit swelling of tomatoes.
- Day and night temperature settings, and not only average temperature, are important for the fruit development.
- The development of the fruit is faster at a higher average temperature.

2 Climate conditions affecting flowering, fruit set and fruit growth

2.1 Temperature and light

Temperature is the cultural management factor best used in greenhouses to steer the partitioning of biomass within the tomato plant (Heuvelink & Dorais, 2005). Combined with the light intensity it strongly affects the floral initiation, floral development, fruit set and fruit growth simultaneously throughout the growing season (Dorais, 2003).

2.1.1 Floral initiation and development

The tomato plant will form flowers with time as long as the climate conditions allow for any growth. However, by regulating the temperature, the time to first flowering can be altered (Kinet & Peet, 1997). The first inflorescence is preceded by at least six to eight leaves, at low temperatures fewer leaves precede the inflorescence but the time to flowering is longer. If the light intensity is low a high temperature will increase the time to flower initiation compared to a lower temperature (Heuvelink, 2005). By increasing the light intensity, the number of leaves is reduced and the time to flowering is shortened; with a light intensity that is high, temperature plays a minor role. The amount of light intercepted by the plants on a daily basis is important for the reproductive development. In favourable light conditions the floral transition occurs during the fourth week and after another four weeks the first inflorescence appears (Kinet & Peet, 1997).

After the emergence of the first truss, truss appearance rate is primarily determined by temperature. It has been reported that an increase in day temperature is more efficient in promoting flower development than an increase in night temperature (Heuvelink, 2005). According to De Koning (1994) there is a linear response between an increase in temperature and the truss appearance rate where an increase in temperature from 17ºC to 23ºC increased the truss appearance rate from 0.11 to 0.17 trusses per day. If the temperature gets too high, especially if light conditions are low, the flowers will abort; they are particularly sensitive to high temperatures 9-5 days before anthesis at the time of pollen formation, after this they become more tolerant again. Should temperatures be low during flower formation there will be an increase in inflorescence branching (Kinet & Peet, 1997). Increased irradiance combined with decreased temperature results in a higher number of flowers per inflorescence (Heuvelink, 2005). Too low temperature however, below 10ºC, is detrimental to the production of pollen and due to this the fruit set will be low caused by poor pollination (Kinet & Peet, 1997). The supply of assimilates is important for both floral initiation and development, where a low assimilate availability leads to a reduced number of flowers and a higher rate of abortion of flower buds. A low light intensity, for example, can be the cause of a low supply of assimilates since the photosynthetic activity is decreased (Ho, 1996).

2.1.2 Fruit set

Successful fruit set is dependent on several processes: pollen development, pollination, germination of pollen grains, pollen tube growth, fertilization and fruit initiation (Picken, 1984). A failure in any of these, results in poor fruit set (Heuvelink, 2005). In a study carried out by Charles & Harris (1972) where several cultivars of both heat and cold tolerant tomato plants were used, it was found that in the range between 10ºC and 26.7ºC the highest percentage of flowers that set fruit were grown in 18.3ºC. The pollen grains developed in the 10ºC treatment were unviable in all selections. At the low temperatures the poor fruit set was primarily caused by the reduced pollen viability, a slow pollen tube growth and in some selections of a high stigma level. At high temperatures it was caused by a high stigma level which reduced the opportunity for pollen to reach the stigma, hence fertilization was reduced (Charles & Harris, 1972). Other studies have shown similar results, such as Ercan & Vural (1994) who also had a low fruit set at low temperatures due to a decreased pollen count and viability.

Extreme temperatures limit fruit set, where temperatures below 10ºC and above 30ºC are detrimental to one or more of the processes leading to fruit set; the exact limits are depending on cultivar. The optimum temperature for pollen grains to be retained by the stigma is between 17ºC and 24ºC, and germination of the pollen grains are highly reduced at temperatures above 38ºC and below 5ºC (Picken, 1984). In a study investigating the effect of night temperature on fruit set it was shown that 20ºC to 24ºC appeared to be optimal when the day temperature was set to 26ºC. However, fruit set exceeded 75 % in all treatments ranging from 18ºC to 26ºC, which demonstrates that day and night temperatures do not affect the fruit set independently but that it is the average daily temperature that is important (Peet & Bartholemew, 1996).

Low light conditions affect the pollen development negatively since low availability of assimilates inhibits the meiosis of some pollen cells. Low light and high temperature can also increase the stigma exsertion which reduces fertilization; it also adversely affects the development of the endothecium that is essential for dehiscence. Further it may cause splitting of the staminal cone as well as fasciation of the style (Heuvelink, 2005). Germination seems to be unaffected by light intensity (Picken, 1984).

2.1.3 Fruit growth and yield

Fruit growth and yield are, like most other developmental processes, primarily dependent on temperature (Heuvelink, 2005). It is the temperature of the fruit that determines the time of ripening whereas the temperature of other plant organs is of little importance (Adams et al., 2001). The time from fruit set until harvest-ripe fruit is determined by a certain temperature sum; i.e. the higher the temperature the shorter the ripening time (Heuvelink, 2005). The fruit growth period can vary from 73 days at a temperature of 17ºC to only 42 days at 26ºC (De Koning, 1994). Similar results were found by Van der Ploeg & Heuvelink (2005) where an increasing average temperature from 14ºC to 26ºC was found to shorten the time from anthesis to mature fruit. High temperatures however often result in smaller fruits. A negative linear relationship between truss weight and mean temperature has been established over a temperature range of 18.4ºC to 22ºC (Newton & Sahraoui, 1999). At higher temperatures the development rate is accelerated leading to a more rapid increase in number of fruits. Assimilate partitioning between reproductive and vegetative parts then change in favour of the fruits, since the sink strength of the fruit increase with increasing temperature (De Koning, 1989). The higher fruit load resulting in less vegetative growth will eventually lead to a shortage of assimilates available for developing and flowering trusses, causing reduced fruit set and even abortion of recently set fruits (Van der Ploeg & Heuvelink, 2005).

Temperature affects the biochemical processes of carbon demand and the import of assimilates. An increased temperature leads to an increased carbon influx accompanied by water, which expands the fruit (Pearce et al., 1993a). The effect of higher temperature though, is only beneficial when the assimilate supply is unlimited and water stress is prevented. Since the assimilate supply is decreased, and water stress is induced by an enhanced canopy transpiration, both due to high temperatures (Ho, 1996), the potential fruit weight at 23ºC is 40% lower than at 17ºC (De Koning, 1994). If temperatures rise above 30ºC the ripening is inhibited caused by inhibition of lycopene synthesis. Tomatoes produced at temperatures above 26ºC are often softer and have an uneven ripening (Mulholland et al., 2003). With a 24 hour regime of 26ºC trusses tend to be abnormal, fruit set is poor and fruits are commonly parthenocarpic (Adams et al., 2001).

High temperatures in the greenhouse during the summer are very common, and they are often followed by a period of high yields. After this period of high yields there will be a depression in yield; since the period of high temperature caused the tomatoes to ripen faster than they normally would, more fruits are picked and hence fewer tomatoes nearing maturity are left on the plant (Adams & Valdés, 2002). Lower temperatures prolongs the time to ripening but also increases the size of the tomato fruits (Van der Ploeg & Heuvelink, 2005). The size of the fruit is related to a difference in number of locules per fruit, where fruits grown in a low temperature regime have a larger number of locules than fruits grown at high temperatures (Sawhney & Polowick, 1984). If temperatures are too low however, hollow and catfaced fruits will become more frequent (Van der Ploeg & Heuvelink, 2005). Fruits grown in 14ºC are often parthenocarpic, small and hard. Tomato plants grown at intermediate temperatures between 18ºC to 22ºC produce the most normal fruits (Adams et al., 2001).

Yield is positively related to the amount of incoming solar radiation intercepted by the plants in a long season crop. Shading reduces the fruit size (Kinet & Peet, 1997), and low light intensities combined with low temperatures cause deterioration of fruit taste caused by a decrease in sugar content (Rylski et al., 1994). Termination of growth of small fruits is sometimes induced by high temperatures and high light conditions (Picken, 1984).

2.2 Effect of Low-Temperature Pulses on fruit growth

LTP treatments are only reported for plant production, where a low-temperature pulse at daybreak results in shorter plants (Gertsson, 1992; Grimstad, 1993). The plant height and leaf petiole length of the tomato plants decreased as the magnitude of the pulse and the time of exposure increased. A significant increase in number of flowers of the first inflorescence caused by the low temperature was observed, and the time to flowering was slightly longer. The yield and quality of fruit from the first three trusses of plants that had been temperature treated during propagation was unaffected by the treatment (Grimstad, 1993).

