YIELD RESPONSES OF TOMATO
(*Lycopersicon esculentum* Mill.)
TO FRUIT THINNING AND PLANT SPACING

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Abstract

Control of individual tomato (*Lycopersicon esculentum* Mill.) fruit weight during a crop cycle is of commercial benefit to improve marketable yield. To assess the main causes of variability in tomato fruit size, plant spacing and fruit thinning effects on fruit yield and individual fruit weight down the truss was examined.

Three fresh market tomato cultivars, Alboran (Standard), Ophir (Beefsteak) and Cherita (Cherry) were grown, in New Zealand during winter and spring months of 2001, in a greenhouse with NFT at three plant densities (2.76, 3.67 and 4.59 plant per m^2). Each tomato cultivar was fruit thinned to three different levels (3, 4 and 5 fruit per truss for Alboran; 1,2 and 3 fruit per truss for Ophir; 4, 8 and 12 fruit per truss for Cherita). Total fruit weight and fruit number were taken at each harvest for all treatments. At the low density (2.76 plants per m^2) individual fruit weights within each truss were taken for all fruit thinning treatments. A total soluble solid measurement was also taken during an August harvest.

Alboran showed a significantly higher final fruit yield per surface area than Ophir and Cherita cultivars, indicating why Alboran is a standard cultivar. No difference in fruit yield or fruit number surface area was observed with both Alboran and Ophir cultivars as plant density increased. This was the result of flower and / or fruit abortion at the higher densities, due to low solar radiation levels observed under winter and spring conditions in this study. Cherita, although not significant, showed a trend of increasing fruit yield per surface area as plant density increased. The low solar radiation levels did not have as larger effect on flower and / or fruit abortion in Cherita. It had a lower fruit (sink) load and was able to support more fruit development with the low levels of photosynthetic assimilate produced under the low solar radiation levels. Larger mean fruit weights, in all three cultivars, were observed with more fruit thinning due to increased photosynthetic assimilate being available to the remaining fruit. No difference in fruit yield per surface area was observed with both Alboran or Ophir cultivars as more fruit were left on the truss, which was due to the smaller mean fruit weight and a greater proportion of flower and / or fruit abortion caused by the high fruit load with low solar radiation levels. However thinning Cherita to 4 fruit per truss did produce significantly lower yields per surface area compared with 8 and 12 fruit per truss.

Individual fruit weight down the truss, of all three cultivars, reduced in size by a constant factor or slope. A slope of -13 g / fruit position was observed for Alboran, which was flatter than that of Ophir (-17 g / fruit position) and steeper than that of Cherita (-0.15 to -0.60 g / fruit position). The number of fruit on the truss did not affect the slope of Alboran and Ophir cultivars, while thinning Cherita to 4 fruit per truss produced a significantly steeper slope (-0.60 g / fruit position) than 8 and 12 fruit per truss (0.25 g / fruit position). More fruit present on a truss produced smaller proximal (first) fruit, thus reducing the size of the remaining fruit on the truss proportionately. Individual trusses within Cherita were also shown to have a constant slope of fruit size down the truss.

These results suggest that plant density and fruit thinning can be used to produce more fruit within the desired marketable fruit size range all year round. However a greater understanding of plant density and fruit thinning interactions during different growing seasons must first be achieved.

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Introduction

Commercial success in the tomato glasshouse production sector, increasingly depends on being able to meet the market requirements. All world markets usually have a strong preference for a certain (class 1) sized round fruit. Therefore for maximum profitability the grower must produce not only high yields of fruit, but also a high proportion of fruit in the preferred size grade throughout the cropping season (Cockshull et al., 2001). Tomato crop yields can vary considerably during the year, with the productivity of glasshouse tomatoes being strongly influenced by the total solar radiation incident upon the crop (Papadoupolous and Pararajasingham, 1997). Cockshull and Ho (1995) demonstrated that tomato crops grown at a fixed low density of 2 plants per m^2 produced a high proportion of their fruit in the preferred size grade range in spring (low light) but produced too many large fruit in summer. When the plant density was increased to 3 plants per m^2, the proportion of fruit in the preferred size grade was highest in summer but too many small fruit were produced in spring. Fruit number on the truss also affects the size of the fruit. Heuvelink and Buiskool (1995) showed that assimilate distribution to the fruit strongly depends on the number of fruit (sinks) per truss, with a reduction in fruit number increasing the mean fruit size of the remaining fruit. However limited information exists on fruit number and plant spacing effects on individual fruit weight within a truss.

The objective of this investigation was to study plant density and fruit thinning effects on greenhouse tomato productivity and thus explore the potential for improving the marketable yield of three tomato cultivars (Alboran, Ophir and Cherita). Additionally, this study aimed to identify and provide information on individual fruit size down the truss for the three tomato cultivars.

Chapter 1

Literature Review

1.1 The tomato

The Tomato (*Lycopersicon esculentum* Mill.) is a member of the Solanaceae family. It is a perennial plant that is universally cultivated as an annual (Kinet & Peet, 1997).

The tomato is commercially important throughout the world, in both the fresh market and processed food industries. There are two main types of tomato currently grown for economic use. The determinate tomato is mainly used for processed food with a compact determinate flowering pattern. The indeterminate tomato is largely used for production of fresh market tomatoes with a sequenced flowering pattern

The tomato is grown in a wide range of climates in the field, under protection in plastic greenhouses and in heated greenhouses (Atherton & Rudich, 1986).

Tomato is the most important greenhouse vegetable crop grown in NZ, with a domestic market of $79 million and an export market of $1 million. There are approximately 560 commercial tomato growers using 120 hectares of greenhouses with a capital investment estimated at $300 million (Vegfed).

1.2 Vegetative growth

The vegetative phase of the tomato plant is usually short, since the floral transition occurs for most cultivars when the third leaf is expanding. Usually only six to eleven leaves are produced before the first inflorescence (Kinet & Peet, 1997). If too few leaves are produced before floral initiation, assimilate supply may be insufficient to support flower and fruit development (Kinet & Peet, 1997).

The rate of leaf initiation and the rate of leaf growth are shown to increase with both temperature and light intensity, with temperature having a greater effect on leaf growth than on the rate of leaf production (Fisher, 1975). Heuvelink and Marcelis (1996) also concluded that vegetative and generative plant growth can be manipulated by factors such as plant density, light level or pruning treatments without influencing plant development rate.

1.3 Flowering

The tomato is an antonymous plant (a plant that does not require particular environmental conditions to initiate reproductive structures) (Kinet & Peet, 1997).

The tomato inflorescence is a cyme initiated by the apical meristem and consisting of a main axis bearing lateral flowers without bracts. The first formed flower of the cyme inflorescence originates at the apex and a lateral growing point that arises below the first flower develops into the second flower, with a succession of flowers developing from lateral growing points in this manner until the inflorescence is complete (Atherton & Rudich, 1986). Inflorescence are continuously initiated most commonly at leaf intervals of three depending on cultivar and environmental conditions, thus leaf appearance rate is closely related to fruit appearance rate (fruit number) (Heuvelink & Buiskool, 1995).

The yellow petaled flowers enclose an ovary that is surrounded with a style, which is surrounded by stamens. The stamens open via internal slits, which release pollen grains onto the stigma surface. The tomato flowers are thus essentially self-pollinated.

The number of leaves preceding the first inflorescence and the rate of leaf initiation determines the number of days to first anthesis. The number of leaves produced before floral transition is under genetic control (Kinet & Peet, 1997). Leaf number before first inflorescence is also strongly affected by environmental condition. Increasing light intensity reduces the number of leaves below the inflorescence and stimulates the rate of leaf initiation, resulting in earlier flowering (Kinet & Peet, 1997). Calvert (1959) showed that reducing the light intensity from 1,000 to 2,500 lux delayed flower initiation by up to 29 days and allowed approximately seven more leaves to be produced before the inflorescence was initiated. Decreasing temperature also reduces the number of leaves before floral initiation (Kinet & Peet, 1997). Calvert (1959) also showed that plants grown at 15°C initiated flowers up to 13 days earlier than those grown at 27°C. However the number of leaves before the first inflorescence is reduced (Kinet & Peet, 1997), with 8 leaves produced before first inflorescence at 15°C and 14 leaves produced at 27°C.

1.4 Pollination

As final fruit weight is generally related to seed number, pollination is a critical process in fruit development (Atherton & Rudich, 1986). All modern tomato cultivars are self-pollinated. Poor pollination is regarded as a major cause of incomplete fruit set and undersized fruit. Pollination can be particularly a problem in greenhouse production due to insufficient shedding of pollen by wind vibration, as vibration of flower clusters is essential for good pollination. Although pollination is facilitated by flower structure, truss movement either by wind, by cultural activities or by artificial means (pollination is usually stimulated using the electric bee or more recently bumble bees) is usually required in greenhouse cultivation during the winter (Kinet & Peet, 1997).

Fruit setting during winter is frequently poor under short days and low light intensity, with high relative humidity and low temperature causing pollen to become sticky and to aggregate (Kinet & Peet, 1997). Therefore pollination during these conditions is very dependant on the use of mechanical aids for pollination (Picken, 1984). Mechanical vibration of flowers is a good method of pollination. Cetinkaya (1999) showed that mechanical vibration of tomato fruit in a greenhouse twice a week was sufficient to promote fruit setting. He also showed that vibration could be used in conjunction with hormones to give effective fruit set. Hormones, like 4-Chlorophenoxyaceticacid (4-CPA), have been used to improve fruit set in tomatoes. However as a result of using hormones there can be poor quality fruit produced causing the technique to loose favour.

1.5 Fruit development

The time required for a fertilised ovary to develop into a red ripe tomato fruit is between 7 and 9 weeks, depending on cultivar, position on a truss and environment (Atherton & Rudich, 1986). Development of the tomato fruit is characterised by cell division during the first week after anthesis, followed by cell expansion for the next 6-7 weeks. (Wolf & Rudich, 1988).

Tomato fruit grow from an ovary weighing 5 – 10 mg to a final fruit weight between 15g for cherry cultivars to 450g for beefsteak cultivars (Atherton & Rudich, 1986). Slow tomato fruit growth occurs during the first 2 – 3 weeks, with the gain in fruit weight less than 10% of the final fruit weight. During the next period of growth (3 – 5 weeks) there is rapid growth, with most of the final fruit weight accumulated by the mature green stage of the fruit (Atherton & Rudich, 1986). Therefore the slow growth rate observed early in the fruit development is caused by cell division, while the rapid growth during the next phase is caused by cell expansion. Finally there is a period of slow growth for 2 weeks where fruit ripening takes place in which there is little change in fruit weight (Atherton & Rudich, 1986).

As the fruit ripens, the colour, flavour, aroma, texture and composition change dramatically. The rise in endogenous ethylene production appears to trigger ripening through stimulating ripening genes in the tomato, e.g. polygalacturonase which breaks down the cell walls which results in the soft, juicy texture of the fruit (Kinet & Peet, 1997).

1.6 Fruit quality

The consumer's demands for good quality produce are high all year round. The main parameters which determine the fruit quality are fruit mass, shape, firmness, content of dry matter, concentration of sugars and acids and the proportions of compounds that contribute to the fruit aroma and colour. These parameters depend on the genetic properties of the cultivar as well as environmental conditions and horticultural practices during fruit growth (Fishman & Genard, 1999).

Johnson et al. (1999) found that colour was one of the most important criteria for the selection of fruit by retailers. However chemical attributes such as sugar content, acid / sugar balance and volatiles are important quality attributes involved in the taste of the tomato. Stevens et al. (1979) have found that the interaction between pH and sugars (which account for 65% of the total soluble solids of a ripe tomato fruit) largely determines sweetness and flavour differences among cultivars. A good measure of flavour in tomatoes can be determined by estimating the sugar (Brix) content, and the titratable acidity content (Fisher & Nichols, 1997).

1.7 Light

Around the world, the productivity of greenhouse tomato crops is strongly influenced by the total solar radiation incident on the crop. The annual yield of long season greenhouse grown tomato crops is closely related to the annual total of solar radiation incident on the crop, whether assessed as sunshine hours (Bewley, 1929) or as radiant energy (Cockshull et al., 1992). In the early part of the cropping season when canopy photosynthesis is limited by low light, fruit yield can be limited by the supply of assimilate. Cockshull et al. (1992) reported that over the first 14 weeks of harvest from February to May in the UK, fruit yield was in direct proportion to solar radiation at 2.01 kg per m^2 fresh weight of harvested fruit for every 100 MJ of solar radiation incident on the crop. De Koning (1989) also found in the Netherlands that fruit yield was in direct proportion to solar radiation at 2.07 kg per m^2 per 100 MJ from commercial tomato plants. A positive correlation between fruit yield and solar radiation with successive plantings of single truss tomatoes was also observed by McAvoy and Janes (1989) in the USA. Adams et al. (2001) showed that increasing light available to the plant gave increases in yield, which was due to an increase in both mean fruit size and number of fruit picked.

The balance between vegetative and reproductive growth is very delicate in tomato. An adequate supply of photosynthates will secure high rates of fruit set, leading to abundant fruit development (Papadopoulos & Pararajasingham, 1997). Therefore a continuous supply of photosynthates is required if continuous production is to be sustained. If not, fruit set rate declines, flower initiation is retarded and the plant reverts to vegetative growth (Papadopoulos & Pararajasingham 1997).

Yield is positively related to the quantity of solar radiation received by the crop in long season crops. Cockshull et al. (1992) reported that fruit number per truss is positively correlated with solar radiation intercepted (most noticeably when less than 1.5 MJm^{-2} day^{-1}) around the time of first anthesis of a truss. Kinet (1977) using an 8-hour photoperiod and exposure to 0.26 MJm^{-2} day^{-1} produced flowers in the first inflorescence which all aborted, while an increased exposure to $0.52MJm^{-2}$ day^{-1} produced flowers in which more than 50% developed into fruit. Atherton and Othman (1983) also found that the number of flowers reaching anthesis in the first inflorescence is related to the irradiance level (Fig. 1.1).

During the early production of tomato crops, sub optimal light conditions in winter and early spring causes low rates of photosynthesis and is the cause of poor reproductive development of the early inflorescence. Similar problems may even be encounted on later inflorescence with improved light conditions (Slack & Calvert, 1977). Mpelasoka et al. (1997) showed flower abortion along with smaller fruit decreased the fruit yield in the winter months when low irradiance occurred. Kronenberg and Van De Hulst (1984) showed that 62 – 74% of the fluctuation in crop yield could be attributed to the differences in the photosynthetically active radiation received by the crop.