2.3 Effect of positive and negative DIF on fruit growth

The use of negative DIF in young plants mainly affects the vegetative growth while a reproductive plant hardly shows any reaction to the temperature regime as long as the 24 hour temperature is the same (Heuvelink, 1989). By lowering the day temperature and raising the night temperature in the plant production phase or early in the season will result in more compact plants with firmer main and truss stems. Firmer truss stems reduce the incidence of kinking (De Koning, 1988). Kinking of the truss stems significantly decrease the fresh and dry weight of tomato fruits since the translocation of assimilates to the fruit is blocked (Horridge & Cockshull, 1998). In a study made by De Koning (1988) it was found that the number of kinked truss stems was highest at a high positive DIF and lowest at equal day and night temperatures or at a low positive DIF. He also found that the yield was equal or higher when a negative DIF was used; the development rate was not affected but the fruits became larger.

Large differences between day and night temperatures can increase the fruit growth period (Van der Ploeg & Heuvelink, 2005), however a large difference results in more generative growth (Peet & Welles, 2005). Plants grown under a large positive DIF early in the season have also been shown to have low yields late in the season (Papadopoulos & Hao, 2000).

2.4 CO_2

CO_2 is the substrate of photosynthesis and enrichment of it in the greenhouse increases plant growth, fruit set, number of fruit and average fruit weight (Dorais et al., 2001). Even in poor light conditions, enrichment of CO_2 during the reproductive phase induces earlier flowering and fruit set (Grouda, 2005). An increase in tomato yield of 21 % could be seen after 4 weeks with a CO_2 concentration of 900 µmol mol^{-1}, and 16 % after 20 weeks with a CO_2 concentration of 450 µmol mol^{-1} compared to ambient levels. The improved growth rate is due to an increase of the net assimilation rate since plants can photosynthesise more at higher CO_2 concentrations (Heuvelink & Dorais, 2005).

2.4 Humidity

If the humidity is high, with a vapour pressure deficit lower than 0.2 kPa, pollen is less likely to be shed from the anthers and if it is very low, above 1.0 kPa, the pollen tends not to stick to the stigma (Grange & Hand, 1987). It then inhibits pollination and fruit set will be lower. A low vapour pressure deficit, approximately 0.1 kPa, influences fruit colour and increase the occurrence of gold specks. It also reduces the yield with as much as 18 % to 21 % compared to a vapour pressure deficit of 0.5 kPa. The high humidity leads to a deficiency of calcium in the leaves which reduces the leaf size, this in turn causes a lower production of assimilates and the fruit growth rate is negatively affected (Dorais et al., 2001). According to Bakker (1990), a high humidity promotes kinking of trusses which restricts the flow of phloem sap into the fruits.

2.5 Fertigation

The amount of nitrogen supplied to the plants affects the size, colour and ripening of the fruit (Dorais et al., 2001). High nitrogen levels promote vegetative growth, therefore it is recommended to keep the nitrogen levels low until fruit set has begun to encourage generative growth; after this the levels can be raised (Peet, 2005). Phosphorus is very important for early root growth and is later necessary for vegetative growth and fruit set (Peet, 2005). Low concentrations have an adverse effect on reproductive growth; it is essential for the development of flowers and fruit (Dorais et al., 2001).

3 Materials & Methods

To be able to analyse the effect of different temperature regimes on the fruit development, plant measurements were carried out in the spring and early summer of 2007 in three commercial greenhouses in southern Sweden. Measurements were made in the greenhouses every week from week 14 until week 25.

3.1 Greenhouses

All three greenhouses use the PRIVA 724 environmental computer, which registers the air temperature every five minutes. The PRIVA system also controls the irrigation by starting the irrigation when a certain light sum has been obtained in the morning, and then continuing the irrigation at certain intervals as the incoming radiation reaches a certain quantity; e.g. one irrigation for every 100 J of incoming light. Since all three market gardens have the same system, with some modifications, the irrigation is not described any further.

Table 1 Overview on the differences and similarities of the three market gardens.

	Market garden A	**Market garden B**	**Market garden C**
cultivar	Elanto	Jerome	Elanto
growing medium	Grodan master dry, 120 cm	Grodan master dry, 90 cm	Grodan master dry, 200 cm
number of plants per slab	3	4	4
plant density, start	2.5 plants per m^2	2.5 plants per m^2	2.15 plants per m^2
plant density, end	3.1 plants per m^2	3.1 plants per m^2	3.5 plants per m^2
CO_2 level	500-1000 ppm	600-1100 ppm	700 ppm
fruit thinning	none	first 4-5 trusses	first 4 trusses
ceiling height	4.5 m	3.5 m	6.5 m
compartment size	10 000 m^2	5400 m^2	10 000 m^2
planting system	single row	v-system	v-system

3.1.1 Market garden A

The greenhouse of market garden A was made of glass which was cleaned once per year. Tomatoes (*Lycopersicon esculentum*) of three different varieties were grown: 'Elanto', 'Aromata' and 'Almeto'. The compartment where the measurements were made was 10 000 m^2 large with a ceiling height of 4.5 m. Rockwool ("Master Dry", Grodan) was used as a growing medium for the tomato plants with three plants in each 120 cm long slab. The rows were 105 cm apart. The tomato plants were placed out in the greenhouse in week three, at this time the seedlings were 48 days old. They were planted in simple rows, in rockwool slabs which were placed directly on the floor, in an eight row system. Plant density at planting was 2.5 plants m^{-2} and 3.1 plants m^{-2} after the additional shoot growth. The first eight to ten weeks the plants were wound around the plastic wires, after this plastic clips were used to keep the plants in place. Plastic supporters were used on the truss peduncles to prevent them from kinking. Each week two leaves, side shoots and empty trusses were removed. No fruit thinning was made. The irrigation water was coming from the local stream as well as from own well. The quality of the water was compensated for in the nutrient solution. Drainage was measured by using crates. There was no recirculation of irrigation water or nutrient solution. One to two times per week pH, electrical conductivity (EC), water content and temperature of the rockwool slabs, was measured. Enrichment of CO_2 was used with the level kept at 1000 ppm, however if vents were open with more than 10 % the CO_2 level was lowered to 500 ppm. Opening of the vents was controlled by humidity, temperature, outside wind velocity and outside temperature. Approximate temperature in the greenhouse during the summer was 20-21 ºC. The temperature was raised during the day depending on light intensity. Low-temperature pulses were not used. Thermal curtains were used between 0.00 am to 5.30 am and were closed completely when outside temperatures dropped below 5ºC. Sprinklers were used on the roof when inside humidity dropped below 65 % or when the temperature raised above 27ºC.

3.1.2 Market garden B

The greenhouse of market garden B was made of glass which was cleaned once per year. Tomatoes of three different varieties were grown: ‘Jerome’, ‘Axion’ and ‘Tiesto’. The compartment where the measurements were made was 5400 m^2 large with a ceiling height of 3.5 m. Rockwool (“Master Dry”, Grodan) was used as a growing medium for the tomato plants with four plants in each 90 cm long slab. The rows were 165 cm apart. The tomato plants were placed out in the greenhouse in week four, at this time the seedlings were 43 days old. They were planted in a V-system, in rockwool slabs which were placed directly on the floor, in an eight row system. Plant density at planting was 2.5 plants m^{-2} and 3.1 plants m^{-2} after the additional shoot growth. Plastic clips were used to keep the plants in place and plastic supporters were used on the truss peduncles to prevent them from kinking. Each week the plants were de-leaved, with the goal of having approximately 20 leaves on each plant; side shoots and empty trusses were removed at the same time. The first four to five trusses were pinched, leaving six or seven tomatoes on each truss. Municipal water was used for irrigation and the quality of the water was compensated for in the nutrient solution. Neither water nor nutrient solution were reused. Measurements of pH and EC were done every week and samples were sent away for analysis approximately 5 times per year. The CO_2 level was kept between 600-1100 ppm. Temperature was raised depending on incoming solar radiation and low-temperature pulses were not used. The thermal curtains were used during the night if the outside temperature dropped below 5ºC and during the day if it became too dry. Sprinklers were used on the roof when the humidity dropped.