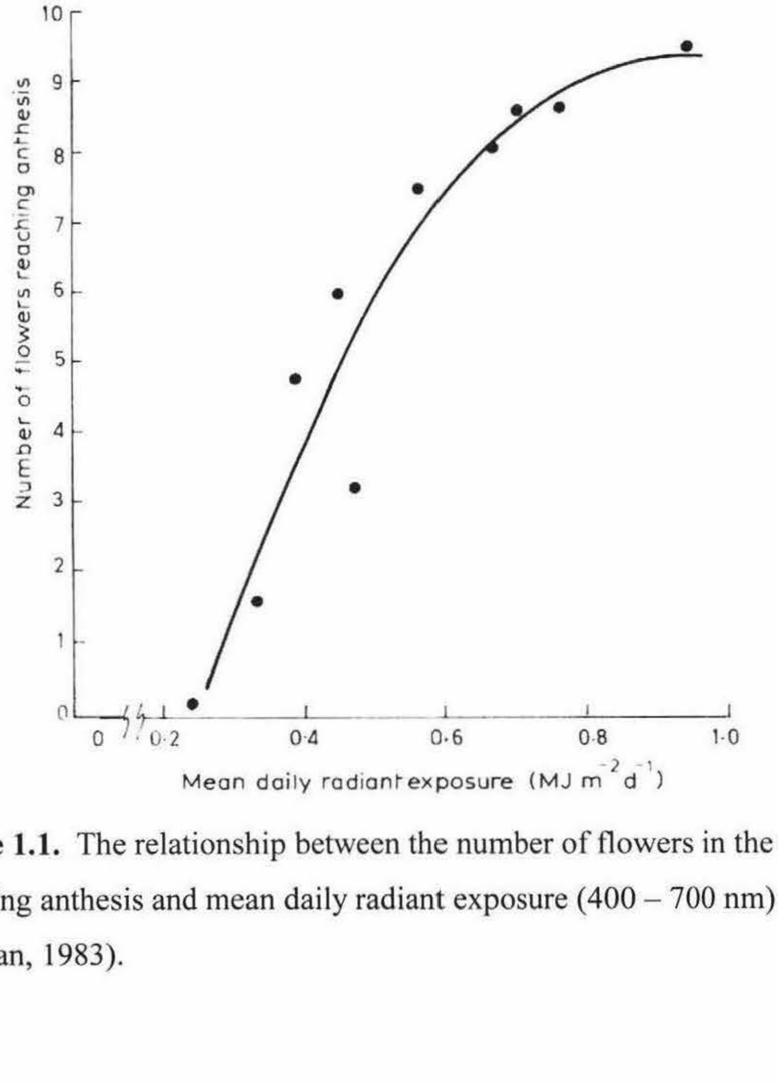

Figure 1.1. The relationship between the number of flowers in the first inflorescence reaching anthesis and mean daily radiant exposure (400 – 700 nm) (Atherton & Othman, 1983).

Demers et al. (1998) showed that supplementary light (110 μmolm^{-2}s^{-1}) increased both growth and yield of the tomato plants compared to natural light. However photoperiods longer than 14 hours did not increase growth or yields of the tomato plants while photoperiods of 20 to 24 hours even caused leaf chlorosis. However, McCall (1992) found that increased intensity of supplementary light (30, 60 & 90 $\mu molm^{-2}s^{-1}$ respectively) over an 18-hour photoperiod significantly increased the plant height, leaf number, leaf area and dry weight of tomato plants. Greater early yield and market value was also found with increasing levels of supplementary light due to an increased number of harvested fruit in the early cropping period. Kinet and Peet (1997) found that the greatest increase in average fruit weight occurred when supplementary light was applied from initial fruit set to the mature green stage, during the period of rapid absolute growth of the fruit, suggesting the amount of assimilates available appears to determine final fruit size. The amount of assimilate produced is regulated by photosynthesis which is dependant on the quantity of solar radiation incident on the crop, the area of foliage available to intercept solar radiation and the average CO_2 concentration by day.

1.8 Fruit thinning

The quality of tomato fruit is defined, among other parameters, by their size and shape. Position and set sequence in the truss are critical factors determining final size of tomato fruit. Usually, fruit developing at the proximal position are larger than distal fruit (Kinet & Peet, 1997).

Fruit size and yield appear to be dependant on assimilate distribution within the fruiting plant which is controlled by the activity of both sources and sinks. When assimilate availability is lower than total demand, competition between sinks becomes the determinant factor for the control of assimilate distribution (Kinet & Peet, 1997). Competition exists between vegetative and reproductive structures, among inflorescence and among fruit on the same truss (Ho and Hewitt, 1986). Hurd et al. (1979) showed that up to 90% of the fresh weight gained per unit of time went into developing fruit, leaving a minimum of resources for the vegetative system and restricting any further increase. With the removal of old leaves, leaf area is actually diminished. Under high fruit load, plants have significantly lower leaf area indicating carbohydrates are the limiting factor (Gautier et al., 2001). Hurd et al. (1979) also reported a greater sensitivity of roots when fruit competition was high, with cessation of root growth and even some root death observed, causing nutrition deficiencies such as iron chlorosis being observed with reduced nutrient uptake from the roots.

Distribution of assimilates among sinks is primarily regulated by the sinks themselves (Heuvelink, 1997). The potential size of a tomato fruit is dependant on its position within a truss and on the cultivar (Ho, 1992) but size achieved is also dependant on the amount of assimilate produced by the foliage and the number of fruit competing for the assimilates (Papadopoulos & Pararajasingham, 1997). Dry matter partitioning in fruit strongly depends on the number of fruit on the plant (Heuvelink and Buiskool, 1995).
It is a well known phenomenon with most tomato cultivars that fruit at the distal end of the truss are smaller than those at the proximal end (Bohner & Bangerth, 1988). Final fruit weight is determined by both the fruit position in the truss and the sequence of pollination among fruit (Bohner and Bangerth, 1988).

Bohner and Bargerth (1988) and Bangerth and Ho (1984) showed that when fruit were pollinated simultaneously down the truss, sizes were similar for both the distal and proximal fruit. The proximal fruit were smaller and distal fruit larger than the control trusses on the rest of the plant indicating there is a set amount of assimilate for each truss. Bangerth and Ho (1984) also showed that when distal fruit were pollinated before the proximal fruit, the distal fruit were larger, but not as large of a difference than would have occurred if the proximal fruit had been pollinated first.

Bohner and Bangerth (1988) showed that the size difference between proximal and distal fruit is caused by the difference in cell number at anthesis, with the early pollination of proximal fruit giving increased fruit cell number. Also since the first induced fruit (Proximal) are larger than the later induced ones (distal) at any time during early growth, there will be a larger pressure gradient between the larger sink and the source (Bangerth & Ho, 1984). Therefore proximal fruit reach larger potential weights than distal fruit because of the natural flowering sequence and the higher number of cells in the proximal ovaries at anthesis (Bohner and Bangerth, 1988).

When number of fruit per plant is increased there is enhanced fruit growth at the expense of vegetative growth. A high fruit yield is desirable and therefore a high biomass allocation to the fruit is important. However, as allocation to fruit is at the expense of vegetative growth, which itself is needed for formation of leaf area and hence light interception, then too high an allocation of biomass to the fruit will adversely affect the future production capacity. Furthermore, too high a fruit load and hence sink / source ratio may result in flower and / or fruit abortion (Heuvelink, 1997).

Fruit thinning aims at adapting the fruit load to assimilate production in order to improve fruit grade and quality. The removal of some fruit in the truss favours the growth of the remaining fruit (Heuvelink, 1995). Reducing the number of fruit per plant strongly diminished the biomass allocation to the fruit, whereas total dry matter production is hardly affected (Heuvelink, 1997). In general, the average weight of individual fruit increases with decreasing fruit numbers. The increased individual fruit weight with a decreased fruit number per plant reflects competition for assimilates among fruit. This increase in weight results from a higher average growth rate of individual fruit, with a 17% higher individual fruit dry weight for a treatment with half the number of fruit per plant (Heuvelink, 1997). He also showed that by reducing fruit number per truss from seven to one almost doubled final individual fruit weight, though reducing total yield per m^2.

Veliath & Ferguson (1972) showed that following deblossoming, determinate tomatoes produced higher average fruit weight and overall total yield. Deblossoming in the earlier stages promoted greater vegetative development and leaf area capable of supporting higher yields. Also the photosynthate that would have gone to the developing fruit was channeled into the remaining fruit giving the high yields (larger fruit). Demers et al. (1998) showed that when they reduced fruit load in indeterminate tomatoes, there was an increase in vegetative growth but a decrease in yield. Fruit or truss pruning does not affect leaf appearance rate (Heuvelink & Marcelis, 1996), but reducing the number of fruit per truss from seven to one increased vegetative dry weight by 62 – 67% (Heuvelink & Marcelis, 1996).

Bertin et al. (1998) found that as the number of fruit (sinks) increased, the weight of the individual fruit is significantly reduced, with the distal fruit being most affected. Cockshull and Ho (1995) showed that the removal of the distal fruit increased the size of proximal fruit. However the redistribution of assimilates within the truss did not completely compensate for the loss of weight by the removal of distal fruit. Flower pruning reduces sink load and consequently increases the amount of carbohydrates available for growth of the remaining organs with increases in vegetative dry matter and increased mean fruit dry matter (Gautier et al., 2001).

Bertin (1995) showed that with winter tomato crops in France, less than one fruit per truss failed to set on plants thinned to three flowers. When the number of flowers per truss was increased to seven there was an abortion of at least one flower bud per truss for the first few trusses which increased to 3 flower buds aborting in each truss from the fifth truss onwards (Fig. 1.2). The percentage of aborted flower buds increases as you move down the truss from the proximal position having no abortion rates to the distal position having 50-60% abortion rates (Fig. 1.3).

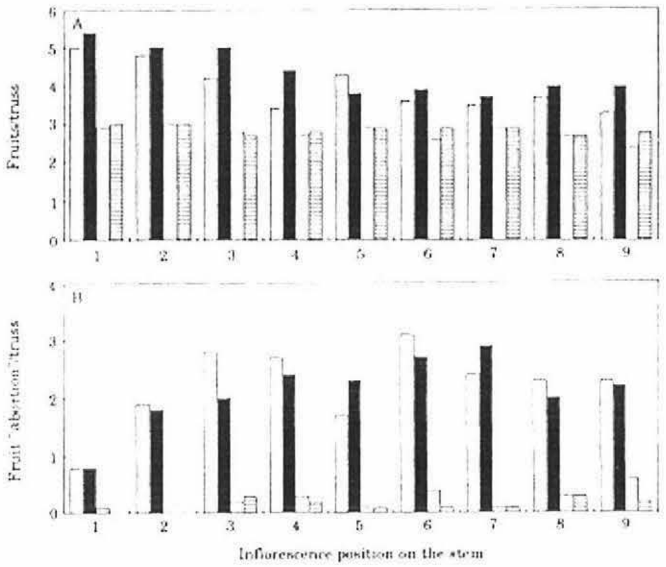

Figure 1.2. Number of fruit per truss (A) and number of fruit aborted per truss (B) recorded on the first nine inflorescence : Bars are 7 fruit per truss, 7 fruit per truss with CO_2 enrichment, 3 fruit per truss, 3 fruit per truss with CO_2 enrichment respectively (Bertin, 1995).

Actual fruit weight results from the balance between assimilate supply by photosynthesis and assimilate demand from all individual competing sinks (Bertin et al., 1998). Hurd et al. (1979) reported that reducing sink activity by removing two-thirds of the flowers in tomato resulted in larger plants with larger fruit. Cockshull and Ho (1995) also showed that removal of some fruit from the first few trusses of plants grown at high density enabled a higher proportion of marketable fruit produced in the UK spring, when low light levels are common . Favaro and Pilatti (1987) also found that by removing fruit within the truss favored the growth of the remaining fruit within the truss. Adams et al. (2001) said that pruning to five fruit resulted in a more uniform fruit set and fruit load. Pruning all trusses to five fruit caused a significant loss of yield with only 48.3 kg/m^2 harvested compared to 52.2 kg/m^2 for the controls. However there was a significant increase in mean fruit size, with 99.3g/fruit for trusses thinned to five fruit compared with 75.6g/fruit for the controls (Adams et al., 2001).

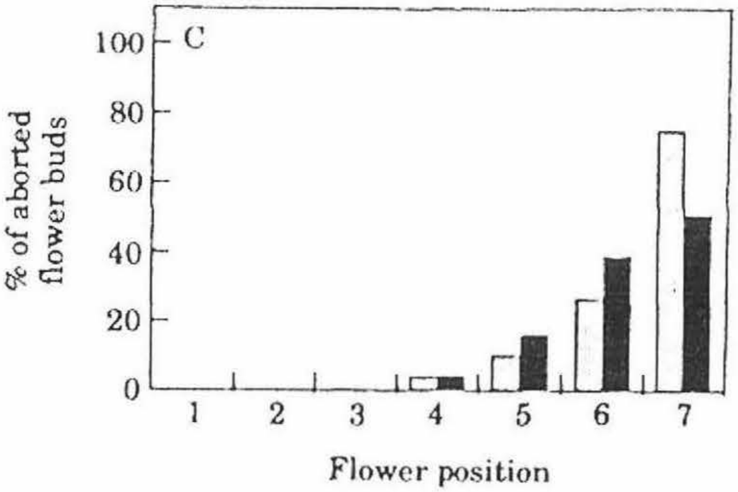

Figure 1.3. Percentage of aborted flower buds for each flower position within the inflorescence (1 is the proximal flower) : Bars are 7 fruit per truss without and with CO_2 enrichment (Bertin, 1995).

Dry matter partitioning to the fruit is to a large extent determined by the number of fruit on the plant with the fraction partitioned into fruit almost halved when fruit number decreased from seven to two per truss (Heuvelink, 1997). Moorby and Jarman (1975) also showed that reducing sink strength by removing fruit from a single-truss plant reduced the rate of export of $^{14}CO_2$ – labeled products from the leaves. This indicates why total fruit yield decreases less than proportionally with decreasing fruit number.

Slack and Calvert (1977) found that removing a truss resulted in an increased yield on the remaining trusses with the largest increase occurring on the trusses adjacent to the one that was removed. The increases in yield from individual trusses were due primarily to higher mean fruit weights. Adams et al. (2001) found that by removing two adjacent flowering trusses resulted in a yield loss that was due to the number of fruit picked. However over the course of the experiment there was no loss of yield as a result of a slight increase in the number of set fruit and mean fruit size on the remaining trusses above and below the ones removed. Fisher (1977) explained that the biggest decrease in yield was occurring through competition from the truss immediately above the truss under consideration.

Growers can therefore use fruit thinning as a tool to improve marketable fruit yield, however there is a need to provide information of how different levels of fruit thinning, within each cultivar, effect the individual weight of fruit down the truss, thus allowing growers better control of individual fruit size of tomatoes.

1.9 Plant density

The normal planting arrangement for greenhouse crops is to use double rows normally around 0.5m apart with pathways for access of around 1.1m between the double rows (Atherton & Rudich, 1986). Manipulation of plant densities is mainly achieved therefore by altering the in-row plant spacing.

An increase in plant density often gives rise to an increase in early and total marketable fruit per unit area (Frost & Kretchman, 1988). High density aeroponic systems used by Leoni et al. (1994) showed that growing at a density of 25 and 35 plants /m^2 can be achieved using a single cluster tomato system. However as densities increase, the yield per plant, fruit size and number of fruit per plant all decrease. Zahara & Timm (1973) found, with process tomatoes (determinate), that the number of fruit set per plant, number of flowers, number of leaves and the stem diameter all decreased as plant density was increased up to 96.3 plants per m^2. Cockshull et al. (2001) also found that while yield per m^2 increased from 32.8 kg/m^2 to 35 kg/m^2 with increasing plant density, the yield per plant fell from 16.1 kg at 2 plants per m^2 (low) to 11.6 kg at 3 plants per m^2 (high). Papadopoulos and Ormrod (1991) and Cockshull et al. (1992) both observed an increase in flower abortion at higher plant densities, due to an inadequate supply of photosynthates due to shading. Shading also reduces fruit size and so reduces the proportion of fruit in the larger sized grades (Kinet & Peet, 1997), thus reducing the total and marketable fruit yields (Cockshull et al., 1992).

Figure 1.4 (Anker et al., 1980) (as in Atherton & Rudich, 1986) shows that there is a linear relationship between plant density and the mean fruit weight for the two different tomato crops. The effects of plant density on dry matter distribution are caused indirectly as a result of the influence of source strength on the number of fruit on the plant. At higher plant densities, growth per plant is reduced considerably but dry matter distribution is not appreciably influenced with 57% to 59% of the total dry matter produced being located in the fruit for all plant densities (Heuvelink, 1995), thus a linear relationship between plant density and mean fruit weight.

Cockshull and Ho (1995) demonstrated that tomato crops grown at a fixed low density of 2 plants per m^2 produced a high proportion of fruit in the preferred size grade range of 50-90 g (UK market) in spring. However in summer this density produced too many large fruit. When grown at a high density of 3 plants per m^2, the proportion of fruit in the preferred size range was now highest in summer, but too many small fruit were produced in spring. They found that by planting at a low density and then using side shoots to increase plant density for summer, they were able to match assimilate supply with the number of fruit (sinks), which enabled a more uniform mean fruit weight throughout the cropping season.

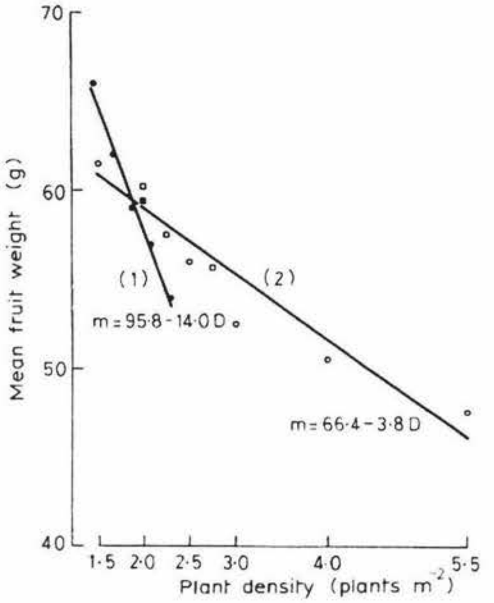

Figure 1.4. Mean fruit weight for different plant densities. (1) Early crop and (2) autumn crop (Anker et al., 1980) (as in Atherton & Rudich, 1986).

Plant growth was strongly influenced by plant density with the highest plant growth rate occurring at the lowest plant density of 1.6 plants/m^2 compared to the higher densities of 3.1 & 2.1 plants per m^2 (Heuvelink, 1995). Plant development was not influenced by plant density with visible trusses flowering at the same time. De Koning (1994) observed no influence of plant spacing on truss appearance rate that agreed with Heuvelink & Marcelis (1996). Papadopoulos and Ormrod (1991) observed that only combinations of high plant densities (greater than 4 plants per m^2) and low light conditions reduced the truss appearance rate.

Decreasing plant density from 3.1 to 1.6 plants per m^2 increased vegetative dry weight per plant by 82% and total dry weight per plant by 75% (Heuvelink & Marcelis, 1996).

Leaf appearance rate was not significantly affected, but leaves were larger at lower plant density, with the leaf weight increasing more than leaf area thus decreasing the specific leaf area (SLA). Nederhoff et al. (1992) concluded that in summer when photosynthesis and thus assimilate supply is high, tomato plants should be grown at high densities to reduce the presence of "short leaves syndrome" (SLS). SLS is undesirable, because light interception and hence crop photosynthesis will be lower than in well-foliated crops. Fruit quality is also affected negatively as fruit are exposed to more solar radiation.

1.10 Greenhouse production

Greenhouse tomato production is very intensive and requires a high amount of input, including in particular energy and manpower. Modern commercial greenhouse tomato production now has considerable control with temperature, CO_2 concentration and humidity with the use of computers. Therefore solar radiation becomes the main limiting factor for the growth of greenhouse tomatoes (Papadopoulos & Pararajasingham, 1997). Supplementing the natural available radiation with additional light would increase yield, however supplementary artificial lighting is currently considered to be commercially unprofitable (Papadopoulos & Ormrod, 1988).

Picken et al. (1986) stated that it is better to maximise the natural lighting by careful alteration to the greenhouse cover, careful design and optimum winter orientation of the greenhouse and the crops within the greenhouse. In a greenhouse the cover is a barrier reducing the amount of radiant energy outside before it reaches the crop. Greenhouse transmission is dependant on the greenhouse construction, the optical properties of the cover and the angle of incoming radiation (Heuvelink, 1997).

Therefore there is a need to maximize the amount of solar radiation incident on the crop. One such method is to design new greenhouses to ensure maximum transmission of solar radiation (Papadopoulos & Pararajasingham, 1997). Another method is to maximize natural radiation interception by the crops by the manipulation of plant density or by using devices such as ground level white reflective plastic sheets (Papadopoulos & Pararajasingham, 1997) to increase solar radiation incident on the leaves.

1.11 Temperature

The growth of tomato plants is temperature dependant and the recommended day / night temperatures for a fruiting crop under glass in the UK is 18 – 20 ^{0}C / 15 – 16 ^{0}C (Atherton & Rudich, 1986). De Koning (1988) found that by lowering the day temperature and raising the night temperature without altering the average 24-hour temperature resulted in shorter tomato plants with an equal number of trusses and of leaves. He concluded that in young plants, a high day / low night temperature regime seems most suitable to achieve a fast increase of light interception and maximum growth. Later a reversed low day / high night temperature regime is preferred to produce the maximum yield without loss of fruit quality. However Slack and Calvert (1978) (as in Atherton & Rudich, 1986) showed that higher night temperatures increases the early marketable yield but decreases the final marketable yield (Fig. 1.5).

The rate of fruit development is markedly affected by temperature. The optimum night temperature for fruit set is in the range of 15 – 20 ^{0}C (Kuo et al., 1979, as in Atherton & Rudich, 1986), with night temperatures below 14 ^{0}C giving poor fruit set (Atherton & Rudich, 1986). Higher night temperatures in combination with low relative humidity lead to an excessive drop of flowers and pollen sterility (Johnson et al., 1999).

By affecting the rates of respiration and starch synthesis in the fruit, the rate of assimilate import is changed by fruit temperature (Walker & Ho, 1977; Walker & Thornley, 1977), with the optimum temperature for net assimilation rate in tomatoes being between 25^{0}C and 30^{0}C (Kinet & Peet, 1997). Low minimum air temperatures delay the development of fruit and reduce the number and weight of fruit (Traka-Mavrona et al., 1995).

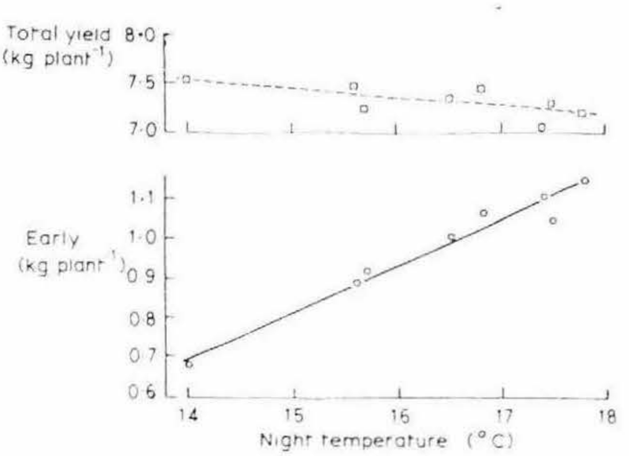

Figure 1.5. Effect of night temperature on early (4 week) and total (20 week) tomato yields (Slack & Calvert, 1978) (as in Atherton & Rudich, 1986).

1.12 Carbon dioxide

In greenhouse cultivation, carbon dioxide (CO_2) enrichment is common practice, with increased CO_2 concentrations increasing both initial photochemical efficiency and light saturated photosynthetic rate (Heuvelink, 1997). The detrimental effect of low light on the early trusses can be offset by CO_2 enrichment. By increasing the CO_2 concentration inside a greenhouse to 3 times the normal level (340 to 1000 $\mu l\ l^{-1}$), complete fruit set in the early trusses can be achieved under low winter light (Cooper & Hurd, 1968). CO_2 enrichment improves fruit set by increasing assimilate supply resulting in both fruit number and fruit size being increased (Picken, 1984).

CO_2 enrichment increases fruit yield by increasing the number and individual weight of the fruit (Atherton & Rudich, 1986). However at high temperatures, greenhouses are usually vented meaning that only a few hours of CO_2 enrichment are possible each day which is lower than the 8 – 10 hour enrichment period that shows significant yield increases (Willets & Peet, 1989). Behboudian and Lai (1994) also found that tomatoes CO_2 enriched at 22 ^{0}C did not grow any more rapidly than non-enriched plants.

Therefore it was concluded that CO_2 enrichment is most important in cold climates when enrichment can be continued for a long period (8 – 10 hours) (Kinet & Peet, 1997).

1.13 Humidity

Bellert, et al. (1998) showed that the fresh yield of tomato fruit during summer was higher in misted greenhouses with a VPD of less than 1.5 kPa compared to greenhouses at 3.5 kPa. This increase in yield resulted from a gain in water rather than from a gain in dry matter.

Adams and Ho (1995) showed that high humidity during the day increased the fruit calcium content, because less Ca was diverted to the leaves. The trend was similar at night but not significant as the total uptake of Calcium is lower at night than in the day.

1.14 Manual operations

Indeterminate tomatoes are favored in greenhouses as they produce a large crop over an extended period. Several manual operations are performed regularly, but not every day as Buitelaar (1988) found reductions in yield of 9% when tomato plants were shaken every day and 17% when they were shaken twice a day.

Lateral shoots are removed manually giving a simple stem, which is easily trained with string keeping the crop in optimal condition as regards to light interception. Navarrete and Jeannequin (2000) showed de-shooting frequency affected both vegetative growth and yield. When de-shooting was preformed seldomly (every 21 days) the stem diameter and the vigor of the tomato plants was decreased. The number of fruit per m^2 was also reduced, decreasing the total yield. Fruit maturity was also later than more frequent de-shooting treatments. They concluded that tomato plants should be de-shooted every 7 to14 days for optimum results. Deleafing consists in removing the oldest leaves that are no longer photosynthetically active in order to avoid plant diseases and facilitate harvesting. As soon as fruit from a truss have been harvested, most producers remove the neighboring leaves from the plant since they no longer export carbon assimilates to fruit (Bellert et al., 1998).

1.15 Nutrient film technique (NFT)

Growing greenhouse tomatoes using the nutrients film technique (NFT) involves supplying all the essential nutrients required for crop growth in the recirculating solution in adequate amounts (Papadopoulos & Pararajasingham, 1998).

NFT avoids soil borne diseases and the associated need for soil sterilization. The total water requirement is lower, and the supply of inorganic nutrients and water can be consistent and optimum (Jackson et al., 1984).

1.16 Nutrient solution conductivity

Continuous recirculation of the nutrient solution provides a means of maintaining virtually constant nutrient concentration. The pH and electrical conductivity's (EC) can be monitored continuously with frequent additions of nutrients being made to avoid depletion in the solution. Nutrient Solutions used for growing tomato plants commercially in the NFT system usually have a constant salinity level in the range of 2-5 $mscm^{-1}$ (Van Ieperen, 1996). Although salinity improves fruit quality, reduced yield and an increased incidence of blossom end rot (BER) commonly accompany the improvement (Sakamoto et al., 1999).

Increases in solution EC are usually done to control vegetative growth under unfavourable conditions during winter and to improve fruit quality (Ismail and Ahmad, 1997). Increased conductivity produces fruit with a higher content of sugars and organic acids and a higher dry matter percentage providing the basis for better tasting fruit (Petersen et al., 1998). However higher ion concentrations may reduce plant growth due to osmotic effects, which lower the availability of water to the roots. Also lower concentrations restrict plant growth due to nutrition being the limiting factor for growth or in extreme cases due to deficiency defects (Van Ieperen, 1996).

The growth of fleshy tomato fruit is mostly based on the influx of water (about 95%), then of carbon (2%) and minerals (0.5%) (Guichard et al., 1999). Pangiotopoulos and Fordham (1995) showed that restricting water supply to tomato plants in soil significantly reduced total fruit yield through reducing fruit size. The total soluble solids and titrateable acidity (fruit flavour) increased significantly under limited water supply. Adams (1994) found that with tomatoes, the uptake of water and nutrients increases with salinity up to 4.8 mscm^{-1} and then decreases at the higher salinity's.