3.1.3 Market garden C

The greenhouse of market garden C was made of glass which was cleaned one to two times per year. Tomatoes of four different varieties were grown: ‘Elanto’, ‘Cedrico’, ‘Sunstream’ and ‘Ministar’. The compartment where the measurements were made as 10 000 m^2 large with a ceiling height of 6.5 m. Rockwool (“Master Dry”, Grodan) was used as a growing medium for the tomato plants with four plants in each 200 cm long slab. The rows were 160 cm apart. The grafted tomato plants were placed out in the greenhouse in week 51, at this time they were 54 days old. They were planted in a v-system, in rockwool slabs which were placed 80 cm above the floor. Plant density at planting was 2.15 plants m^{-2} then increased to 3.2 plants m^{-2} and finally, after week 16, ending on 3.5 plants m^{-2}. Plastic clips were used to keep the plants in place; these were placed out every two weeks. Plastic supporters were used on the truss peduncles, on the first couple of trusses, to prevent them from kinking. Each week the plants were de-leaved and side shoots and empty trusses were taken off. Due to an inadequate heating during early spring, the first four trusses were pinched to six fruits to promote more vegetative growth. Rain water, 80 %, and water from own well, 20 %, was used for irrigation, and the quality of the water was compensated for in the nutrient solution. The drainage was measured by using crates and there were also tensiometers to check the water content of the rockwool slabs. There was a re-circulating system in the greenhouse with a UV-filter disinfestations system; 25 % of the re-circulated water was mixed in with the irrigation water. Every other day the pH and EC as measured and every week samples from drip irrigation, drainage and water from the slabs were sent away for analysis. The CO_2 level was approximately 700 ppm. The temperature followed the amount of incoming light. If the outside temperature dropped below 8ºC the thermal curtains were used with 85-90 %.

3.2 Plant measurements

The tomato varieties used were 'Elanto' and 'Jerome'. Fourteen plants in each greenhouse were selected for vegetative and generative measurements; these were all situated close to the temperature transmitters. In the greenhouse in market garden C all of the plants had one additional shoot while at market garden B only three of the plants had an additional shoot, and at market garden A five plants had additional shoots. Measurements were made on both main and additional shoots, where available. Four trusses on each shoot were selected for measurements.

3.2.1 Vegetative measurements

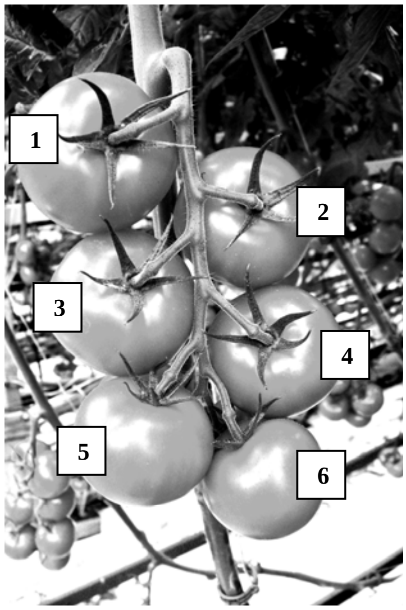
Every week the growing point of the tomato plants were marked with adhesive tape on the wire so that the weekly growth could be measured. The following week, stem diameter was measured at the same tape-mark. Leaf length of the youngest fully developed leaf, length of truss peduncle, and peduncle diameter were also included in the vegetative measurements.

3.2.2 Generative measurements

On the selected trusses number of fruits and flowers, fruit diameter and height of the first and fifth fruit (Pic. 1), as well as final fruit weight of the first and fifth fruit were measured. The total number of fruit on each plant was also determined. Amount of harvested fruit was monitored until week 35.

Table 2 Vegetative and generative measurements made on tomato plants during a ten week period.

Vegetative measurements	Generative measurement
1. weekly growth	1. number of flowers
2. stem diameter	2. number of fruits
3. leaf length	3. fruit diameter
4. length of peduncle	4. fruit height
5. peduncle diameter	5. fruit weight
	6. total number of fruits



Picture 1 Tomato truss (Author, 2007)

3.3 Statistical analysis

The statistical analyses were carried out using ANOVA followed by Tukey's test, $p<0.05$. Stepwise regressions and regression analyses were also made on number of fruit, weekly growth, stem diameter, leaf length, and night temperature. All statistical analyses were carried out in the statistical program Minitab (version 14, Minitab Inc.).

4 Results

4.1 Climate

In greenhouse production of tomatoes where PRIVA computer systems are used the days are usually divided into five or six temperature periods. These consist of pre-night, night, early morning and day periods I, II and III. An example of this is shown in figure 1. The temperatures of the different periods are set by the grower, the PRIVA program is then allowed to increase the temperature with a few degrees if light conditions are favourable during mid-day.

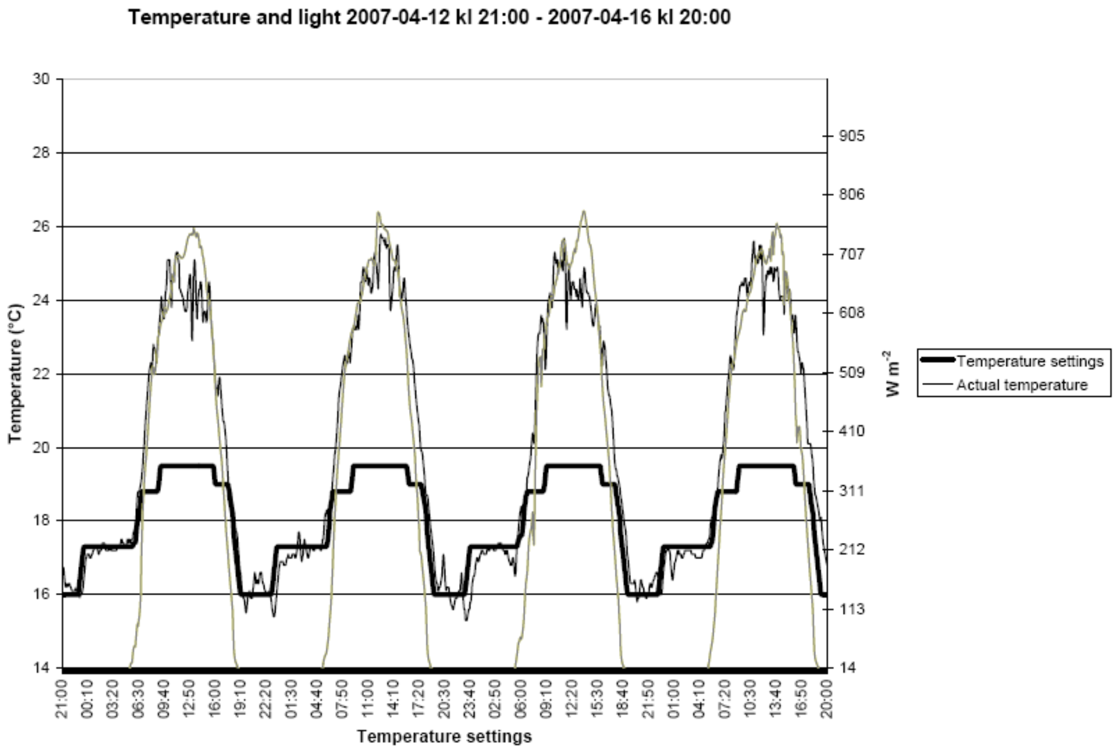


Figure 1 An example of the type of temperature charts that have been analysed for this master thesis. The grey line shows the incoming solar radiation in W m^{-2}.

Unfortunately there where no temperature settings available from market garden A, the actual temperatures however are very much alike for companies A and B which means that the temperature settings are likely to be similar.

4.1.1 February-March

The average monthly temperatures in February and March were significantly higher in market garden A and B compared to C; with a difference of approximately 0.5 °C (Fig. 2). The average weekly temperature (Fig. 3-5) showed the same pattern up to week 13, the last week of March, where the three market gardens reached the same average temperatures. In general market garden C had a lower night temperature throughout February which was the reason for the difference in average temperature. During the days the temperatures approached approximately the same level. In March the difference in average temperature was caused by a lower night temperature in C: during the pre-night the three market gardens had similar night temperatures ranging from 15.5-16°C, however when the night period started market garden C continued with the same low temperature as during the pre-night while market gardens A and B raised their temperatures between 1-1.5°C until the start of the first day-period.

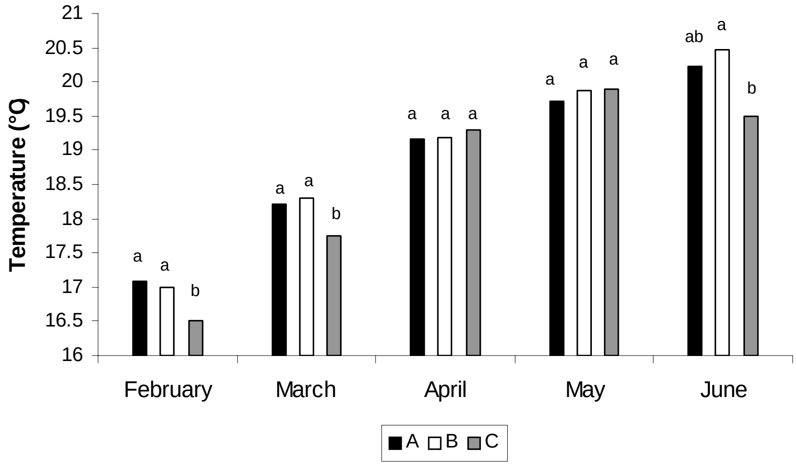


Figure 2 Average temperatures per month ranging from February to June at market gardens A, B and C. Columns labelled with different letters within the same month were differing significantly according to ANOVA followed by Tukey's test ($p<0.05$).