Sakamoto et al. (1999) showed that with single truss tomatoes that an increase in salinity (EC), either at 5.0 mscm^{-1} or 8.0 mscm^{-1} at the mature green stage improved fruit quality more than increasing salinity at the colouring stage of fruit development. Salinity increased the concentration of soluble solids, citrate, ascorbic acid, potassium, chlorophyll, lycopene, and carotene in the fruit but the absolute amount of these per fruit was not affected compared to the control. There was a reduction in fruit weight, but not number. This shows that the improvement in fruit quality is caused by the reduction of water import into the fruit. Mpelasoka et al. (1997) and Okano et al. (2000) also found that fruit increased in total soluble solids (TSS), titratable acidity (TA) and dry matter concentration (DM) with increasing EC levels, resulting from the fruit receiving less water, not more photosynthates.

Increased salinity decreased plant growth through reducing leaf area, which was due to osmotic stress (Hao et al., 2000). Stanghellini et al. (1998) showed a high salinity (10 mscm^{-1}) reduced leaf area by 15% compared to plants at 2 mscm^{-1}. Schwarz and Kuchenbuch (1998) showed leaf area was 20% less compared to plants grown at 1 mscm^{-1}.

Dorais et al. (2000) showed that increasing the EC up to 2.0 – 5.6 mscm^{-1} showed a beneficial effect of fruit quality without affecting the total yield or fruit size. Gough and Hobson (1990) also found with cherry tomatoes, that a nutrient solution of 5 mscm^{-1} gave little loss in total fruit yield compared to lower nutrient solution conductivity's, with improved effects on fruit size and flavour. However Nichols et al. (1994) found that fruit yield fell with increasing salinity, from 2 mscm^{-1} to 8 mscm^{-1}, which was due to a reduction in fruit size. The quality of the fruit however was found to improve with the increasing salinities. Hao et al. (2000) found that an EC of 6.0 mscm^{-1} and over reduced fruit size, especially that of the larger fruit. Ismail and Ahmad (1997) showed that increasing the solution concentration from 3 to 6 mscm^{-1} resulted in a 50% reduction in fresh fruit weight in NFT grown tomatoes. Schwarz and Kuchenbuch (1998) also found plants grown at 6 mscm^{-1} gave 50% less yield than that of plants grown at 1 mscm^{-1}. However, the dry matter content of the fruit increased at the higher EC values. But Massey et al. (1984) (as reported in Adams et al., 1995) reported that tomato yields decrease by 1% when the salinity increased from 2 to 4 mscm^{-1} and by 10% from 4 to 6 mscm^{-1}.

Dorais et al. (2000) showed that NaCl can be used to raise the EC of the nutrient solution without any detrimental effects on yield or quality, which is cheaper than using major nutrients to increase the EC level. Raising the EC to 3.0-4.6 mscm^{-1} with NaCl or major nutrients improved tomato fruit quality without yield loss (Hao et al. 2000). Papadopoulos et al. (1999) also found increasing the EC with NaCl or K_2SO_4 showed no detrimental effects on the growth, yield or fruit quality of the tomato, with NaCl improving the quality in terms of a increase in acidity. Nukaya and Hashimoto (2000) demonstrated that the yield of tomato was not affected by the concentration of Cl up to 7.5 mmol/L. Hand and Fussell (1995) actually observed that when chloride salts were used to raise the EC of the nutrient solution, the elevated chloride enhanced calcium uptake.

Flavour is an important aspect of fruit quality. The levels of sugar, acids and volatile in tomato fruit largely determine flavour. Fisher and Nichols (1997) showed that increased conductivity improved soluble solids and acidity content. However, there was a yield trade-off from increased conductivity, which was caused by reduced water uptake and thus reduced size of the tomato. The improvement in fruit flavour occurs because the content of acid and sugars per fruit is the same, but as the fruit is smaller there is a higher concentration. Gough and Hobson (1990) with taste tests done confirmed that the higher salinity's (5 $mscm^{-1}$) were preferred over the lower ones. Also, a taste test panel scored the fruit from high salinity levels of NaCl as significantly sweeter than fruit from the same salinity level with major nutrients (Petersen et al., 1998). Adams (1991) found that addition of NaCl increased the concentration of reducing sugars more than addition of major nutrients. However Petersens et al. (1998) showed that NaCl did not increase the concentration of reducing sugars, explaining that NaCl enhances the sensory perception of sweetness and thus the taste of the tomato.

1.17 pH

Controlling nutrient solution pH is essential because the pH of the root environment is a major determinant of the availability and uptake of nutrients (Papadopoulos & Pararajasingham, 1998). They showed that using the cheaper acid (HCl^-) to control pH resulted in an increase in marketable fruit yield of up to 14% with no apparent changes in fruit yield.

1.18 Blossom end rot (BER)

A high incidence of blossom end rot (BER) of fruit is a serious problem in cultivation of tomato, especially in summer hydroponics (Suzuki et al., 2000). BER usually occurs early in fruit development when the fruit is growing rapidly and the concentration of calcium in the trusses is decreasing. It can be due to an inadequate supply of calcium in the feed, poor absorption of calcium by plants due to water or osmotic stress or a disproportionately low distribution of calcium toward the fruit or to the distal fruit tissue at the critical stage of fruit growth (Ho et al., 1995).

A disadvantage of high EC is increased blossom end rot and reduced fruit yield (Hohjo et al., 1995). Nutrient uptake is considered proportional to net photosynthesis of the crop. Klaring et al. (1999) showed that by mapping nutrient demand (EC) to nutrient supply depending on the climate of the greenhouse resulted in reductions in BER without yield or quality effects.

Ho et al. (1995) showed that plants with a greater leaf area had a greater transpiration rate that gave greater uptake of calcium, which reduced BER. However plants with greater fruit load seemed to show more effects of BER, indicating that BER or calcium deficiency is somehow linked with low partitioning of dry matter to the fruit. The concentration of calcium in the distal positions of the fruit also tends to be lower than the proximal ones indicating that BER is more likely to develop in fruit at the end of the truss than the fruit close to the main stem (Petersen et al., 1998).

Stanghellini et al. (1998) showed that by manipulating the greenhouse environment to give reduced transpiration, led to less yield reductions and less BER when growing at a high salinity. It was shown with a low transpiration environment, the decrease in yield was 2% for each unit of EC exceeding 2 mscm^{-1} where as in a high transpiration environment the decrease in yield was 4% for each end of EC exceeding 2 mscm^{-1}. Also reducing transpiration rate significantly reduced the incidence of BER. High transpiration rates are thought to induce BER by creating a preferential flow to leaves that inhibits calcium diversion to the fruit.

Dorais et al. (2000) showed foliar and cluster calcium applications significantly reduced the incidence of BER, regardless of the level and source of salinity of the NFT solution. Hao et al. (2000) found that calcium spraying (0.1 M $CaCl_2$) reduced the incidence of BER in early production, but not the overall incidence of BER.

Chapter 2

Materials & Methods

2.1 Research site

The experiment was conducted at the Plant Growth Unit (PGU), Massey University, Palmerston North during March through to December 2001.

A greenhouse (Maxihouse) of 24 ½m X 8 ½m and growing height of 3m was selected. A NFT (nutrient film technique) system was constructed in one half of the greenhouse giving a total experimental area of 12m X 8 ½m. Seven-meter long channels made from pandafilm ran parallel across the width of the greenhouse in double rows spaced at 40cm on a slope of 1 in 35. These double rows were spaced at 1m intervals.

2.2 Crop establishment

Seeds of the tomato cultivars Alboran (Standard), Ophir (Beefsteak) and Cherita (Cherry) were all sown on 1 March 2001 into a peat based seedling medium. The Seed was germinated on a heated (22°C) capillary bench in a greenhouse. From 9 to 13 March 2001 the seedlings were pricked out and transplanted singularly into one hydroponic cell. These transplants were placed on a wire mesh bench so the roots would not grow out of the trays. The greenhouse was maintained to heat at 14°C and vent at 20°C. The transplants were liquid fed (Appendix 1) every 2-3 days until planting to ensure continued growth and development. The seedlings were transplanted out into the NFT channels on 11 April 2001.

2.3 Treatments

Each cultivar was grown at three different densities. Densities of 27 plants per double row (2.76 plants/m^2), 36 plants per double row (3.67 plants/m^2) and 45 plants per double row (4.59 plants/m^2). Each cultivar was thinned on fruit formation to three fruit thinning truss numbers by removing the distal (end) fruit. Alboran was thinned to 3, 4 or 5 fruit per truss (Table 2.1 & Plate 2.1). Plate 2.1 shows one of the Alboran trusses thinned to 5 fruit. Ophir was thinned to 1, 2 or 3 fruit per truss (Table 2.1). Cherita was thinned to 4, 8 or 12 fruit per truss (Table 2.1). The truss thinning was achieved by thinning from the distal end of the truss to the required truss numbers.

Table 2.1. Fruit thinning treatments indicating how many fruit per truss was maintained.

Alboran	Ophir	Cherita
3 Fruit	1 Fruit	4 Fruit
4 Fruit	2 Fruit	8 Fruit
5 Fruit	3 Fruit	12 Fruit

2.4 Experimental Layout

A Split-split plot design was used. The three tomato cultivars were put into sub plots within each of the three different densities (mainplots), and nested into each of the tomato cultivar sub plots was the three different fruit thinning treatments (Appendix 2). Two blocks were used with a guard row of tomato plants put on the perimeter between the greenhouse wall and the treatment blocks.

Plate 2.1. Alboran truss thinned to 5 fruit.

2.5 Crop management

2.5.1 Nutrient solution

Nutrient (Appendix 3), acid or base solutions with water was added to a main tank which maintained an EC of 3.0-4.0 $mscm^{-1}$ and a pH between 6-7. The main tank nutrient solution was monitored daily.

2.5.2 Training of plants and fruit set

All tomato plants were trained on a single stem with laterals being removed every two to four days. The tomatoes were trained up strings when required and lowered when the tops reached the supporting wire running along the line of the rows at a height of 3 m

(Plate 2.2). Bumblebee hives were put into the greenhouse every two months to promote good fruit set on all tomatoes.

2.5.3 Temperature control

Greenhouse temperatures were maintained to ventilate at 22°C and heat at 15°C throughout the whole growing season.

Plate 2.2. Tomato plants in NFT channels, being trained up string supports.

2.5.4 Pest and disease control

Naem oil with an Azadirachtin content of over 1500 ppm was sprayed once or twice a week to control whitefly infestations. Removal of the bottom leaves up to the last fruiting truss was preformed to eliminate any onset of disease.

2.6 Data collection and analysis

2.6.1 Fruit yield

The number and weight of visually judged red fruit for each treatment was taken at regular harvests from 18 June to 18 December 2001. Tukey's test was performed on the data using SAS statistical package (version 8.2).

2.6.2 Effect of fruit position within a truss

For the first 3 months of harvesting (June, July, August) the actual red fruit weight was recorded at each fruit position in the truss. This was done for the lower density treatment of 27 plants per double row (2.76 plants/m^2). Regression analysis and LSD was performed using SAS statistical package (version 8.2). LSD test was performed over Tukey's test, as there were missing values within the data set.

2.6.3 Total soluble solid (TSS) measurement

The TSS of ripe fruit was determined using a brix meter on the harvest date of 15 August 2001. Five to seven ripe fruit, which were uniform in colour, were collected in each of the Cherita tomato treatments. Two to three ripe fruit, which were uniform in colour, were collected in each of the Alboran and Ophir tomato treatments. After determining their fruit weight, the fruit samples were juiced, and then after the particles had settled the clear supernatant was put onto an Abbe refractometer (brix meter) which read the TSS value of the fruit. This was performed for all the tomato samples. Tukey's test was performed on the data using SAS statistical package (version 8.2).

Chapter 3

Results

3.1 Fruit Yield

3.1.1 Final fruit yield

3.1.1.1 Final fruit yield per m^2

No significant differences in final fruit weight per surface area (m^2) were found with increasing plant density for all three tomato cultivars (Fig. 3.1 & Table 3.3). However Cherita cultivar showed a trend of increasing final fruit weight per surface area with increasing plant density (Fig. 3.1 & Table 3.3). Figure 3.1 also shows that the Alboran cultivar produced significantly greater final fruit yields (per surface area) than the other two cultivars.

All fruit thinning treatments within the Cherita cultivar showed increased final fruit weight per surface area as the plant density increased (Fig. 3.2). However thinning to 12 fruit per truss resulted in the least increase in final fruit weight per surface area as plant density increased, with thinning to 8 fruit per truss giving the greatest increase in final fruit weight per surface area as plant density increased (Fig. 3.2).

Figure 3.2 also shows that thinning Cherita cultivar to 4 fruit per truss gave significantly lower final fruit yields per surface area, at all plant densities, than the other two fruit thinning treatments. No significant differences were observed between fruit thinning treatments for both Alboran and Ophir cultivars (Table 3.1 & 3.2).

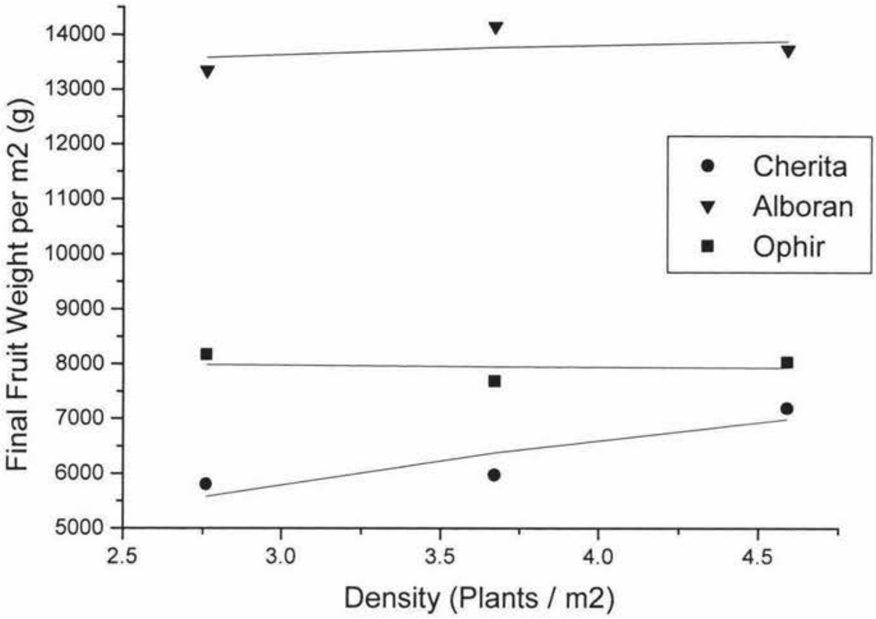

Figure 3.1 Final fruit yield per m^2 of the three tomato cultivars against plant density.

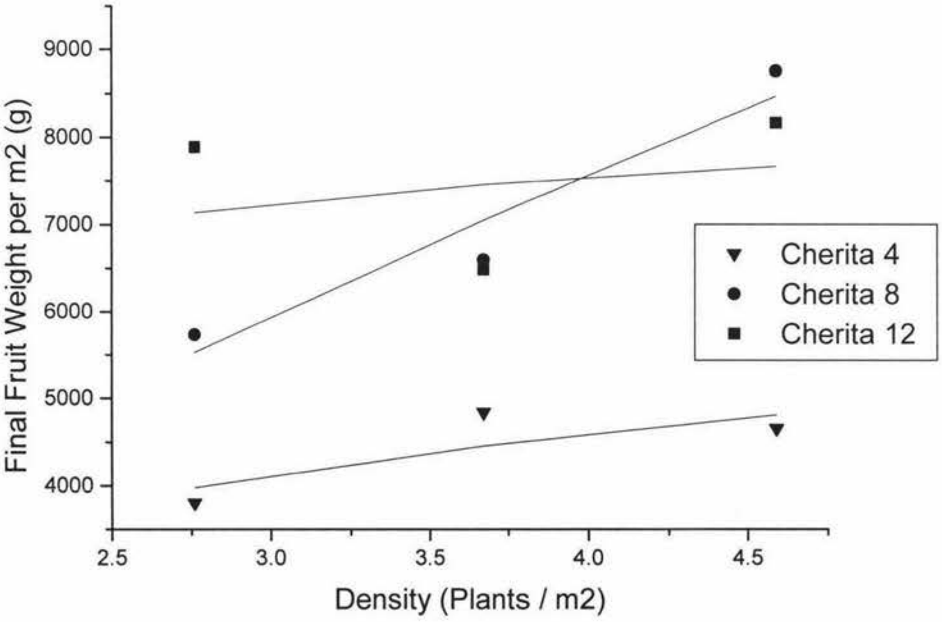

Figure 3.2 Final fruit yield per m^2 for Cherita tomato at different fruit thinning treatments against plant density.

Table 3.1. Final yield per m^2 for Alboran tomato at different fruit thinning treatments. ns indicates that figures within columns are not significant using Tukey's test at $P \leq 0.05$.

Thinning Treatment	Final Fruit Weight per m^2 (g)
Alboran 3	13460
Alboran 4	12771
Alboran 5	15003
Significance	ns

Table 3.2. Final yield per m^2 for Ophir tomato at different fruit thinning treatments. ns indicates that figures within columns are not significant at $P \leq 0.05$ using Tukey's test.

Thinning Treatment	Final Fruit Weight per m^2 (g)
Ophir 1	7331
Ophir 2	8547
Ophir 3	8028
Significance	ns

3.1.1.2 Final fruit yield per plant

All three tomato cultivars showed a significant increase in the final fruit weight per plant as the plant density decreased from the high density of 4.59 plants per m^2 to the low density of 2.76 plants per m^2 (Table 3.3).

Table 3.3. Final fruit yields per plant and per m^2 for the three tomato cultivars at different plant densities. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

Density	Cherita		Alboran		Ophir	
	(g / plant)	(g / m^2)	(g / plant)	(g / m^2)	(g / plant)	(g / m^2)
Low	2104 a	5808	4834 a	13342	2962 a	8175
Medium	1628 b	5976	3857 ab	14156	2096 b	7693
High	1568 b	7196	2993 b	13736	1752 b	8039
Significance	*	ns	*	ns	*	ns

3.1.2 Yield parameters (Mean fruit weight, fruit weight and fruit number per month)

3.1.2.1 Alboran tomato

No interactions between yield parameters and harvest month were observed.

3.1.2.1.1 Fruit thinning

No significant differences in mean fruit weight were observed between thinning treatments (Table 3.4). As with final yield results (3.1.1) no significant differences in fruit weight per surface area were observed between thinning treatments (Table 3.4). Thinning to 3 fruit per truss resulted in significantly less fruit per surface area being harvested than 5 fruit per truss in every month (Table 3.4). The expected fruit number was also calculated for the three thinning treatments to assess how many fruit should have been present for each treatment, assuming that thinning to 3 fruit per truss resulted in no flower or fruit abortion (Table 3.4).

Table 3.4. Yield parameters per m^2 for Alboran tomato at different fruit thinning treatments. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

Thinning Treatment	Mean Fruit Weight	Fruit Weight	Fruit Number	Expected fruit Number
	(g / fruit)	(g / month)	(no / month)	(no / month)
Alboran 3	105.6	2189	20.9 b	20.9
Alboran 4	93.5	2093	22.4 ab	27.9
Alboran 5	96.1	2496	25.7 a	34.8
Significance	ns	ns	*	

3.1.2.1.2 Plant density

No significant differences in mean fruit weight were observed with different plant densities (Table 3.5). Fruit weight and fruit number per surface area gave no significant differences (Table 3.5).

Table 3.5. Yield parameters per m^2 for Alboran tomato at different plant densities. ns indicates figures within columns are not significant at $P \leq 0.05$ using Tukey's test.

Density	Mean Fruit Weight	Fruit Weight	Fruit Number
	(g / fruit)	(g / month)	(no / month)
Low	102.6	2202	21.3
Medium	99.9	2323	23.8
High	92.6	2253	24.0
Significance	ns	ns	ns

3.1.2.2 Ophir tomato

3.1.2.2.1 Fruit thinning treatments

No significant differences in fruit weight per month were observed between the fruit thinning treatments (Table 3.6). Thinning to 1 fruit per truss produced significantly larger mean fruit weights than thinning to 2 and 3 fruit per truss, with 2 fruit per truss also producing larger mean fruit weights than 3 fruit per truss (Table 3.6). Thinning to 1 fruit per truss also produced less fruit per month to be harvested compared with 2 and 3 fruit per truss (Table 3.6). The expected fruit number was also calculated for the three thinning treatments, assuming that the treatment of 1 fruit per truss had no flower or fruit abortion (Table 3.6).

Table 3.6. Yield parameters per m^2 for Ophir tomato at different fruit thinning treatments. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

Thinning Treatment	Mean Fruit Weight	Fruit Weight	Fruit Number	Expected fruit Number
	(g / fruit)	(g / month)	(no / month)	(no / month)
Ophir 1	161.7 a	1202	7.6 b	7.6
Ophir 2	131.7 b	1400	11.1 a	15.2
Ophir 3	107.0 c	1293	12.5 a	22.8
Significance	*	ns	*	

3.1.2.2.2 Plant density

Growing at the low plant density resulted in significantly larger mean fruit than with the medium and high densities (Table 3.7). On a monthly basis, apart from August, where the low plant density produced a higher fruit weight per surface area, no significant differences in fruit weight were observed between plant densities (Table 3.8). On a monthly basis, apart from July, where the high plant density produced a greater number of fruit per surface area, no significant differences in fruit number were observed between plant densities (Table 3.9).

Table 3.7. Mean fruit weight for Ophir tomato at different plant densities. Figures within columns followed by different letters shows a significant difference at $P \leq 0.05$ using Tukey's test.

Density	Mean Fruit Weight
	(g / fruit)
Low	144.5 a
Medium	128.0 b
High	126.6 b

Table 3.8. Fruit weight each month per m^2 for Ophir tomato at different plant densities. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

Month	Low	Medium	High	Significance
		(g)		
July	2100	1692	2288	ns
August	1650 a	993 b	940 b	*
September	1449	1340	1252	ns
October	1194	1578	1699	ns
November	832	1012	979	ns
December	878	784	708	ns

Table 3.9. Fruit number each month per m^2 for Ophir tomato at different plant densities. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

Month	Low	Medium	High	Significance
		(count)		
July	14.9 b	14.2 b	20.7 a	*
August	12.1	8.7	7.3	ns
September	10.3	11	8.6	ns
October	7.7	11.3	12.4	ns
November	7.1	8.1	8.4	ns
December	7.8	7.8	8.3	ns

3.1.2.3 Cherita tomato

There were interaction effects observed between fruit thinning treatments and harvest month, and between density treatment and harvest month.

3.1.2.3.1 Fruit thinning

Thinning to 4 fruit per truss resulted in a significantly larger mean fruit weight for the first four months (June – September) of harvesting compared with 8 and 12 fruit per truss, with the last three months (October – December) showing no significant differences (Fig. 3.3).

Thinning to 4 fruit per truss showed a trend of lower monthly fruit weights and fruit numbers per surface area than thinning to 8 and 12 fruit per truss (Fig. 3.4 & 3.5). Four fruit per truss produced significantly lower fruit weights per surface area in June, July and November than 8 and 12 fruit per truss. However the other months showed a difference in fruit weight per surface area between 4 fruit per truss and 8 and 12 fruit per truss, though not significant (Fig. 3.4). Fruit number per surface area with 4 fruit per truss gave significantly less fruit, for all months except October, than 8 and 12 fruit per truss (Fig. 3.5).

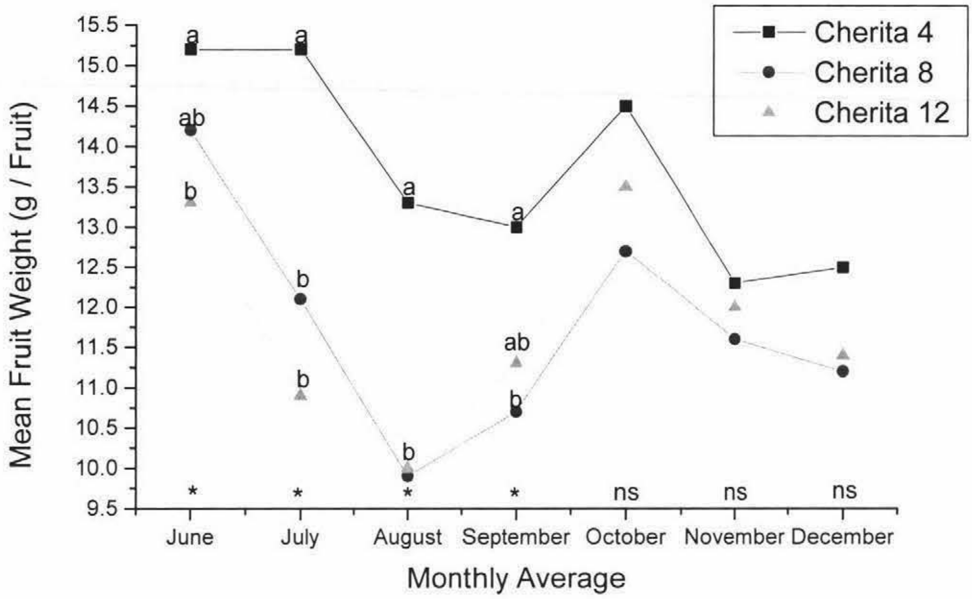

Figure 3.3. Mean fruit weight each month for Cherita tomato at different fruit thinning treatments. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

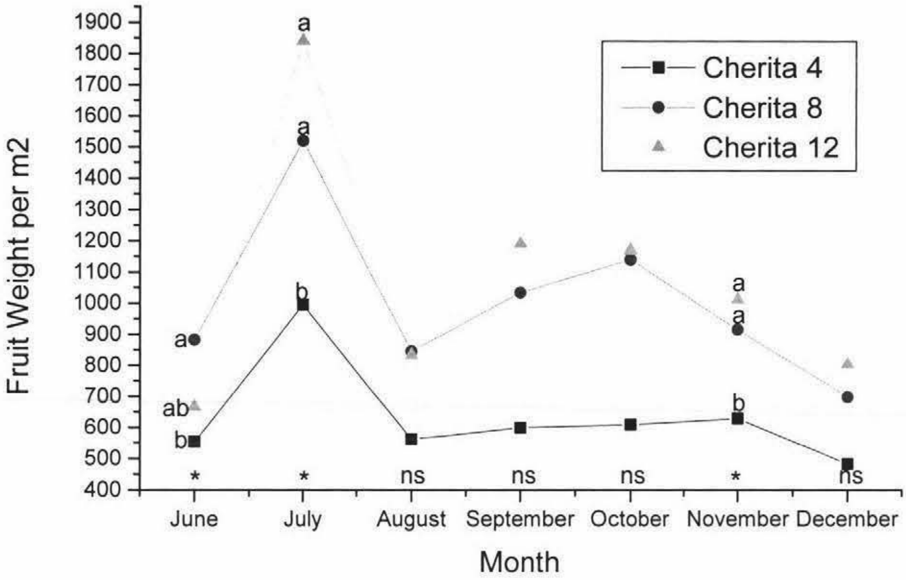

Figure 3.4. Fruit weight each month per m^2 for Cherita tomato at different fruit thinning treatments. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

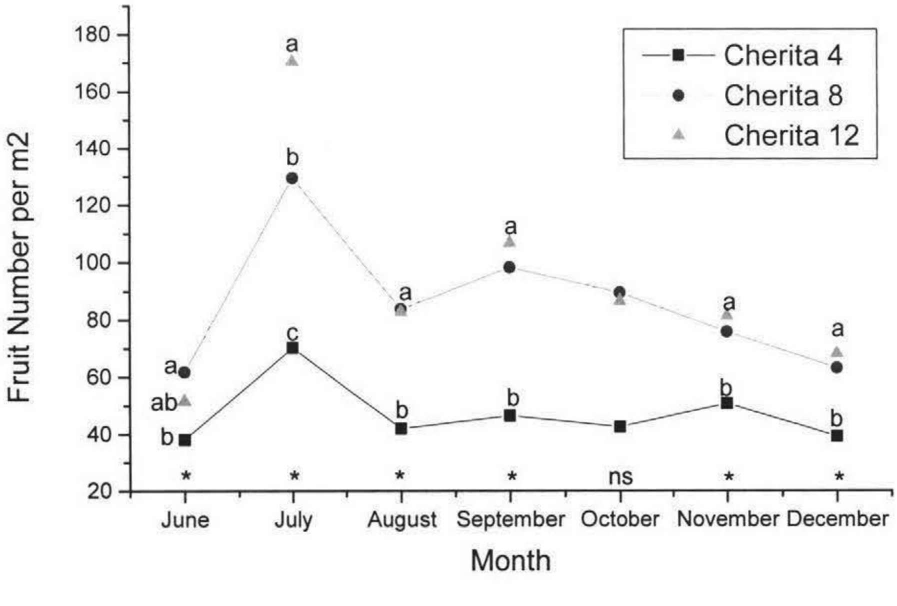

Figure 3.5. Fruit number each month per m^2 for Cherita tomato at different fruit thinning treatments. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences

3.1.2.3.2 Plant density

Significant differences in mean fruit weight between the low plant density and the medium and high plant densities were observed in the first 5 months (June – October) of harvest, with the low density giving significantly larger fruit (Table 3.10).