Through February and March market garden C reached the high midday temperatures later than A and B but moved towards the low pre-night temperatures at approximately the same time - i.e. C had a shorter period of high temperature almost every day which contributed to the low average temperature. For a couple of weeks in February market garden C used a low temperature pulse in the beginning of the day. From the temperature settings it can be seen that C had constantly lower settings compared to A and B. Mid-day temperatures in February commonly reached 20-22°C and 23-24°C in March in all three market gardens.

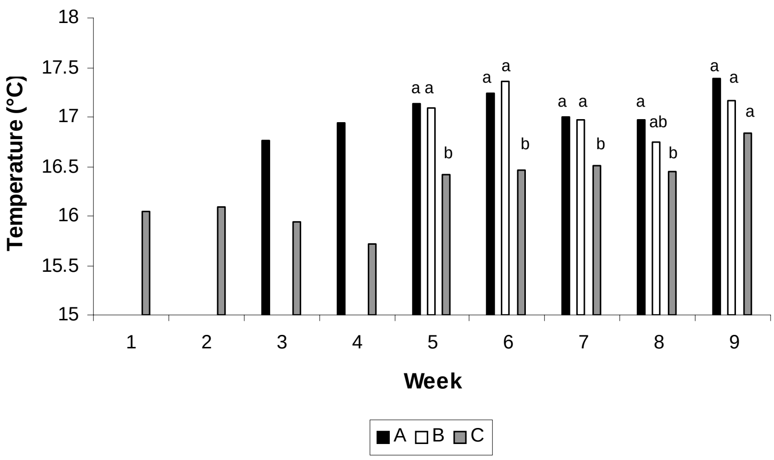


Figure 3 Average temperatures per week ranging from week 1 to week 9 at market gardens A, B and C. Columns labelled with different letters within the same week were differing significantly according to ANOVA followed by Tukey's test ($p<0.05$)

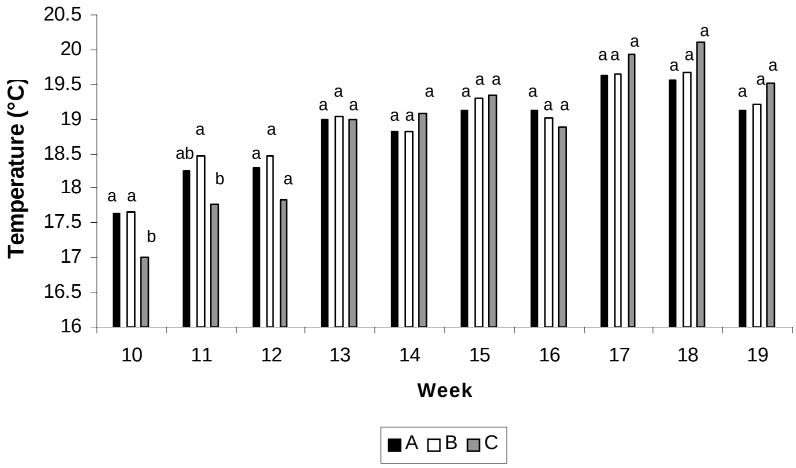


Figure 4 Average temperatures per week ranging from week 10 to week 19 at market gardens A, B and C. Columns labelled with different letters within the same week were differing significantly according to ANOVA followed by Tukey's test (p<0.05).

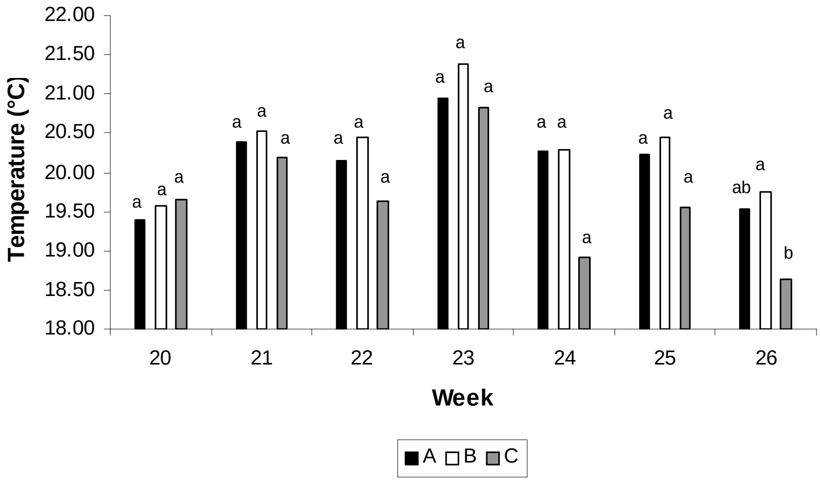


Figure 5 Average temperatures per week ranging from week 20 to week 26 at market gardens A, B and C. Columns labelled with different letters within the same week were differing significantly according to ANOVA followed by Tukey's test (p<0.05).

4.1.2 April-June

In April the most striking difference between the companies was the temperature settings for the nights. Market garden C had a constant night temperature of 17.3 °C while both A and B had a pre-night temperature of 16 °C and a night temperature of 17.3 °C. These temperature settings gave A and B a higher positive DIF throughout April. Also in April market garden C had shorter periods of high midday temperatures. Most of the days, with the exception of days with bad light conditions, market garden A and B used the five different temperature periods per day, while C only used two periods – night and day.

During the first half of May, company C started to use a pre-night period of 17 °C and a night period of 18 °C, then they went back to two periods per day. The last week of May market garden C kept 17 °C both day and night with very short periods of higher temperatures during midday. In B the five temperature periods were still used with a pre-night of 16 °C, a night temperature of 17.3 °C, the first day period was 18.8 °C, midday was 19.2 °C, and late afternoon was approximately 19 °C. The length of the first day period and the late afternoon period depended to a large degree on the amount of incoming light.

In June the average monthly temperatures differed significantly between market garden B and C with average monthly temperatures of 20.46 °C and 19.50 °C respectively (Fig. 2). The average monthly temperature of market garden A, 20.23 °C, did not differ significantly from either B or C. During the last three weeks of June, week 24-26, the average weekly temperatures differed with as much as 1.4 °C, 0.9 °C, and 1.1 °C between B and C (Fig. 5). The low average temperature in C was mainly a result of low night temperature settings of 13-14 °C during the last three weeks of June. In general the temperature settings during mid-day were lower and the high temperature periods were shorter in C compared to the other two market gardens.

4.2 Plant start

At the first week of measurements the plants were evaluated concerning the number of leaves to the first truss, position of flowering trusses, number of fruits on each truss, etc. The averages can be seen in Table 3. The developmental stages of the plants in the three market gardens at the start of measurements were similar. In market garden C, the most interesting observation was that the main shoots and side shoots differed in length; this was not observed in A or B.

Table 3 Crop developmental data for the three greenhouse market gardens at the start of the measurements (n=14).

	Market garden A	**Market garden B**	**Market garden C**
Number of leaves to first truss	6.9	6.2	7
Number of fruits on truss 1	6.9	7.1	5.3
Peduncle length truss 1 (cm)	6.5	6.1	7.2
Kink on truss 1	2 of 14	11 of 14	2 of 14
Flowering truss number	8.9 main, 6.4 side shoot	7.9 main, 6.3 side shoot	6 main, 8 side shoot
Number of fruits truss 2-5	7.2/7/7.3/7	5.9/7.6/7.4/7.2	5.8/5.4/6.1/-
Number of visible trusses	10	11	11
Leaf length (cm)	21.8	20.2	21.8
Average fruit size fruit 1*(mm)	14.4	21.8	13
Average fruit size fruit 5*(mm)	6.3	11.6	6.4

*=from the first truss out of the four chosen for measurements

4.3 Plant measurements

4.3.1 Vegetative measurements

The vegetative parts of the plant - represented as weekly growth, stem diameter and leaf length (Fig. 6-8) - did not seem to follow the same growth pattern. Whereas the weekly growth changed quite a lot between the measuring occasions the leaf length remained almost constant without significant differences either within or between the greenhouse market gardens. The stem diameter showed a trend towards thinner stems, in all three market gardens, as the season progressed. There were significant differences between the market gardens most weeks regarding both the weekly growth and the stem diameter. Greenhouse market garden C most often demonstrated the most growth and the thinnest stems.