Apart from June and November, in which the low plant density produced lower fruit weights than the higher plant densities, there were no significant differences observed between the different plant densities (July – October & December) (Table 3.11).

Table 3.10. Mean fruit weight each month per m^2 for Cherita tomato at different plant densities. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

Month	Low	Medium	High	Significance
		(g / fruit)		
June	16.3 a	13.8 b	12.9 b	*
July	16.2 a	11.0 b	11.0 b	*
August	13.0 a	9.9 b	10.3 b	*
September	12.8 a	10.4 b	11.8 ab	*
October	14.5 a	12.4 b	13.9 ab	*
November	11.7	11.9	12.4	ns
December	12.4	11.2	11.6	ns

Table 3.11. Fruit weight each month per m^2 for Cherita tomato at different plant densities. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

Month	Low	Medium	High	Significance
		(g)		
June	428 b	691 ab	983 a	*
July	1591	1283	1481	ns
August	866	625	747	ns
September	913	822	1088	ns
October	983	893	1045	ns
November	522 b	997 a	1036 a	*
December	505	664	815	ns

No significant differences were observed in fruit number from July – October (Table 3.12). However in June, November and December the low plant density produced less fruit than the higher plant densities (Table 3.12).

Table 3.12. Fruit number each month per m^2 for Cherita tomato at different plant densities. ns, * Non significant or significant at $P \leq 0.05$ using Tukey's test. Letters within the columns show the significant differences.

Month	Low	Medium	High	Significance
		(count)		
June	26 c	51 b	75 a	*
July	106	126	138	ns
August	68	67	74	ns
September	70	84	97	ns
October	68	72	79	ns
November	44 b	82 a	82 a	*
December	40 b	61 ab	69 a	*

3. 2 Effect of fruit position within a truss

3.2.1 Fruit weight down truss

3.2.1.1 Alboran tomato

Fruit weight, in all three fruit thinning treatments, decreased down the truss with the proximal fruit being significantly larger than the distal fruit (Table 3.13). Thinning to 3 fruit per truss resulted in the 1st fruit (proximal) having a significantly greater fruit weight than the bottom two fruit (Table 3.13). Thinning to 4 fruit per truss resulted in the 1st fruit (proximal) having a significantly greater fruit weight than the 3rd and 4th (distal) fruit. The 2nd fruit also had a significantly greater fruit weight than the 4th fruit (distal) (Table 3.13). Plate 3.1 shows the size difference in individual fruit weight down the truss observed when thinned to 4 fruit per truss. Thinning to 5 fruit per truss resulted in the 1st fruit (proximal) being significantly different from all other fruit on the truss. The 2nd position fruit had significantly greater fruit weight than the 3 fruit below it, while the 3rd fruit had a significantly greater fruit weight than the 5th (proximal) fruit (Table 3.13).

Table 3.13. Fruit weight of Alboran tomato thinned to 3, 4 and 5 fruit per truss at different fruit positions down the truss at a plant density of 2.76 plants / m^2. Figures within columns followed by different letters shows a significant difference at $P \leq 0.05$ using LSD test.

Fruit Position	Alboran 3	Alboran 4	Alboran 5
		(g)	
1	139.3 a	108.3 a	100.1 a
2	123.8 b	102.1 ab	87.2 b
3	112.1 b	87.6 bc	73.0 c
4		71.6 c	62.6 cd
5			49.4 d

Plate 3.1. Alboran mature truss thinned to 4 fruit

3.2.1.2 Ophir tomato

No significant differences were observed between the fruit when thinned to 2 fruit per truss. However the trend of the 1st (proximal) fruit being heavier than the 2nd (distal) fruit was observed (Table 3.14). Thinning to 3 fruit per truss resulted in the 1st (proximal) fruit having a significantly greater fruit weight than the two fruit below it. The 2nd fruit also showed a significantly greater fruit weight than the 3rd (distal) fruit (Table 3.14).

Table 3.14. Fruit weight of Ophir tomatoes thinned to 1, 2 and 3 fruit per truss at different fruit positions down the truss at a plant density of 2.76 plants / m^2. ns, * Non significant or significant at $P \leq 0.05$ using LSD test. Letters within the columns show the significant differences.

Fruit Position	Ophir 1	Ophir 2	Ophir 3
		(g)	
1	206.6	151.0	120.9 a
2		133.0	105.3 b
3			87.1 c
Significance		ns	*

3.2.1.3 Cherita tomato

Fruit weight, in all three thinning treatments, generally decreased down the truss at each fruit position (Table 3.15). Thinning to 4 fruit per truss resulted in the 4th fruit position (distal) having a significantly lower fruit weight than the 1st fruit position (proximal) (Table 3.15). Thinning to 8 fruit per truss resulted in the 7th and 8th (distal) fruit positions having a significantly lower fruit weight than the 1st fruit position (proximal) (Table 3.15). Thinning to 12 fruit per truss resulted in the first 6 fruit being significantly heavier than the last 6 fruit, with the 11th fruit position having a significantly lower fruit weight than the first 8 fruit positions. The 12th fruit position was significantly lighter than all the other fruit before it on the truss (Table 3.15).

Table 3.15. Fruit weight of Cherita tomatoes thinned to 4, 8 and 12 fruit per truss at different fruit positions down the truss at a plant density of 2.76 plants / m^2. Figures within columns followed by different letters shows a significant difference at $P \leq 0.05$ using LSD test.

Fruit Position	Cherita 4	Cherita 8	Cherita 12
		(g)	
1	17.3 a	13.5 a	15.2 a
2	16.9 ab	13.1 ab	15.1 a
3	16.4 ab	13.1 ab	14.9 a
4	16.0 b	12.9 ab	14.7 a
5		13.0 ab	14.3 ab
6		13.2 ab	14.3 ab
7		12.7 b	13.8 b
8		12.4 b	13.7 b
9			13.5 bc
10			13.3 bc
11			12.4 cd
12			11.8 d

3.2.2 First fruit on truss

3.2.2.1 Alboran tomato

Weight of first fruit on truss generally increased as more fruit were thinned from the truss (Table 3.16). Thinning to 3 fruit resulted in significantly heavier first fruit than first fruit in the 4 and 5 thinning treatments (Table 3.16).

Table 3.16. Weight of first fruit on truss for Alboran fruit thinning treatments at a plant density of 2.76 plants / m^2. Figures within columns followed by different letters shows a significant difference at $P \leq 0.05$ using LSD test.

Fruit Thinning	Proximal fruit (first)
	(g)
Alboran 3	139.3 a
Alboran 4	108.3 b
Alboran 5	100.1 b

3.2.2.2 Ophir tomato

Weight of first fruit on truss increased significantly as more fruit were thinned from the truss (Table 3.17). Thinning to 1 fruit per truss resulted in a heavier first fruit than when thinning to 2 fruit per truss. First fruit weight in the 2 fruit thinning treatment was also significantly heavier than the first fruit when thinned to 3 fruit per truss (Table 3.17).

Table 3.17. Weight of first fruit on truss for Ophir fruit thinning treatments at a plant density of 2.76 plants / m^2. Figures within columns followed by different letters shows a significant difference at $P \leq 0.05$ using LSD test.

Fruit Thinning	Proximal fruit (first)
	(g)
Ophir 1	206.6 a
Ophir 2	151.0 b
Ophir 3	120.9 c

3.2.2.3 Cherita tomato

Thinning to 4 fruit per truss resulted in significantly larger first fruit on the truss than both the 8 and 12 thinning treatments (Table 3.18). However thinning to 12 fruit per truss produced significantly larger first fruit on the truss than the 8-thinned treatment, which does not follow the expected trend of less fruit on the truss producing larger first fruit (Table 3.18).

Table 3.18. Weight of first fruit on truss for Cherita fruit thinning treatments at a plant density of 2.76 plants / m^2. Figures within columns followed by different letters shows a significant difference at $P \leq 0.05$ using LSD test.

Fruit Thinning	Proximal fruit (first) (g)
Cherita 4	17.3 a
Cherita 8	13.5 c
Cherita 12	15.2 b

3.2.3 Slope of fruit down the truss

3.2.3.1 Alboran and Ophir tomatoes

No significant differences were observed between the slopes of the three Alboran thinning treatments (Table 3.19), which have a slope centering around –13g per each fruit position down the truss. Ophir tomatoes thinned to 3 fruit per truss showed a slope of –17g per each fruit position down the truss which is a significantly steeper slope than all three Alboran thinning treatments (Table 3.19).

Table 3.19. Slopes of Alboran and Ophir fruit thinning treatments down the truss at a plant density of 2.76 plants / m^2. Figures within columns followed by different letters shows a significant difference at $P \leq 0.05$ using LSD test.

Fruit Thinning	Slope down truss (g / fruit position)
Alboran 3	-13.7 b
Alboran 4	-12.5 b
Alboran 5	-12.6 b
Ophir 3	-17.0 a

With no significant differences in slope between the three Alboran fruit thinning treatments, the fruit weight decreases at the same rate down the truss, showing that the difference observed with the first fruit (Table 3.16) are continued down the truss (Fig. 3.6).

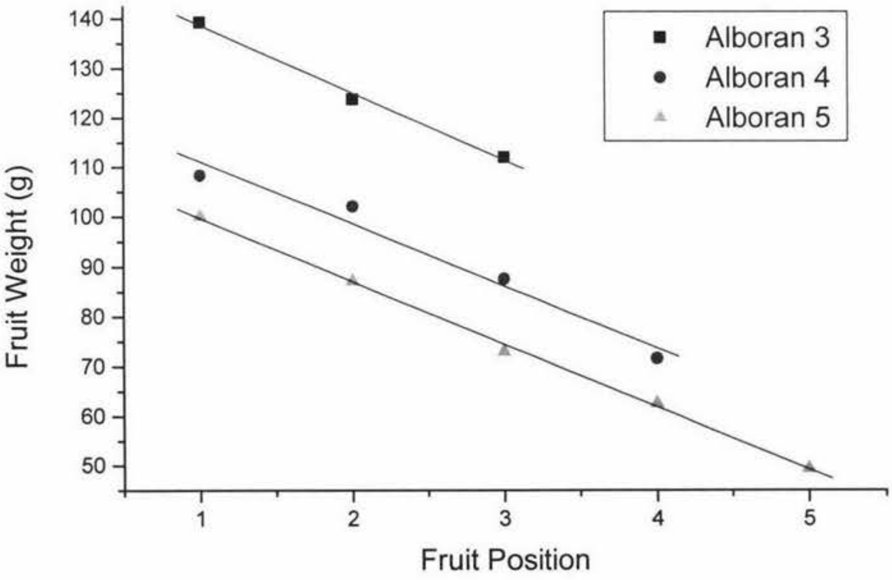

Figure 3.6. Regression lines of Alboran tomato fruit down the truss for the three fruit thinning treatments at a plant density of 2.76 plants / m^2.

The difference observed between the Ophir first fruit (Table 3.17) is shown to continue down the truss between the 2 and 3 fruit thinning treatments (Fig. 3.7).

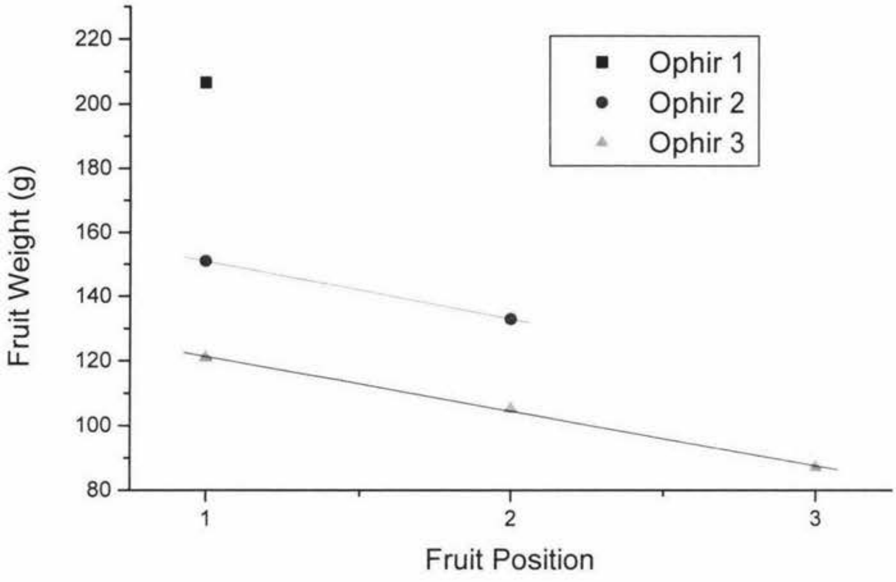

Figure 3.7. Regression lines of Ophir tomato fruit down the truss for the three fruit thinning treatments at a plant density of 2.76 plants / m^2.

3.2.3.2 Cherita tomato

Thinning to 4 fruit per truss produced a significantly steeper slope of –0.597g per fruit position compared to the 8 and 12 thinning treatments (Table 3.20). No significant differences were found between the 8 and 12 thinning treatments (Table 3.20).

Table 3.20. Slope of Cherita fruit thinning treatments down the truss at a plant density of 2.76 plants / m^2. Figures within columns followed by different letters shows a significant difference at $P \leq 0.05$ using LSD test.

Fruit Thinning	Slope down truss
	(g / fruit position)
Cherita 4	-0.597 a
Cherita 8	-0.148 b
Cherita 12	-0.296 b

3.2.4 Individual truss slopes

3.2.4.1 Alboran and Ophir tomatoes

Due to inadequate data, no reliable regression lines could be obtained to produce individual truss slopes down each truss.

3.2.4.2 Cherita tomato

All Cherita thinning treatments produced the same slopes down the truss at each truss on the plant, with only the intercept or first fruit weight differing between the trusses.

Thinning to 4 fruit per truss resulted in every truss produced on the plants having the same slope of –0.597g per fruit position (Table 3.20). Differences were observed in the intercepts of each truss showing an overall trend of decreasing fruit weight at each truss up the plant (Fig. 3.8).

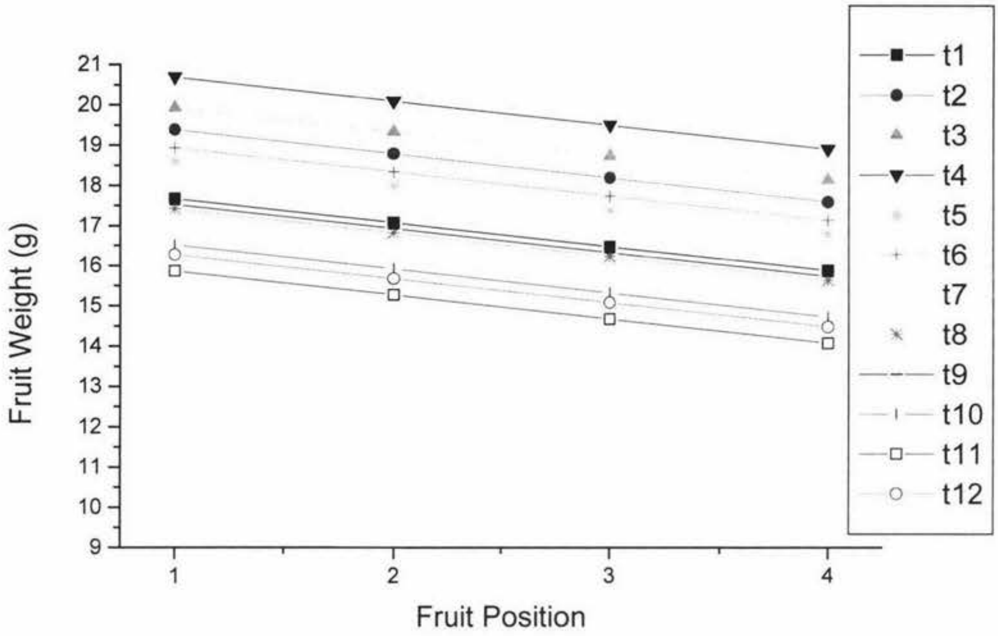

Figure 3.8. Regression lines of fruit weight down the truss for Cherita tomato when thinned to 4 fruit per truss at a plant density of 2.76 plants / m^2.

Thinning to 8 fruit per truss resulted in every truss produced on the plants having the same slope of –0.148g per fruit position (Table 3.20). Differences were observed in the intercepts of each truss showing again an overall trend of fruit weight decreasing at each truss up the plant (Fig. 3.9).

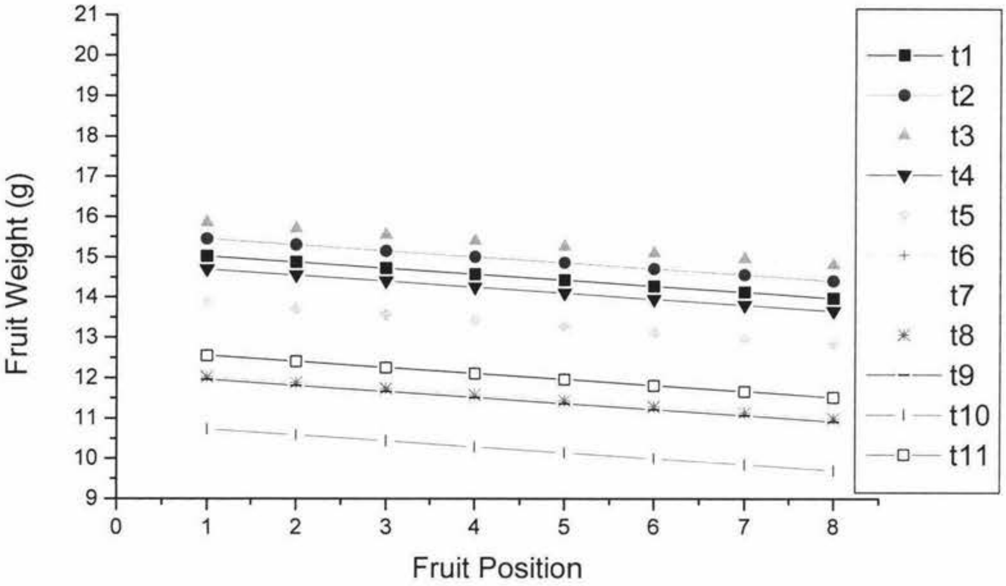

Figure 3.9. Regression lines of fruit weight down the truss for Cherita tomato when thinned to 8 fruit per truss at a plant density of 2.76 plants / m^2.

Thinning to 12 fruit per truss again resulted in every truss produced on the plants having the same slope of –0.296g per fruit position (Table 3.20). Differences were observed in the intercepts of each truss showing again an overall trend of fruit weight decreasing at each truss up the plant, but not as spread out as the previous thinning treatments (Fig. 3.10).

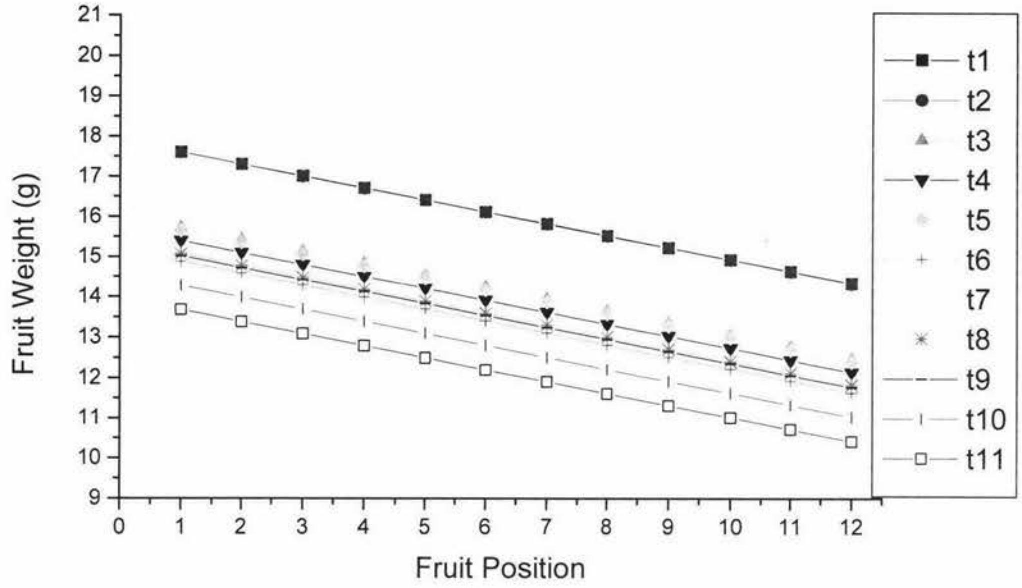

Figure 3.10. Regression lines of fruit weight down the truss for Cherita tomato when thinned to 12 fruit per truss at a plant density of 2.76 plants / m^2.

3.3 Total Soluble Solids measurement

Cherita red ripe tomatoes at harvest showed a significantly higher soluble solids content than the red ripe tomatoes of Alboran and Ophir (Table 3.21).

Table 3.21. Brix readings of red ripe fruit for three tomato cultivars. Figures within columns followed by different letters shows a significant difference at $P \leq 0.05$ using Tukey's test.

Cultivar	Soluble Solids
	(brix)
Alboran	4.8 b
Ophir	4.8 b
Cherita	7.0 a

Chapter 4

Discussion

4.1 Fruit yield

Alboran showed a significantly higher final yield than the Ophir and Cherita cultivars (Fig. 3.1). This is an indication of why Alboran is a standard grown cultivar, as it produces higher fruit yields over Ophir or Cherita.

4.1.1 Plant density

Alboran showed no increase in final fruit yield per surface area (Fig. 3.1 & Table 3.3), mean fruit weight or fruit number per surface area (Table 3.5) as plant density increased. The similarities in fruit number per surface area were caused by significant reductions in fruit number per plant as the plant density increased (Data not shown). High densities have been shown to have a detrimental effect on fruit set, because of an inadequate supply of photosynthates due to increased shading (Papadopoulos and Pararajasingham, 1997). Cockshull et al. (1992) also found that a high sink / low source ratio, caused by low light or high fruit load caused abortion of flowers with 50% of flowers being aborted when solar radiation was less than 1.5 MJ $m^{-2}day^{-1}$. Therefore the decrease in fruit number per plant as density increased can be explained by an increase in flower and/or fruit abortion due to an inadequate amount of photosynthates being produced at the high densities, with shading in the low light conditions of winter and spring when the crop was grown and harvested. Growing at a plant density of 4.59 plants per m^2 (31 cm plant spacing) and 3.67 plants per m^2 (38 cm plant spacing) therefore seemed to be too high a plant density for the light conditions that occurred. This is in agreement with Papadopoulos and Ormrod (1991) who showed that in spring (low light conditions) fruit set rate declined with decreasing plant spacing (increased plant density). The set figures were 58%, 52%, and 13% for the spacing of 60 cm, 45 cm, and 23 cm respectively.

Ophir also showed no increase in final fruit yield per surface area (Fig. 3.1 & Table 3.3) as plant density increased. However mean fruit weight was significantly larger when grown at the lowest density compared with the two higher plant densities (Table 3.7). This differed from Alboran where no difference in mean fruit weight and fruit number was observed. Ophir fruit number per surface area, although not significant (apart from July), was less in the lowest plant density (Table 3.9). The fewer fruit therefore off set the larger mean fruit weight resulting in similar final yields. However August was the exception in which the low plant density produced more fruit than the medium and high densities, although not significant (Table 3.9), and resulted in significantly greater fruit yield per surface area. Cockshull and Ho (1995) demonstrated that growing at a low density of 2 plants per m^2 in spring (low light) produced a larger mean fruit weight compared to the high density of 3 plants per m^2. July on the whole produced more harvested fruit and greater fruit weight per plant for all three densities grown for Ophir compared with the other months of harvesting. This is most likely the result of a lower fruit load on the plant as they were the first trusses. This agrees with Cockshull et al. (1992) who showed that high fruit loads caused abortion of young fruit.

Although not significant, Cherita showed an increase in final fruit yield per surface area as the plant density increased (Fig 3.1 & Table 3.3). Also it was shown that all fruit thinning treatments of Cherita showed this increase in final fruit yield per surface area as plant density increased (Fig. 3.2).

Apart from July and August harvests, the remaining months, although not always significant, showed a greater fruit weight per surface area at the high density than at the low density (Table 3.11). This was due mostly to a greater (not always significant) number of fruit being harvested at the high plant density, which offset, like Ophir, the lower mean fruit weight being observed at the high plant density (Table 3.10 & 3.12).

There seemed to be a substantial difference (not always significant) in fruit number harvested, with the high density producing more fruit than the low plant density (Table 3.12). This substantial difference in fruit number produced an increase (not significant) in final fruit yield per surface area, which was not seen in the Alboran or Ophir cultivars. This can most likely be explained by the fact that Cherita has a lower overall sink capacity compared with the other two cultivars. Therefore as there is a lower sink capacity, the inadequate amount of photosynthates that is produced at the high density for Alboran and Ophir cultivars is now of greater proportion to the lower sink capacity of Cherita giving more assimilates available as there is less competition between the fruit. This can be backed up by the fact that Cherita fruit had a significantly higher soluble solids content than Alboran and Ophir tomatoes, indicating that Cherita tomatoes have more assimilates available to them (Table 3.21).

4.1.2 Fruit Thinning

Alboran showed no difference in final fruit yield per surface area between different levels of fruit thinning (Table 3.1). Cockshull and Ho (1995) found that total fresh weight at the end of their experiment was not significantly affected by truss thinning through redistribution of assimilates between the remaining fruit. Although not significant, the mean fruit weight (Table 3.4) when the trusses were thinned to 3 fruit was larger compared with thinning to 4 and 5 fruit per truss. The lack of significant differences in mean fruit weight was probably the result of more flower and/or fruit abortion as more fruit were left on the truss. Although there showed to be a significant increase in fruit number as more fruit were left on the truss (Table 3.4), this difference was not in direct proportion to the number of fruit that should have been produced for each fruit thinning treatment, assuming the rate of fruit development was the same for each treatment (Table 3.4). This indicates that the higher fruit load obtained with leaving more fruit on the truss was too high for the low light conditions of winter and spring, which in turn caused flower and/or fruit abortion. This agrees with Heuvelink (1997) who reported that too high a fruit load (high sink/low source ratio) resulted in flower or fruit abortion in low light conditions.

Ophir, like Alboran showed no difference in final fruit yield per surface area between different levels of fruit thinning. The number of fruit per surface area at each harvest was significantly less as fruit thinning increased (Table 3.6). This lower fruit number caused an increase in mean fruit size of the remaining fruit. Heuvelink (1997) reported that the increase in individual fruit weight when fruit number decreased through thinning reflected the competition for assimilates among fruit. This also agrees with Cockshull and Ho (1995) who found that when flowers from the distal end of the truss were removed, the average fruit weight of the remaining proximal fruit was significantly larger through the redistribution of assimilates to the remaining fruit. However like Alboran, Ophir showed signs of flower and / or fruit abortion, as the fruit number (although significantly greater) with more fruit present on the truss was lower than expected (Table 3.6).

Thinning to 4 fruit per truss in Cherita resulted in significantly lower fruit yield per surface area than the other two fruit thinning treatments (Fig. 3.2). Fruit weight per month showed a clear (Although not always significant) pattern of 4 fruit per truss giving lower fruit weights per surface area than thinning to 8 and 12 fruit per truss (Fig. 3.4). Although the mean fruit weight was larger when thinned to 4 fruit (Fig. 3.3), this was counteracted by the lower number of fruit harvested (Fig. 3.5).

Although thinning to 12 fruit produced a higher number of fruit harvested in July, no other differences were observed in fruit weight per month, fruit number per month and mean fruit weight between 8 and 12 fruit per truss. This is again like Alboran and Ophir, where the increased fruit load of 12 fruit per truss is too high a fruit load compared with 8 fruit per truss, which in turn would have resulted in greater flower and/or fruit abortion with 12 fruit per truss.

4.2 Fruit position effect

Alboran produced a slope of around -13 g / fruit position in all three fruit thinning treatments (Table 3.19 & Fig. 3.6). This slope produced significant differences between the proximal (1st fruit) and the distal fruit (last fruit) in all three fruit thinning treatments (Table 3.13). Bohner and Bangerth (1988) and Bangerth and Ho (1984) found that this difference in fruit weight between proximal and distal fruit was because of the natural flowering sequence and the higher number of cells in proximal ovaries at anthesis, with cell number on average 18% less in distal fruit (Bangerth and Ho, 1984). Simultaneously, the higher IAA content in proximal fruit may explain their greater sink activity (Bangerth and Ho, 1984 and Bangerth, 1989).