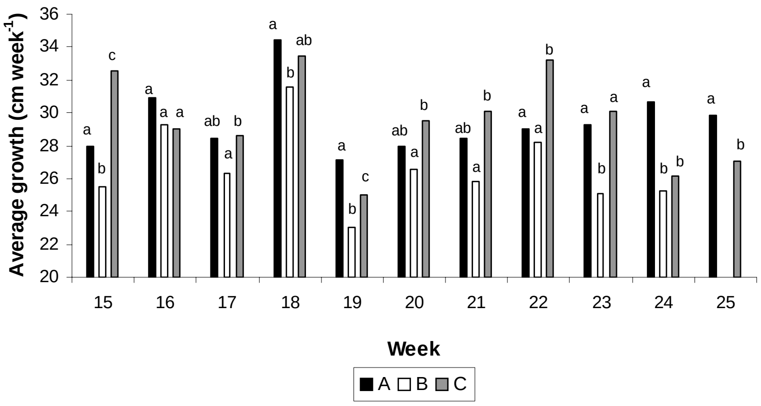


Figure 6 The average weekly growth at market gardens A ('Elanto', n=19), B ('Jerome', n=17) and C ('Elanto', n=25). Columns labelled with different letters within the same week were differing significantly according to ANOVA followed by Tukey's test (p<0.05).

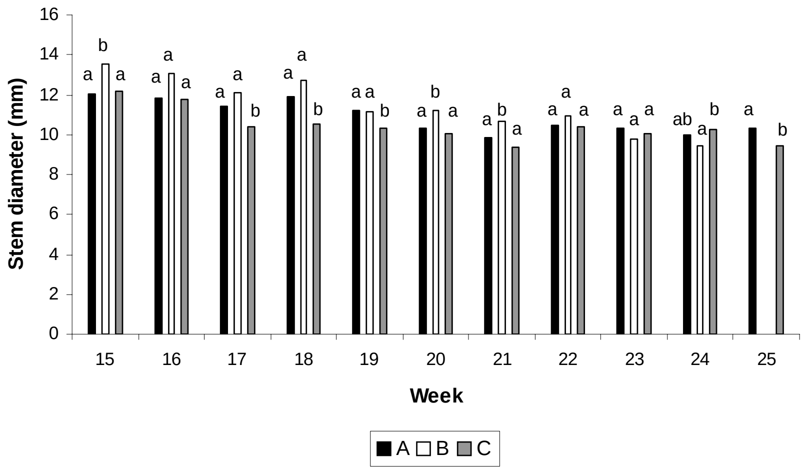


Figure 7 The average weekly stem diameter at market gardens A ('Elanto', n=19), B ('Jerome', n=17) and C ('Elanto', n=25). Columns labelled with different letters within the same week were differing significantly according to ANOVA followed by Tukey's test (p<0.05).

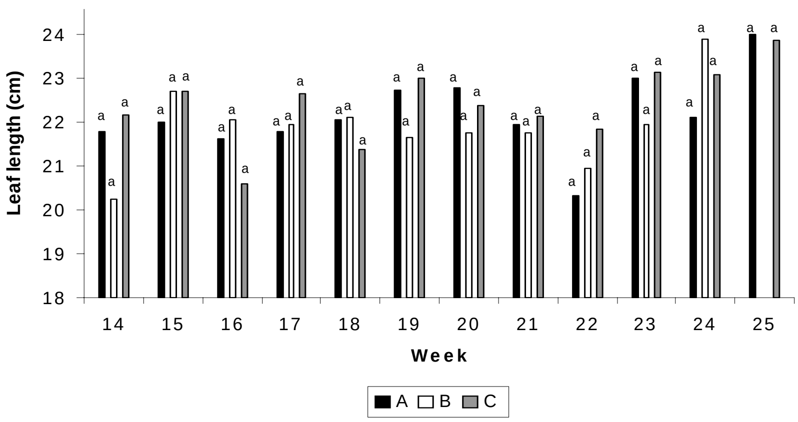


Figure 8 The average weekly leaf length at market gardens A ('Elanto', n=19), B ('Jerome', n=17) and C ('Elanto', n=25). Columns labelled with different letters within the same week were differing significantly according to ANOVA followed by Tukey's test (p<0.05).

Tomato plants of market garden A and C had grown significantly more vigorous during the ten weeks of measurements with aspect to total stem growth (Fig. 9) and peduncle diameter (Fig. 10), compared to market garden B.

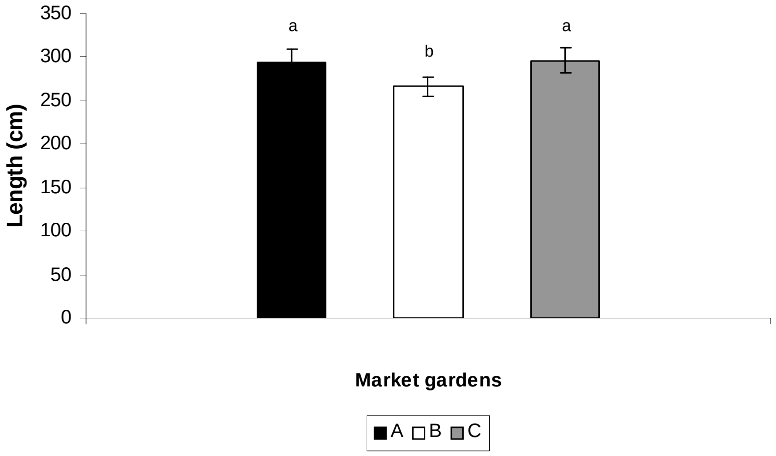


Figure 9 The average total growth in length at market gardens A (‘Elanto’, n=19), B (‘Jerome’, n=17) and C (‘Elanto’, n=25), from week 15-24. Columns labelled with different letters were differing significantly according to ANOVA followed by Tukey’s test ($p<0.05$).

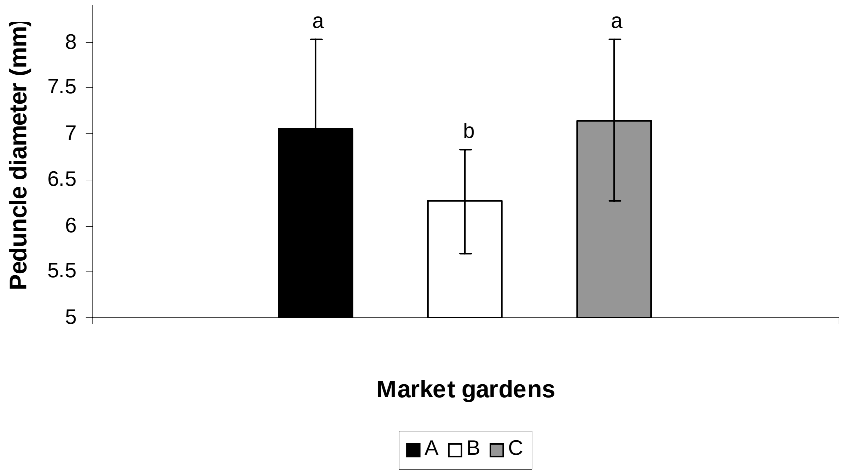


Figure 10 The average final peduncle diameter at market gardens A (‘Elanto’, n=19), B (‘Jerome’, n=17) and C (‘Elanto’, n=25). Columns labelled with different letters were differing significantly according to ANOVA followed by Tukey’s test ($p<0.05$).

At market garden A, the longest peduncles were found in the first truss which differed significantly from the length of trusses three and four (Fig.11). At market garden B the length of the peduncles was equal for all trusses while at market garden C the length of the first peduncle was significantly longer than the other three.

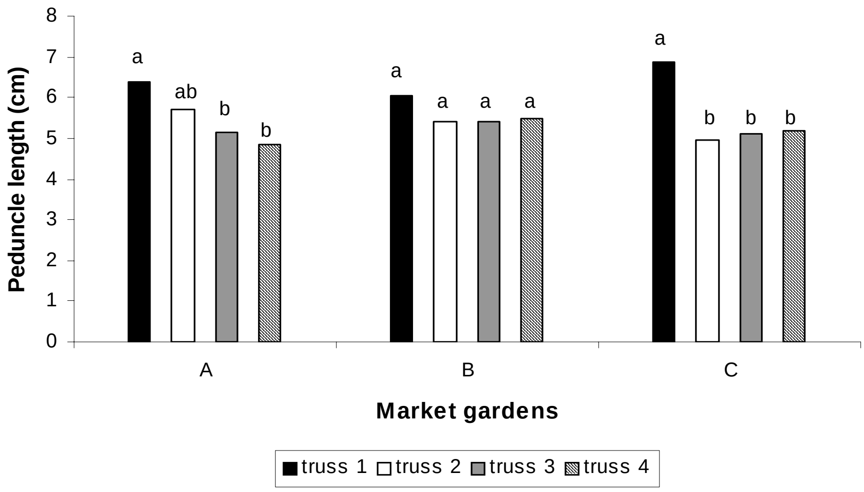


Figure 11 The average final peduncle length at market gardens A (‘Elanto’, n=19), B (‘Jerome’, n=17) and C (‘Elanto’, n=25), showing differences between trusses within the market gardens. Columns labelled with different letters within the same market garden were differing significantly according to ANOVA followed by Tukey’s test (p<0.05).