Thinning to 3 fruit per truss resulted in significantly heavier proximal fruit compared to thinning to 4 or 5 fruit per truss (Table 3.16). This difference in proximal fruit weight was then observed down the truss as shown in Figure 3.6. This indicates that by reducing the number of fruit on a truss or sink size, the remaining fruit (with more photosynthetic now available to them) increased in proportion to each other within the truss, thus keeping the same slope.

Ophir tomato was slightly different in that it was thinned to only 1, 2 and 3 fruit per truss. Therefore a slope could only be calculated on the thinning treatment that contained 3 fruit per truss (Table 3.19). This slope of -17g / fruit position, was shown to be significantly steeper than the Alboran cultivar. It was also observed that thinning to 2 fruit produced what looks like a similar slope down the truss (Fig. 3.7). This slope produced significantly higher proximal fruit compared to the distal fruit when thinned to 3 fruit per truss, but this difference was not significant when thinned to 2 fruit per truss. Ophir as well as Alboran showed that proximal fruit were significantly heavier as less fruit remained on the truss (Table 3.17).

Proximal fruit with all Cherita fruit thinning treatments was shown to be significantly heavier than the distal fruit similar to Alboran and Ophir (Table 3.15). However, thinning to 4 fruit per truss resulted in a significantly steeper slope down the truss than the other two fruit thinning treatments (Table 3.20). However this significant difference was only in the range of 0.3 – 0.45 g / fruit position. This is because Cherita fruit unlike Alboran and Ophir cultivars are very similar in weight down the truss shown by their flat slope.

Each truss on the plant was able to be measured for all 3 Cherita fruit thinning treatments. (Figs. 3.8-3.10). It was shown that all trusses up the plant followed the same slope in each of the three fruit thinning treatments. There was also a trend of the earlier trusses having a heavier proximal fruit, and thus heavier fruit down the truss, compared with the later trusses. This was probably the case of the later trusses developing under a high plant fruit load with increased competition for available assimilate, while the earlier trusses had less competition for available assimilate.

Fruit thinning to 8 fruit per truss in Cherita resulted in significantly smaller fruit than thinning to 12 fruit per truss as was shown with the proximal fruit (Table 3.18). No reason can be given for this except that in both blocks of plants, the 8 fruit per truss treatment plants were by chance randomly positioned on the eastern part of the glasshouse where solar radiation is lowest. Therefore the reduced solar radiation would cause less assimilates to be produced causing lighter proximal fruit.

Therefore it seems that fruit on the truss decrease proportionately in size down the truss irrespective of how much assimilate is available. Assimilate supply only seems to affect the weight of the first fruit, with more assimilate supply (observed with less fruit on the truss) giving a larger proximal fruit in which the rest of the fruit follow proportionately from that. This agrees with Bohner and Bangerth (1988) and Bangerth and Ho (1984) as the natural flowering sequence (pollination) of proximal fruit is always going to be (at a set time period) earlier than the distal fruit. Also the difference in the number of cells in proximal fruit and distal fruit is always going to be roughly the same within each cultivar. Therefore as the difference in the time of natural flowering sequence and number of cells in the ovaries between the proximal and distal fruit is the same in each cultivar, the assimilate supply only effects the weights of all the fruit proportionately down the truss, with the slope not being affected.

4.3 Potential of manipulating plant density and fruit number per truss on individual fruit size

This research poses the question of "Can we use fruit thinning and plant density to produce more fruit in the desired marketable fruit size range?" As fruit thinning and plant density can vary the amount of assimilate available per fruit, it would be feasible on these results to modify fruit size by fruit thinning and plant density. For example, a fruit size range between 90g – 110g may be preferred for Alboran cultivar. Under winter and spring conditions observed in this experiment, where low levels of assimilate was available, one would grow the plants at the low density of 2.76 plants per m^2 and thin to 4 fruit per truss which produced more fruit closer to the desired size range (Table 3.13). However, as the fruit weight down the truss follows the same slope irrespective of thinning treatment (Table 3.19 & Fig. 3.6), it would likely be more beneficial to thin to 3 fruit per truss and grow at a higher plant density. This would result in less difference between the proximal (first) and distal fruit , thus resulting in a greater proportion of fruit within the desired size range when grown at the optimum plant density. In summer and autumn when photosynthetic rates are higher and more assimilate is available, one would want to increase the number of fruit (sink) per unit area. Increasing the plant density and thinning again to 3 fruit per truss would most likely be the best option for increasing the sink strength and producing more fruit in the desired size range. Cockshull and Ho (1995) demonstrated that growing tomato crops at a low density of 2 plants per m^2 produced a high proportion of fruit in the preferred size grade range in spring. However, in summer a high density of 3 plants per m^2 was required. This process of determining what plant density and fruit thinning treatment should be used to produce the greatest number of fruit in the desired size range can be summarised by a simple schematic diagram (Fig. 4.1)

Increased photosynthesis can also be achieved by elevated CO_2 levels and is commonly used by growers for this reason. By increasing CO_2 concentration inside a greenhouse to 3 times from the normal level of 340 to 1000 $\mu l\ l^{-1}$, complete fruit set in early trusses was achieved under low winter light conditions (Cooper and Hurd, 1968). Picken (1984) explained that this improved fruit set by elevate CO_2 levels was the cause of increased assimilate supply with both fruit number and fruit size increasing. Therefore if a grower is using CO_2 enrichment, the CO_2 concentration needs to be taken into account along with light conditions to make a decision on the appropriate plant density and fruit thinning strategy to use.

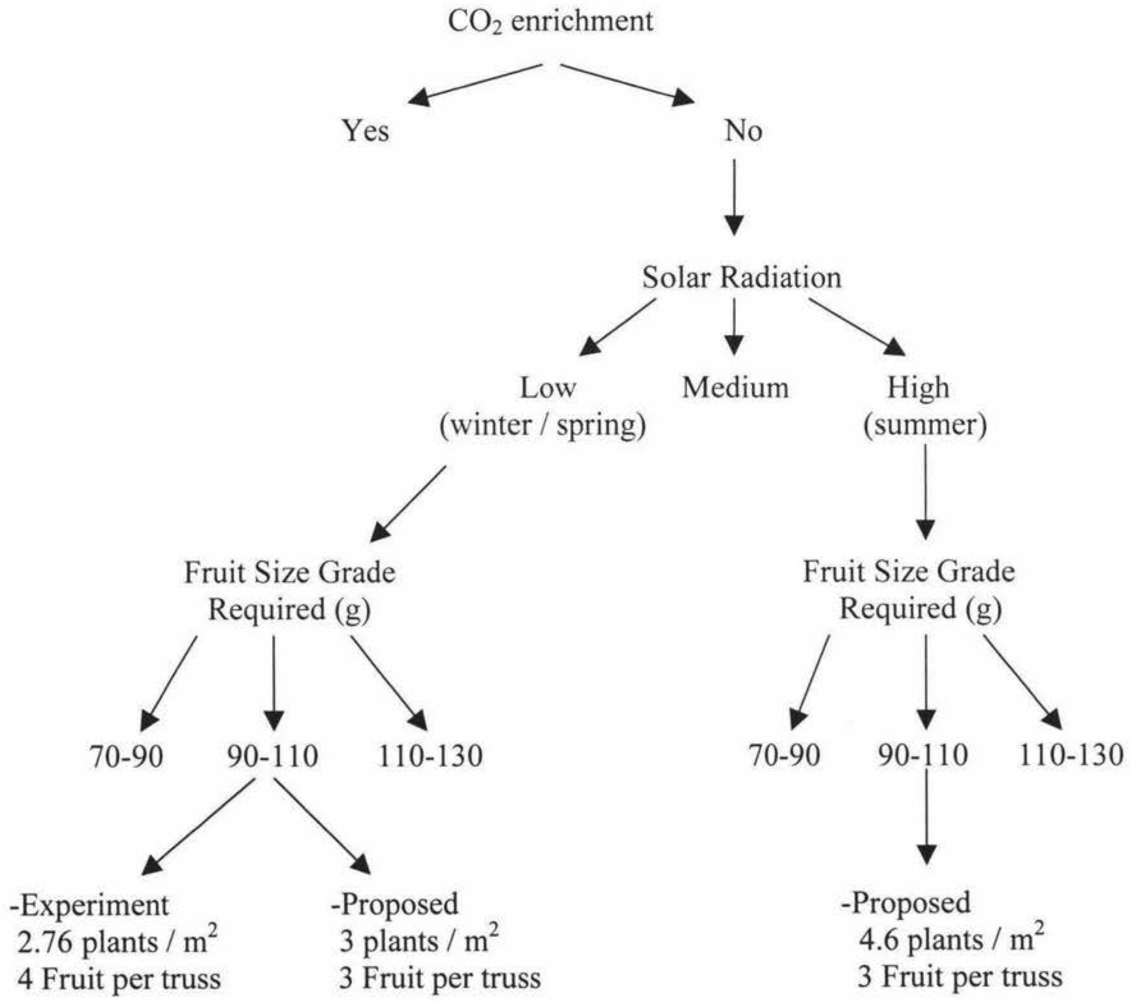

Figure 4.1. Simple schematic diagram of manipulating fruit size by plant density and fruit thinning

4.4 Further Research

This study should be regarded as an initial critical look at how a combination of plant density and fruit thinning can be used to manipulate the size of a tomato fruit on a truss. The present study, through time constraints, showed limitations. The crop was grown only in winter and spring months when solar radiation was lowest. The individual fruit weights down the truss were not observed at different plant densities. Therefore a more detailed study is required in which the crop is grown all year round with both plant density and fruit thinning effects examined on fruit position within the truss.

As shown with the three tomato cultivars used in this experiment, their slopes of fruit weight down the truss were all significantly different from each other. Therefore with this in mind there needs to be more research on other tomato varieties in which one can show their slopes of fruit weight down the truss. This will provide information on each variety's slope allowing another dimension in selecting the tomato variety a grower uses.

Cherita tomato differed in that it produced an almost flat slope of fruit weight down the truss. What is the reason for this? Like Alboran and Ophir there is a difference in pollination time for each flower. Therefore is the number of cells in Cherita fruit similar, or is there some other physiological reason. These questions need to be answered so a greater understanding can be achieved, which will help produce standard cultivars that can be manipulated into flattening the slope down the truss in order to produce more fruit in the desired size range. This would also be of great consideration for the production of truss tomatoes, which are defined as tomatoes marketed and sold as a whole truss of tomatoes.

The use of supplementary lighting may also be of use in the winter and spring months if required. This would decrease variation in fruit size caused by fluctuating radiation. For example, growing at a density of 2.76 plants per m^2 and thinning to 4 fruit per truss in the winter and spring months might require a daily integral of 1.6 MJm^{-2} day^{-1} to be incident on the crop to produce most of the fruit on the truss in the desired range. Therefore on days when the solar radiation was not reached, supplementary lighting could be used to get closer to this value. This would most likely reduce the variation between each truss on the plant.

Bohner and Bangerth (1988) and Bangerth (1989) showed that when all flowers in the same truss were simultaneously pollinated, both the proximal and distal fruit showed no considerable difference in fruit size. Therefore if it were possible to induce pollination of all flowers within a truss simultaneously, there would most likely be a reduction or flattening of the slope of fruit weight down the truss resulting in a greater number of fruit in the desired range available.

4.5 Conclusion

- Alboran cultivar (standard) showed a significantly greater final fruit yield compared with Ophir and Cherita.

- Too high a sink (fruit) load through high plant densities and minimal fruit thinning resulted in abortion of flowers and / or fruit during the low solar radiation levels observed under the winter and spring months.

- The decrease in fruit weight down the truss was a similar slope within Alboran and Ophir cultivars regardless of the level of fruit thinning achieved. However thinning Cherita to 4 fruit per truss resulted in a significantly steeper fruit weight slope down the truss than 8 and 12 fruit per truss.

- Increased fruit thinning, within each cultivar, made more photosynthates available and resulted in a larger proximal (first) fruit, which the remaining fruit on the truss proportionately followed.

- The decrease in fruit weight at each fruit thinning treatment within individual trusses for Cherita were shown to be a similar slope. A larger proximal fruit and thus remaining fruit on the truss was observed for the first few trusses, as they received less competition for photosynthates.

- Using plant density and fruit thinning techniques to increase the proportion of individual fruit in the desired size range has a potential. However, further work is needed to fully test and understand the ideas put forward in this study.

Chapter 5

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Appendices

Appendix 1 Transplant liquid feed

100ppm N, 30ppm P, 100ppm K transplant liquid feed made up from:

Ammonium nitrate	13.7g per 100 litres
Mono-ammonium phosphate (MAP)	13.3g per 100 litres
Potassium nitrate	25.6g per 100 litres

Appendix 2 Experimental layout

Main plot (2.76 plants / m2) 27plants	Main plot (3.67 plants / m2) 36 plants	Main plot (4.59 plants / m2) 45 plants
Sub plot (Cultivar) 9 plants	Sub plot (Cultivar) 12 plants	Sub plot (Cultivar) 15 plants
Nested plots (Fruit thinning) 3 plants	Nested plots (Fruit thinning) 4 plants	Nested plots (Fruit thinning) 5 plants

Appendix 3 NFT nutrient solution

Stock Solution A	kg per 1000L	kg per 200L
Calcium Nitrate	99	19.8
Potassium Nitrate	65.8	13.16

Stock Solution B	kg per 1000L	kg per 200L
Magnesium Sulphate	49.7	9.94
Potassium dihydrogen phosphate	27.2	5.44
Iron Chelate	3	0.6
Manganous sulphate	0.5	0.1
Boric Acid	0.18	0.036
Copper sulphate	0.03	0.006
Ammonium molybdate	0.008	0.0016
Zinc sulphate	0.035	0.007

Large 500 litre tank

CF should be around 20

500mls of solution will raise the CF one point

e.g if CF is 16 add 2litres of A and B solution.

Small 100 litre tank

CF should be around 20

100mls of solution will raise the CF one point

e.g if CF is 16 then add 400mls of A and B solution

To adjust the pH

pH should be in the 6.0 to 6.5 range at all times

Add phosphoric acid at 10% solution- this will lover the pH of the NFT solution ins pH is higher than 6.5 potassium hydroxide at 0.5% solution is used to raise the pH if it drops below 6.0.