Significant differences between the market gardens were also found concerning peduncle length (Fig. 12). However, there were no trends showing that the tomato plants in one of the market gardens had longer peduncles than the others; it changed depending on the truss position.

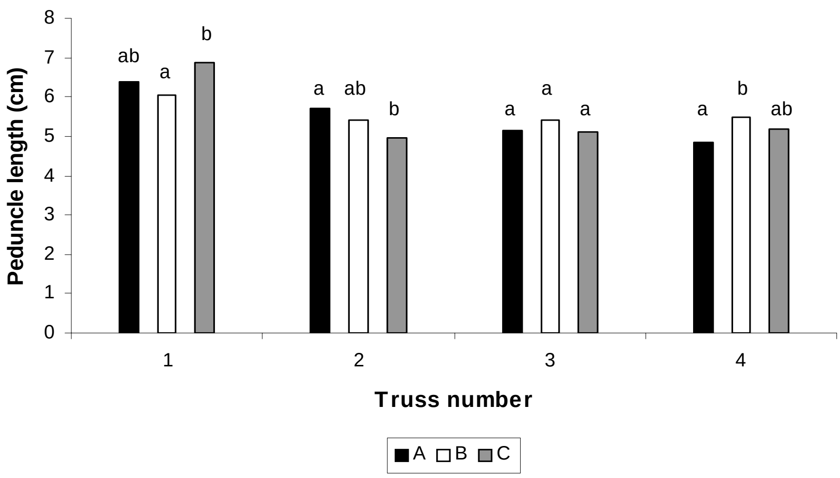


Figure 12 The average final peduncle length at market gardens A (‘Elanto’, n=19), B (‘Jerome’, n=17) and C (‘Elanto’, n=25), showing differences between the market gardens. Columns labelled with different letters within the same truss were differing significantly according to ANOVA followed by Tukey’s test (p<0.05).

4.3.2 Generative measurements

The number of fruits present on each plant every week is shown in Figure 13. There were significant differences between the market gardens; in general market garden C had fewer fruits per plant than A and B. Although they were not significantly different, probably caused by large standard deviations, market garden B seemed to have more fruit per plant than A.

The same pattern is seen in Figure 14, which shows the accumulated number of fruits from week 15 to week 25.

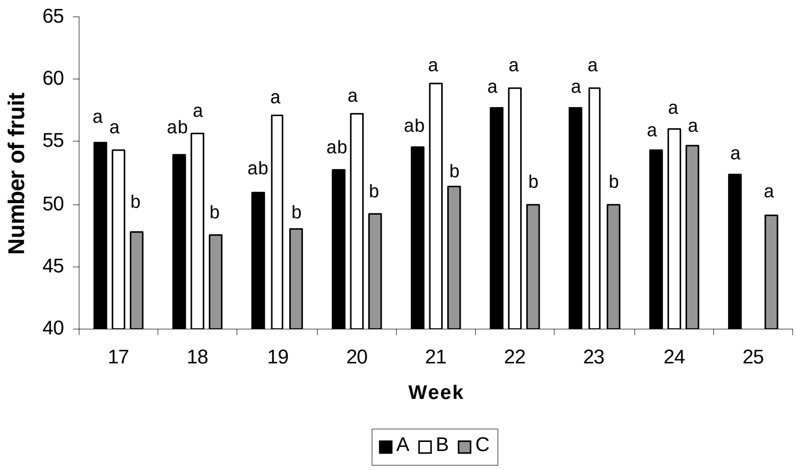


Figure 13 The average weekly number of fruit per plant at market gardens A ('Elanto', n=19), B ('Jerome', n=17) and C ('Elanto', n=25). Columns labelled with different letters within the same week were differing significantly according to ANOVA followed by Tukey's test (p<0.05).

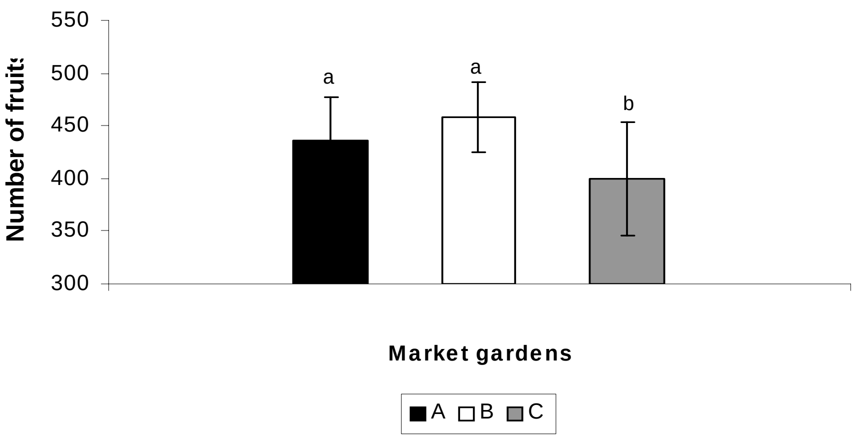


Figure 14 The total number of fruit per plant, from week 17 to 25, at market gardens A ('Elanto', n=19), B ('Jerome', n=17) and C ('Elanto', n=25). Columns labelled with different letters were differing significantly according to ANOVA followed by Tukey's test (p<0.05).

Concerning the fruit weight (Fig. 15), market garden C had the significantly highest fruit weight while market garden A had the lowest. When comparing the average fruit weight per truss between the market gardens it showed that C had the highest fruit weights on truss one and truss four, while all three market gardens had equal fruit weights on truss two (Fig. 16). On truss three market garden A had significantly lower fruit weights compared to the other two.

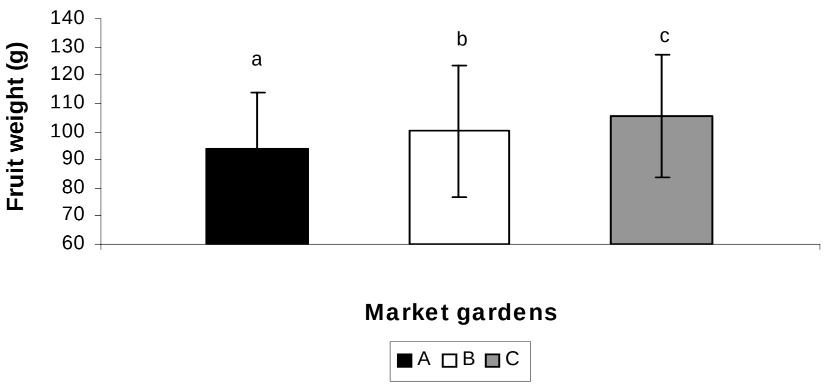


Figure 15 The average fruit weight of all fruits from the four selected trusses at market gardens A ('Elanto', n=373), B ('Jerome', n=448) and C ('Elanto', n=190). Columns labelled with different letters were differing significantly

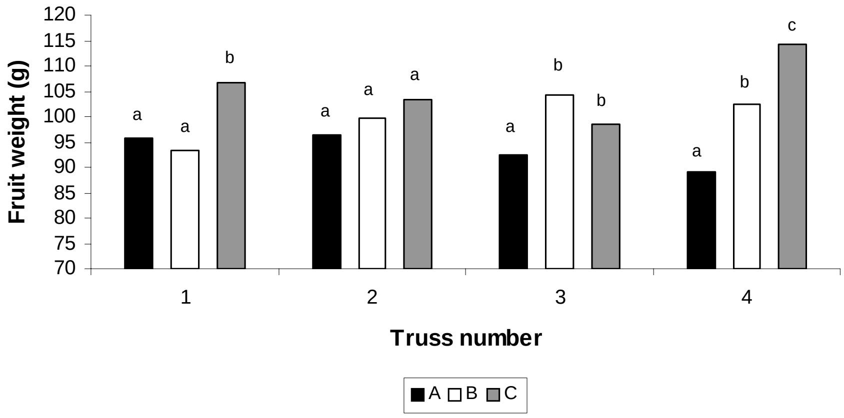


Figure 16 The average fruit weight of truss one to four at market gardens A ('Elanto', n=373), B ('Jerome', n=448) and C ('Elanto', n=190). Columns labelled with different letters within the same truss were differing significantly according to ANOVA followed by Tukey's test ($p<0.05$).

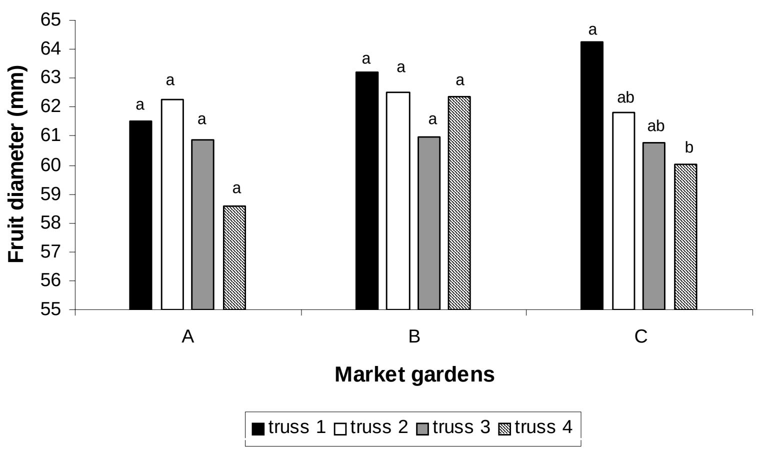


Figure 17 The average fruit diameter of fruit one on truss one to four at market garden A ('Elanto', n=19*4), B ('Jerome', n=17*4) and C ('Elanto', n=25*4). Columns labelled with different letters within the same market garden were differing significantly according to ANOVA followed by Tukey's test ($p<0.05$).

The diameter of the first fruit on trusses one to four (Fig. 17) showed, in both market gardens A and C, that it decreased with time. The height of the fruits was highest in greenhouse market garden B (Fig. 18), making the fruits of 'Jerome' slightly rounder than 'Elanto'.

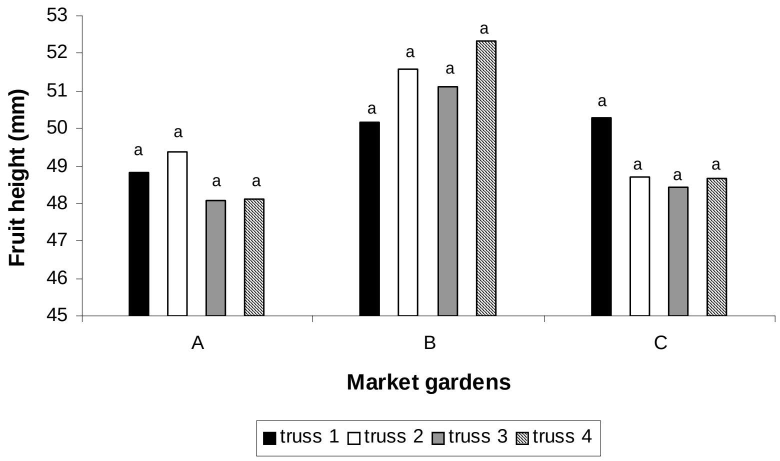


Figure 18 The average fruit height of fruit one on truss one to four at market gardens A ('Elanto', n=19*4), B ('Jerome', n=17*4) and C ('Elanto', n=25*4). Columns labelled with different letters within the same market garden were differing significantly according to ANOVA followed by Tukey's test ($p<0.05$).

The harvest started first at market garden A in week 11; the numbers of kilos however was small and were not registered by the grower (Fig. 19). The three market gardens followed the same pattern for weekly harvest although market garden C was a bit behind up to week 20. The total harvest by week 35 at market garden B exceeded the others with 2 (A) and 3 (C) kg m^{-2} (A: 40.7 kg m^{-2}; B: 42.6 kg m^{-2}; C: 39.7 kg m^{-2}).

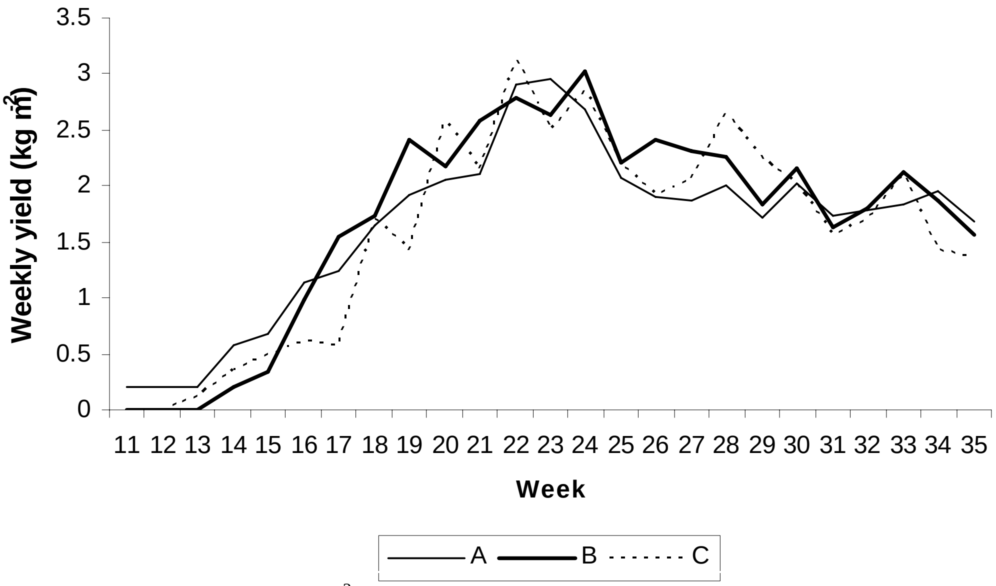


Figure 19 Weekly harvest (kg m^{-2}) every week from week 13 to 35 at market gardens A ('Elanto'), B ('Jerome') and C ('Elanto').

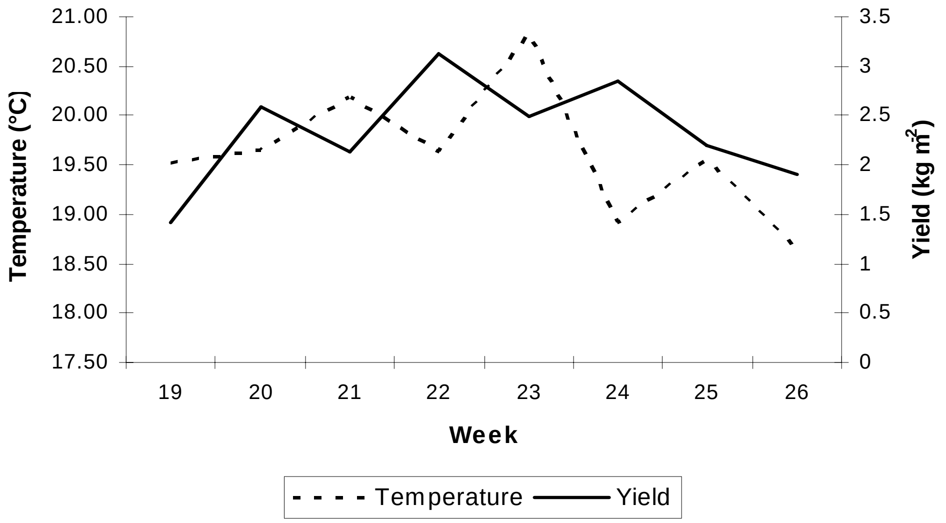


Figure 20 Interaction between **a**verage temperature and yield in market garden C from week 19-26.

The harvest followed the average temperatures very closely some weeks. As seen in Figure 20 a high average temperature one week gives a high yield the following week and vice versa.

4.4 Correlations

From the regression analyses it can be seen that there was a weak correlation between the stem diameter and the number of fruit in market gardens A and B; R^2 values of 4.1 % and 3.1 % respectively. In market garden C, the stepwise regression analysis picked out both the stem diameter and the leaf length as important predictors for the number of fruit. The combined R^2 value for the two predictors was 3.7 % (Eq. 1). There were no correlations at all between the number of fruit and the weekly growth in any of the market gardens.

The night temperature was also tested for correlations in a multivariate regression analysis with number of fruit, weekly growth, stem diameter and leaf length as predictors. Night temperature was defined as the mean temperature over the period when the incoming radiation was zero. In both market gardens A and C night temperature was correlated to all predictors (combined R^2 values of 20.2 % and 9.5 % respectively), however, the correlations differed in strength and load on the equation. In market garden B, the weekly growth was not incorporated into the regression (combined R^2 value of 13.4 %).

Number of fruit

- **For greenhouse market garden C**: number of fruit = 36.0 + 0.216 leaf length + 0.992 stem diameter (Eq. 1)

Night temperature

- **For greenhouse market garden A**: night temperature = 18.2 - 0.0900 stem diameter + 0.00932 number of fruit - 0.0147 weekly growth - 0.0125 leaf length (Eq. 2)
- **For greenhouse market garden B**: night temperature = 17.2 + 0.00967 number of fruit - 0.0396 stem diameter - 0.0144 leaf length (Eq. 3)
- **For greenhouse market garden C**: night temperature = 16.8 + 0.0195 weekly growth - 0.0146 leaf length + 0.0497 stem diameter - 0.00850 number of fruit (Eq. 4)

5 Discussion

The purpose of the present study was primarily to look at the effects of low temperature pulses on fruit growth. The reason for this was that several tomato extension officers, mainly from Denmark and the Netherlands, recommend the growers to use LTP, despite no support in the literature. Therefore an empirical study like this one could help to clarify a few of the question marks surrounding LTPs. Unfortunately, the growers who took part in the study were reluctant to use LTPs; except for market garden C who used it during early morning for a brief period in February. This reluctance from the growers is to a large part based on worries about reaching condensation points when the temperature is altered. Condensation on the plants can cause infections of grey mould (*Botrytis cinerea*) which can lead to large economical consequences for the grower. The grey mould risk could perhaps be prevented by more efficient humidity control.

Although the growers' choice of not using LTPs seems reasonable, it leaves the first hypothesis- *Low temperature pulses during early morning and pre-night have a positive effect on the fruit swelling of tomatoes* – unanswered, since no data could be gathered in this empirical study. The theory behind the hypothesis was that a pre-night LTP could enhance the amount of assimilates partitioned to the fruits. When the temperature is lowered quickly the fruits will stay warmer than the other plants parts due to their high mass. The higher temperature in the fruits, compared to other plant parts, would favour the fruits in terms of an increased carbon and water influx (Pearce et al., 1993). According to Adams et al. (2001) it is the temperature of the fruit that is important for the time to ripening and the temperature of other plant parts are of little importance; hence a short period of sudden changes in temperature would not affect the fruit ripening negatively. To control the effect on the tomatoes of such sudden temperature changes it would be advisable to use temperature sensors in the fruits.

The second hypothesis: *Day and night temperature settings, and not only average temperature, are important for the fruit development,* will have to be discarded. There were correlations between night temperature and the number of fruit, but the R^2 values were very low which means that hardly any of the variation in the plant parameters can be explained by the night temperature. Also, when looking at the other results, these can only be linked to the average temperatures after analyses of the temperature curves. This is confirmed in many articles. For example Heuvelink & Dorais (2005) wrote that the average temperature is most important for the overall growth; which means that low night temperatures can be compensated for by high day temperatures and vice versa without adverse effects on the plants. The third hypothesis however - *The development of the fruit is faster at a higher average temperature* - has been confirmed in many different research papers, and also in this one. It can clearly be seen when comparing market gardens B and C. The lower average temperature in C has lead to larger but fewer fruits, while the higher average temperature in B has lead to slightly smaller first fruits, but a higher yield.

The combination of lack of LTPs, different tomato varieties, and the fact that some of the fruit at the market gardens were picked before there was a chance of weighing them, leads to limitations concerning results and conclusions. This is often a difficulty when doing field-based empirical studies. The following discussion is therefore mainly based on small scale differences between the market gardens.

5.1 Plant start

According to the literature the number of leaves preceding the first truss can be altered by temperature (Heuvelink, 2005). Market garden B had the lowest number of leaves to the first truss (Table 3), but since market garden A and B had very similar mean temperatures when the plants were first placed out in the greenhouses the difference can not be ascribed to temperature. On the other hand, it could be a response to temperature in the small plant stage. Another indication of this is that a lower temperature not only leads to a lower number of leaves to the first inflorescence, but also to a later flowering (Papadopoulos & Hao, 2000). When the measurements began, truss number 8.9 flowered in market garden A while truss number 7.9 flowered in B. These indications can not be confirmed though since data from the small plant stage are not available. The results however, either means that the tomato plants in market garden B had a lower temperature in the small plant stage, or that the difference is due to different tomato varieties.

Kinking of the truss stems was most frequent in market garden B, while the frequency was quite low in market garden A and C. According to the De Koning (1988) this phenomenon is most common when a large positive DIF is used, although no such connection can be seen here. Since market gardens A and C were so similar in kinked truss stems and they both grew the same variety, ‘Elanto’, it could be a variety characteristic.

5.2 Vegetative measurements

At higher temperatures more assimilates move into the fruits at the expense of vegetative growth (De Koning, 1989). In this study the weekly growth (Fig. 6) does not seem to be affected negatively by higher temperatures. In fact, there is no pattern that is indicating a general increase or decrease in the length as the season progresses. As an example: in week 18 the weekly growth was strong compared to the other weeks. When looking at the temperature curves from the week before, which can be assumed to have a large influence on the growth of week 18, the temperatures were higher than before. Considering that the plants had a high fruit load at the time, a higher average temperature would theoretically favour the fruits. Therefore, it is likely that additional factors to temperature affected the growth. During the same week there is a significant difference between market gardens A and B, despite similar temperature in the two greenhouses. The slightly lower growth in market garden B, as compared to A and C, might be due to the compact growth habit of the cultivar ‘Jerome’ (Christensen, 2007); also seen in Figure 9.

A positive DIF promotes generative growth (Peet & Welles, 2005), which might affect the weekly growth negatively. Most of the weeks during the period of measurements, the weekly growth was largest in market garden C (Fig. 13). The larger positive DIF in market gardens A and B could be the reason for that difference. The fruit load in A and B were also considerably higher than in C except the last two weeks of measurements; hence more assimilates were available for vegetative growth in market garden C. Week 24 and 25 the weekly growth in market garden C became significantly lower than in A; possibly a consequence of the rise in fruit load (Fig. 13) and the decrease in average temperature (Fig. 5).

Peet and Welles (2005) wrote that *“…the stem should be 1 cm thick 15 cm below the growing point. Thicker stems indicate excessive vegetative growth and are usually associated with poor fruit set and low productivity. Thinner stems usually indicate carbohydrate starvation, slow growth and, ultimately, low overall productivity”*. As the season progresses the plants became more generative and stem diameters became thinner; this could indicate that too few assimilates were available for vegetative growth. However, the same trend could not be seen in the other vegetative measurements - weekly growth and leaf length. Leaf length (Fig. 8) did not seem to be affected much by either temperature or the generative state of the plant.

5.3 Generative measurements

Except for the last two weeks of measurements (week 24 and 25) market garden C had a constantly lower number of fruits. This could be an effect of the difference between the main- and side shoots; there was a large variation in fruit set between the shoots in market garden C, with approximately 50 fruits less on the main shoots per plant. In market gardens A and B the side- and main shoots were more similar. This difference might have lowered the average value which is presented in the figure. It can also be a result of the low average temperature in the early spring in market garden C; according to the literature higher temperatures lead to higher fruit set (De Koning, 1989). Market gardens A and B had a larger positive DIF during the spring which also promotes more generative growth.

Low average temperatures lead to a longer fruit growth period and therefore also to larger fruits (De Koning, 1994). The fruit weights from market garden C though, are misleading because it was mainly the first fruit of the trusses that were weighed there while Figure 15 shows the average weight of all fruits. Unfortunately most fruits in market garden C were picked before there was a chance of weighing them. Therefore it would be more correct to look at Figure 17, the fruit diameter, to get a more accurate view of the fruit sizes. Market garden C had very large first fruits on the first truss out of the four selected for measurements. This was probably caused by the low average temperatures in the spring. The differences in fruit size between A and B cannot be described by temperature since it has been very similar in the two market gardens, it could however be a difference in variety.

5.4 Harvest

According to Adams & Valdés (2002) fruits that are nearing maturity are much more sensitive to temperature and therefore a period of higher temperatures one week would result in an excess of ripe fruits the following week. This rapid fruit ripening would then lead to a lower amount of fruits nearing maturity and hence a lower yield two weeks after the high temperature period. This is confirmed in Figure 20. The highest harvest was in market garden B, which could be expected since it had the significantly highest number of fruits on the plants during the period of measurements.

5.5 Irradiance

The amount of incoming solar radiation is imperative to the growth and yield of all plants. In this study however, the focus is on temperature only, for two reasons: i) the temperature of the three market gardens follow the amount of incoming light very closely, which makes it difficult to single out any specific effects of irradiance alone, and ii) according to Adams et al. (2001) the growth of tomato fruits is more closely related to temperature than irradiance since the growth in the short term is not affected by a limited assimilate supply. This was also found by Pearce et al. (1993a) when they analysed the fruit growth rate. They showed that the fruit growth rate was highest in high temperatures, independent of light or dark. They found that the plants had a sufficient reserve of assimilates to keep a high fruit growth rate for at least 20 hours after darkening, and that the effect on growth rate of irradiance was mainly through plant water status; i.e. a high irradiance leads to water stress through increased transpiration and therefore decreases the fruit growth rate.

5.6 Concluding remarks

To really be able to differentiate the effects of temperature from other effects, such as salinity, nutrients, humidity, irrigation, etc., data from all cultural management factors would have to be closely followed. On the one hand, it is known that temperature has a very large effect on the fruit development; on the other hand high EC levels could greatly affect the fruit size (Dorais et al., 2001). For further studies on this subject it would be advisable to closely monitor all cultural management factors, measure the actual temperature of the fruit and not just air temperature, and stick to the planned climate programs in order to achieve more accurate results.

6 Acknowledgements

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